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Detection, Diagnosis, and Prognosis

MFPG
28th Meeting

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MFPG
Detection, Diagnosis, and Prognosis

Proceedings of the 28th Meeting of the
Mechanical Failures Prevention Group,
held at San Antonio, Texas
November 28-30, 1978

Edited by

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National Bureau of Standards
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FOREWORD

The 28th meeting of the Mechanical Failures Prevention Group was held November 28-30 at the Oak Hills Motor Inn in San Antonio, Texas. The program was organized by the Detection, Diagnosis, and Prognosis Committee under the chairmanship of Henry R. Hegner of the ManTech of New Jersey Corporation. The committee, the session chairmen, and especially the speakers are to be commended for the excellent program.

Most of the papers in these proceedings are presented as submitted by the author on camera ready copy. Some moderate editorial changes were required in a few instances.

The MFPG is grateful for the cooperation and assistance provided by the Southwest Research Institute in hosting the meeting. Special thanks go to Richard B. Curtin, Director, Data Systems Department of SwRI for coordinating the meeting, and to David Black of the SwRI Special Programs Office and Mrs. Thelma Greene for making the hotel and meeting arrangements.

Special appreciation is extended to Jerry Philips of the Naval Ship Research and Development Center for his handling of the meeting publicity and to Robert M. Whittier, Endevco Corporation, for assistance in the mailing and distribution of the meeting announcements.

Appreciation also is extended to the following members of the NBS Fracture and Deformation Division: T. Robert Shives and William A. Willard for their editing, organization, and preparation of the proceedings, and Leonard C. Smith and Joel C. Sauter for photographic work. Gratitude is expressed to the following members of the NBS Center for Materials Science. Larry W. Ketron for drafting work and Marian L. Slusser for typing.

HARRY C. BURNETT
Executive Secretary, MFPG

Center for Materials Science
National Bureau of Standards

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*Indicates speaker when a paper had more than one author.

ABSTRACT

These proceedings consist of a group of twenty five submitted papers from the 28th meeting of the Mechanical Failures Prevention Group which was held in San Antonio, Texas, November 28-30, 1978. The central theme of the proceedings deals with detection, diagnosis, and prognosis as related to mechanical failure prevention. Special emphasis is on aerospace applications, land based applications, marine applications and industrial applications.

Key Words: Bearing analysis; condition monitoring; engine diagnosis; failure detection; failure diagnosis; failure prevention; maintenance; performance monitoring.

UNITS AND SYMBOLS

Customary United States units and symbols appear in some of the papers in these proceedings. The participants in the 28th meeting of the Mechanical Failures Prevention Group have used the established units and symbols commonly employed in their professional fields. However, as an aid to the reader in increasing familiarity with and usage of the metric system of units (SI), the following references are given:

NBS Special Publication, SP330, 1977 Edition, "The International System of Units."

ISO International Standard 1000 (1973 Edition), "SI Units and Recommendations for Use of Their Multiples."

E380-76 ASTM/IEEE Standard Metric Practice (Institute of Electrical and Electronics Engineers, Inc., Standard 268-1976).

Disclaimer:

Certain trade names and company products are identified in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose. Views expressed by the various authors are their own and do not necessarily represent those of the National Bureau of Standards.

SESSION I

AEROSPACE APPLICATIONS

Chairman: Robert R. Holden

Hughes Aircraft Company

Co-Chairman: John George

Parks College of St. Louis University

SPACE SHUTTLE DIAGNOSTICS

Dennis J. Webb
NASA Johnson Space Center
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Houston, Texas 77058

Abstract: The Space Shuttle Orbiter employs an elaborate onboard failure diagnosis system. Failure detection, accomplished in a variety of ways by the vehicle's data processing system, provides aural and visual cues to the flight crew on vehicle anomalies. In some cases, redundancy management is automatically performed to compensate for the failure. The flight crew then refers to a comprehensive body of malfunction procedures, developed by mission control center personnel, to analyze the detailed symptoms, identify the scope of the failure, and reconfigure the vehicle for safe continuation of the mission. Operational verification of the diagnosis system and training in its use by the flight crew and mission control center personnel is accomplished by classroom instruction and simulation experience. Examples and philosophy of the diagnosis system design and the responsibilities of the flight crew and mission control are discussed.

Key words: Manned spaceflight failures; automatic monitoring; failure annunciation; redundancy management; malfunction procedures; training for diagnosis.

Introduction

The Space Transportation System, with the reuseable Orbiter vehicle, represents a significant challenge to existing procedures and philosophies of failure detection and diagnosis in manned spaceflight. The Orbiter is one of the most complex space vehicles ever built, incorporating many systems new to manned spaceflight; e.g., hydraulic aerosurface actuation powered by hydrazine energized turbine, a flexible data processing system of five computers capable of redundant program execution, and large reuseable rocket engines. The high volume of flights with up to three vehicles in orbit simultaneously, indicates a more limited ground support effort per vehicle and a more autonomous flight crew and spacecraft. The Orbiter must be flexible enough to support different payloads or payload combinations with only a seven-day ground turnaround period for vehicle reconfiguration. Clearly the business of operating the Orbiter is different from that of previous space programs where unique, single use vehicles were managed with a large ground support effort.

The consequences of failures in manned spaceflight range from minor irritation to very serious circumstance. Often the required action is merely the operation of a switch by the flight crew to engage a redundant system, but there are failures which require major reconfiguration of the vehicle or significant change in the management plan.

In order to effectively cope with the serious implications of failure in spaceflight, NASA has taken a number of significant steps. First, although a description is beyond the scope of this paper, the Orbiter has been designed and is being built and qualified by the exhaustive processes which have become standard in the high technology aerospace industry. A significant design feature is the implementation of an extensive and flexible system of redundancy. Second, the Orbiter has been endowed with a powerful onboard data processing system which is tasked with a significant share of the monitoring and control activity. Finally, the flight crew and ground support team prepare for the mission through participation in the Orbiter design process, development of operational and malfunction procedures and guidelines, classroom training, and a comprehensive sequence of flight simulations.

Failure Detection System

The central element in the failure detection system is the data processing system (DPS) which is composed of five unique computers interfaced with a variety of input/output devices so that the computers can monitor vehicle status and send commands to the hardware subsystems which include a cathode ray tube (CRT) display and keyboard system for crew interaction. For the critical phases of ascent, on-orbit maneuvers, and entry, the computers are run redundantly, synchronously executing the same programs to protect against DPS failures. The flight software utilization is divided between flight critical functions (guidance, navigation, and flight control) and mission critical functions (electrical power, environmental control, communications, mechanical systems and payload support). Included across all of these programs is a failure detection and identification system.

Fault Detection and Annunciation

To use the DPS resources and design effort most efficiently, automatic monitoring is accomplished where possible by processors operating repetitively on tabularly formatted data. One such processor is fault detection and annunciation (FDA), a part of the mission critical systems management program. FDA processes approximately 450 measurements including discretes, analogs (voltages, currents, pressures, temperatures, flow rates, etc.), and other more unique indicators.

FDA detects failures by comparing the current value of each measurement to a specified set of high and low limits which bound an acceptable range of system behavior. If the referenced value is outside of this range for more than a specified number of samples, the out-of-limits condition is annunciated. Orbiter standard annunciation (Table 1) is composed of a scale of criticality which maps to a priority scheme of crew response. In case of a rapid sequence of annunciation, the crew must respond to the most critical failures first.

ALARM CLASS/TITLE	IMPLICATION	AURAL CUE	VISUAL CUES
1: EMERGENCY	RAPID LOSS OF CABIN PRESS DETECTION OF SMOKE	KLAXON SIREN	RAPID ΔP LIGHT SMOKE LIGHTS MASTER ALARM LIGHTS
2: CAUTION & WARNING	IMMEDIATE CREW SAFETY EVENTUAL LOSS OF VEHICLE	DUAL TONE	INDIVIDUAL C&W LIGHT BACKUP C&W LIGHT RED MASTER ALARM LIGHTS FAULT MESSAGE:
3: ALERT	LOSS OF CAPABILITY	SINGLE TONE (FIXED DURATION)	BLUE ALERT LIGHT FAULT MESSAGE
4: (SPARE)	———	NONE	FAULT MESSAGE
5: OPERATOR ERROR	ILLEGAL OPERATOR COMMAND TO DATA PROCESSING SYSTEM	NONE	FAULT MESSAGE ONLY ON CRT WHERE ERROR OCCURED "ILLEGAL ENTRY"

Table 1 Orbiter Annunciation

Two classes of computer annunciation are of particular interest. Class 2 is a backup to the traditional caution and warning system which detects and annunciates failures which relate directly to crew safety. Class 3 or "Alert" annunciation signifies the loss or impending loss of a capability which by itself does not relate immediately to crew safety. Each class provides unique aural and visual cues which include a fault message which indicates the time of occurrence, the general area of failure, and the number of the appropriate display format that can be viewed by the crew on the CRT's. The fault message appears flashing at the bottom of each of the four CRT units and remains until acknowledged by the crew via the keyboard.

In many cases, systems and parameter behavior is a function of changing vehicle or systems configuration as well as failure. To cope with this problem, FDA allows a measurement to have multiple limit sets, each equipped with a logical statement which defines the corresponding configuration. The logical statements are composed of a logical combination of one to four configuration measurements, usually discretes. This process of automatic limit set selection is called preconditioning.

A useful example of the FDA process is the design for monitoring the pressure across one of the water coolant loop pumps. As a critical component in the vehicle cooling system, the water pump must be monitored to detect line blockage or leaks, pump degradation or failure, so that the system may be reconfigured to compensate for or correct the problem. Pump 2 (Figure 1) is controlled by a three-position switch which allows ON, OFF, and GPC (general purpose computer) modes of operation. ON and OFF are self-evident and GPC mode enables the DPS to periodically turn on the pump. One water loop is circulating all the time, leaving the redundant loop stagnated. To prevent the stagnated loop from freezing, the computer automatically commands the pump on for four minutes every 6 hours. The computer subtracts the pump inlet pressure from the outlet pressure to give a delta pressure value that indicates pump and loop health as well as on/off status of the pump. Further, the position of the switch is monitored via discrete indicators wired from the ON and GPC positions.

The FDA process is illustrated in Figure 2. First, the configuration is determined. The pump should be running if either the switch is in the ON position, or if the switch is in the GPC position, and the computer has commanded the pump ON. This logical statement, when true, will select the "pump running" limit set. The pump will not be running if

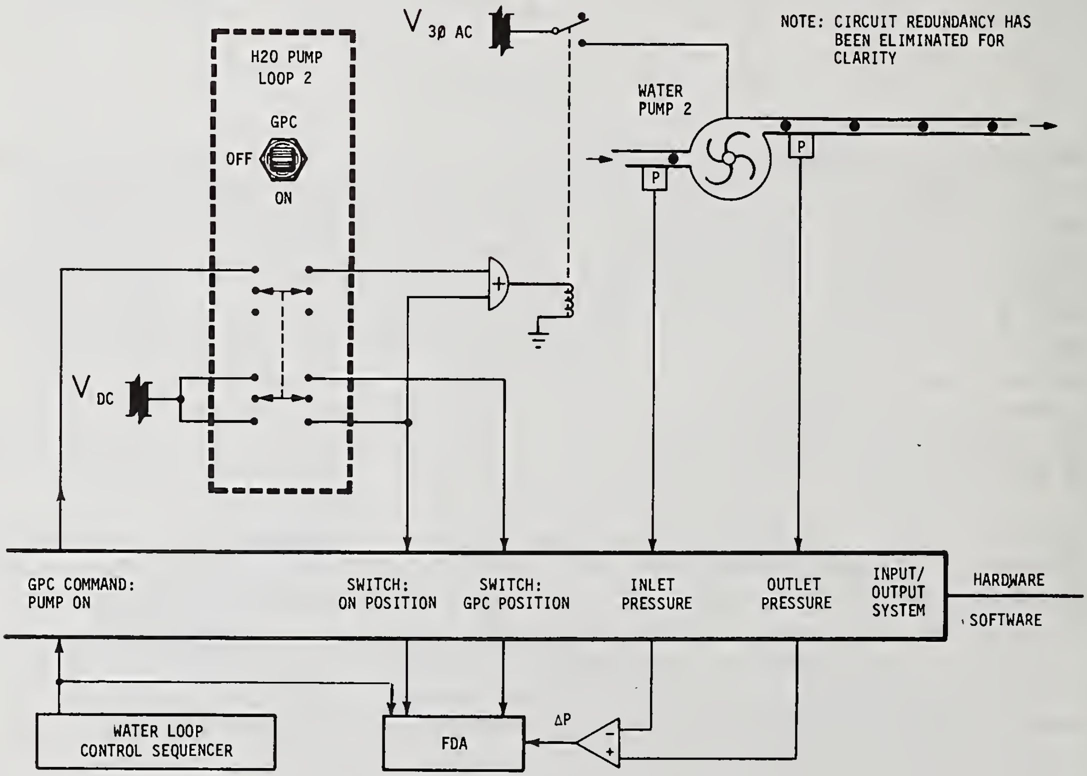

Figure 1 Water Pump 2 Control and Monitoring.

the switch is in the OFF position (not ON and not GPC) or if the switch is in the GPC position but the computer has not commanded the pump on. This logical statement, when true, will select the pump not-running limit set. Should both statements be true or false due to failure of the switch, power source, or data acquisition device, the "pump running" limit set will be selected. FDA then compares the current sample of the delta pressure across the pump to the selected limit set, and if the value is greater than the high limit or less than the low limit, FDA will initiate annunciation. As this is a class 3 alert parameter, annunciation takes the form of the 4-second 500 Hz alert tone, illumination of the blue alert light at the front of the cockpit, which persists until acknowledged by the crew via the keyboard, and the fault message "S88 THERMAL H_2O" flashing on the crew CRT which refers the crew to CRT page 88 where they may view the delta pressure value and associated measurements and proceed with the diagnosis.

REDUNDANCY MANAGEMENT

The Orbiter uses an extensive system of redundancy across all vehicle systems. The flight critical systems which control the vehicle are required to be tolerant to one failure with no loss of capability and a second failure leaving the vehicle in a safe configuration; this attribute is called fail-operational, fail-safe. Due to the complexity of

- PUMP RUNNING: (SWITCH=ON) OR [(SWITCH=GPC) AND (GPC COMMAND=ON)]

  ACCEPTABLE RANGE: 35 TO 50 PSID

- PUMP NOT RUNNING: [(SWITCH≠ON) AND (SWITCH≠GPC)] OR [(SWITCH=GPC) AND (GPC COMMAND=OFF)]

  ACCEPTABLE RANGE: 0 TO 5 PSID

IF THE SELECTED LIMIT SET IS VIOLATED:

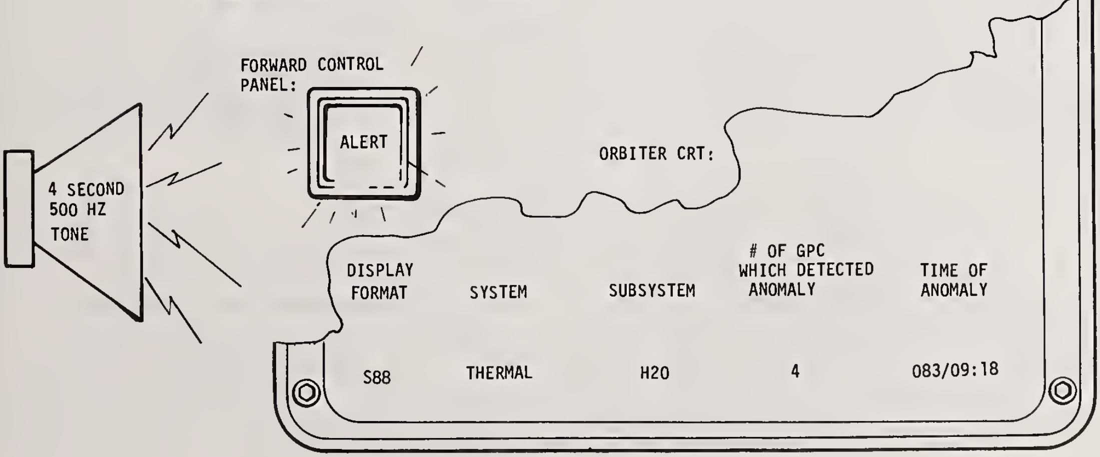

Figure 2 Water Pump 2 Fault Detection and Annunciation

the redundancy scheme in these systems, the DPS often performs automatic redundancy management (RM) to reconfigure around a failure. This processing is particularly beneficial because the crew is freed to make the decisions which are beyond the capability of the simple logic and the computer can respond faster than the crew could. In some cases, failures of redundant data or control items are annunciated either as information to the crew or as a request for a decision.

While RM is performed on a variety of devices (inertial measurement units, engine control systems, switches), the RM program which processes the rotation hand controllers (RHC) is a useful illustration. The RHC, loosely defined, is the "stick" which enables the crew to manually control the vehicle attitude as is occasionally required during on-orbit maneuvers and the glide to the landing field as a conventional aircraft. As a failure of the RHC capability could lead to loss of the crew and vehicle, RM is performed on three redundant stick position channels for each of the three degrees of freedom of pitch, roll, and yaw.

Figure 3 is a block diagram illustrating the hardware and associated RM design for each of the three RHC's. Each degree of freedom (pitch illustrated) has three independent redundantly powered transducers which

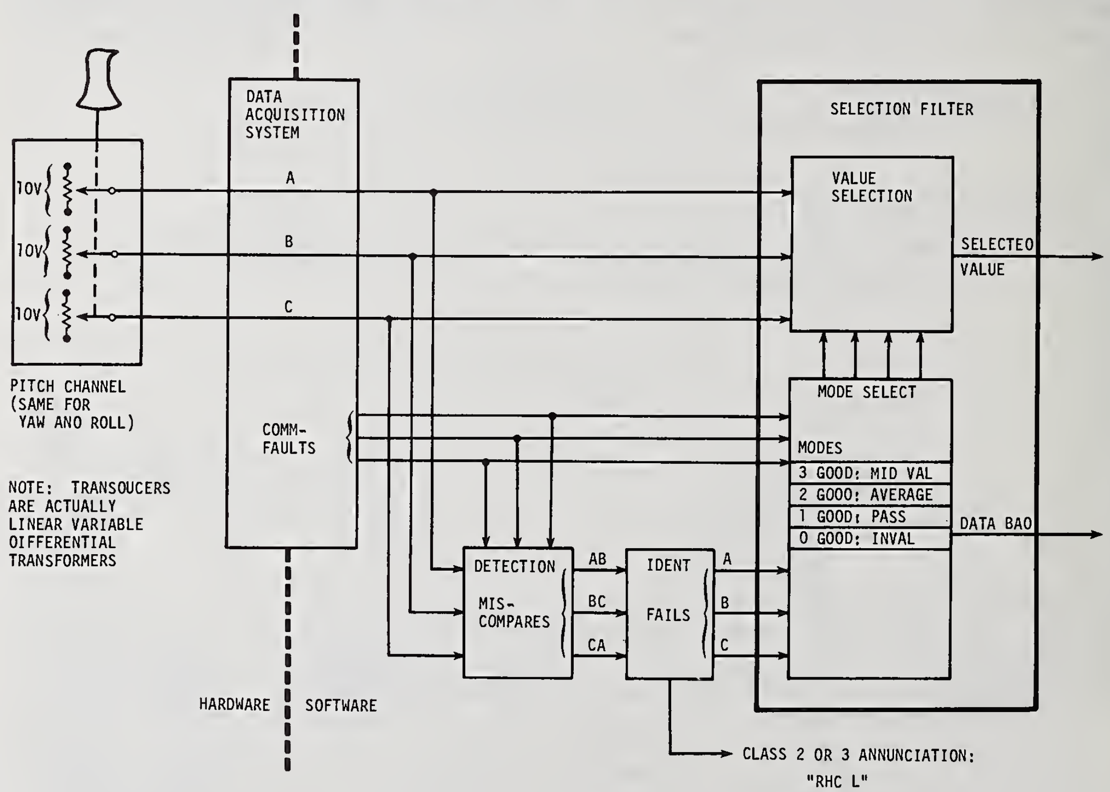

Figure 3 Rotation Hand Controller Redundancy Management (RHC RM)

put out a -5-volt to +5-volt signal which is a function of position of the RHC. These measurements are made available to the software by the data acquisition system; the signals are routed through redundant data acquisition units and data buses to the computers which are also operating redundantly for failure tolerance. Should the failure of acquisition hardware or timing cause loss of current data to the computers, a "commfault" bit associated with each affected parameter is set so that subsequent processing may be aware that the data should not be used. Failures in the data acquisition system are annunciated by other programs as class 3 alerts.

RM first processes the values and their commfaults to determine if any of the transducers have failed. This fault detection is accomplished by comparing the position values (A, B, and C) and providing signals which indicate which of the three comparisons (AB, BC, CA) indicate that two signals disagree by more than a specified amount. A miscompare is not declared if one of the two parameters is commfaulted because this does not positively represent a transducer failure. The commfault is factored into the selection filter processing discussed later. The miscompares are evaluated to determine which of the transducers is failed; for example, if AB and BC miscompares are flagged, transducer B is identified as failed. This information is passed on for annunciation as a class 3 alert with fault message "RHC X" where "X" is "A" for AFT, "L" for left (commander), and "R" for right (pilot) indicating which RHC has a single failure. On the second failure, class 2 caution and warning annunciation (with the same fault message as the class 3) is issued which would warn the crew that RHC is unuseable. The fail/not fail states of the three transducers are passed, with the commfaults and values, to the selection filter which ultimately determines the pitch command value to be used by subsequent processing which rotates the vehicle to the desired attitude. The fail/not fail states and commfaults are processed to determine the current level of redundancy. For a signal to be considered, it must not be failed and not be commfaulted. If all signals are good, then the middle value of the three is sent out as the position of the RHC. If one of the signals is bad, the average of the other two is sent out. If only one value is good, it is sent out. If all are bad, no value is sent out and a data bad flag is set as an indication to the subsequent processing which subsequently ignores that RHC.

This system of RM is representative of the generic capability. In more complex systems, more failure indicators are available in the form of built in test equipment (BITE) which is a part of many of the more complex devices. BITE indicators are usually formed from a group of bilevel indicators, each indicating the result of a particular self-test operation within the device. A simpler form of RM processes redundant switch contacts, where switch position is determined by two-out-of-three voting, "or" operations or "and" operations depending on the circumstance and level of redundancy.

Other Failure Detection Methods

In many cases, failure detection cannot be accomplished by a standardized process such as FDA or RM, due to the complexity of subtlety of the monitored hardware or transducers. Here, unique software accomplishes the necessary monitoring. Where the subsystem hardware and software are closely bound in a closed-loop control system, the detection is often imbedded in this unique software as an integral part of the control process, in many cases, automatically safing the system until the crew can take corrective action. Some failures generate symptoms that are readily apparent to the flight crew and therefore require no software monitoring. Such symptoms include "cabin uncomfortably hot" or "loss of communications with the ground."

Failure Diagnosis

Once a failure has been detected and recognized, the flight crew begins the failure diagnosis. Having determined the general area of the anomaly from the fault message, the crew refers to a malfunction procedure associated with the symptom. The malfunction procedures form one volume of the onboard library of documentation which also includes normal operating procedures, checklists, and reference data that the crew uses as

2011/ /088 APU/ENVIRON THERM 2 083/16:05:26
000/01:26:42

FREON LOOP	1	2
ACCUM QTY	78	81
FREON FLOW	1500	0↓
PL HX FLOW	500	0↓
AFT CP FLOW	550	0↓
RAD IN T	100	95
CNTLR OUT T	38	38
EVAP OUT T	37	78
OFI FLOW	460	

H2O LOOP	1	2
PUMP OUT P	70	15↓
OUT T	60	76↓
ΔP	55	0↓
ICH FLOW	50	55
OUT T	59	62
CAB HX IN T	56	76↑
ACCUM QTY	87	88

EVAP TEMP		DUCT	NOZ
HI LOAD	INBD	90	260
	OUTBD	90	89
TOPPING	FWD	260	
	AFT	260	
	L	155	50
	R	155	50
EVAP FDLN T		A	B
	FWD	70	70
	MID 1	70	70
	MID 2	70	70
	AFT	70	70

APU	1	2	3
FUEL T			
TK SURF	+60	+61	+60
TK HTR	+61	+62	+59
ISOL VLV	+60	+63	+58
TEST LN	+59	+59	+58
FEED LN	+61	+60	+63
PUMP IN	+62	+59	+64
DRN LN	+61	+60	+61
OUT	+100	+102	+101
BYP LN	+100	+101	+102

S88 THERMAL H2O 4 083/09:18

Figure 4 - APU/ENVIRON THERM Typical Display

"paper memory" in their operation of the vehicle. A malfunction procedure is a flow diagram which guides the crew through a logical process of anlaysis and decision to identify the cause of the anomaly and specify appropriate system reconfiguration to prevent further system damage and to minimize the effect of the failure on the mission.

A failure of the previously discussed water pump is a convenient example of this diagnosis process. The fault message "S88 THERMAL H_2O" signals an anomaly in the thermal control system water coolant loop. The crew calls up display format 88 (Figure 4) on one of the computer-driven CRT's by request through the keyboard. This display, titled APU/ENVIRON THERM displays each current measurement value to the right of a descriptive title. The H_2O loop section is at the upper right of the display. In this case, FDA has determined that the H_2O loop 2 pump P has dropped below the low limit and has flagged the anomaly with a "down-arrow" character to the right of the displayed value. The crew then locates the associated malfunction procedure (Figure 5) and proceeds with the diagnosis.

The malfunction procedure starts with a statement of the symptom, indicated at the lower left of Figure 5. The crew refers to display 88 (Figure 4) as the procedure guides them through the analysis which, for this example, is shown with darkened flow lines. Note that for efficiency, analysis which is common to more than one procedure appears only once, in this case, on Figure 6. Throughout the analysis, other measurements, pump outlet pressure and accumulator quantity, are examined to validate the out-of-limits condition and determine its precise cause. Figure 6, block 10, has the crew perform a test by manual operation of a switch with the system response making the next decision. In this case, the diagnosis led to Figure 6, block 13, which identifies the failure as a short in pump winding or loss of one phase of the three-phase AC power supply and indicates that the effect is degraded thermal control. Other failures that could have been diagnosed include failure or shift of one of the two pressure transducers, leakage at the interchanger or a blockage of the lines. Since the failure is a pump degradation, the pump is shut down (block 16) and the water loops are reconfigured to minimize the effect of the failure.

Several features of the malfunction procedure are apparent. First, the language is very terse for maximum use of page space so that the crew need not flip back and forth as they diagnose the symptom. Identification of switches or display nomenclature is in capitals to separate action from object of action. Also, the conclusion blocks, which complete the diagnosis, are shown in bold outline. Clarifying remarks (see explanation of preconditioning, note 6, Figure 5) appear at the right to explain system behavior or subtleties which may not be readily obvious to the crew. This basic format has been used as far back as the Apollo program and is the result of manned spaceflight experience.

SYMPTOM	PROCEDURE	REMARKS
ECLSS (ARS H2O) 7 (Cont) SM ALERT BLUE Light on if:		
7b (4) S88 H2O PUMP P 1(2) H2O LOOP 1(2) PUMP OUT P < 50 psia > 75 psia	1 | H2O LOOP 1(2) PUMP OUT P '↓' ? YES → 7a | 4 NO → 2 | H2O LOOP 1(2) PUMP OUT P '↑' ? YES → 7a | 5 NO → 3 | CLASS 3 ALARM SOFTWARE FAULT OR SNSR FAILURE	(4) Preconditioning will inhibit this check unless the (L1) H2O PUMP LOOP 1(2) switch is in the GPC position and 1A OR 1B GPC ON signal is present. Preconditioning will default to this set of limits if the H2O PUMP LOOP 1(2) switch is in the ON position
7c (5) S88 H2O PUMP P 1(2) H2O LOOP 1(2) PUMP OUT P < 20 psia	1 | H2O LOOP 1(2) PUMP OUT P '↓' ? NO → 2 | CLASS 3 ALARM SOFTWARE FAULT OR SNSR FAILURE YES → 3 | H2O LOOP 1(2) ACCUM QTY '↓' ? NO → 4 | FAILED OR SHIFTED H2O LOOP 1(2) PUMP OUT P TRANSDUCER YES → 5 | EXTERNAL LEAK DEPLETED ACCUM	(5) Preconditioning will inhibit this check unless (L1) H2O PUMP LOOP 1(2) sw is in the OFF position or in the GPC position without the presence of GPC ON signal (used to check for static loop leaks)
7d (6) S88 THERMAL H2O H2O LOOP 1(2) PUMP ΔP < 35 psid > 50 psid (> 5 psid - dormant)	1 | H2O LOOP 1(2) PUMP ΔP '↓' ? NO → 2 | H2O LOOP 1(2) PUMP ΔP '↑' ? NO → 3 | CLASS 3 ALARM SOFTWARE FAULT OR SNSR FAILURE YES → 4 | H2O LOOP 1(2) PUMP OUT P '↓' ? NO → 7a | 8 YES → 7a | 5 YES (from 1) → 5 | H2O LOOP 1(2) PUMP OUT P '↓' ? NO → 6 | SHIFT OF H2O LOOP 1(2) PUMP IN PRESS SENSOR YES → 7a | 4 To Figure 6	(6) Preconditioning will inhibit the limit range of 35-50 psid to an upper limit of 5 psid when the pump switches are in the OFF position or in the GPC position without presence of GPC ON signal (used to check for out of configuration or blockage) OV102/ECLSS/7b-d PRELIM PCN1

Figure 5 Water Pump 2 Malfunction Procedure

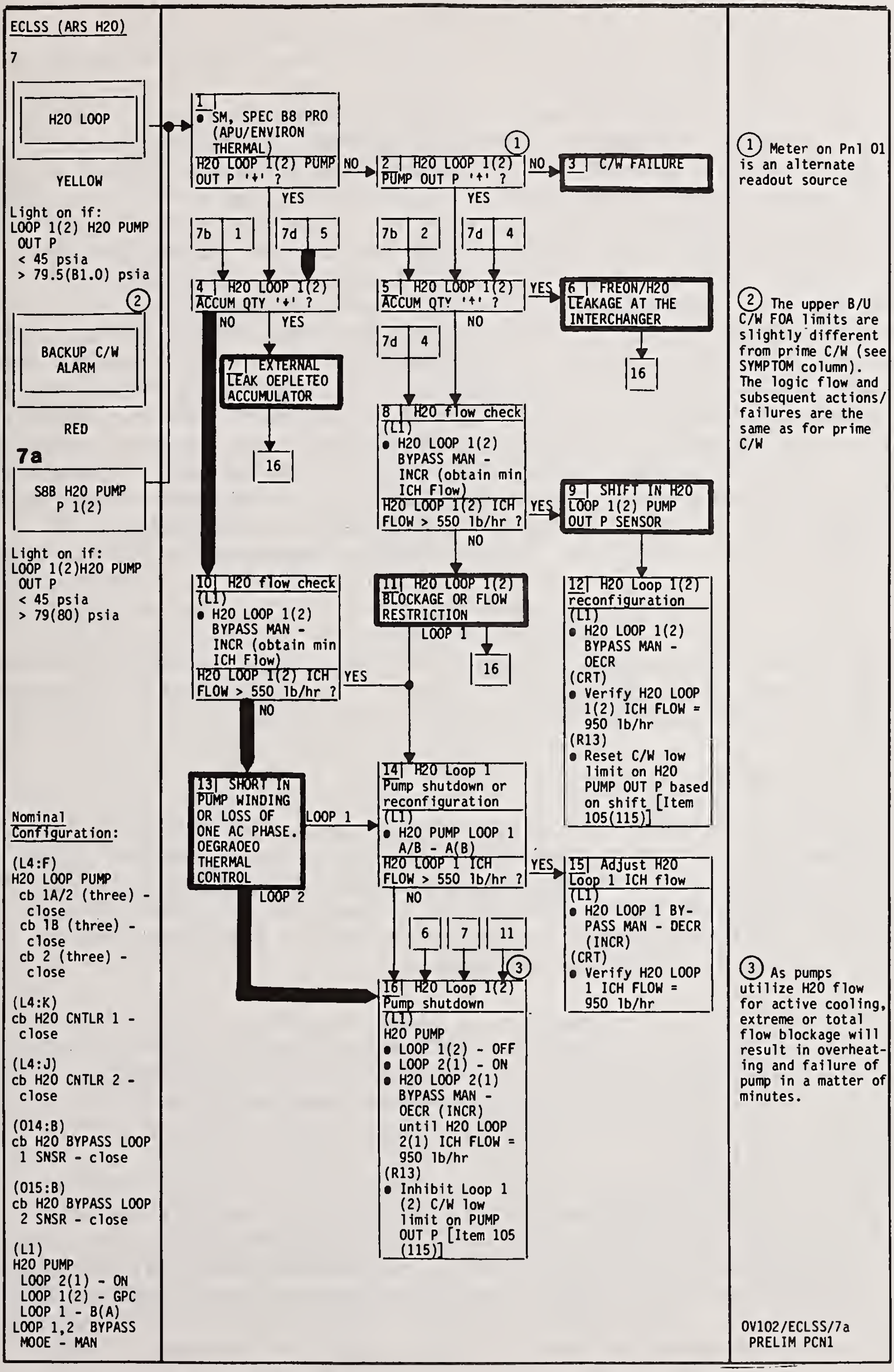

Figure 6 Water Pump 2 Malfunction Procedure (cont'd)

Detection and Diagnosis System Philosophy

The failure detection and diagnosis system has been designed using several ground rules for consistency to simplify training and to maximize the design effectiveness within the DPS and flight crew capabilities. First, although an apparently obvious consideration, is the exclusion of those failures for which there is no corrective action or effect on the continuation of the mission. Second, is the exclusion of failures which do not require corrective intervention within two hours, the longest expected period without communication with the mission control center. The Houston facility receives telemetered vehicle systems data at a greater level of detail than is displayed onboard the Orbiter, and is therefore responsible for "catching" these failures. Also, while the detection system will indicate any anomaly which occurs, the malfunction procedures are designed for diagnosis of only single failures within a unit or subsystem. This rule is grounded in the fact that the probability of several independent failures occuring within a system is equal to the product of their individual probabilities, a value which decreases rapidly as the number of failures increases. Experience has shown that the amount of analysis (or complexity of malfunction procedures) is approximately proportional to the power of the number of failures. Multiple failures are therefore also the responsibility of the mission control center, thus simplifying the onboard malfunction procedures and crew training. Where the malfunction procedure cannot diagnose the actual failure, it instructs the crew to invoke a redundant unit or to safe the system. With these rules enforced, the detection and diagnosis will yield a rapid and effective response to failure.

Training for Diagnosis

The flight crews and mission control center personnel follow an intensive program of training for each mission, the primary goal being an integrated common base of understanding of vehicle systems and onboard and ground procedures among the personnel involved in actual mission operations. This, of course, includes training in the detection and diagnosis system described in this paper.

Training is composed of a sequence of classes produced within the mission control organizations for informal crosstraining among specialists and formal classroom training by an independent training division for more general use. Detailed exercises in the interaction with the detection system and use of malfunction procedures first occur in the various simulator facilities.

The first facility which exercises procedures is a low cost medium fidelity simulator called the Single Systems Trainer (SST), which can model at a given time one of the major subsystems (electrical, environmental, navigation, etc.) with a computer modeling the subsystem hardware and software. The simulator is under the control of an instructor who initiates simulated failures for the student to diagnose. This facility has been instrumental in debugging not only malfunction procedures but normal systems operations as well. This provides early feedback to correct the procedures prior to their use in the actual vehicle.

The final stage of training is the integrated simulation which has the flight crew stationed in the Shuttle Mission Simulator (SMS) and the mission controllers at their consoles in the mission control center (MCC). The SMS is a high fidelity flight deck simulator which features computer generated visuals, a motion base to give the appropriate "feel" of vehicle dynamics and Orbiter GPC's, processing flight software, interfaced with other computers simulating input/output devices which in turn connect with software models of the vehicle subsystems. The SMS provides a two-way voice and data link with the MCC, just as the Orbiter would during a mission. The MCC, configured as it would be for a mission, is staffed by the mission controllers who can view simulated systems data to perform the detailed analysis and management function. The simulation is conducted by the training division personnel who create failures for the crew and MCC to diagnose. Generally, over the course of integrated simulations, all onboard and MCC procedures are exercised as a final premission verification and test of compatibility among the elements of the operational system.

Conclusion

The Orbiter failure detection and diagnosis system, composed of the data processing system, the flight crew, the mission control center, and the malfunction procedures, is responsible for reaction to failure occurrence during a Space Transportation System mission. Failure detection is usually the responsibility of the data processing system, which provides, through a variety of programs, a standardized annunciation in response to an anomaly. The crew, aided by the malfunction procedure, performs the detailed diagnosis to identify the cause of the symptom. The mission control center provides any monitoring and analysis which is beyond the capability of the Orbiter and crew. The flight crew and mission control personnel follow a sequence of training activities which provides commonality of knowledge and verification of the detection and diagnosis system.

Currently, NASA is preparing for the first orbital test of the Space Shuttle. Although the Approach and Landing Test flights, during the fall of 1977, verified the airworthiness of the vehicle and its fly-by-wire control system for landing, the program only began to scratch the surface of automatic onboard failure detection. The design discussed will be used for the first few orbital flights and therefore reflects a healthy caution that is due a test vehicle during shakedown trials. As in past programs, these missions will be conducted with extensive real-time monitoring, management and troubleshooting by the Houston mission control center. The present design is the response to this particular challenge.

The mature Space Transportation System will rely heavily on the independence of the spacecraft and crew to accomplish the mission objectives without exhaustive MCC support. Coincident with the increasing confidence in the basic vehicle systems will be an increase in payload support activities which include detection, diagnosis, and action for recovery. The standards and methods discussed here will be applied to the design of this Orbiter support of the payloads which, on examination of present commitments, form a wide-ranging spectrum of unique mission requirements. The standardization of the response to failure, with remote autonomy, are essential to the cost-effectiveness of a truly operational Space Transportation System. This is the challenge of the immediate future.

MULTISPECTRAL SCANNER ON LANDSAT

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Abstract: The multispectral scanner (MSS) is described; it is an instrument onboard the earth resources satellite that was formerly called ERTS, but is now referred to as LANDSAT. Since July 1972, three scanners have been launched that have provided tens of thousands of pictures of the earth. The scanning mechanism that produces these pictures has proven to be extremely reliable and repeatable. After the first scanner was turned off after five years of operation in orbit, the scan mirror had accumulated 90 million cycles and was still performing flawlessly. The design approach that was taken in order to achieve reliability is discussed as well as the scan monitor that serves both to provide a correction signal for data processing on the ground and as a diagnostic device to detect impending trouble.

SCANNER OBJECTIVES

The four-band multispectral scanner (MSS) system is designed to provide the capability for collecting earth imagery from the LANDSAT spacecraft. The scanner portion of the system employs all reflective optics to accommodate the four spectral bands, which occupy a broad spectral range from visible to near infrared. Use of a single optical system for all spectral bands ensures the excellent registration needed for signature analysis of agricultural scenes. Systematic coverage of the earth with nearly uniform lighting is obtained via the near-polar sun synchronous orbit. The 496-nmi altitude permits the scanner to image the entire earth every 18 days with a usable resolution of 225 ft.

SCANNER

The scanner is designed to scan a 100-nmi swath on the earth and to record imagery in each of four spectral bands simultaneously. An oscillating mirror provides the crosstrack scan, and the orbital progress of the spacecraft provides the scan along the track. The scan mirror, shown schematically in Figure 1, is at 45° with respect to the earth and the double-reflector, Ritchey Cretien type telescope. The $\pm 2.9^{\circ}$ motion of the mirror scans a field of view of 11.6°.

A four by six fiber optics array is placed in the focal plane of the telescope: there are six fibers in a column and there is one column for each of four colors. Each fiber defines an instantaneous field of view (IFOV) of the earth. The image of the earth is swept across the fiber array each mirror scan. Light impinging on the glass fiber is conducted to an individual detector. An optical filter is combined with each detector to determine the spectral band. By operating the mirror at a rate of 13.62 Hz, the orbital velocity is precisely such that the sub-spacecraft ground track advances six IFOVs, and the next line imaged by the first detector in each band is contiguous to the sixth line of the previous scan.

The 13.62-Hz mirror drive signal is derived by the multiplexer from its master oscillator, which operates at approximately 30 MHz. Word and bit rates are derived from internal division of the 13.62-Hz scan frequency and are maintained uniformly from scan to scan. Only the line start synchronization pulse need be acquired in each scan. The line start pulse, generated by the scan monitor, is used to reset and initiate the multiplexer sampling sequence. Resetting the sampling frame with the scan monitor makes the start of sampling completely angle dependent and therefore immune to small timing variations that could arise from the scan mechanism. The 24 channels are multiplexed into a 15-Mbps stream, which is sent along with a bit clock to the spacecraft recorders and transmitters.

SCAN MONITOR

Angle crossings of the scan mirror, which denote the west edge, center, and east edge of the 100-nmi swath, are indicated by means of an optical pickoff situated so as to view the scan mirror. The beginning pulse is supplied to the multiplexer wherein it is used to initiate video sampling. The center pulse can be transmitted upon command and is provided for checkout and troubleshooting. The end of line pulse is transmitted in the data to allow line-to-line corrections should the scanning mirror show minor variations in time to scan a line.

The scan monitor system shown in Figure 2 consists of a gallium arsenide laser diode emitter (operating in a sublasing mode), an optical projection system, a series of reflectors, and a pair of detectors. The system has a built-in redundancy in the form of two light sources in one package, only one of which will operate at any given time; one is installed on-axis, while the backup must be offset by their minimum center-to-center dimension. If one source fails, the redundant unit is selectable by ground-originated commands.

Any malfunction of the scan mirror mechanism will show up as a sudden or erratic change in the time needed to scan a line. Except for temperature sensors, the scan monitor is the only diagnostic device on the scan mirror mechanism.

SCAN MIRROR MECHANISM AND OPERATION

The MSS scan mirror mechanism is shown schematically in Figure 3. It consists of a lightweight beryllium mirror suspended on a pair of flex pivots. There are bumpers, return springs and dampers, an electromagnetic torquer, and an optical switch. Figure 4 is a drawing of the MSS scan mirror assembly.

The requirement for the scan mirror assembly is that it provide a constant-velocity scan that is repeatable from one scan to the next. This ensures a ground picture free of distortion with the resolution elements of one scan lined up with the appropriate resolution elements of another scan. The design has the mirror rotate on a "frictionless bearing" with no drive forces acting on it during scan. A flexure pivot is, for the accuracies required of this device, a frictionless bearing over the scan angles required. It has a small repeatable torsional spring constant that results in a small but predictable picture distortion. For most user requirements the distortion is insignificant. For the most accurate mapping a correction can be made during ground processing to remove this nonlinearity.

At the end of scan the mirror impacts the bumpers and compresses the turnaround springs. Most of the kinetic energy of the mirror is stored in the springs and returned to the mirror in the retrace direction. During retrace, an electromagnetic torquer adds the energy lost during the turnarounds. During the forward scan the mirror coasts. Imagery is produced only during this half of the cycle. The dampers eliminate any residual motion in the bumper/spring assembly before the next impact in order to ensure repeatable turnaround performance.

The mirror is controlled by a 13.62-Hz mirror drive signal that is developed from a high-frequency clock aboard the spacecraft and by an optical switch. The optical switch consists of a light source with a slit that is imaged onto a photodiode. A reflective surface attached to the scan mirror is part of the optical path. Motion of the scan mirror causes the photodiode to see or not see the slit. The mirror position at which the signal goes off is determined by the location of the optical switch.

The relationship of mirror position to the mirror drive and optical switch signals is shown in Figure 5. The torquer is turned on by the mirror drive signal and turned off by the optical switch. The result is a simple but stable control system. If the mirror scans too fast its position advances relative to the mirror drive and the torquer turns itself off sooner by means of the position-sensitive optical switch. Less energy is added to the mirror, thus reducing its net velocity. The opposite is true for a mirror that runs slow. The mirror position is stable relative to the mirror drive to less than 3 μrad or 4% of a resolution element.

BUMPERS AND SPRINGS

A cross-sectional view of the bumper, spring, and damper assembly is shown in Figure 6. The bumper impact interface consists of an impact bar made of 17-4 stainless steel and a nylon bumper surface bonded in the turnaround cups. Nylon was chosen because of its good wear and impact resistance, suitability for adhesive bonding, and acceptable properties in a space environment.

A reliability test was conducted by using a bumper/spring/damper unit with a reduced travel bumper cup assembly driven against the impact bar. The impact velocity and the force-time history of mirror turnaround were increased 20% over unit operation. A total of 142,000,000 cycles were run. The acceptable wear was 2.0 mils; the measured wear was only 0.2 mils. Besides indicating acceptable wear the test proved the integrity of the bond between the nylon and aluminum bumper cup. As part of the test, the turnaround springs were also tested at a deflection 20% above their normal deflection. In addition to these tests an intensive analysis of the spring was conducted to make sure that the stress levels were well within values for indefinite life.

DAMPERS

Two elastomeric dampers operate with each bumper/spring unit. These dampers dissipate energy via shear distortion as they are displaced ±0.019 inch during each scan cycle. A damping coefficient of 0.020 lb-sec/in at a frequency of 125 Hz is specified to correspond with 4-msec half sine wave turnaround. The dampers must have acceptable outgassing characteristics for space environment, maintain an acceptable damping coefficient, and show no failure in the elastomer-metal bond. A number of materials and configurations were tested during the development phase of the program.

Checks were made during the thermal vacuum test for condensable materials after four days at the real-time temperature and in a vacuum environment of 10^{-6} torr. For a silicone damper to pass this test, a postcure at elevated temperature was required. From the results of tests on the Surveyor, it had been determined that silicone elastomers postcured at 350°F showed the least change from the initial physical properties while still reducing the outgassing to an acceptable level. Tests made on dampers showed that after a 5-day bake at 350°F in air the parts had less than a 0.1% weight loss when exposed to 4 days in hard vacuum, and no oily deposits or condensables could be found.

Life tests were performed on an apparatus that was designed to simultaneously flex six pairs of dampers. The life test was conducted with a cyclic shear displacement amplitude of ±0.023 inch. This displacement is approximately 20% greater than that actually produced during impact in the scan mirror mechanism. Three pairs of dampers were tested in the condition in which they were received, and two additional pairs were tested after an elevated temperature postcure. Dampers were test cycled under the conditions of no prestress, a 0.030-inch compression prestress, and a 0.046-inch shear offset prestress. These mounting variations were evaluated to determine the effect they would have on the damper fatigue life: no fatigue failures occurred and the damping changes were comparable; therefore, no prestress was used in the system. The postcure dampers were harder and had higher damping constants. At equal displacements, the postcured dampers received a higher stress under the test conditions than the dampers in original condition. The actual values of the damping constant are compared in Figure 7 for two pairs of dampers from the commercial source that were postcured. A damping value constant within 5% was maintained. As a result of the vacuum tests and life testing, the dampers produced by the Lord Manufacturing Company of Erie, Pennsylvania, were selected for use on the flight system.

Specifications were generated to provide the necessary controls and screening procedures. The manufacturer is required to produce parts from one controlled lot of materials. After receipt, the dampers are subjected to a postcure at 350°F. As a lot-acceptance test, ten % of the lot is tested for condensables and outgassing. Each device that is used in the system has the damping characteristics measured on a pair basis.

FLEXURE PIVOTS

Two flexure pivots provide the suspension points for the scan mirror. These pivots must withstand the launch environment and subsequently operate at ±2.9° rotation for 150,000,000 cycles. These commercially available devices are 90° symmetrical two-strip pivots; one of the strips has been divided to ensure greater lateral rigidity. The stationary portion of the pivot is brazed to a cylindrical barrel and the rotating portion is brazed to another cylindrical barrel. The flexing elements bend to allow rotation of one barrel with respect to the other. The flexure elements are stamped from close tolerance, cold-rolled spring stock of type 420 stainless steel. Flexure pivots do not have a fixed center of rotation. The amount of the change of center of rotation during rotational displacement of one sleeve with respect to the other is called centershift. The flexure pivots being used are 5/8 inch in diameter and are designed for flexing up to ±15°. The flexing strips are 0.0135 inch thick.

The two important tests that these parts must pass before being included in any flight system are vibration and life testing. The pivots used on MSS have successfully passed tests that simulate the launch environment. Vibration tests were conducted on an early engineering model and later on the systems using the final design. There is negligible inherent damping in flexural pivots, and this results in high transmissibilities of input vibration levels. The pivots passed vibration levels in the qualification unit that were twice those expected in the launch environment.

To demonstrate compliance with the system life requirement, it was necessary to determine the fatigue-life characteristics of the flexure pivots. A test program to produce a curve of stress as a function of cycles to failure for the parts was performed. The results are shown in Figure 8. The equivalent angle is included on the right of the figure for the $\pm 15^{o}$ pivot design, and the MSS operation required is also noted.

The expression used to calculate the stress for pure rotation is

$$S = \frac{Et}{2L} \theta$$

where S = stress, E = modulus of elasticity (29×10^{6} psi for 420 CRES), t = flexure thickness, θ = angle through which pivot is rotated (radians), and L = effective length of flexure.

The test grouping is typical of fatigue testing. Some scatter in results is expected because of the inhomogeneous nature of metals and tolerances used in manufacturing the parts. These particular pivots closely follow the life curve that is predicted by the manufacturing data.

In addition to meeting life and environmental requirements, the pivots must meet critical parameters regarding mirror support. Two pivots from each manufacturer lot are subjected to destructive static-load test and to a metallurgical examination. Each pivot is visually examined with both a conventional microscope and a small-diameter borescope for surface defects - it is examined for burrs, nicks, or scratches that might reduce the strength or life of the part. Each pivot is subjected to a dye-penetrated inspection for evidence of surface and subsurface cracks. All flight pivots are subjected to a radial load of 220 pounds to test for defective braze joints.

To ensure minimum stress and satisfactory mirror alinement under scan conditions, each pivot is tested for center-shift and torsional spring rate at $\pm 3^{o}$ rotation. Pivots are then paired to have closely matched torsional spring rates so that when they are rotated the center shifts are of the same magnitude and in the same direction. Only matched pairs of pivots that pass all visual and physical tests were used in the flight units.

LIFE TEST PROGRAM

A flight quality scan mirror assembly (as shown in Figure 2) was subjected to a life test program. The purpose of this test was to verify that the scan mirror assembly would reliably support the mission requirement of one year in space at a 20% operational duty cycle (approximately 20 minutes on and 80 minutes off).

The unit was subjected to a complete acceptance program involving unit test and vibration and thermal vacuum testing. Space operation was simulated by operating the unit at a pressure of less than 10^{-5} torr and a base temperature of 90°F. To compress the test time, the operational duty cycle was raised to 50% (20 minutes on and 20 minutes off). The unit was operated on a full-time basis with periodic performance checks at approximately 4-week intervals with more frequent checks at the beginning of the life test. During these performance checks eleven parameters were measured and compared to specifications. Changes from initially measured values were carefully monitored. At the conclusion of the test the scan assembly had been operated for 140% of the required mission life without a failure or degraded performance. The active scan time had decreased by less than 1%, which was within allowable limits.

LINE LENGTH MEASUREMENTS

Line length is defined as the time elapsed from the start-of-scan pulse to the end-of-scan pulse. Line length measurements have been made for extended periods of operation for the engineering model during life testing and for both LANDSAT I and II. LANDSAT III has been successfully operated in orbit but line length trends have not been established. Table I lists the pertinent information.

TABLE I. LINE LENGTH VARIATIONS

	Launch Date	Data Span, years	Number of Scan Cycles x 10^6	Line Length Variation, μsec
Life Test	(1972)	<1	120	-200
LANDSAT I	7/23/72	>5	90	-100
LANDSAT II	1/22/75	>2	52	-80
LANDSAT III	3/5/78	<1	3	-

The trend seems to be clearly established toward shorter line lengths for longer periods of operation. Table II compares line lengths with time for LANDSAT I and II.

TABLE II. LINE LENGTH IN ORBIT

Line Length, msec	LANDSAT I	LANDSAT II
At launch	32.21	32.50
First year	32.19	32.49
Second year	32.17	32.48

A more detailed description of line length variation as a function of time can be seen in Figure 9, in which data for the first three years on orbit for LANDSAT I is shown. The fluctuations are not understood. The general trend towards shorter line lengths is attributed primarily to changes in the elastomer damper. LANDSAT I was turned off in January 1978 because of difficulties with the spacecraft control system. The scan mirror mechanism was still performing as designed. The specified mission life was one year.

CONCLUSIONS

The long life of the scan mirror assemblies without failure or degradation may be attributed to the exhaustive development program - consisting of analysis and test that preceded their construction. A key factor was the design approach, wherein stress levels were kept well below allowable limits. This was combined with a philosophy of testing to levels above normal expected values and careful screening of manufactured parts.

ACKNOWLEDGEMENTS

We wish to thank J. Olson and W. Quinn for their descriptions of the bumpers and dampers published in the article referenced, and to J. Balla of NASA, Goddard, for supplying the on orbit data.

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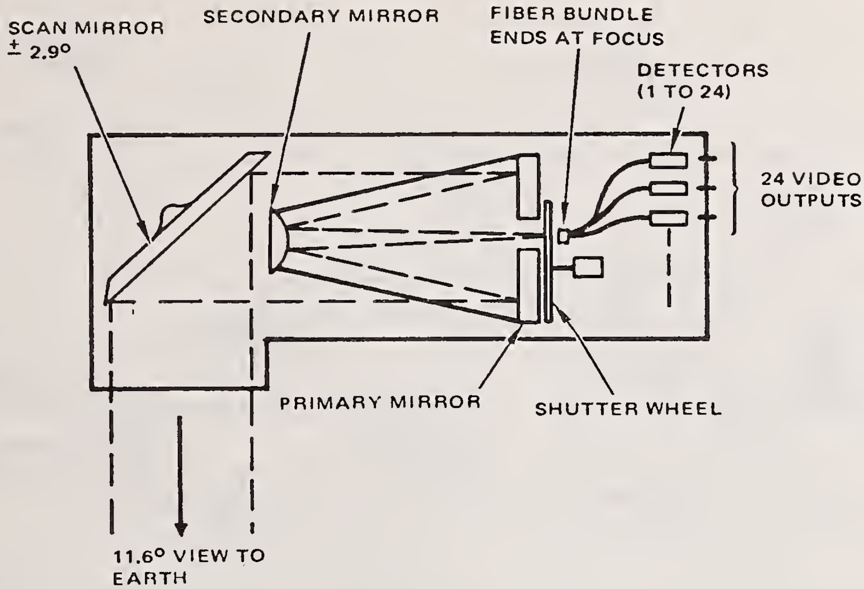

Figure 1. Simplified schematic of scanner

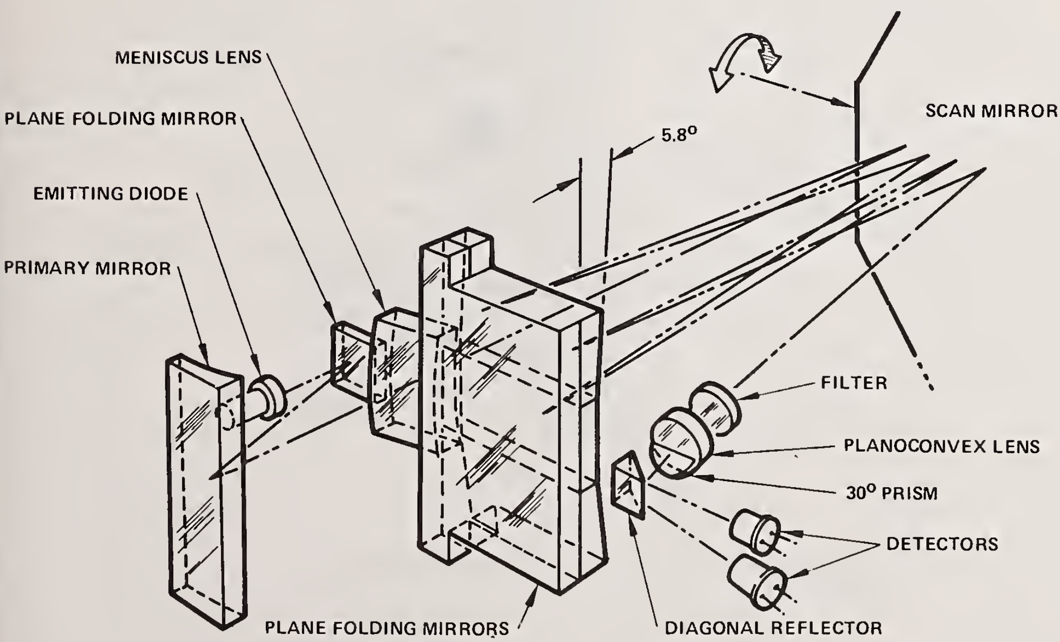

Figure 2. MSS scan monitor optical system

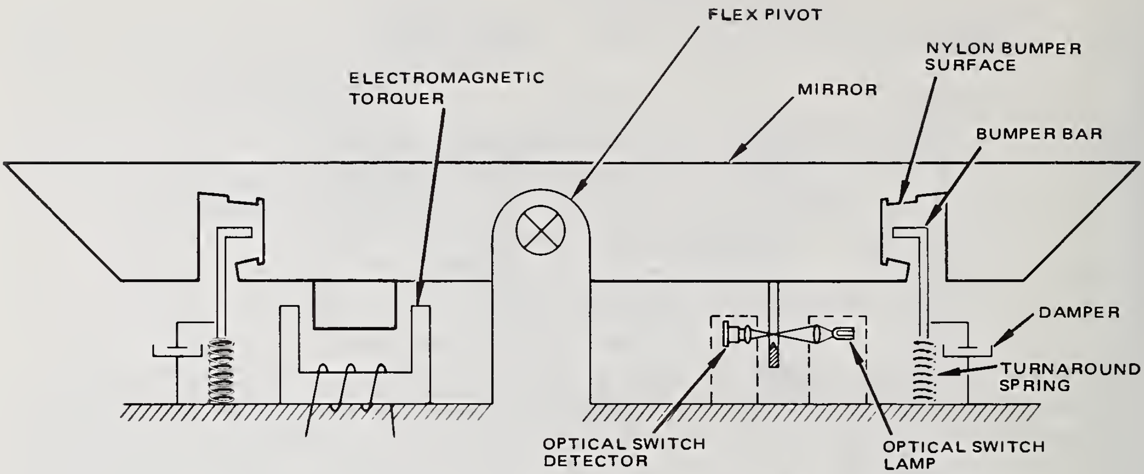

Figure 3. Schematic of MSS scan mirror mechanism

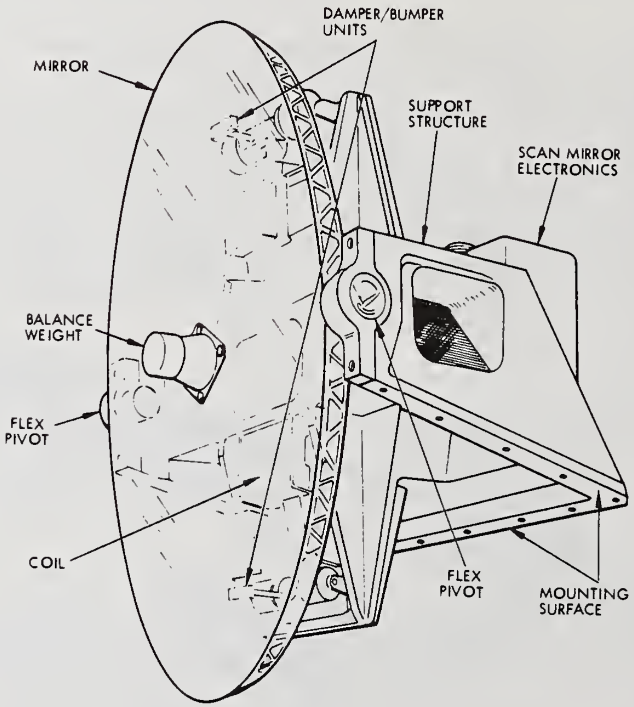

Figure 4. MSS scan mirror assembly

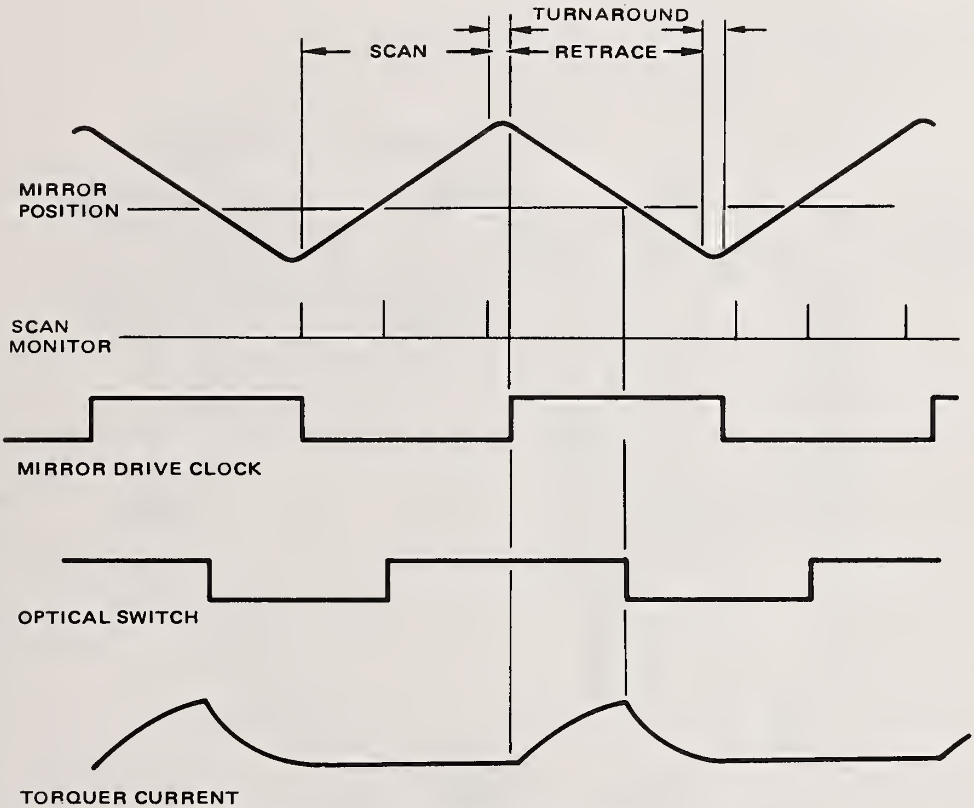

Figure 5. Timing diagram

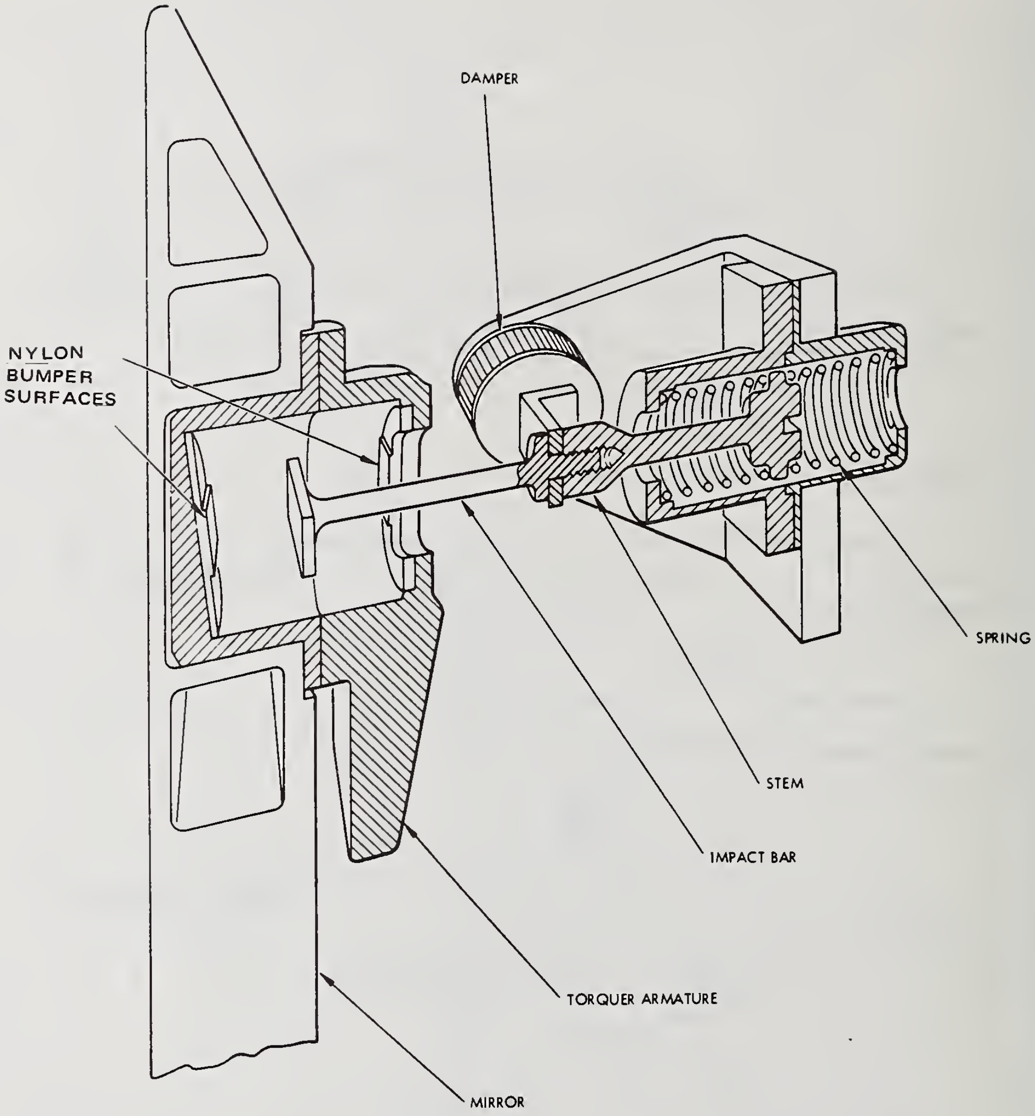

Figure 6. Sectional view of combined bumper, spring, and damper

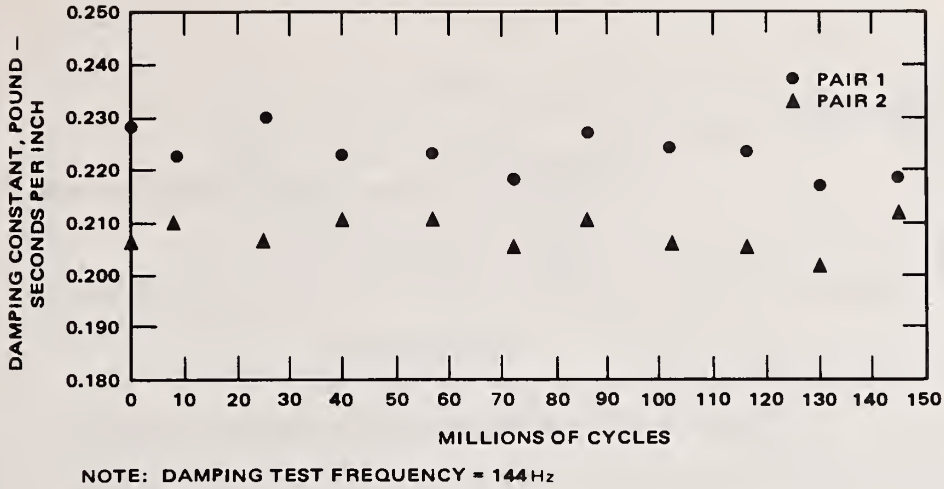

Figure 7. Damping as a function of life

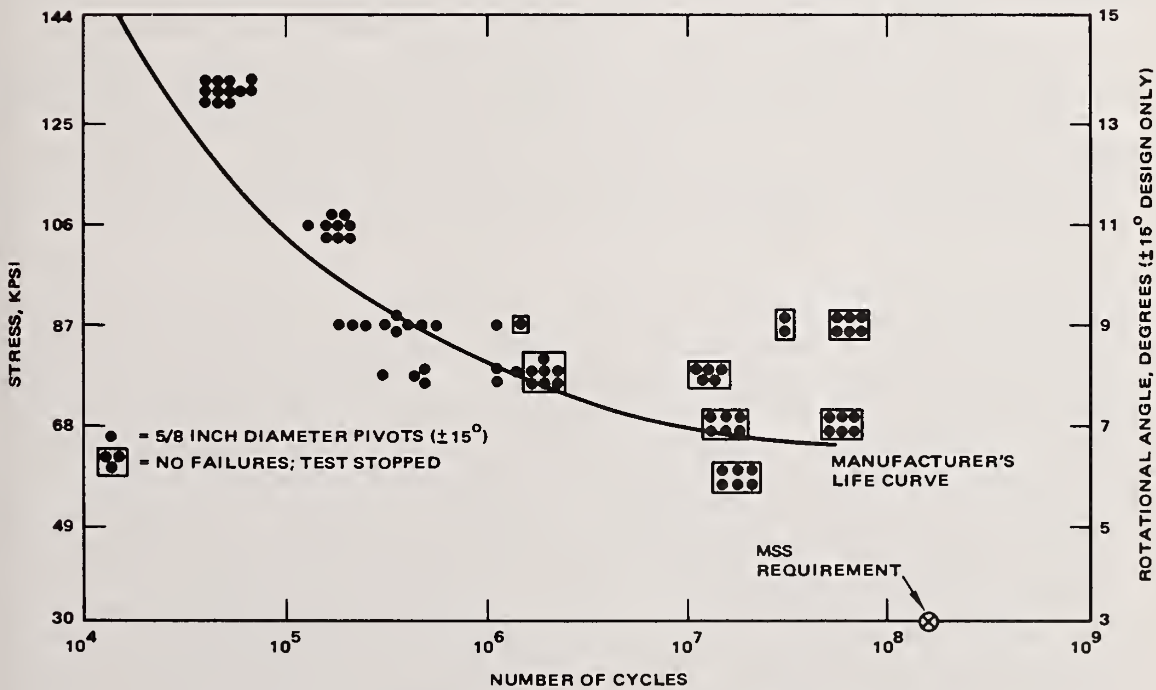

Figure 8. Flexure pivot fatigue test results

Figure 9. Line length variation for LANDSAT I

DRIVETRAIN BEARING ANALYSIS

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Key Words: Aircraft Diagnostics, Diagnostic Equipment, Condition Monitoring, Bearing, Shock Pulse.

Introduction: The US Army has recognized for some time the need for improved condition monitoring and diagnostic equipment for helicopter drivetrain systems. Recent studies[1] have confirmed that an unacceptably high false removal rate exists on many helicopter drivetrain components and that "phenomonal savings" would accrue to the Army by improving the diagnostic effectiveness. There have been several attempts at developing cost effective, affordable and reliable equipment. It now appears that such a system exists. It is the Small Portable Analyzer Diagnostic Equipment (SPADE). The equipment has been under development for several years and is currently in a Development Test at Ft. Rucker and an Operational Test at Ft. Hood. The purpose of this paper is to briefly review the program, the equipment characteristics and to review in detail the results of the Contractor Demonstration Phase.

System Description: The SPADE is an item of ground support equipment designed to semi-automatically inspect and diagnose bearing faults in selected aircraft components. It functions on the principle of detecting and measuring shock pulses generated by the release of kinetic and frictional energy within the monitored component. The history of the shock pulse[2] has been discussed in earlier MFPG proceedings as has its application to helicopter drivetrain diagnostics.[3] Briefly the theory is that when the rolling elements in a bearing contact a surface discontinuity, repetitive impacts of short duration and very short rise time are created, hence the shock pulse. This signal then propagates through the mechanical structure. It decays as a function of the distance it travels and is further attenuated at each mechanical interface. The signal is detected with an accelerometer and with appropriate processing is correlateable to mechanical condition.

The SPADE is a derivative of the commercial SKF MEPA-10A. It functions on the shock pulse principle as does the MEPA-10A but it is implemented in a slightly different fashion. Where the MEPA-10A requires manual data collection and interpretation of data, the SPADE is automated. Specifically, the MEPA-10A requires the interpretation of a plot of the rate of the shocks vs. the amplitude of the shocks. The critical factors are the area under the resultant curve and the shape of the curve. The SPADE measures the area by driving a voltage to frequency converter with a demodulated signal and measuring the output directly with a counter. This measurement is proportional to the level of the defect and is compared to preset limits that are representative of good, marginal and discrepant conditions. The status of the monitored components is then displayed on the instrument control panel.

Contractor Demonstration Phase: This phase began with delivery of first SPADE in February of 1978 and was concluded in September 1978. During this time parts with known defects were implanted in various UH-1 gearboxes. Baseline data was also taken on the UH-1, AH-1 and OH-58. The purpose of this phase was to finalize the limits and to demonstrate that the SPADE was ready for the Government testing phase. The SPADE was operated without preprogrammed limits so that the maximum amount of information would be available for correlating the SPADE measurement with the actual part condition. Three different accelerometers were also evaluated.

The following is a summary of the implant testing results on the UH-1H drivetrain components:

Component	Correct Indication	Incorrect Indication	Instantaneous Probability of Detection (P_{4i})
Main Trans	15	3	.83
42 Gearbox	10	0	1.00
90 Gearbox	9	1	.90
Hangar Bearings	0	0	0
TOTALS	34	4	.89

NOTE: The results of the hangar bearing test will not be proven until after the bearings are analyzed.

SPADE Fault Detection Capability: The implant approach is not a perfect test technique in that certain variables which are difficult to quantify are introducted. Thus each case must be carefully evaluated to eliminate as many of these as possible. The process of implanting a discrepant component into an "alien" gearbox results in decreased levels of kinetic energy due to misindexing of the defect relative to its natural location in its "native" gearbox, removal of trapped debris generated by the defect, and various tolerance and clearance changes which are a direct result of the component disassembly.

This above data was, for the most part, accumulated from bearings with defects that were small relative to the levels of damage which would result in loss of load carrying capability for a bearing. Since SPADE readings are proportional to the level of damage within a bearing, higher readings and higher detection rates would result if larger defects were implanted or if implants when tested were allowed to progress to more significant levels of damage. Therefore, the actual accuracy of naturally occuring defects may be different and would be better determined by a different test technique.

Although these results approach the design requirements, another concept should be considered; that is the cumulative probability of detection. The detection probabilities listed are for each time that a SPADE measurement is taken on a discrepant bearing. However, since bearings do not fail instantaneously, the SPADE can be used several times (on a regularly scheduled basis) between the time an intial discrepancy appears and the time a bearing is so badly damaged that it loses its load carrying capability. This period between initial discrepancy and loss of function for a bearing is called the Failure Progression Interval (I_f). The number of aircraft operating hours between scheduled SPADE inspections is known as the Utilization Interval (U). The cumulative detection probability (P_{4c}) for SPADE is greater that its instantaneous value (P_{4i}) because during the failure progression interval there are several chances (I_f/U) for finding the defect, and only one detection is required to remove the failing component from service. The mathematical relationship between the cumulative probability of detecting an ongoing failure and these other diagnostic parameters is:

$$P_{4c} = 1- (1 -P_{4i})^{I_f/U}$$

Given this relationship and the experimental values for P_{4i}, it remains to estimate the failure progression interval, I_f, for bearings, and to select a SPADE Utilization Interval (U) that yields a satisfactory cumulative probability of fault detection. Of the twenty-eight (28) bearings used for implant testing during this and preceding Army diagnostic test programs, none have shown evidence of significant failure progression. Of these same bearings, eleven have been operated for times in excess of 100 hours and three in excess of 200 hours with a maximum spalled bearing operating time of just over 290 hours. Figure 1 shows SPADE's cumulative probability of fault detection as a function of its utilization interval. The curves in this Figure represent a range of instantaneous fault detection probabilities which "bracket" the results of testing during the Contractor Evaluation of SPADE. The important message from this Figure is that even for the worst case estimate of SPADE accuracy, a high cumulative probability of fault detection can be achieved with a 25 hour SPADE inspection interval. For example an accuracy of P_{4i} = .45 would indicate a cumulative probability of fault detection in excess of 99% at a 25 hour inspection interval and better than 90% at a 50 hour interval. In addition, any increase of the failure progression interval above 200 hours will result in an increase in the cumulative probability of fault detection.

The other side of the coin, of course, is the false indication rate that can be expected when employing the same limits that are associated with the detection accuracy just discussed. The caution and remove indication limits in SPADE are set at the mean plus 2-sigma ($m + 2\sigma$) and mean plus 3-sigma ($m + 3\sigma$) values respectively of all the confirmed baseline data accumulated for four (4) UH-1H aircraft during the Contractor Evaluation. Assuming a normal distribution of measurements, this should result in an instantaneous probability of false removal indication (P_{2i}) of .0027. The cumulative probability of false removal indication (P_{2c}) would then be the product of the number of SPADE measurements times (P_{2i}). Over one hundred SPADE measurements of baseline components were made during the Contractor Evaluation but no removal limit exceedances were observed. This record tends to confirm that P_{2i} for SPADE is .0027 or less. The Mean Time Between Removals due to false indications or ($MTBR_{fi}$) for each drivetrain component monitored by SPADE can be calculated from the equation:

$$MTBR_{fi} = \frac{\text{SPADE UTILIZATION INTERVAL}}{\text{No. of sensors on component X } P_{2i}}$$

Table I lists the $MTBR_{fi}$ and corresponding false removal rate for each aircraft component at two SPADE Utilization Intervals (U=25 hr & U=50 hr). This Table also summarizes false removal rates for the total UH-1H drivetrain and the gearboxes vs. tail rotor driveshaft hangar bearings as separate component classes. It is important to note from this Table that even for a 25 flight hour SPADE Utilization Interval, the false removal rate is only slightly over one removal per thousand aircraft flight hours.

Conclusion: In summary then, even a pessimistic assessment of SPADE Contractor Evaluation test results indicates a high fault detection capability and a false removal rate of one per thousand flight hours. This accuracy exceeds the design requirements of 90% fault detection capability and 2 false removals per thousand flight hours.

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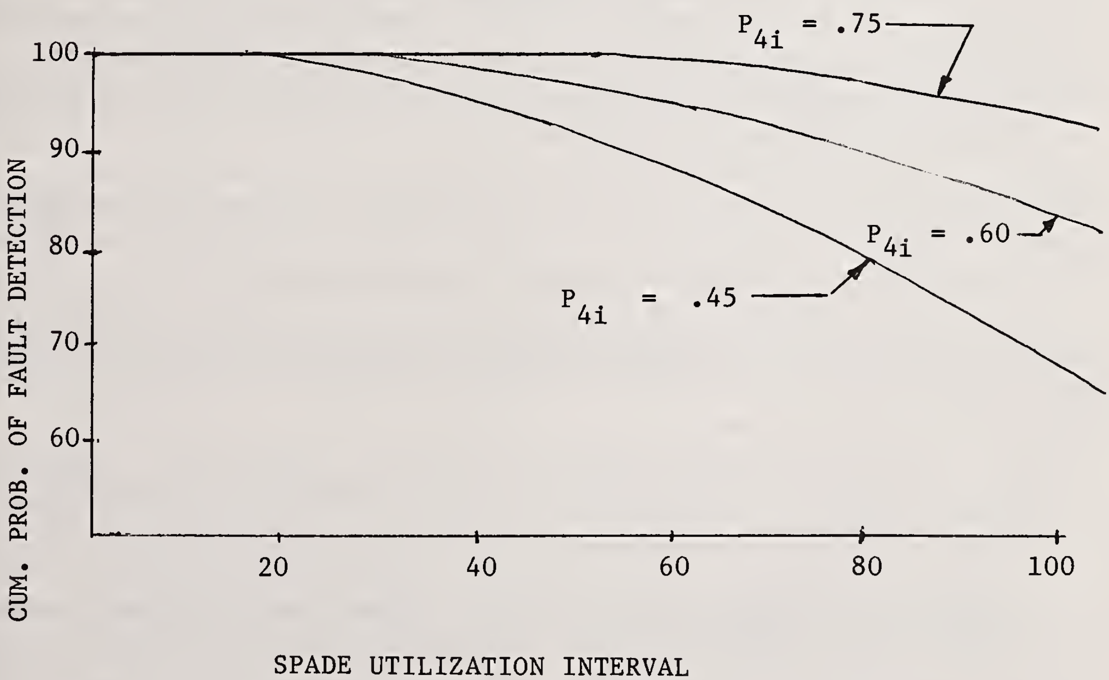
AIRCRAFT COMPONENT	$MTBR_{fi}$ - Flt Hr		False Removals/1000 Flt Hr	
	U = 25	U = 50	U = 25	U = 50
Main Transmission	3086	6173	.324	.162
42 Gearbox	4630	9259	.216	.108
90 Gearbox	9259	18519	.108	.054
Hangar Bearings(4)	2315	4630	.432	.216
TOTAL DRIVETRAIN	926	1852	1.080	.540

U - SPADE UTILIZATION INTERVAL

SPADE CAUSED FALSE REMOVAL RATES

TABLE I



CUMULATIVE FAULT DETECTION CAPABILITY VERSUS SPADE UTILIZATION INTERVAL

FIGURE I

LIGHT HELICOPTER DETECTION, DIAGNOSIS AND PROGNOSIS OBJECTIVES AND APPLICATIONS

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Abstract: The need for obtaining adequate diagnostic data on aircraft and helicopters and the processing thereof for practical utilization has long been recognized by both the airlines and the military. The implications in regard to flight safety, operational availability of the vehicle, and maintenance and logistics economics are too tremendous to ignore. The techniques for obtaining and processing such diagnostic information have been the subject of considerable experimental research and development over the past several years. The advent of reliable miniaturized transducers as well as data processors/computers has now made onboard diagnostics a current technical feasibility for even a light helicopter such as the Hughes 500D.

Data projected to be measured and processed include engine condition, gearbox condition, vibration levels, rotor hub and swashplate bearings condition, and flight structural envelope exceedance.

Detection, diagnosis and prognosis (DD&P) applications that either have been, or are being, considered by Hughes Helicopters in regard to its 500D light helicopter are:

1. Use of the recently developed and FAA certificated onboard computer system.

2. Installation of a system for providing a quantitative display in the cockpit in the event of tail rotor imbalance.

3. Development of an engine data recording and analysis system with the objective of establishing criteria and method for substantially extending the time between overhaul (TBO) on all engine components.

4. Sampling and analysis of oil from main transmission and tail rotor gearbox at regular intervals with the objective of developing criteria and technique for extending the TBO.

Key words: Detection; diagnosis; prognosis.

Introduction: For many years the military services and the airlines have been testing and using DD&P systems on the larger, more sophisticated aircraft and helicopters. Within the last few years further technological advances in regard to both sensors and data processors/computers have, through miniaturization, reduced the size, weight, and cost of such equipment to the point where it is now feasible and practical to apply it to a light helicopter such as the Hughes 500D (Figure 1). The type of data to be detected, diagnosed, and prognosed ranges from engine condition and performance data to tail rotor imbalance.

Objectives for such a DD&P system for helicopters can be subdivided under three major headings: (1) in-flight, onboard DD&P; (2) test-flight, onboard DD&P; and (3) on-ground-interrogative DD&P for maintenance and record purposes. Because of the unusual extent of rotating mechanical systems in a helicopter, as compared to a fixed-wing aircraft, helicopter DD&P is much more concerned with rotor imbalance, vibration levels, and gears and bearings deterioration. Therefore, the greatest program effort at Hughes Helicopters has been in these areas.

This paper will consider, first, the needs/objectives for a light helicopter DD&P system, and second, the DD&P applications, either existing or in work, at Hughes Helicopters for the 500D light helicopter.

Discussion: The need for obtaining adequate onboard diagnostics data and the processing thereof for practical utilization has long been recognized by both helicopter manufacturers and operators. Until recently, this type of equipment was too large, too heavy, and too costly to consider for installation in a light helicopter such as the Hughes 500D. However, the advent of reliable miniaturized transducers, as well as miniaturized solid-state computer/data processing technology, has now made onboard DD&P systems technically feasible, and even practical, for light helicopters. The benefits to be derived from such a system include: improved safety, improved operational availability, reduced maintenance costs, etc.

As an example, miniature vibratory transducers are now available that are roughly the size of a pencil eraser. Similarly improved sensors are also available for pressure, temperature, noise, displacement and the like. Even so, an onboard detection, processing, and display/warning system should be held to the practical minimum consistent with flight safety and operational needs. More detailed and more sophisticated DD&P equipment could be installed or added to only as required for occasional test flights or for specific problem analysis and correction. Also, additional data in unprocessed form could be simply recorded for interrogation and analysis by ground based equipment at a later convenient time, or for occasional sampling and reporting on the ground.

The three main categories of DD&P systems are shown in Figure 2. The objectives for the overall DD&P system have been so categorized in order to provide the most important in-flight information first, with the test flight portion to be installed only as needed for more detailed troubleshooting. The on-ground portion would be interrogated and analyzed at a convenient time and location for routine maintenance and operational purposes. These would include prediction of needed replacements or overhauls. Economics, as well as safety, of operation would benefit significantly from greater reliance upon "on-condition," instead of arbitrary, replacements and overhauls.

<u>Needs/Objectives of a Light Helicopter DD&P System</u>: First, a list of potentially critical helicopter mechanical and structural problem areas was compiled and broken down into the three aforementioned categories, as shown in Table I and diagramed in figure 3. These potential problem areas were broken down by (1) system or major component, (2) description of the potential problem in each case, and (3) the type of information in need of detection by the DD&P system. Then the type of sensor/transducer needed for measuring each type of data was considered. The type of processing and presentation of the DD&P results was then considered, including the display thereof. Table II shows a summary of the DD&P objectives for a light helicopter. It is evident that, in the area of structural information, we are most concerned with the structural deterioration of the main and tail rotor blades and with the vibratory loads imposed on the remainder of the airframe structure by rotor imbalance, out of track, etc. In the area of mechanical/propulsion systems, on the other hand, we are concerned with gears, bearings and engine deterioration. The methods of

sensing these items are also indicated in the table. Other factors; such as, counting the number of engine/rotor stop/starts, and the number of exceedances of design rpms, speeds, g-limits, yaw limits, blade flapping limits, hard landings, etc, would also be very useful both to the pilot and to the owner/operator. Once such information has been detected and measured, it must be processed and compared to some preestablished norm to determine whether it is of sufficient magnitude for either display or warning to the pilot. The type of display and/or warning is also a factor to be considered. Figure 4 diagrams a typical helicopter DD&P system from sensor to display and/or warning.

DD&P Applications: The remainder of this paper deals with various DD&P applications on the Hughes 500D light helicopter (Figure 5).

Onboard Computer: In mid-1978, the FAA issued to Computer Avionics Corporation of Santa Clara, California, a supplementary-type certificate for installation of its helicopter computer system (HCS) on the Hughes Model 500 helicopters (Figure 6).

This small computer system starts with a basic manual mode configuration. It accepts inputs from the pilot which are the basis for feeding back to the pilot flight status information. Safety of operation of the helicopter is thus substantially enhanced. The pilot does not have to depend on memory. He is not distracted by the necessity of thumbing through pages of graphs or tables to obtain vital information regarding the condition or performance capability of his helicopter in regard to speed, power available, external load carrying capability, hover capability in- or out-of-ground effect, fuel utilization, etc.

In the more sophisticated optional automatic mode, a sensor support package is added to the basic system. This automatic mode system accepts information not only from the pilot but also from a number of sensors located throughout the helicopter, such as pressure altitude, outside air temperature, engine torque, turbine outlet temperature, fuel flow, airspeed, sling weight, etc. All these serve as the basis for computing; data storage; supplying immediate flight information to the pilot; and, subsequent to the flight, supplying information to the maintenance crew when interrogated.

By a suitable choice of sensors and programming relative to the typical flight scenarios of the operator, the display can bring to the attention of the pilot conditions which warrant his immediate attention; such as, overtemperature, overtorque, rotor overspeed, unusual unbalance conditions, excessive sling load weight relative to hover capability, etc. Moreover, the storage mode provides the capability of accumulating these data for later retrieval on interrogation by the maintenance personnel. These latter are thus informed as to the magnitude, duration, and frequency of exceedance events. Appropriate inspections and corrective action can then be promptly initiated.

The weight of this complete onboard computer system is approximately 15 pounds, (0.5 percent of the gross weight) including the various sensors located throughout the helicopter. The basic manual mode system is several pounds lighter. The display, located above the cockpit instrument panel, is approximately 3 inches high by 9 inches wide. Electrical power required is approximately 50 watts.

Tail Rotor Balance Indicator: A system is currently under development by Chadwick-Helmuth, Inc., which, when installed on the 500D Helicopter, will provide quantitative indications in the cockpit of the status of the tail rotor balance. This system consists of an accelerometer located at the tail rotor gearbox, suitable electronic circuitry (black box), and a cockpit display (Figure 7). This display will provide an indication of vibration velocity in inches per second.

A proper level of tail rotor balance is essential. The level represents a compromise between practical production balancing techniques and the adverse effects of unbalance on the fatiguing of blades, stabilizing surfaces, and tail boom. Because of the tail rotor speed (normally 2933 rpm), the effect on vibration level due to small changes in the blade mass, either in initial production or subsequent service, is substantially magnified.

Limits of unbalance, format for the monitor display, and the circuitry time delays will be finalized during the testing of the prototype installation. The production installation will enable the pilot to immediately determine, by reference to his cockpit display, the status of tail rotor balance. The monitor will indicate the vibration level normal for cruise flight and provide a caution indication when it is approaching an unsatisfactory level and a warning indication when corrective rebalancing should be initiated. A more detailed presentation of the system capabilities is provided in the Appendix.

Engine Condition Monitoring: Hughes Helicopters has under study the development of an electronic data recording and analysis system to monitor the gas turbine engine in its 500D helicopter. The objectives of this system are the extension of time on components, the extension of TBO, and establishing "on-condition" maintenance. Such objectives appear attainable on completion of an initial data collecting and analysis phase in which the correlation is established between the cumulative operating history of an engine and the state of its health at that time. This would be in lieu of the current situation wherein the fixed TBO as specified by the engine manufacturer requires overhaul no matter how excellent the state of health of specific engine may be.

The favorable impact on operational costs is obvious. The type helicopter which delivers payload with less horsepower demands on the engine, and the user, whose operational scenario does not cause a succession of exceedances, will be able to take advantage of these factors in terms of a longer engine life and less maintenance costs. Improved safety will also result because of an increased awareness of engine condition at any point in time.

There are a number of detailed engine criteria which apply in establishing the TBO. Typical criteria are the limitations for the first- and second-stage gas producer wheels; i.e., 1775 maximum operating hours or 3000 cycles, whichever first occurs. A cycle is defined as a start or start attempt. It is recorded by means of an engine-furnished counter which records the number of times the ignition exciter is energized. It is reasonable to assume that a cold start is harder on the engine than one starting from an elevated temperature, such as may exist within a short period following a normal shutdown. The rationale for such an assumption is that in the cold start the engine experiences a much greater temperature gradient on each cycle. Similarly, an engine whose history is one of operating through wide, rapid excursions in N_1 (gas producer rpm), a large percentage of the time at or near the limiting turbine outlet temperature (TOT), or with a number of N_1 or temperature exceedances, will be degraded lifewise more rapidly than one more conservatively operated.

Currently under study is the defining of a suitable data acquisition system. Its "black box" will provide the capability of recording the following data (Figure 8):

1. Start cycles.

2. N_1 (gas producer rpm) excursions.

3. Time at temperature (TAT).

4. Engine start temperature peak.

5. Engine start ΔT (incremental temperature).

Items 1 and 2 contribute to the low cycle fatigue failure mode due to cyclic mechanical stresses imposed on the turbine wheels. Item 3 contributes to the stress rupture failure mode due to thermal stress imposed on the turbine blades. Items 4 and 5 contribute to the thermal mechanical fatigue (rim cracks) failure mode, a function of engine start temperature gradients.

The next phase in the development of the system requires the collecting of a substantial amount of data from a number of helicopter users for operating hours over a time period of up to 2 years. Choice of these users will be such as to provide a wide range of environmental conditions and operational scenarios. The analyses of the operational data will be correlated with data collected during subsequent engine overhauls. Based on these correlations, criteria will be established dealing with each of the detail specifications which currently define the TBO for all engines. Once established, these criteria will permit appropriate extension to the TBO of a specific engine based on its actual operational history.

The end hardware (black box) system which will ultimately be used to monitor the engine condition will be defined based on the data analysis, correlations, and criteria established by the initial phases outlined above. Such end hardware will also provide suitable cockpit displays.

Extension of Time Between Overhaul (TBO): The long-term objective is to increase the TBOs of the main rotor transmission (Figure 9) and the tail rotor gear box (Figure 10) to on-condition overhaul. Currently inspection and overhaul are at 1800 hours. Current oil changes are at 300-hour intervals. Extension of time between oil changes is a short-term objective. A program has been established to document data obtained from TBO transmissions returned from service to determine problem areas. As such discrepant conditions are uncovered, corrective action will be incorporated. Extensions to the TBO will be possible once an adequate data base from Field Service has been compiled.

Implementation of this program has been initiated through a cooperative plan between Hughes Helicopters and a fleet operator of the Model 500D. This operator is achieving a utilization of approximately 1500 hours per year per helicopter. The oil changes for the helicopters of this fleet have been increased from the maintenance manual interval of 300 hours to a 600-hour interval. Oil samples are taken from the main transmission (100 cc out of 6 quarts) and the tail rotor gearbox (100 cc out of 0.4 pint) at 100-hour intervals. A single oil analysis firm has a contract to conduct a spectrochemical analysis of each of these samples with reports being sent to Hughes Helicopters and to the appropriate helicopter service center. On one helicopter the 600-hour spectrochemical analysis has already been completed. To date none of these spectrochemical analyses have indicated any measurable wear.

When the main transmissions and tail rotor gearboxes of any of these helicopters reach the present factory recommended overhaul (1800 hours), Hughes Helicopters will provide an exchange transmission for use while the fleet operator's transmission or gearbox is at Hughes Helicopters. Hughes Helicopters will tear down and examine the unit and, upon reassembly without overhaul, return it to the same service center for reinstallation and continued service in the same helicopter from which it was removed. The accumulation of reports from the oil samples in conjunction with inspections of TBO transmissions and gearboxes will provide a basis for increasing the usable service time on the helicopters of this specific operator. Instead of specific periodic overhauls, maintenance will be a direct function of the actual condition of the transmission.

A program has been established for systematically logging the results obtained on inspection of each transmission returned for overhaul at 1800 hours. This covers the helicopters of all operators. Action will be taken to initiate corrective action on all discrepant conditions uncovered by these TBO inspections. Thus, a data bank will be accumulated covering a very wide range of service environment for the main rotor transmission and the tail rotor gearbox.

The criteria which must be met prior to an increase in TBO beyond 1800 hours or to "on-condition," may be summarized as follows:

1. All discrepant conditions revealed by the fleet service experience shall be corrected and incorporated into the fleet.

2. Inspections of not less than 10 transmissions/gearboxes at 1800 hours must prove that all components appear to be satisfactory for at least another 1800 hours of operation.

3. Analysis of results of abusive testing, i. e., overload horsepower runs in a test cell, must support such an extension.

Caution and Warning Indicators: A number of caution and warning lights are located across the top of the cockpit instrument panel (Figure 11). These indicator light circuits are completed through their respective fault sensors. They function as follows:

1. Engine out. The warning light flashes when engine speed decreases to approximately 55 percent N_1, (gas producer rpm) or less, and/or when the rotor speed (N_R) decreases to approximately 98 percent or less.

2. Main transmission oil temperature. If transmission oil temperature rises to 250°F, a temperature-sensing switch actuates to energize the flashing warning light.

3. Main transmission oil pressure. In case of reduction or loss of transmission oil pressure (below approximately 15 psi), a pressure-sensing sender energizes the warning light.

4. Battery temperature. The warning light illuminates at a battery temperature of 160°F. The caution light illuminates at 140°F.

5. Chip detector caution lights. When sufficient loose ferrous material is magnetically accumulated on the chip detectors, the appropriate caution light illuminates. There are two detectors in the engine oil system, two in the main transmission, and one in the tail rotor gearbox.

6. Fuel low. When supply fuel weight decreases to 35 pounds, a spring wire contact is made by the tank unit float arm to complete a ground circuit and illuminate the warning light.

7. Fuel filter. If the engine fuel pump filter becomes clogged, a warning light is illuminated by a case-grounded differential pressure switch.

8. Generator out. If the generator output voltage falls below battery voltage, a reverse current relay disconnects generator from the 28-vdc bus and causes the light to illuminate.

Because of the obvious serious nature of "engine out," an audible warning horn is activated in conjunction with the panel warning light. In addition, available as a separate kit, there is an engine automatic reignition system. It provides a means to automatically reignite the engine when either or both of the following conditions exist:

1. Engine N_1 (gas producer rpm) is less than 55 percent or

2. The N_R (rotor rpm) is less than 98 percent (i.e., less than approximately 460 rpm).

Conclusions: DD&P applications are now feasible for a light helicopter such as the Hughes 500D. This results from miniaturization and cost reduction of the system components, all the way from the sensors to the displays. Improved flight safety, improved operational availability, and reduced maintenance costs are the significant benefits to be expected.

APPENDIX

ON BOARD VIBRATION MONITOR SYSTEM

CHADWICK-HELMUTH COMPANY of Monrovia, California is actively engaged in developing a miniaturized version of their VIBREX helicopter vibration measuring equipment. The new version is designed to be used as a continuously operating "on-board" monitor to indicate in-flight conditions and trending of from one to six vibration modes in either or both the main and/or tail-rotor drive trains and mechanisms.

The approach taken consists of detecting of the vibration signals by one or more accelerometers permanently mounted on the rotor mounts and feeding these signals into a set of miniaturized active "band-pass" filters and amplitude detectors. These filters are pre-set to respond only to the pertinent frequencies at selected aircraft operating speeds. The pass bank shaping of the filters is such that normal tolerance variations of speed of the helicopter components will not affect the output significantly.

Cockpit indication of vibration level is observed on a vertical set of five Light Emitting Diode (L. E. D.) indicators for each channel. The threshold levels of the detectors are set such that the second light from the bottom, a green indicator, will be lit in normal operation. The bottom indicator will only be lit when the channel is not receiving any signals, thus indicating a faulty channel or accelerometer. Third from the bottom is a yellow L. E. D. to indicate "above normal" operation, or caution. The fourth light is red to show excessive vibration. The fifth, or top, L. E. D. is also red, but "latches on" to show that the excessive level has been reached for a time considered to suggest a dangerous vibration/time level.

Only one light per channel is lit at any time except when the time limit at excessive level has been passed. A reset switch is provided to "unlatch" any exceedance indicator so that the pilot can restore normal indication if vibration levels fall back to safe ranges as indicated by the green indicator. The pilot might do this, for example, if the excessive vibration level were knowingly exceeded in a necessary violent maneuver as would occur in an emergency or in violent weather conditions. The latched "danger" indicator would have shown the exceedance of maximum level/time conditions, after the event, even if the pilot had not noticed the fourth level red light at the time of occurrence.

The instrument is packaged in two configurations at this time. The first one is a single unit to be mounted in the instrument panel. This unit is 2-1/2 inches high and its width is dependent upon the number of channels desired. Each channel is a plug-in module, three quarters of an inch wide, with one additional module for power and reset switches in each frame. In this configuration a four channel, a vertical and a horizontal tail rotor, and a vertical and a horizontal main rotor indicator set for example, would require a panel space of 3-3/4 inches wide by 2-1/2 inches high. Depth behind the panel is approximately seven inches including relief for cables and connectors. Weight of the four-channel indicator is slightly under 14 ounces. A six channel unit would be 5-1/4 inches wide and weigh approximately 18 ounces.

The alternate model puts four channels in a one pound package placed somewhere conveniently behind the instrument pod or elsewhere on the aircraft with the indicator L. E. D.'s, all twenty of them, mounted in an instrument indicator bracket, approximately 3/4 inch high by one and 1/4 inch wide, with the push button "Power On" and "Reset" switches mounted nearby. The L. E. D.'s are 1/8 inch by 1/4 inch rectangular units so that a normal flight indication would be an almost continuous line of green horizontally, with yellow or red vertical excursions above the normal position at the indicating channel position.

In both configurations, the instrument operates from the ship's 24-volt d. c. power with a power consumption of less than 10 watts.

The band-pass filters in both configurations of the instrument are small plug-in modules. Each module can be tuned to any frequency within a twenty-to-one range and the series of modules are available from 5 R. P. M. to 100,000 R. P. M., for measuring rotating mechanisms, and from approximately 1 Hz to 10 KHz for other types of higher order vibration.

The accelerometers are either Chadwick-Helmuth standard piezoelectric units for single axis monitoring or a new two-axis unit for simultaneous vertical and horizontal channels from one mounting. These same accelerometers and cables can then be used with the full Vibrex equipment to correct an "out-of-balance" or "out-of-track" condition when indicated by the in-flight monitor.

Preliminary flight tests of the prototype units have been performed and further, more extensive "permanent" mountings and flight tests are scheduled within the next two months. Release of the product is forecast to be early to mid 1979.

TABLE I. POTENTIAL HELICOPTER DD&P AREAS

Item	Information Desired	Detectable Phenomena	Sensor/Transducer
Main Rotor	Blade continuity	crack detection	fine wire
	Hub shake	cyclic acceleration	accelerometer
	Hub bearings condition	temperature and noise	thermocouple and microphone
	Swashplate bearing condition	temperature and noise	thermocouple and microphone
Tail Rotor	Blade continuity	crack detection	fine wire
	Hub shake	cyclic acceleration	accelerometer
	Swashplate bearing condition	temperature/noise	thermocouple/microphone
Main and Tail Gearboxes	Metallic debris	loose ferrous particles	magnetic detector
	Loss of lubrication	oil temperature	thermocouple
	Bearings and Gear condition	noise	microphone
Engine	Flameout/loss of power	gas producer pressure/temperature/rpm	pressure/thermocouple/rpm
	Loss of lubrication	oil temperature	thermocouple
	Gearbox and bearings condition	noise	microphone
Airframe	Flight envelope exceedance	excessive strains	strain gages
	Operating maneuver spectrum	"g" levels	accelerometer
	Landing severity	"g" levels	accelerometer

TABLE II. SUMMARY - HELICOPTER DD&P OBJECTIVE

I. Flight Operations Onboard DD&P
   A. Vibration levels.
   B. Structural deterioration.
   C. Primary bearings deterioration.
   D. Gearbox deterioration.
   E. Engine deterioration.
   F. Flight envelope exceedances.

II. Test Flight Onboard DD&P
   A. Vibration analyzer.
   B. Rotor track/pattern analyzer
   C. Stress/strain analyzer.
   D. Performance analyzer.
   E. Stability/control analyzer.

III. Ground Interrogative DD&P
   A. Rotor balance analyzer.
   B. Engine gearboxes oil analyzer.
   C. Flight controls rigging and wear data.
   D. Landing gear oleos condition.
   E. Function and continuity of detection/warning system.

Figure 1. Hughes 500D Light Turbine Helicopter

- FLIGHT OPERATIONS ONBOARD DD&P
- TEST FLIGHT ONBOARD DD&P
- GROUND INTERROGATIVE DD&P

Figure 2. Categories of Helicopter Diagnostic Systems

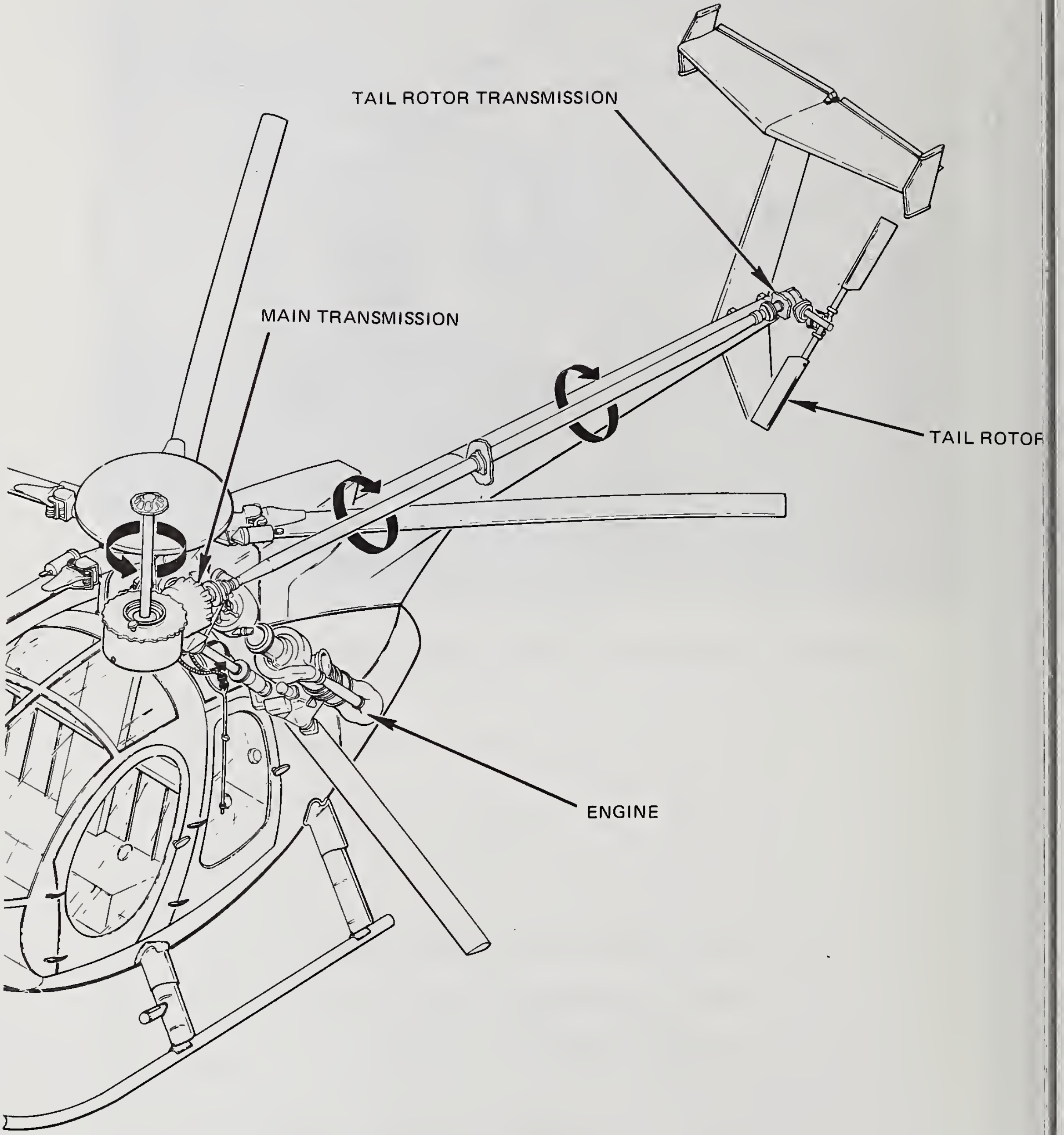

Figure 3. Hughes Model 500D Helicopter - Potential DD&P Items

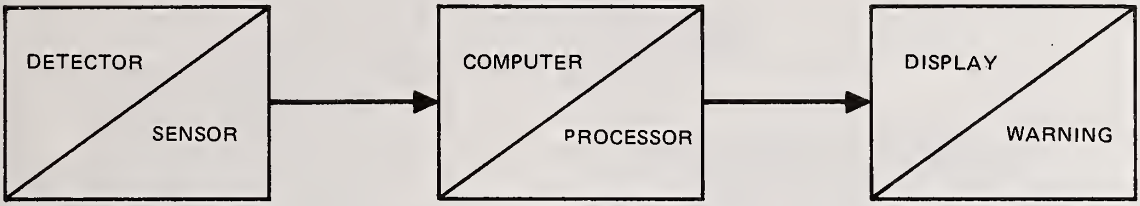

Figure 4. Block Diagram of Typical DD&P System

- ONBOARD COMPUTER
- TAIL ROTOR IMBALANCE INDICATOR
- ENGINE CONDITION MONITORING
- TRANSMISSION TBO EXTENSION
- CAUTION AND WARNING INDICATORS

Figure 5. Hughes 500D Helicopter DD&P Applications

Figure 6. Hughes 500D Helicopter — On Board Computer

Figure 7. Tail Rotor Imbalance System — Hughes 500D Helicopter

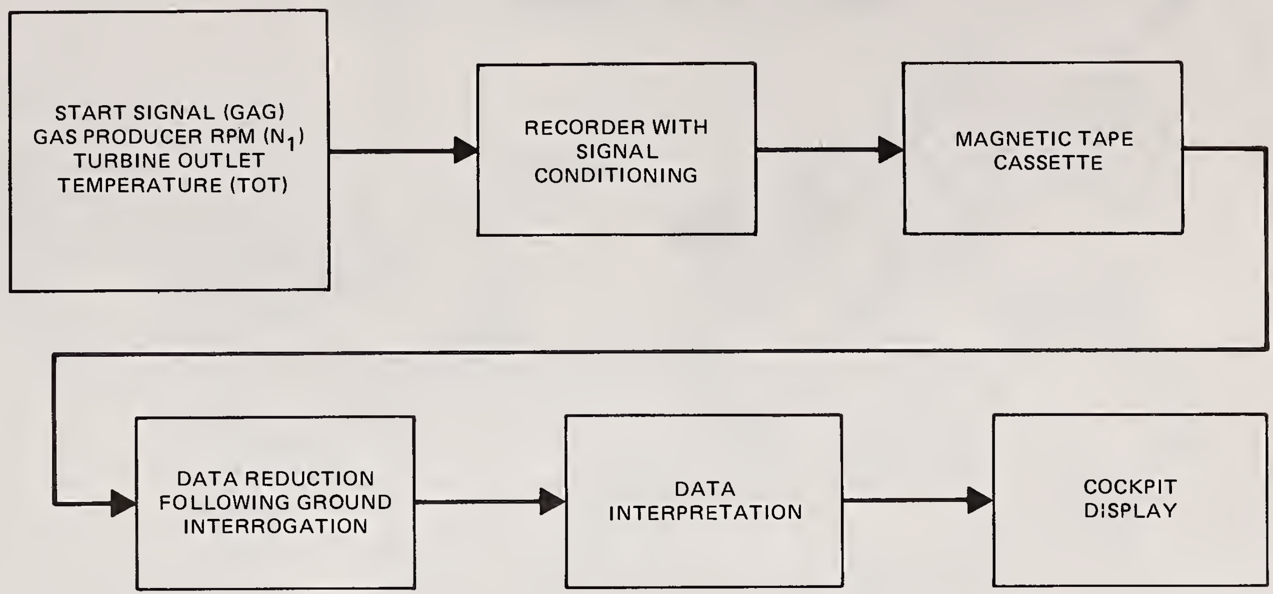

Figure 8. Engine Condition Monitoring System

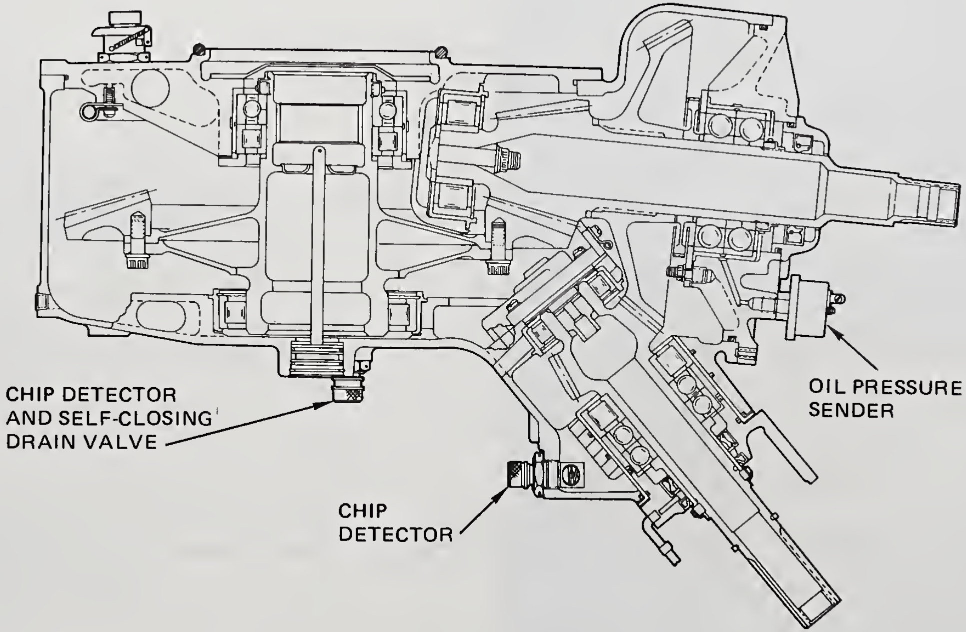

Figure 9. Hughes 500D Helicopter-
Main Rotor Transmission

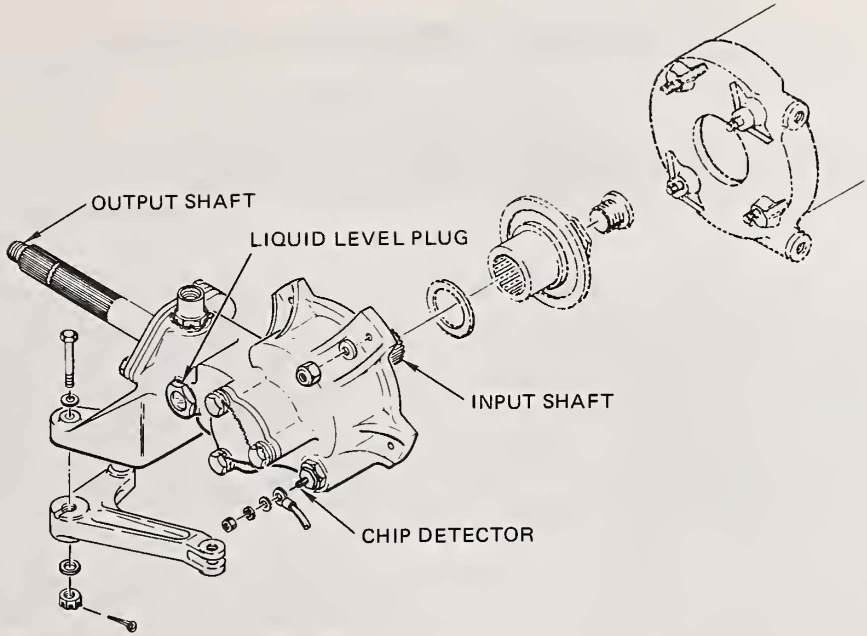

Figure 10. Hughes Model 500D Helicopter – Tail Rotor Gearbox

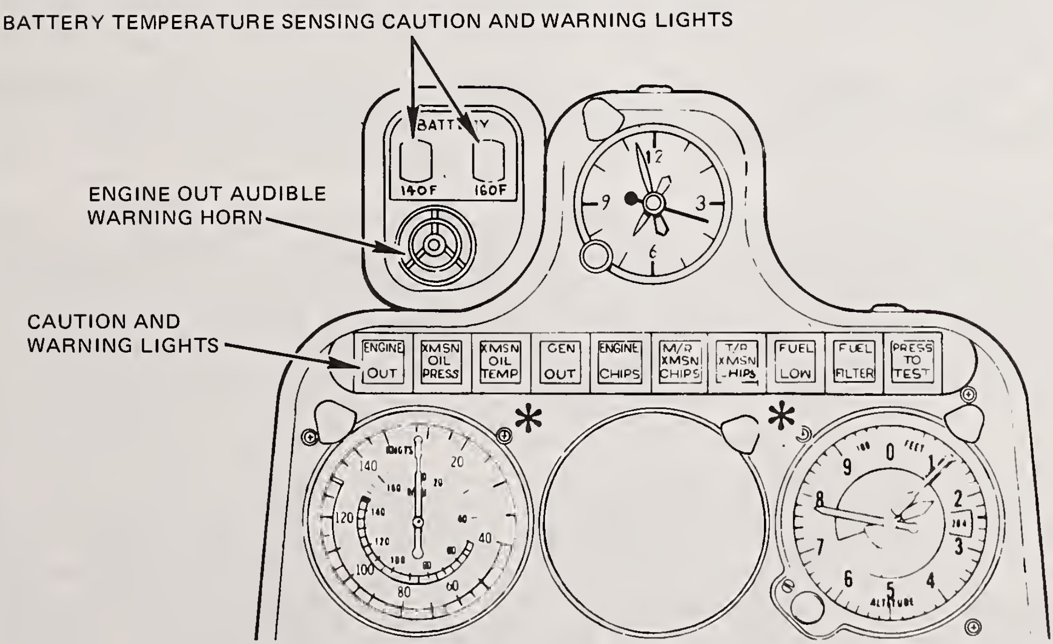

Figure 11. Hughes Model 500D Helicopter – Caution and Warning Display

GAS TURBINES AND MILLIMETER-WAVE RADAR

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Abstract: The Doppler Effect is widely used for detection and analysis of remote moving objects via radar, sonar and beacon systems. Doppler radar at millimeter wavelengths has been used to measure vibration amplitude and frequency in physically confined systems at short ranges. Methods for calibration of the radar for accurate vibration amplitude and static displacements have been worked out in principle. Limited testing has been done on an operating gas turbine proving the feasibility of the millimeter radar technique.

Some background to support the doppler radar technique is presented. However, the principal point to be made is that in the last several years, significant advances have been made in extending the frequency range of practical millimeter hardware to 100 GHz and above and in building extremely tiny and simple radar sensors to operate at these frequencies. This means that sensors for a wide variety of applications can be tailored to exact requirements and produced at low cost. Practical considerations for gas turbine measurements include probe design and transmission and absorption of millimeter radiation in various materials and gases.

Key Words: Advanced sensors; gas turbine monitoring; vibration measurement; doppler millimeter radar; remote motion detection; static displacement measurement.

The Doppler Effect is widely used for detection and analysis of remote moving objects via radar, sonar and beacon systems. Doppler radar at millimeter wavelengths can also be used to measure motion, including vibration amplitude and frequency, of mechanical systems at short ranges. Radial motion of the object (target) relative to the radar results in frequency shift (doppler shift) of the reflected signal (echo) that is proportional to the relative target velocity. No frequency shift results from purely angular motion of the target relative to the radar. A simple radar can be constructed (See Figure 1) that employs a non-linear element (mixer diode) as a detector. The transmitted signal and the echo signal are combined and applied to the mixer diode. Sum and difference frequencies of the two signals and their harmonics are produced by the non-linearity of the diode. Filtering can eliminate all but the difference, Δf, of the fundamental frequencies. This signal at the frequency Δf can then be amplified and analyzed. For purely radial motion of the target at velocity v the doppler shift is

$\Delta f = 2f_0 \frac{v}{c}$ where f_0 is the transmitted radar frequency, and c is the velocity of light.

When the echo from a vibrating target is mixed with the transmitted signal the filtered output of the diode can be expressed as a voltage, V, with two components.

$$V = V_0 + V_1 \cos 2\pi ft \qquad (1)$$

Both dc component, V_0, and ac component, V_1, depend on target size and position, i.e., the amount of reflected RF power and its phase. For target vibration amplitudes that are a small fraction of an RF wavelength it turns out that V_1 is directly proportional to the vibration amplitude and vibration frequency is simply f. This provides a convenient and accurate way of measuring vibration waveforms remotely. For example, if a doppler radar is pointed at a distant operating hi-fi speaker and the mixer diode output is amplified and fed into an earphone an excellent rendition of the music is heard.

A key feature of a radar system is directivity achieved by columnating the electromagnetic energy into a confined beam. In this way reflection from the desired target can be enhanced and reflections from nearby unwanted reflectors near the target can be minimized. As the wavelength of the radiated energy is decreased the size of the radiating probe or antenna can be made smaller (in direct proportion to the wavelength) while preserving the same degree of beam confinement. Thus radar at millimeter wavelengths (λ = 1 to 10 mm) is convenient to use where small size probes are desired (See Figure 2). This is an important advantage for the utilization of radar probes on turbines or other rotating machinery where introduction of large perturbing mechanical structures could degrade turbine performance.

Practical millimeter-wave radar techniques for mechanical diagnostics depend critically on the availability, cost and performance of semiconductor devices and RF components to perform the functions indicated in the block diagram of Figure 1. All of the necessary components are now available from Hughes and from other manufacturers. Hughes has also developed a simple, single-diode, self-mixing doppler sensor that accomplishes all of the functions shown in Figure 1.

A prototype doppler radar operating at 50 GHz corresponding to Figure 1 has been built and tested. Initial experiments were conducted using off-set round stock in a lathe with attachments to simulate rotor blades. It was verified that the signal output from the mixer was proportional to the amount of off-set and the frequency was the rotation frequency of the lathe. The rotor blades were apparent as a harmonic of the rotation frequency.

A probe was constructed with an open ended waveguide antenna that could be screwed into a gas turbine case. Experiments on an operating gas turbine in an engine test stand showed that the radar output waveform could be directly correlated with the output from magnetic probes that had been previously installed in the turbine. Thus the feasibility of millimeter-wave doppler radar for measuring vibration in operating gas turbines has been demonstrated.

The questions remaining about the usefulness of this general technique for the analysis of mechanical systems operating in adverse environments can be listed as follows:

1. Can an accurate method for in-situ calibration be implemented?

2. Can static displacements, e.g., shaft expansion, be measured accurately?

3. Will reflections from surfaces other than the target surface cause errors or ambiguities in data interpretation?

4. Can a simple, accurate and reliable radar probe capable of withstanding the harsh environment of an operating turbine be manufactured at a reasonable cost?

All of these questions have already been examined in detail and techniques have been devised that give promise of providing all of the desired features. What remains to be done is to couple a radar probe design effort tightly with an engine test program so that these problems can be worked out in an orderly and thorough manner.

Acknowledgements: The contributions of Harry Northern of Detroit-Diesel Allison Division of General Motors in testing the prototype radar are gratefully acknowledged.

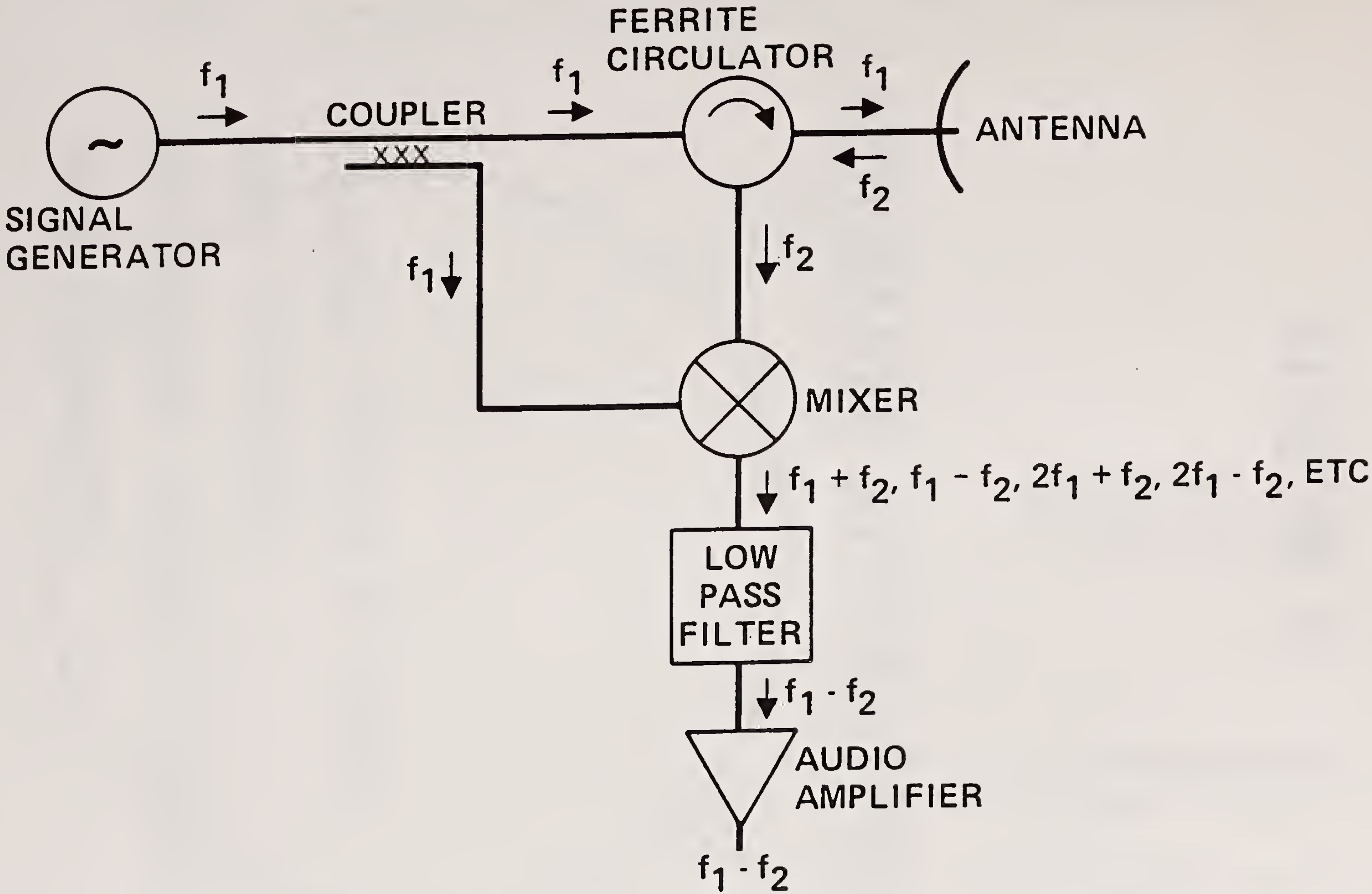

Figure 1. Block diagram of homodyne doppler radar.

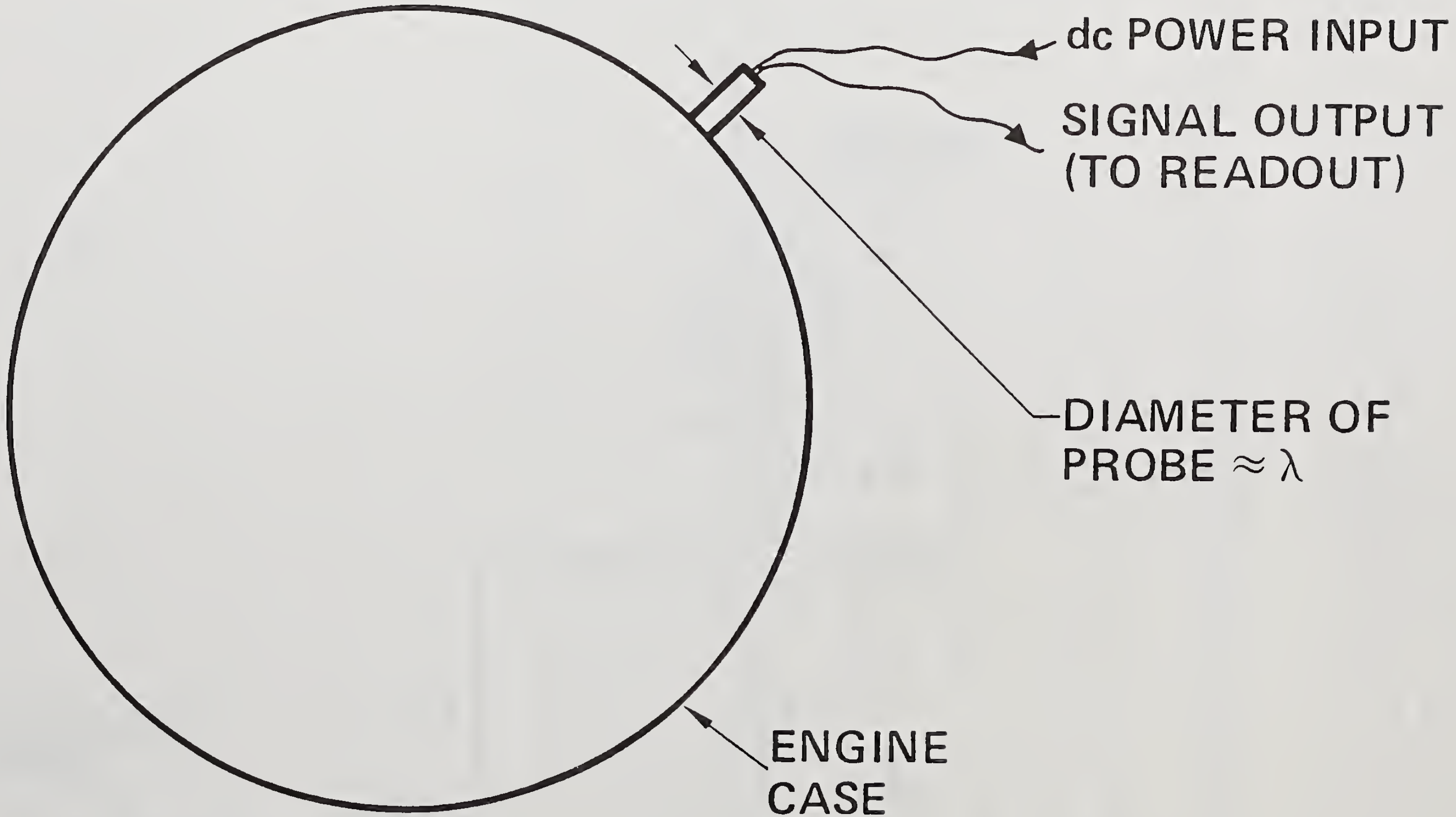

Figure 2. Schematic representation of radar probe mounted on a gas turbine.

SESSION II

LAND BASED APPLICATIONS

Chairman: Richard G. Salter

Rand Corporation

Co-Chairman: William J. Whelan

Rand Corporation

IMPROVING VEHICLE LIFE-CYCLE RELIABILITY BY PROGNOSTIC MAINTENANCE MANAGEMENT THROUGH GERIOMETRY

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Abstract: Land vehicle life cycle reliability is a topical subject. The military is recognizing the necessity to survive the peacetime environment in order to improve combat readiness. Government intervention in the automotive world increases on behalf of energy, the environment, and the consumer. This intervention forces the implementation of revolutionary* designs and technology while insisting on concurrent reductions in consumer maintenance problems and costs. Automobile first costs are showing the effects.

On-vehicle computing instrumentation technology now offers new capabilities to fight the battle through prognostic maintenance management (PMM). Prognosis enables the selection of the best time for maintenance while reducing inspection requirements, vehicle breakdowns and secondary failures. A PMM program enables an improved user confidence while maximizing the productivity of scarce maintenance resources.

On-vehicle microdata systems enable two prognostic techniques: (1) the automation of condition trend analysis, and (2) a new capability--geriometric accounting--the cumulative recording of stress energy and cyclic stress functions which contribute to wear and fatigue damage.

Some homework is required, however--on-vehicle data acquisition sufficient to identify the service parameters to monitor and the necessary maintenance criteria expressed in terms of these parameters. In a practical sense, a bootstrap program is required in which an initial system design will provide for both an operational PMM program as well as the acquisition of data with which to improve both the hardware and the software of the evolving system. We are now in a position to design such an initial system.

The Problem Context

The problem is to reduce the cost of maintaining vehicles while improving their reliability and availability for service. The difficulty is that maintenance systems are falling far short of the desired

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*As opposed to evolutionary changes on a time scale consistent with good automotive development practice.

goals of vehicle users. New maintenance management techniques are now possible through the employment of on-vehicle microcomputers. This paper describes an approach using condition trend analysis and geriometric accounting.[1] This approach is made possible by recent developments in LSI electronic technology.

A key part of the problem is the vehicle itself. Good vehicle development practice requires a deliberate evolution of the vehicle design so that new design concepts can be thoroughly tested in the hands of the user. With this technique, each incremental change and its effect on the entire vehicle system can be evaluated without potentially complex interactions among a great many concurrent changes. This ideal concept is currently practiced only in the commercial trucking industry. The military produces vehicles that are designed for worst-case combat conditions, which means they are not ideally suited to survive the peacetime environment. The combat vehicles are usually of revolutionary design in order to benefit from the latest advances in technology and doctrine. The tactical vehicles tend to be of traditional design, not having benefited from even evolutionary trends. The automotive industry is of course highly competitive and tends to introduce revolutionary designs in order to beat the competition in styling, performance and price. In recent years another influence, emissions and fuel consumption regulations, has strongly forced the implementation of revolutionary technology in new car designs.

The resources expended in maintaining vehicle fleets are significant, but the results obtained are not satisfactory. The Army spends $1.3 billion each year below depot to maintain a $13 billion inventory. The achieved availability is often quoted at the 90 percent level, however most unit commanders would be happy to see 60 percent of their vehicles rise to any given occasion. As for automobiles, the NHTSA has estimated[2] that consumers spend $50 billion annually for maintenance on a $500 billion investment. They estimate that $20 billion of this maintenance cost is improper or unnecessary. It is possible that even more of the cost is avoidable; that increment that is due to the tendency of automobile owners to delay the maintenance of their cars and to drive them until failure occurs. This delay is primarily due to a hesitancy to commit themselves to the time, inconvenience, and expense of the process, particularly when uncertainty surrounds these factors as well as the necessity for the maintenance itself.

There is considerable interest and activity ongoing in the improvement of the maintenance systems. The Defense Advanced Research Projects Agency (DARPA) has been sponsoring the Vehicle Monitoring System (VMS) project which is concerned with the on-vehicle acquisition of use pattern, condition and maintenance data on Army vehicles operating in the field. This effort has been broadened to include geriometric data for use in the development of prognostic maintenance management. The Army is currently fielding the STE-ICE diagnostic test system for better off-vehicle condition assessment and fault isolation of Army vehicles. The

NHTSA is actively investigating the commercial maintenance system, and in particular the potential for diagnostic inspection as a solution to some of the problems. Both the automotive and test equipment industries are implementing new equipment and techniques based on advanced technology and on evolving consumer requirements.

A Taxonomy

Vehicle maintenance[3] is required to offset degradation which occurs as the vehicle is employed. The causes of this degradation are components of normal use, abnormal use or abuse, storage, neglect and the drive-to-failure ethic. Deterioration mechanisms include fractures, fatigue (due to mechanical, electrical, chemical and thermal stresses), wear, age, corrosion, etc. The effects of deterioration are manifested as noise, low power, stalling, breakdown, and secondary failures.

Detection of degradation can be accomplished by visual, audio, or tactile observation by the people involved, employing in some cases an administrative record-keeping system; by testing the system for emissions, function, or alignment with testers such as STE-ICE, Autosense, or built-in test equipment (BITE); or by monitoring the system in-use for status, mileage, or cumulative stress by panel instruments and on-vehicle systems such as VMS.

Maintenance can be categorized as corrective, preventive, or prognostic. Corrective maintenance is the repair of obvious problems and failures. It fixes the effects extant--the failure that has already occurred. It is performed as necessary. Preventive maintenance is intended to slow the deterioration mechanisms--changing the oil will reduce the wear rates. It is usually performed on a time or mileage criteria. Prognostic maintenance is the interception of the deterioration mechanism before the effect happens, thus forestalling the effect altogether. Prognosis can be based on two criteria: condition trends, and cumulative geriometric accounts.

Why Geriometry

Geriometry is the measurement of the causes of vehicle degradation, whereas all other maintenance techniques measure effects. Geriometry can provide prognostic criteria for vehicle subsystems with: unpredictable degradation trend patterns--the degradation curve for these subsystems might, for example, drop so suddenly that anticipation is not possible; wear or fatigue failure mechanisms which represent the most significant failure mode; and inspection difficulties represented by a requirement for significant dissassembly with risk of maintenance-induced failure.

It is estimated that several vehicle subsystems are prime candidates for prognosis based on Geriometry. Brake wearout has been determined to be a function of cumulative energy absorption.[1] Electrical and starting system life might be expected to correlate with their cumulative load-energy flux. Power plants might have several parameters that would correlate with life. These may include a piston travel function for upper cylinder life in reciprocating engines, and a thermal cycle function for both reciprocating and gas turbine engines.

Why Prognosis

Even assuming that Geriometry is important to prognosis, why is prognosis important to maintenance management? The answer, of course, is that some technique is necessary to choose the time for maintenance which will minimize maintenance costs while achieving a desired reliability and availability. The technique must be quantified in terms of measurable parameters and the precision and variance with which these parameters describe the subsystem life must yield decision criteria with close confidence limits. The rationale for prognosis as an effective technique for vehicle maintenance is somewhat subjective since data to prove the contention do not yet exist. It is anticipated by many persons in the maintenance field, however, that a number of benefits will accrue to the implementation of prognosis. Among these benefits are the reduction of secondary failures--the anticipation of the primary failure obviates the possibility of its causing the secondary failure; the reduction of physical inspection requirements--the continuous measurement of the trends and geriometric accounts can be thought of as continuous inspection; and the reduction of "unnecessary" maintenance--by definition, maintenance based on 'optimized' criteria will eliminate premature actions and reduce the tendency to delayed action. It is also anticipated that a proven prognosis technique will improve vehicle owner confidence in the basis for maintenance decisions and indeed allow the owner to concur in and even initiate the maintenance decision. Also, given a cost-benefit criteria, the owner can choose to increase the reliability and availability of his vehicle(s). And finally, these benefits would lead to a better productivity of the maintenance resource system, which is currently highly overtaxed.

Instrumentation Attributes

It is appropriate to comment on the differing attributes of on-vehicle and off-vehicle instrumentation systems. Obviously, on-vehicle systems can measure variables and compute parameters essentially continuously. This capability allows for the automation of trend analysis and the accumulation of geriometric accounts. On-vehicle systems can also advise the operator of emergency situations and perform the functions of the currently popular trip/fuel management computers. All monitoring is accomplished during the normal vehicle use.

Negative attributes for on-vehicle systems include the fact that one system is required for each vehicle to be monitored and thus the cost of the system must be low. Also, the sensors to which the system connects must not only be of low cost, but must also be capable of living continuously in a very difficult environment. The same can be said, however, for the systems and sensors the industry is developing for electronic engine controls and so we may anticipate early solutions.

Off-vehicle instrumentation systems, on the other hand, cannot monitor continuously, but rather must engage in periodic testing, which can support, along with a record keeping system, trend analyses of at least certain variables. Although this capability is more limited, it may still be useful in the overall scheme of maintenance management. Another difficulty is that testing sessions must be scheduled outside of the normal vehicle operating/use patterns. At these sessions, the vehicle must be warmed up and the sensor harness installed. The off-vehicle system however has a number of positive attributes. Chief among these is the capability, through the use of more pervasive sensors, to perform more detailed fault isolation than on-vehicle systems. Thus, off-vehicle systems can be thought of as competent to fault isolate at the component level, whereas, on-vehicle systems are in a practical sense limited to fault isolation at the subsystem level. A final positive attribute of off-vehicle systems is the fact that they can be used across many vehicles and for this reason can contain more expensive components with the attendant advantage of higher precision, etc.

In consideration of the relative attributes, it may be anticipated that a rational maintenance system will contain both on-vehicle and off-vehicle systems and facilities.

Implementation Problems

Primary to the difficulty of implementing prognostic maintenance management is the complexity of existing vehicle systems and their maintenance systems. Compounding the problem is the variability of the use and maintenance patterns in which the vehicles are employed. And fundamental to all of these is a lack of data with which to quantify the system from a cost and performance standpoint. Without this quantification, the benefits of improvements as compared to their cost of implementation cannot be assessed.

Implementation Procedure

Given the frailty of existing data, an implementation program must be designed to bootstrap, that is to take all possible advantage of existing intuition, based on experience, to estimate the actual data requirements and to perform the initial system designs. These designs must not only serve the prime objective of providing owners with a meaningful prognostic maintenance management capability but they must also help to create a better data base with which to evolve and assess the hardware and software of better future systems.

Prognostic Data Development

The size of the "experiment" necessary to achieve a confident characterization of the prognostic parameters for a given vehicle model is determined by the maximum number of variables in any one parameter used to characterize any of the life/failure functions of the vehicle system, and by the inherent variance of this characterization. For most vehicles it is assumed that a maximum of one, two or three variables will be required for any parameter, and that a factor of three will handle the variance of the parameter. Thus, an experiment comprised of ten life/failure cycles should suffice to prove the parameter formulation hypotheses. It might also be assumed that the experiment necessary to prove the generic character of these parameters across various vehicle types would require the testing of ten vehicle types for ten life/failure cycles each.

The engineering of prognostic parameters requires an understanding of the physical degradation process and how the significant variables enter into the motivation of the process. It is expected that this understanding will derive from the experience gained from the many years of vehicle development and use. As an example, we might define a parameter for upper cylinder wear in a reciprocating engine. Engine development lore suggests that the parameter will be a function of the accumulation of engine revolutions, each weighted by its piston speed, its Brake Mean Effective Pressure (BMEP) (a torque function), and by its clearance situation as characterized by its cooling temperature. An expression for this parameter is defined as the product of these factors summed over the engine running history. The formulation must, of course, incorporate estimates of the coefficients and exponents to be used. In this case, nominal values for RPM, EGT, and coolant temperature (CT) (selected to represent the three factors) are estimated at 1000 RPM, 200°F, and the thermostat control temperature. Exponents are assumed to be square, linear and cube for the three factors respectively. The memory requirement needed to accumulate this parameter is quite nominal--essentially just one register which is continually updated so that it always represents the total sum to date.

In the early period of developing parameters to characterize significant vehicle life/failure functions, multiple parameter formulations can be recorded simultaneously--employing different variable sets, coefficients, exponents and even basic formulations. This is possible because of the aforementioned modest memory requirement for each parameter.

The purely statistical technique for developing a prognostic data base requires the continuous time recording of a comprehensive set of fundamental variables, so that they can be analyzed with a regression model. This will allow the derivation by correlation techniques of the significant parameters describing the various life/degradation/failure functions. An alternative technique is to "engineer" these parameters using intuitive engineering judgment. The benefits of using the latter technique are compelling when considering that the memory requirements of the former are over 100 times greater for a similar achievement.

Variables/Parameters

Chart 9 lists a set of variables/parameters, some of which are directly sensed and some of which are computed from sensed variables and/or time, which have been distilled from a much larger set of possibilities. The current list, subject to change as time and experience are accumulated, requires 18 vehicle connections or transducers, most of which will be common with those needed to provide data to engine, spark, and fuel control systems. The prospects for concurrent use of sensors for realtime control and for prognostics reduces considerably the number of additional sensors dedicated only to prognostics.

A Preliminary System Specification

It is now possible to specify and design an initial system with which to begin the implementation process. The system would need approximately 18 sensed inputs and would sense or compute on the order of 30 parameters, incorporating approximately 10 formulations for each parameter. Facilities would include continuous display of critical variables, such as oil pressure, demand display of all variables and parameter registers, and would include the features of trip and fuel management computers. (For rally buffs, it could also provide rally computations.) Other features would include a short term high resolution realtime record, similar to the airline flight recorder, in order to ascertain what happened in the 30 minutes prior to and during a traumatic occurrence. Also, long term trend and geriometric function registers would be incorporated. Trends would be characterized by three values: a time or distance parameter since initialization, a degradation since initialization, and the instantaneous slope or derivative of the degradation curve.

In order to support prognostic maintenance management, the system would be programmed to annunciate the fact that a parameter has reached its maintenance decision criteria level. The display would identify which parameter(s) has reached its criteria. Reset of system *could* be relegated to an inspection system (or a motor sergeant) if appropriate. The system would also be designed to enable a readout device to interrogate the memory and store useful data so that it can be incorporated in a general data base for use in parameter development. This data must be read out in computer-readable format and the readout device must be capable of receiving input describing the maintenance actions that were required. In the case of component overhaul or replacement, the readout device must also be capable of initializing the necessary parameters. Many of these features are now incorporated in the DARPA Vehicle Monitoring System.

Based on the VMS experience and on that with the after-market trip computer devices, it is estimated that the memory requirements for such a system will be of the order of 8k BYTES. Early design might require more memory in order to support program flexibility.

References

1. Salter, Richard G., Geriometry: A Cumulative Stress/Damage Measurement of Useful Life, The Rand Corporation, P-5952, March 1978.

2. Claybrook, Joan B., (Administrator), Statement before the House Committee on Interstate and Foreign Problems concerning Auto Repair Problems and Titles II and III of the Motor Vehicle Information and Cost Savings Act, NHTSA/DOT, September 14, 1978.

3. Salter, Richard G., Maintenance Management Through Diagnosis, The Rand Corporation, P-5867, June 1977.

VEHICLE MAINTENANCE: THE PROBLEM CONTEXT

THE VEHICLES

- MILITARY (DESIGNED FOR WORST-CASE COMBAT):
  - COMBAT – REVOLUTIONARY DESIGNS
  - TACTICAL – TRADITIONAL DESIGNS
- NON-MILITARY:
  - AUTOMOBILES – REVOLUTIONARY DESIGNS
  - TRUCKS – EVOLUTIONARY DESIGNS

THE MAINTENANCE SYSTEM

- MILITARY:
  - $1.3 B ANNUAL MAINTENANCE ON $13 B INVENTORY
  - LOW AVAILABILITY, SHORT VEHICLE LIFE
- NON-MILITARY:
  - $50 B ANNUAL MAINTENANCE ON $500 B INVENTORY
  - $20 B (+) UNNECESSARY, MUCH CONSUMER FRUSTRATION

ACTIVITIES

- DARPA:
  - VMS PROGRAM
  - USE PATTERN AND PROGNOSTIC DATA
- ARMY STE-ICE/ATEPS DEVELOPMENTS
- NHTSA:
  - DIAGNOSTIC INSPECTION EFFORTS
- AUTOMOTIVE/TEST EQUIPMENT INDUSTRIES:
  - MANY COMPUTERIZED TESTERS

CHART 1

A TAXONOMY

VEHICLE DEGRADATION

CAUSES	MECHANISMS	EFFECTS
USE	FRACTURE	NOISE
ABUSE	FATIGUE	LOW POWER
STORAGE	WEAR	STALLING
NEGLECT	AGE	BREAKDOWN
DRIVE-TO-FAILURE	CORROSION	SECONDARY FAILURE

DETECTION

OBSERVATION	TESTING	MONITORING
VISUAL	EMISSIONS	STATUS
AUDIO	FUNCTION	MILEAGE
TACTILE	ALIGNMENT	CUMULATIVE STRESS
BY	BY	BY
PEOPLE	STE-ICE	PANEL INSTRUMENTS
ADM. RECORDS	AUTO-SENSE	VMS
	BITE	

MAINTENANCE

CORRECTIVE	PREVENTIVE	PROGNOSTIC
FIXES EFFECTS	SLOWS MECHANISMS	FORESTALLS EFFECTS
CRITERIA	CRITERIA	CRITERIA
"AS NECESSARY"	TIME	CONDITION/TREND
	MILEAGE	GERIOMETRIC ACCOUNT

CHART 2

WHY GERIOMETRY

- MEASURE CAUSES AS WELL AS EFFECTS
- PROVIDE PROGNOSTIC CRITERIA FOR SUBSYSTEMS WITH:
  - UNPREDICTABLE TREND PATTERNS
  - WEAR OR FATIGUE FAILURE MECHANISMS
  - INSPECTION DIFFICULTIES (DISASSEMBLY)
- SUBSYSTEMS:
  - BRAKES – CUMULATIVE ABSORBED ENERGY
  - ELECTRICAL – CUMULATIVE LOAD ENERGY
  - STARTING – CUMULATIVE STARTING ENERGY
  - POWER – CUMULATIVE OPERATING STRESS AND/OR THERMAL CYCLES

CHART 3

WHY PROGNOSIS

- REDUCE:
  - BREAKDOWNS
  - SECONDARY FAILURES
  - INSPECTION REQUIREMENTS
  - UNNECESSARY MAINTENANCE
- IMPROVE:
  - OWNER / OPERATOR CONFIDENCE
  - VEHICLE AVAILABILITY / RELIABILITY
  - PRODUCTIVITY OF MAINTENANCE RESOURCES

CHART 4

INSTRUMENT ATTRIBUTES

ON VEHICLE

CONTINUOUS MONITORING

- GERIOMETRIC ACCOUNTING
- SUBSYSTEM DIAGNOSIS
- EMERGENCY WARNING
- AUTOMATED TREND TESTING
- OPERATING PARAMETER DISPLAY (TRIP COMPUTER)
- ONE FOR EACH VEHICLE
- SENSORS MUST LIVE ON VEHICLE
- TESTS WHILE OPERATING

OFF VEHICLE

PERIODIC TESTING

- COMPONENT DIAGNOSIS (FAULT ISOLATION)
- TREND TESTING WITH ADMINISTRATIVE PROCEDURE
- ONE FOR MANY VEHICLES
- SPECIAL TEST SESSIONS
  - VEHICLE WARM-UP
  - HARNESS HOOK-UP

CHART 5

IMPLEMENTATION PROBLEMS

- COMPLEX VEHICLE SYSTEMS
- COMPLEX MAINTENANCE SYSTEMS
- HIGHLY VARIABLE EMPLOYMENT
  - USE
  - ABUSE
  - ENVIRONMENT
  - NEGLECT
- DATA
  - EMPLOYMENT PATTERNS
  - DEGRADATION/FAILURE MODELS
    - PROGNOSTIC PARAMETERS/CRITERIA
- SENSORS

CHART 6

PROPOSED IMPLEMENTATION PROCEDURE

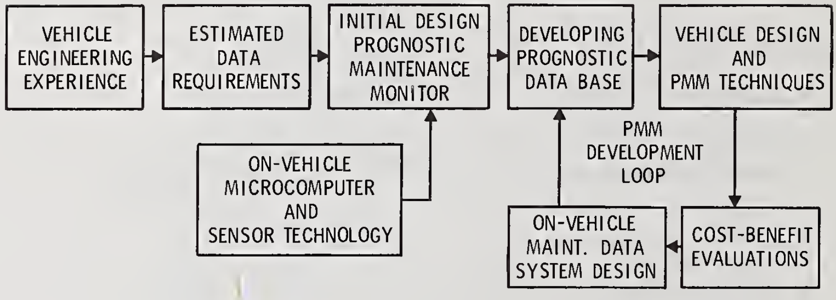

CHART 7

PROGNOSTIC DATA DEVELOPMENT

- FOR EACH VEHICLE MODEL TEST FOR N FAILURE/LIFE CYCLES
  - N = MAX. NUMBER OF VARIABLES IN ANY PARAMETER TIMES f(VARIANCE)
    - ASSUME: N = 3 AND f = 3 OR 10 LIFE CYCLES REQUIRED
- TO ESTABLISH GENERIC CHARACTER OF PARAMETERS
    - ASSUME: 10 VEHICLE MODELS
- "ENGINEERING" A PROGNOSTIC PARAMETER
  - ENGINE CYCLE LIFE: $$\sum_{i=0}^{i=n} (\text{REVOLUTION})_i \, (RPM_i / RPM_0)^a \, (EGT_i / EGT_0)^b \, (CT_0 / CT_i)^c$$
    - ASSUME: a = 2, PISTON SPEED IS SQUARE FUNCTION, RPM_0 = 1000
      b = 1, BMEP IS LINEAR FUNCTION, EGT_0 = 200° F
      c = 3, CLEARANCE IS CUBE FUNCTION, CT_0 = THERMOSTAT TEMP.
  - USE MULTIPLE FORMULATIONS
- DATA MEMORY
  - $$\begin{bmatrix}\text{ENGINEERING PARAMETERS} \\ \text{(VARIANCE MODEL)}\end{bmatrix} = 10^{-2} \begin{bmatrix}\text{STATISTICAL PARAMETERS} \\ \text{(REGRESSION MODEL)}\end{bmatrix}$$

CHART 8

VARIABLES/PARAMETERS

SENSED	COMPUTED
FUEL FLOW (C)	MILES PER GALLON (T)
DISTANCE (C)	BRAKING ENERGY (C)
BRAKE SWITCH (C)	RPM (C/E)
REVOLUTIONS (C)	EGT MANIFOLD BALANCE (T)
EXHAUST GAS TEMPERATURE (2) (C/D)	ENGINE WEAR FUNCTION (C)
COOLANT TEMPERATURE (C/E)	RUNNING TIME FRACTION (C)
OIL PRESSURE (C/E)	NO. COLD STARTS (NO. TRIPS) (C)
BEARING TEMPERATURE (S) (T, C/E)	TOTAL STARTS (C)
VERTICAL ACCELEROMETER (C)	STARTING SYSTEM POWER (T)
IGNITION SWITCH (C)	STARTING SYSTEM ENERGY (C)
STARTER SWITCH	COMPRESSION BALANCE (T)
BATTERY VOLTS (T)	ENGINE POWER (T)
START CURRENT (T)	COOL DOWN TIME (C/D)
CHARGING CURRENT (T)	TRIP LENGTH (C/D)
AIR FILTER ΔP (T)	TRIP SPEED (C/D)
OIL FILTER ΔP (T)	
COOLANT LEVEL (T)	
OIL LEVEL (T)	

C — Cumulative T — Trend E — Excursions D — Distribution Moments

CHART 9

A PRELIMINARY DATA ACQUISITION SYSTEM SPECIFICATION

- 18 SENSED VARIABLES
- 30 SENSED OR COMPUTED PARAMETERS
- TRIP / FUEL MANAGEMENT FUNCTIONS
- CONTINUOUS OR DEMAND DISPLAY
- SHORT TERM HIGH RESOLUTION TIME RECORDING
- LONG TERM STORED DATA:
  - TREND FUNCTIONS
  - CUMULATIVE GERIOMETRIC ACCOUNTS
- PROGRAMMED WARNING AT CRITERIA FOR TREND / CUM
- COMPUTER READABLE OUTPUT
- MEMORY ~ 8 K

CHART 10

MOTOR VEHICLE FAULT DETECTION AND DIAGNOSIS

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Abstract: Motor vehicle diagnostic inspection demonstration projects conducted by the National Highway Traffic Safety Administration under Title III of the Motor Vehicle Information and Cost Savings Act indicate that high volume diagnostic inspections can result in greater safety, improve fuel economy, and reduce the number of faulty and unnecessary repairs and the amount of motor vehicle pollutants. The projects conducted periodic safety and emissions inspections for a period of 15 months. They provided direct experience and documentation of the benefits and costs of diagnostic motor vehicle inspection.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation, recently completed phase one of a multimillion dollar motor vehicle diagnostic inspection (MVDI) demonstration program. The goal of the federally funded demonstration was to determine if a national system of diagnostic inspection centers would be cost effective in the sense that the public benefits would exceed the program costs. The specific objectives of the program were to provide information and data on the following subjects:

1. The relative costs and benefits of the project.
2. The capability of the motor vehicle repair industry to correct diagnosed deficiencies or malfunctions and the cost of such repairs.
3. Vehicle-in-use standards and feasible reject levels.
4. The efficiency of facility designs employed.
5. The degree of standardization of diagnostic systems and test equipment.
6. The development of diagnostic equipment designed to maximize the interchangeability and interface capability, and
7. Vehicle designs which facilitate or hinder inspection and repair.

To meet these objectives, NHTSA established a comprehensive program for the acquisition, processing and analysis of information and data. At the Federal level, NHTSA provided the basic support -- It established test criteria and diagnostic inspection procedures, designed the experiment and provided the overall technical management to assure timely and successful implementation of the projects. To satisfy the provisions of the Motor Vehicle Information and Cost Savings Act, five such demonstration sites were selected competitively; and through cooperative agreements, Federal funds were awarded to the states in the form of grants with matching state contributions. The five projects selected for the demonstration were located in the States of Alabama, Arizona, Tennessee, the District of Columbia and the Commonwealth of Puerto Rico. Under the technical supervision of NHTSA's staff the D.C. motor vehicle diagnostic inspection pilot lane was dedicated to the demonstration and six new facilities were constructed and equipped with modern diagnostic equipment to conduct safety and emission inspections. While much of the diagnostic equipment employed in this demonstration was of necessity off-the-shelf, some modifications were encouraged to improve system performance.

Two contractors were engaged to provide essential support activities. An engineering support contractor monitored the quality control and reported on project operations and equipment calibration through periodic on-site audits. The focal point for collecting, processing and analyzing data was provided by a program evaluation support contractor. This source was responsible for the ADP activities including periodic data evaluation reports as prescribed by NHTSA to aid overall project management. Although these early data returns could not be used to reach definite conclusions concerning diagnostic inspection, the data were useful in identifying and explaining certain trends with regard to vehicle failure rates, outages by system, subsystem and components as well as the vehicle recruiting efforts. Thus, these early trends facilitated corrective measures in vehicle recruiting activities by identifying hard to fill cells and aided in the assessment of the pass/fail criteria and repair cost information to assure statistical validity of data.

MOTOR VEHICLE DIAGNOSTIC INSPECTION CONCEPT

Inspection/Maintenance Cycle

In order to make a meaningful evaluation of the relative costs and benefits of the projects, two similar groups of vehicles were established at each site. One group was designated the diagnostic or "treatment" group, i.e., the group of vehicles which received specific technical diagnostic information in order to facilitate correction of any component failing inspection. The second group was designated the "control" group, i.e., the group against which the costs and benefits of diagnosis were measured. This group received only pass-fail information. Both groups received a periodic safety and emission inspection in accordance with established criteria. However, only the vehicles in the treatment group received the diagnostic information. A flow chart of the inspection and repair cycle for vehicles enrolled in the demonstration is shown in Figure 1. In addition to the normal periodic inspection, vehicles were inspected whenever the title was transferred to another person, unless the transfer was for the purpose of resale, or whenever the vehicle sustained substantial damage to any safety or emission-related system as prescribed by regulation.

Data Collection and Reporting

Inspection forms were designed to facilitate transfer of information to 80-column punch cards. Although the projects in areas with mandatory periodic motor vehicle inspection (PMVI) were permitted to use their normal (PMVI) inspection forms for the control group and compatible forms for the diagnostic group, NHTSA had the final word on the design to assure uniformity and to facilitate data processing and evaluation. The flow of information is shown in Figure 2.

In addition to the pass/fail and diagnostic information, it was extremely important that repair and maintenance costs were gathered over the entire time span that a vehicle was in the program, not only for inspection-related repairs, but repair costs for normal maintenance between inspections were also reported. This was necessary for both the control and diagnostic groups so that a comparison could be made between the two to see if a reduction in overall repair costs is achieved by the diagnostic group. To the extent possible, parts and labor costs were listed separately for each operation so that inspection-related costs could be separated from owner-requested repairs not associated with the inspection.

THE COMPUTERIZED DIAGNOSTIC INSPECTION LANE

Computer System

Although participating States were provided latitude in the design of facilities and selection of diagnostic equipment, only the District of Columbia engineering pilot lane was designed and equipped with a computerized AVCO 210 diagnostic inspection system (Figure 3).

The system was designed to provide on-line, real time computer control over all inspection sequences. The AVCO System 210 was built around a Digital Equipment Corporation Minicomputer (PDP 11/05) with a 20,000 word memory and a (DEC RK05) disc system with unformatted capacity of 24.4 million bits which interfaces the computer with DEC RK11-DE/DJ disc controller.

In addition to directing all inspection sequences, the computer system acquired manually fed inspection data from visual observations and direct outputs of major pieces of test equipment, and made pass-advise/reject decisions against stored tables of limits. It also compiled lane statistics, and transmitted data to a master computer bank on command.

A motor vehicle to be inspected is first identified to the computer system by entry of pertinent vehicle information via a cathode ray tube (CRT) keyboard terminal at the entrance to the inspection lane (Figure 4). The system then establishes a data file for the vehicle and selects appropriate inspection standards to which vehicle data--derived automatically from test machines or manually via remote entry and display terminals (READIT's) is entered. All communication between the inspectors at each test station and the computer is carried on via the hand-held, overhead-supported READIT pendants. Five of these pendants are suspended along the lane--one each at inspection stations 1, 3, and 4, and two at inspection station 2. A close-up of a READIT pendant is shown in Figure 5. The system file contains tables of specification limits against which front end alignment and ball joint play measurements are compared to determine the acceptability or unacceptability of the vehicle being tested. In addition to using data from these tables, the system selects appropriate tests based upon the body style and model year of each vehicle tested.

Each test station in the lane contains one or more items of motor vehicle test equipment directly connected to the computer, and each is also assigned a sequence of manual tests to be conducted in a prescribed order. The inspector need only determine that a specific test is required or unacceptable. The computer makes all advise or reject decisions on the basis of criteria entered in the system.

All direct interfaces between the computer and the test equipment involve test equipment output data only and in no way influence the normal operation of this equipment. In all instances, the test equipment is operated using the same procedures as would be used without the direct computer tie. Thus this equipment may be operated manually at any time without regard for the status of the computer. A description of the major pieces of equipment shown in Figure 4 and the automatic interface with the computer system follow:

Entrance Station

Contains a cathode ray tube (CRT) display and integral keyboard unit used for entering vehicle identification information into the system and for all communication with the computer system. The CRT also provides means for editing test sequences, viewing lane statistics, changing modes of operation, detecting and correcting anomalous operation, and for all off-line communications with the computer.

This unit is an entirely self-contained alphanumeric video display unit that can display up to 1440 characters large and legible enough to be easily read under most ambient lighting conditions.

Station 1

Contains READIT pendant 1, a roller brake tester, an exhaust emission tester, and a chassis dynamometer. The READIT provides a 15-character alphanumeric display for presenting computer-generated instructions to the inspector, and a compact keyboard containing 14 keys (10 numeric and 4 special function) used by the inspector to enter judgments and commands to the system. A code book affixed to the front of the READIT (see Figure 5) provides a complete listing of all GENERAL, SPECIAL, and TEST ID codes for convenient reference.

Roller Brake Tester. The system interfaces directly with the output of the minicomputer-controller of the tester. All front panel MARGINAL and FAIL light indicators of that equipment are monitored directly by the AVCO System 210 computer upon command of the inspector via the READIT. The system records all MARGINAL and FAIL lamps operated during the brake test. In April 1975, this minicomputer-controller was shut down and the brake analyzer was operated manually. The chassis dynamometer described next is integral with this brake analyzer.

Chassis Dynamometer. The system interfaces directly with the chassis dynamometer, and both the ROADSPEED and HORSEPOWER analog meters of that device are monitored by the computer. Upon command of the inspector via the READIT, the system records the meter values and stores them in the Vehicle Processing File for the vehicle under test. These readings are taken simultaneously with the exhaust emission readings in response to a single inspector command.

Exhaust Emissions Tester. The system interfaces directly with the exhaust emissions analyzer, and both the Hydrocarbon (HC) and Carbon Monoxide (CO) analog meters and their associated range switches are monitored by the computer. Upon command of the inspector via the READIT, the system records the meter values and compares them to standard values for the model year of the vehicle under test.

Station 2

Contains READIT pendants 2 and 3, and a scuff gauge. Since READITs 2 and 3 are used in the same station, they are so coupled into the system that all testing assigned to each READIT at that station must be accompanied before a vehicle can be logically cleared from this station. They operate as independent READITs in all other respects.

Scuff Gauge. The system interfaces directly with the scuff gauge, and both the scuff value and direction are monitored by the computer. Upon command of the inspector via the READIT, the system records the peak scuff value and direction of scuff and compares these values to the standard value stored in the system.

Station 3

Contains READIT pendant 4 and a dynamic front end alignment tester.

Front-End Alignment Tester. The system interfaces directly with the dynamic front-end alignment tester, and all CAMBER, CASTER, and TOE analog meter outputs are monitored by the computer. Upon command of the inspector via the READIT, the system records the meter values and compares the caster, camber, and toe values to the specification values for the make, model, and year of the vehicle under test.

Station 4

Contains READIT pendant 5 and a platform brake tester.

Platform Brake Tester. The system interfaces directly with the platform brake tester, and the force levels on all four platforms are monitored by the computer. Upon command of the inspector via the READIT, the system records the peak platform force levels; computes the side-to-side imbalance ratios of both axles, and the front to rear imbalance; and compares these imbalance values with standard values. The system also compares the imbalance values with those determined during the roller brake test (conducted earlier in the lane).

Exit Station

Contains a line printer with an integral keyboard unit.

The printer generates a concise report (with a carbon copy) of inspection results at the lane exit. One copy is given to the vehicle owner and the other is retained on file at the inspection facility. The print-out is made automatically on special forms pre-printed with general information. The form used by the District of Columbia, Bureau of Motor Vehicle Services is extremely functional in relaying diagnostic information to owner and garage.

This unit prints from a set of 64 characters at speeds of up to 30 characters per second. Data is entered from a 96-character keyboard. It is also used in changing the number of sequence of the stickers used to indicate that vehicles have satisfactorily completed inspection.

ASSESSMENT OF MOTOR VEHICLE DIAGNOSTIC INSPECTION

Impact on Safety

One of the objectives of the MDVI demonstration projects was to provide a comprehensive analysis concerning vehicle-in-use (VIU) standards and the sensitivity of rejection rates to changes in these standards. Degradation data were analyzed at the system and component levels, and related quantitative data were analyzed by site. Life-cycle data were limited to the first, second and third periodic inspections of approximately six month duration for each cycle.

Although each project site was required to perform certain basic diagnostic inspections, they were allowed to expand the list of criteria, e.g., states or cities with PMVI programs were allowed to include mandatory system or component inspections. All projects also performed inspections of additional safety-related items not addressed by the Federal VIU Standard. These varied somewhat among the projects, and included headlamp function and aim, other lamps and reflectors, seatbelts, body condition, glazing condition, exhaust system, fuel system, underhood and electrical items. The criteria common to all project sites as promulgated by the NHTSA is expressed in Part 570, Vehicle In Use Inspection Standards, of Chapter V, Title 49, Code of Federal Regulations. The VIU Standards address the brakes, steering system, suspension system, and tire and wheel components. These are the systems and components which vehicle safety research has shown to be safety critical.

An analysis of the data from over 125,000 in-depth inspections (including reinspections after repairs) covering a 15-month period yields some startling statistics. One the average, 74 percent of the vehicles in the program failed the initial periodic inspection. In states without a mandatory PMVI program, over 90 percent of the vehicles failed the initial inspection (Table 1). It is encouraging to note that the safety and emissions systems of vehicles in the program show a 23 percent reduction in the reject rates for the relatively short period of the demonstration. Furthermore, the reject rate decrease from the initial inspection to the third cycle inspection is statistically significant to a high level of confidence. The values shown in Table 2 reflect inspection failure rates for the Federal VIU safety and emission systems criteria. Again, in all cases a significant improvement in the mechanical condition of the systems and components was realized from the initial (P 1) to the final (P 3) inspection. Analysis of the pass/fail rate data from the first and third periodic diagnostic inspections show 57 percent improvement in the condition of the vehicle safety and emissions systems. In the safety critical brake system area alone, 35 percent of vehicles diagnosed had unacceptable system or component degradation. This unusually high failure rate has substantial safety implications, as brake problems account for nearly half of the vehicular factors which caused accidents. However, it is noteworthy that the reject rates were steadily decreasing over the life of the demonstration. A low reject rate is a measure of the roadworthiness of a vehicle from the safety point of view. One final point that must be made is the fact that advisories, which are an important part of the long-term safety condition of vehicles, were not reflected in the above tables but could enhance safety under extended life cycle test conditions.

Impact on Emissions

In addition to periodic safety inspections, the demonstration projects were required to conduct emissions inspections pursuant to the criteria promulgated by NHTSA in consultation with the Environmental Protection Agency. The pass/fail levels for emissions were based on EPA recommendations and on comments from the private sector. As such, the criteria represent a fair balance between low and high rejection rates to avert adverse public reaction to the demonstrations. The compromise emissions criteria and test procedures provided for both the no-load or idle test and the loaded-mode test conditions. In each case two major air pollutants were measured -- carbon monoxide (CO) and hydrocarbons (HC). The relative HC and CO emission levels determined under loaded mode inspection were also used in diagnosing engine malfunctions.

Although NHTSA did not issue standards concerning specific emission-related components and systems, the Guidelines for State Proposals suggested that the projects consider inspection of the PCV valve, air filter, idle speed, sparkplug firing voltage, available coil voltage, coil/condenser oscillations, ignition point operation and dwell, ignition timing and variation, vacuum advance condition, mechanical advance condition, dynamic cylinder balance, and manifold vacuum condition.

No project inspected all items suggested, and there was some variation among the projects. Most of the projects inspected the PCV valve, idle speed, sparkplug firing voltage, available coil voltage, ignition point dwell, ignition timing variation, and dynamic cylinder balance. inspections of the battery and charging system were also frequently performed. Those projects which conducted loaded-mode emission inspections used the results in a "truth chart" matrix to further identify carburetion or ignition problems as the probable source of the high emissions.

Table 3 shows the average emission levels reported for the loaded and no-load modes for each of the inspection cycles. The combined average HC and CO levels were down 22% and 12%, respectively, from the initial to the final inspection. The composite failure rates for the emission tests shown in Table 2 were also reduced significantly, from 22.8% to 9.9%, over the program duration. Results of loaded mode testing show that:

- Idle test failures accounted for 60 to 80 percent of all emissions outages
- CO failures accounted for 48 to 65 percent of all emissions failures
- Idle CO accounted for 26.5 to 48.7 percent of all emissions failures, and
- Idle CO and HC accounted for from 50 to 64 percent of all emission failures.

Program results support the claim that specific diagnostic information on the condition of the engine help the industry to properly correct emissions. The information provided apparently assisted the repair industry in providing adequate repairs at reasonable cost. During the first inspection cycle the rate of faulty emission repairs was about 25 percent for both the diagnostic and control groups. During the second cycle, however, the diagnostic group had a faulty emissions repair rate of only 11.5 percent, which was nearly 30 percent less than the 16.3 percent rate experienced by the control group.

In addition to the clean air benefits resulting from the reduced pollution reported by the data evaluation contractor, fuel consumption data under day-to-day driving conditions indicate a significant improvement in fuel economy (Table 4). The results are based on a representative sample of all model years and vehicle weight classes. The before/after tune-up analysis was conducted for all sites by model year, by weight, class, and by diagnostic versus control groups. The major findings were:

- All vehicles combined resulted in before/after tune-up fuel economy of 4.7%.

- Diagnostic group generally exhibited a greater improvement in fuel economy than the control group (non-diagnostic).

The encouraging fuel economy results based on participant fuel consumption before-and-after tune-ups were substantiated by a joint EPA/NHTSA audit of 57 vehicles enrolled in the Phoenix, Arizona project. These vehicles were subjected to the standard EPA Federal Test Procedures (FTP) urban and highway driving cycle tests. As in the case of the owner-submitted fuel consumption data, the EPA test results show an improvement of 4.9% in fuel economy for compact cars and a FTP composite of 5.3% for intermediate cars.

Conclusions drawn from these data are that periodic diagnosis followed by corrective maintenance reduced exhaust pollution levels of HC and CO, and significantly improved fuel economy for vehicles in the demonstration program.

Impact on Repairs

One measure of the impact on the repair process is an assessment of the capability of the repair industry to repair diagnosed deficiencies and the cost of such repairs. The capability of the repair industry to repair specific outages was determined by reinspecting each item initially rejected. The reinspection failure rate can be a direct numerical measure of the industry's inability to perform adequate repairs in response to inspection results. A vehicle is considered to have failed reinspection of the repair of a defect was attempted unsuccessfully or if no repair was performed on the vehicle. The vehicle reinspection failure rates for the five diagnostic demonstration projects are shown in Table 5. The rates are presented by project and by periodic inspection cycle. The values range from a low of 1.1 percent for the first cycle D.C. control group, to a high of 50.0 percent for the first cycle Alabama control group.

The objective of this task was to determine if detailed knowledge of the specific problem can facilitate correction and impact repair costs. The brake and emissions systems were particularly sensitive to the effect of diagnosis. Analysis showed that approximately 6 percent cost savings was realized from tune-ups and carburetor work for the group with diagnostic information. In other areas, only a marginal savings can be observed. Some of the true value of diagnostic inspection appears to be lost, either as a result of the short duration of the program or the dependence on the consumer and repair industry to effectively use diagnostic information. However, in spite of the modest cost benefits, the concept of an independent, objective diagnostic inspection with no vested interest in the actual repair process was well received by both the consumer and the repair industry. Program participants voluntarily spent approximately $2.4 million on vehicle repairs, many of them spent money for repairs that were clearly discretionary. Furthermore, a closer examination of the results indicate that a vehicle owner armed with diagnostic information has a greater likelihood of receiving correct repairs, particularly for emissions systems. The distribution of repair dollars by subsystems is shown in Figure 6. Brakes, tires and wheels, emissions, and suspension systems account for two-thirds of the repair cost dollars. The average expenditure for vehicle repaired in response to inspection during the program was 57 dollars.

CONCLUSION

The results of the demonstration show that the use of this technology to determine the condition of vehicle safety and emissions systems is viable and that it offers great promise to consumers and repair industry alike. Diagnostic motor vehicle inspection will benefit consumers by providing them information on the condition of vehicles, which if used properly, can result in greater safety, lower pollution, improved gas mileage and in the case of complex vehicle systems generally lower overall repair and maintenance costs.

Perhaps the most gratifying aspect of the demonstration was the consumer reaction to the diagnostic inspection program. A survey of consumer demographic attitudes and experience conducted by a nationally prominent market research group shows that over 78 percent of a national sample of vehicle owners agreed that vehicle inspection should be required by law. When participants were asked if they would join a diagnostic inspection program again, 93 percent said they would. When asked about the amount they would be willing to pay for a diagnostic inspection, over 60 percent were willing to pay $10 or more. Obviously the concepts of an independent, objective diagnostic inspection with no vested interest in the actual repair process was well received by both the consumer and the repair industry. Furthermore, the benefits of diagnostic inspection can be considerably greater by improving communication between the inspection facility and the repair industry. Since the consumer and the repair industry play key roles in the effective use of diagnostic information, further improvement in this critical communication link is highly desirable.

During 1979 NHTSA will continue its diagnostic inspection concept program to compile, analyze, and document a practical set of alternatives by which States, local governments, or consumer groups could make unbiased automotive diagnostic inspection more available to motorists. NHTSA's planning for diagnostic inspection programs is especially timely now because of related activities of the Environmental Protection Agency (EPA). Section 105 of the Clean Air Act authorizes the EPA to make grants to the States to develop and maintain motor vehicle inspection and maintenance programs for vehicle emissions. To date, $5 million have been authorized for this effort and additional funds were appropriated should the need arise. The EPA's program must be consistent with the Periodic Motor Vehicle Inspection program under our Highway Safety Act. That Act authorizes the Secretary of Transportation to make grants to the States to inspect vehicles for safety purposes, and to set minimum Federal standards.

Table 1
Vehicle Reject Rates (%) by Project Location
for the First, Second, and Third Periodic Inspections
(Composite of All Items Inspected)

Site	P1 Inspection %	P2 Inspection %	P3 Inspection %
Alabama	93.2	82.9	85.6
Arizona	91.9	89.6	84.9
Puerto Rico	90.4	64.9	*
Tennessee	47.4	37.8	31.5
Washington, D.C.	48.0	22.1	27.9
Average	74.2	60.7	57.5

* Sample too small to compute reject rate.

Table 2
Reject Rates for Vehicle In Use
Safety and Emissions Systems

System	P1 Inspection %	P2 Inspection %	P3 Inspection %
Brakes	34.9	21.1	14.9
Alignment	18.7	11.8	6.8
Tires & Wheels	15.1	10.6	8.3
Suspension	11.6	5.9	3.7
Steering	6.5	5.0	3.4
Emissions	22.8	13.9	9.9

Table 3. Average Emission Levels

Inspection Cycle	Loaded Mode						No-Load Mode			
	Idle		Low Cruise		High Cruise		Idle		2250 RPM	
	HC (PPM)	CO (%)	HC (PPM)	CO (%)	HC (PPM)	CO (%)	HC (PPM)	CO (%)	HC (PPM)	CO (%)
1	292	3.98	216	1.29	206	1.44	309	3.20	248	1.29
2	259	3.79	190	1.09	180	1.04	311	3.63	219	1.41
3	223	2.74	173	1.02	172	1.38	264	3.35	159	1.19

Table 4. Fuel Economy Improvement Based on Before/After Tune-up Data

State	Treatment				Control			
	Number of Vehicles	MPG Before	MPG After	Change	Number of Vehicles	MPG Before	MPG After	Change
Washington, D.C.	50	12.128	12.594	3.80%	50	11.506	11.662	1.40%
Alabama	14	15.980	17.080	6.90%	28	13.750	14.640	6.50%
Arizona	42	13.650	14.400	5.50%	46	13.960	14.474	3.70%
Tennessee	49	12.737	13.637	7.07%	43	12.490	13.040	4.40%
Composite	155	13.080	13.820	5.66%	167	12.810	13.290	3.75%
	Number of Vehicles	MPG Before	MPG After	Change				
Total All Sources	322	12.940	13.550	4.70%				

Table 5

Vehicle Reinspection Failure Rate in Percent

	Period 1		Period 2	
Project	Treatment	Control	Treatment	Control
Alabama	49.2	50.0	40.0	47.7
Arizona	33.2	33.6	23.1	25.1
Puerto Rico	13.9	13.8	9.2	8.3
Tennessee	9.4	10.5	8.9	11.1
Washington, D.C.	3.0	1.1	2.9	4.2
Weighted Average	30.7	31.8	19.7	21.6

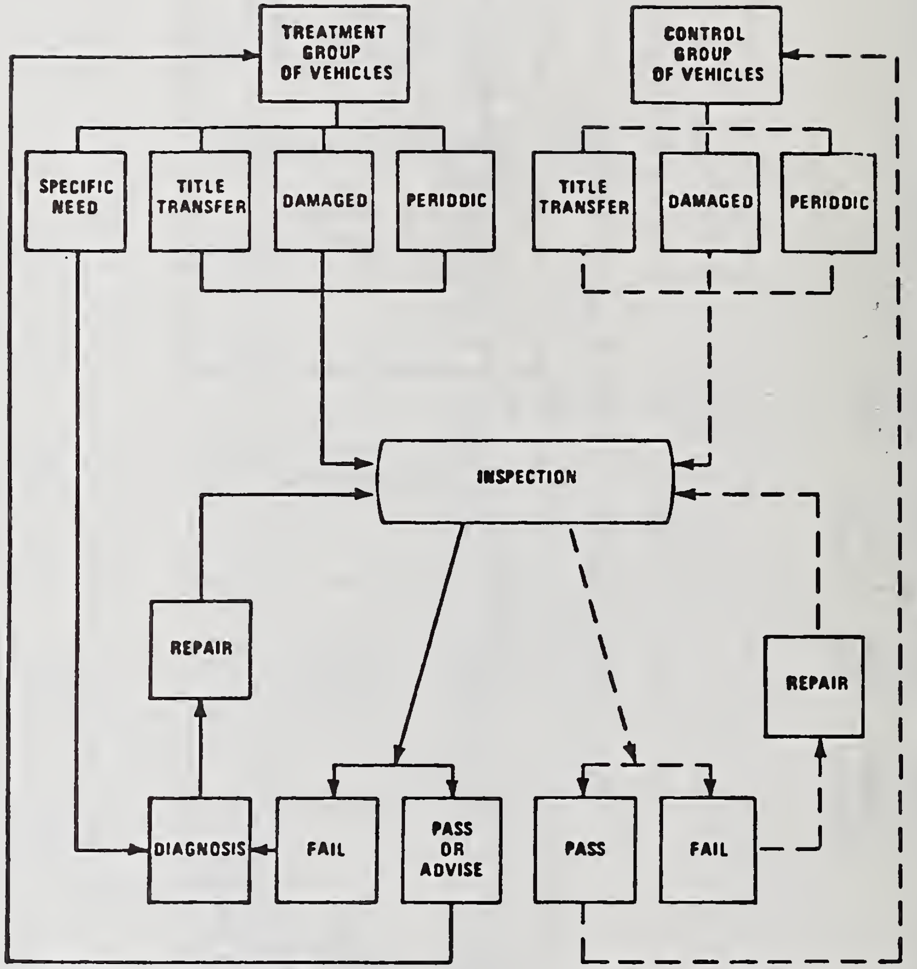

Figure 1. Vehicle Inspection and Repair Cycle Flow Chart

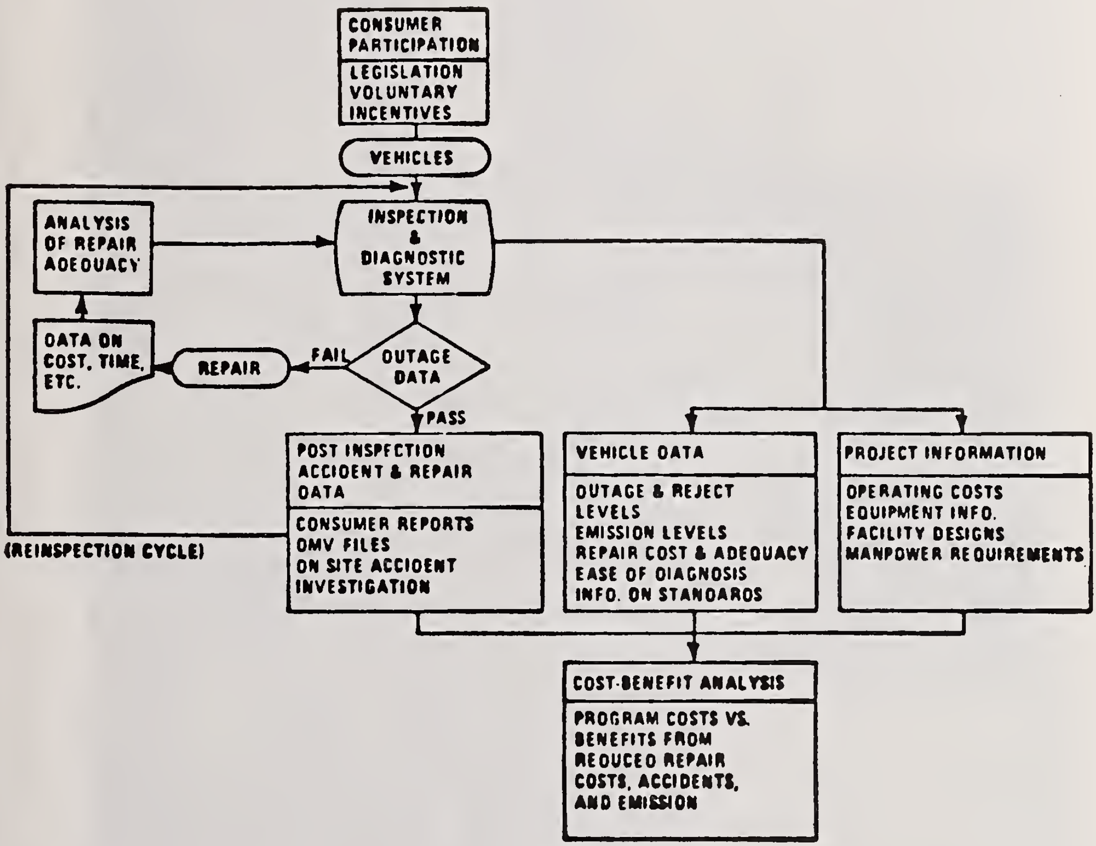

Figure 2. Motor Vehicle Diagnostic Inspection Data Flow Chart

Figure 3. Motor Vehicle Diagnostic Inspection Computer System.

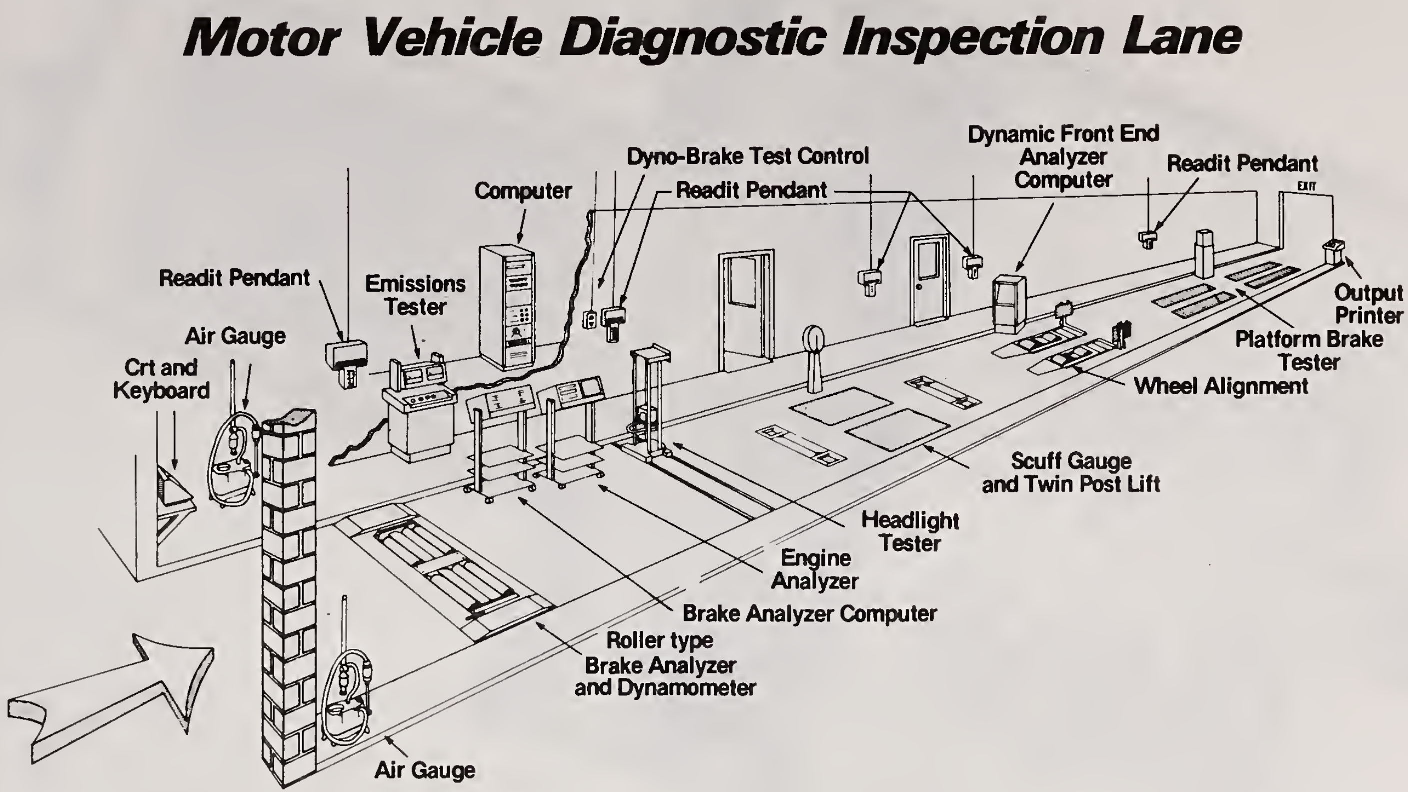

Figure 4. Motor Vehicle Diagnostic Inspection Lane

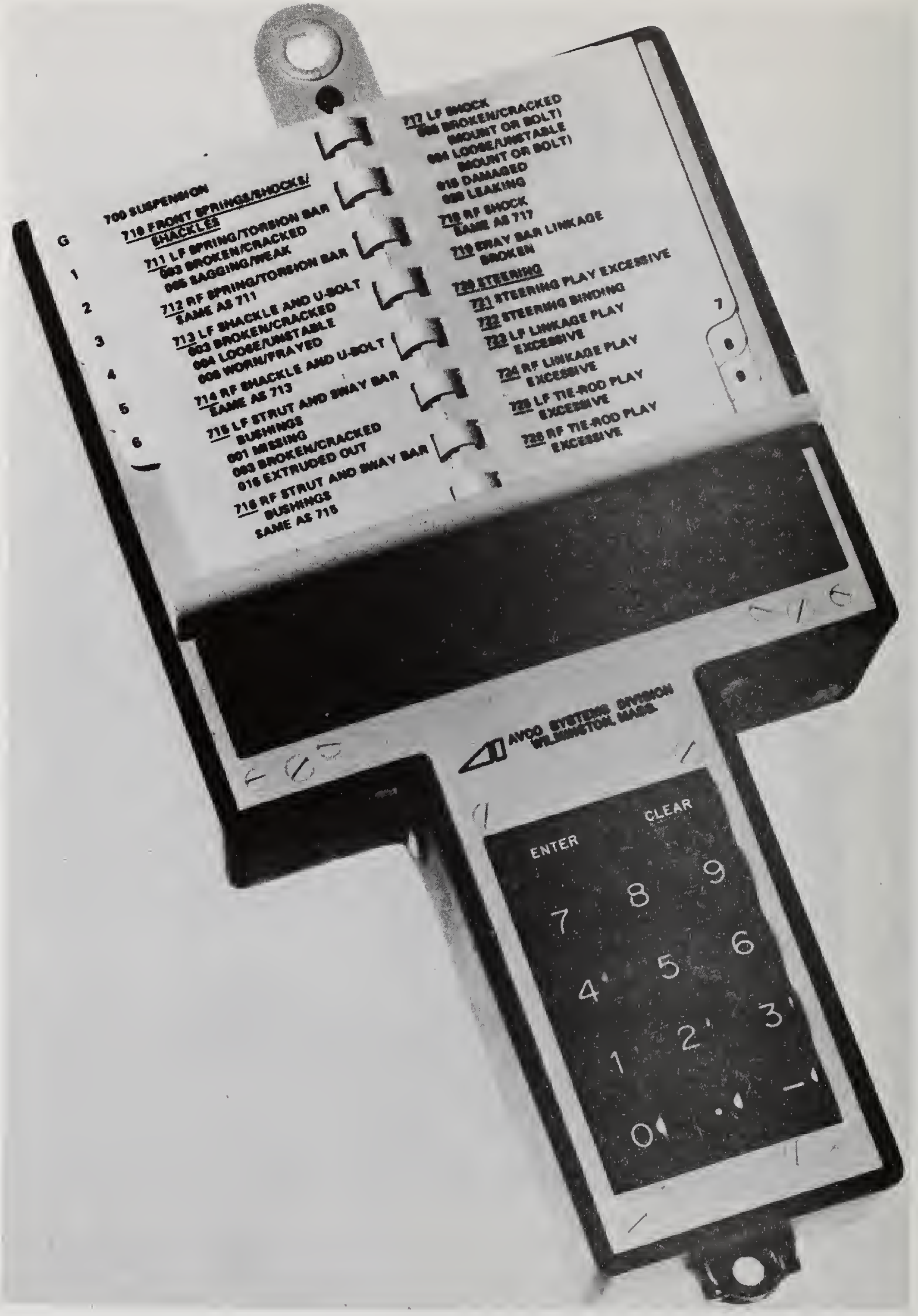

Figure 5. Remote Entry and Display Inspection Terminal (READIT)

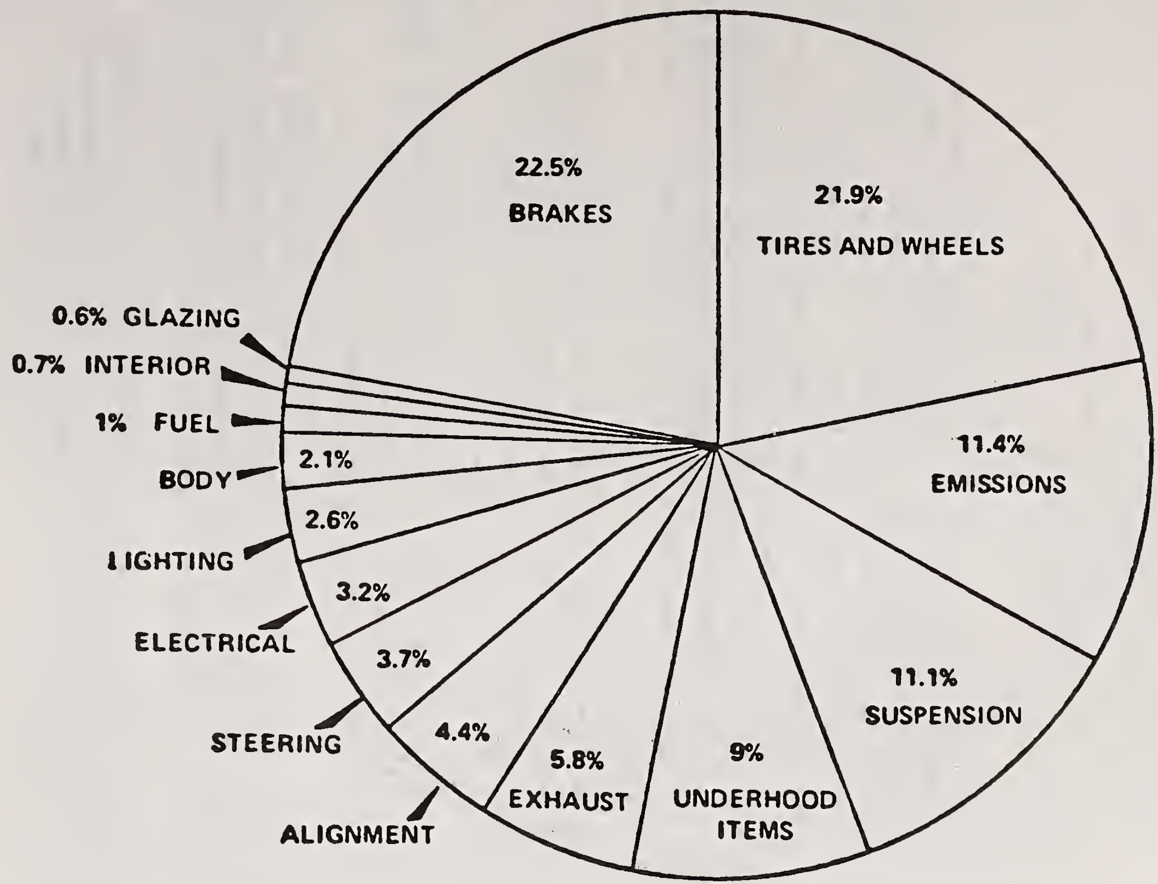

Figure 6. Distribution of Vehicle System Repair Costs.

DIAGNOSIS OF COMBAT VEHICLE SYSTEMS USING SIMPLIFIED TEST EQUIPMENT

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Abstract: In response to the current requirement to improve both the efficiency and the effectiveness of U.S. Army vehicle maintenance, the U.S. Army Tank-Automotive Research and Development Command has developed Simplified Test Equipment for Internal Combustion Engines (STE/ICE)*. Although the STE/ICE system has been developed for applicability across the entire Army vehicle fleet, this paper describes the STE/ICE application to combat vehicles only. Because of the complexity of combat vehicle systems and attendant problems associated with test accessibility, maintenance training and documentation, combat vehicle maintenance represents the most demanding challenge to the U.S. Army vehicle combat service support mission.

This paper discusses the STE/ICE application to Combat Vehicle Hull systems. A specific vehicle application is described as an example of STE/ICE test capability within the framework of the standard vehicle diagnostic connector interface definition.

A newly developed extension of STE/ICE test capability to Turret Systems is also presented. This extension demonstrates that test of the entire Combat Vehicle with a single test system is possible.

The STE/ICE System, capable of hull system test of the existing combat vehicle fleet, and its demonstrated suitability for turret test extension provides a basis for conclusions relative to test system and vehicle design approaches for enhanced combat vehicle maintenance.

Key words: Combat vehicles; Diagnostic Connector Assembly; Fighting Vehicle Systems; generic DCA; Hull systems; Simplified Test Equipment for Internal Combustion Engines; Turret Systems; vehicle maintenance.

*STE/ICE was developed for the U.S. Army Tank Automotive Research and Development Command by RCA Government Systems Division, Automated Systems.

INTRODUCTION. Simplified Test Equipment for Internal Combustion Engines (STE/ICE) has been described in detail at several points in its development process and it is not proposed to repeat that description herein. Rather, the principal thrust of this paper is to report recent STE/ICE developments which have verified and facilitated STE/ICE application to the existing U.S. Army Combat vehicle fleet in the conventional STE/ICE role of power pack diagnosis and to report on an extension of STE/ICE application to the mission of total vehicle test support.

Through recently completed Design/Operational Testing, the STE/ICE System capability to test U.S. Army vehicles has been confirmed. The definition of a new and "adaptable" vehicle/test system interface has facilitated vehicle design for "testability". Finally, an application of STE/ICE to test a fighting vehicle system has demonstrated that the STE/ICE system is capable of filling the mission need of a single test system for organizational or "on-vehicle" support of the total combat vehicle system.

Given the STE/ICE test capability to support the power packs in the present U.S. Army combat vehicle fleet and the system's ability to extend beyond the power pack into turret system test, a prospective exists from which to view a new and now viable possibility; organizational support of the total combat vehicle fleet via a single simplified test system. While this possibility is yet to be achieved, the progress reported here-in seems to bring this essential goal a significant step closer to accomplishment.

Both the use of the "adaptable" vehicle - STE/ICE interface and the extension of STE/ICE capability into turret system test have been demonstrated in the development of a new family of U.S. Army Fighting Vehicles.

Two of these vehicles are the XM2 Infantry Fighting Vehicle (IFV) and the XM3 Cavalry Fighting Vehicle (CFV).

The IFV and CFV vehicles combine high mobility and fire-power. Mobility is achieved by the combination of a 500 HP turbocharged diesel engine and a hydro-mechanical transmission. Firepower is provided by the following vehicle subsystems:

- o All electric stabilized turret
- o 25 MM automatic cannon
- o 7.62 MM machine gun
- o Two turret mounted TOW anti-tank missiles
- o A day/night integrated sighting system employing thermal imaging techniques
- o Six firing port weapons - 5.56 MM (IFV only)

An early focus of vehicle design addressed forward maintenance support and the human factors considerations associated with both the vehicle's operational crew and the vehicle mechanic. Consistent with the goal of simplified, facile vehicle maintenance, a single test system STE/ICE, was designated for "on-vehicle" or organizational diagnosis of all hull and turret equipment problems.

In the following sections, the application of STE/ICE to combat vehicle hull systems and the FVS turret system is described. The concluding section summarizes the benefits of the FVS test equipment approach, the concepts validated in the course of test equipment implementation and the future steps in the evolution of a user optimized test system for organizational support of the combat vehicle fleet.

STE/ICE - COMBAT VEHICLE HULL SYSTEM TEST CAPABILITY. The Combat Vehicle Hull diagnostic problem is complicated by the restricted accessibility characteristic of armored combat vehicles. Figure 1 illustrates the major systems and subsystems of the vehicle hull and indicates the main areas of diagnostic significance and test equipment requirements (faults in drive, suspension, and armor are more readily apparent and diagnosable without aids). The STE/ICE system (Simplified Test Equipment/Internal Combustion Engine) was developed by RCA to meet just those requirements for the U.S. Army Tank-Automotive Research and Development Command (TARADCOM).

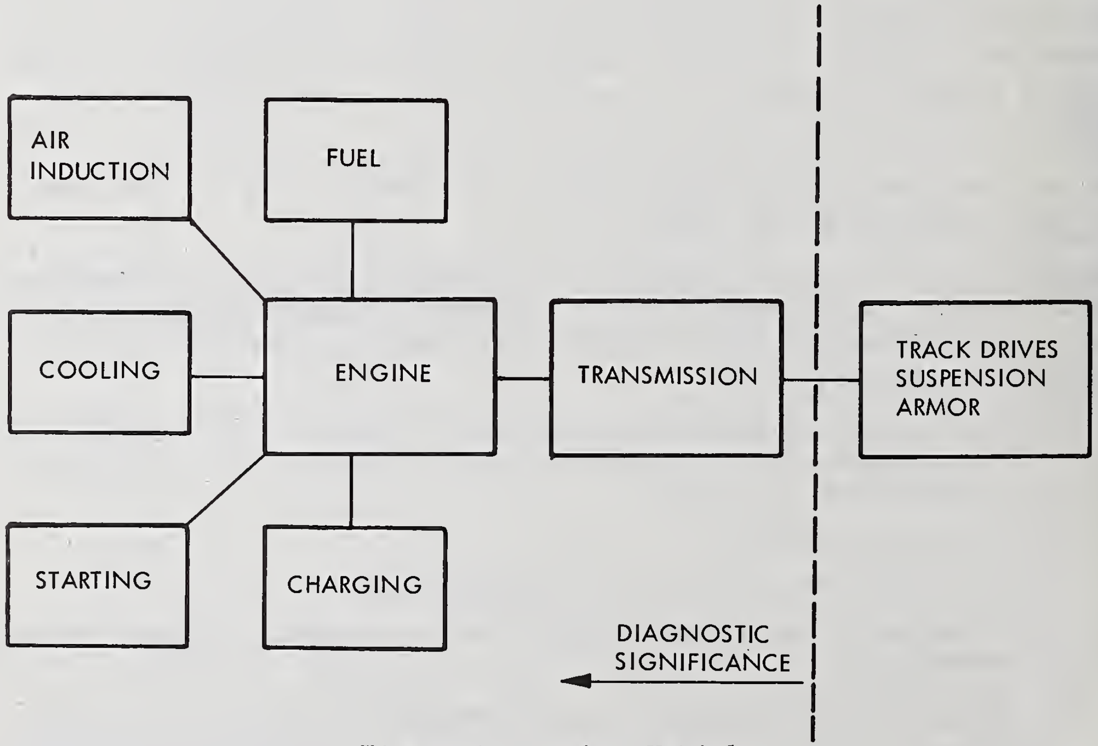

Figure 1. Combat Vehicle

The heart of the STE/ICE system is the VTM (Vehicle Test Meter) shown in Figure 2. It has been carefully designed to be simple to operate and understand. The man-machine interface has been limited to a digital readout for displaying measurement results, two ten digit indexing switches used to select the desired test, a test initiation button and an on-off switch. This microprocessor controlled device measures parameters and displays the results as either a pass/fail message or as digital values in appropriate units familiar to the mechanic (i.e. psi, rpm, volts, ohms, amps, etc.).

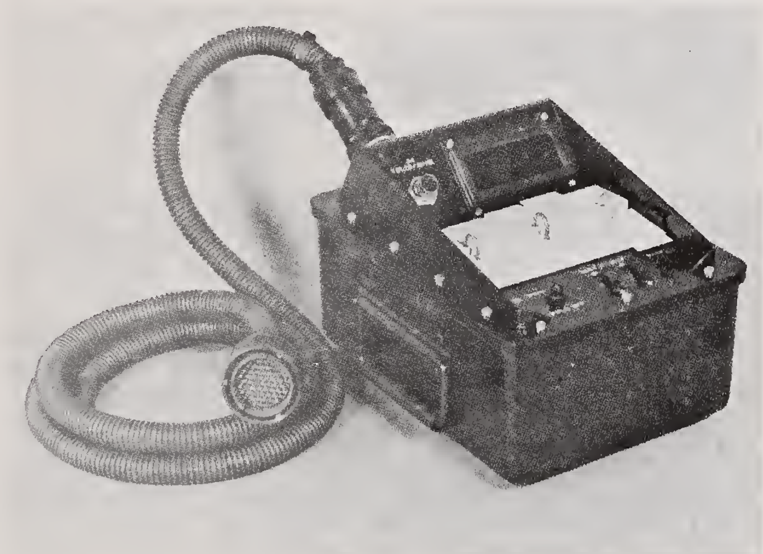

Figure 2. STE/ICE VTM

The VTM interfaces to the vehicle in two modes: built in Diagnostic Connector Assembly (DCA) and Transducer Kit (TK). Although the DCA mode is the mechanic optimized mode of operation, practical limitations preclude pre-wiring of all possible measurement parameters. Therefore, the transducer kit (TK) has been included as a part of the STE/ICE Set to supplement DCA measurements as well as to provide test capability for the present vehicle fleet which is not yet equipped with DCAs.

The transducer kit consists of four sensors; two pressure transducers (vacuum to 25 PSI, and 25 to 1,000 PSI), a Hall effect clamp-on current probe (0 - 1500 amps) and a tachometer pick-up for diesel engine speed measurement. Also provided as a part of the transducer kit are cables and fittings required to connect the test system to the vehicle under test.

While the transducer kit affords less than the optimum connection to the vehicle under test, it remains both a simple and powerful test approach. As an example of the effectiveness of the TK operating mode, with three attachments to a diesel powered vehicle, it is possible to execute fourteen tests to assess the condition of the engine, starting and charging systems. This simple hook-up and the attendant tests can be performed in twenty minutes, even on a combat vehicle given test point accessibility complications.

The STE/ICE, in the Transducer Kit operating mode, is now applicable to the following U.S. Army Combat Vehicles:

- M48 and M60 Series Tanks
- M551 Armored Reconnaissance Airborne Assault Vehicles
- M113 Armored Personnel Carrier
- M107 Gun Field Artillery, Self Propelled
- M109, M110 Howitzer, Self Propelled
- M579 Recovery Vehicle

The Diagnostic Connector Assembly operational mode has been developed through evolution in parallel with STE/ICE Set development to facilitate the mechanic's task in test and diagnosis of vehicle systems. Prototype DCA's were developed to be vehicle specific, that is, each vehicle type was assigned a code resistor and had a defined complement of sensors. By looking at the code resistor, the VTM would know what vehicle type was being tested and utilize Read Only Memory (ROM) tables to identify the assigned transducer complement and appropriate scale factors. This concept would, however, necessitate updating all STE/ICE ROM sets every time a new vehicle DCA is introduced. With STE/ICE sets issued to troops all over the world, the logistics burden of such change programs would become impractical. A generic DCA concept was, therefore, developed where fourteen general DCA types (Table 1), each with its own code resistor, were defined by software tables programmed for each category. Each of these "DCAs" is really a "ceiling DCA" with a maximum test complement defined for it. The vehicle developer then has the flexibility to define the appropriate subset of measurements applicable to his vehicle. Special wiring conventions allow the VTM to determine unused test functions so that appropriate operator messages can be displayed when a non-instrumented DCA test function is called for.

Table 1. STE/ICE Generic DCA (Partial Listing)

DCA Type Number	General Class of Vehicles	Engine Types
1	Vehicles with medium sized diesel engines	Turbocharged and non-turbocharged engines with single plunger distributor type funnel systems and turbocharged engines with unit injector fuel systems
2	Vehicles with medium sized diesel engines	Non-turbocharged engines with unit injector fuel systems

Table 1. STE/ICE Generic DCA (Partial Listing) (Continued)

DCA Type Number	General Class of Vehicles	Engine Types
3	Vehicles with medium sized diesel engines	Cummins engines with PT type of fuel system (turbocharged or not)
4	Vehicles with medium sized diesel engines	Caterpillar and Mack engines with multiple plunger type fuel systems (turbocharged or not)
5	Vehicles with large sized diesel engines	Turbocharged and non-turbocharged engines with single-plunger distributor type fuel systems and multiple air cleaners and turbochargers
.	.	.
.	.	.
.	.	.
13	Optional Second DCA connector	Those vehicles with more test points than can be handled with one DCA connector provide additional voltage temperature, and pressure test points
14	Special Purpose DCA	Not defined at this time

The Fighting Vehicle Systems vehicle family was the first U.S. Army beneficiary of this generic DCA concept as well as the first vehicle to test the validity and comprehensiveness of this approach.

The FVS vehicles have been outfitted with two DCAs in the vehicle hull to maximize the benefit obtained through the use of STE/ICE for vehicle support. Table 2 lists all the test functions available through the two DCAs. The first DCA is the normal vehicle DCA (Generic DCA Number 3 from Table 1) and the second is an optional DCA (Number 13 from Table 1). Between the two connectors, the mechanic has extensive test capabilities in all the significant vehicle systems shown in Figure 1. In many cases, he will be able to isolate system problems to an individual component through the available DCA functions and avoid unnecessary removal of parts restricting access to test points.

Table 2. STE/ICE - FVS Hull DCA Test Functions

Function	DCA #1 (Type 3)	DCA #2 (Type 13)
Engine Tests		
Speed	X	X
Power	X	X
Compression Balance	X	X

Table 2. STE/ICE - FVS Hull DCA Test Functions (Continued)

Function	DCA #1 (Type 3)	DCA #2 (Type 13)
Engine Tests (Continued)		
Oil Pressure	X	
Oil Temperature	X	
Coolant Temperature	X	
Air Cleaner Pressure (switch)	X	
Fuel Filter Pressure (switch)	X	
Fuel Rail Pressure	X	
Turbocharger Outlet Pressure	X	
Transmission Tests		
Oil Pressure		X
Oil Temperature		X
Electrical Tests		
Battery Voltage	X	
Battery Current	X	
Battery/Starter Resistances	X	
Battery Electrolyte Level		
Series Pair #1	X	
Series Pair #2		X
Starter Voltage	X	
Starter Solenoid Voltage	X	
Starter Switch Voltage		X
Starter Switch Return Voltage		X
Alternator Output Voltage	X	
Alternator Field Voltage	X	
Alternator Field Control Voltage		X
Fuel Pump Voltage	X	
Fan Speed Solenoid Voltage		X

STE/FVS - TURRET TEST CAPABILITY. The FVS Turret presented the vehicle developer with a different and more complex diagnostic problem. Figure 3 illustrates the complexity of the turret in terms of its electrical components. The initial parameter measurement requirements defined for maintenance support of this turret included 241 different test signals. The rest of this section describes how the Simplified Test Equipment concept was extended to include full turret test capabilities for this vehicle family.

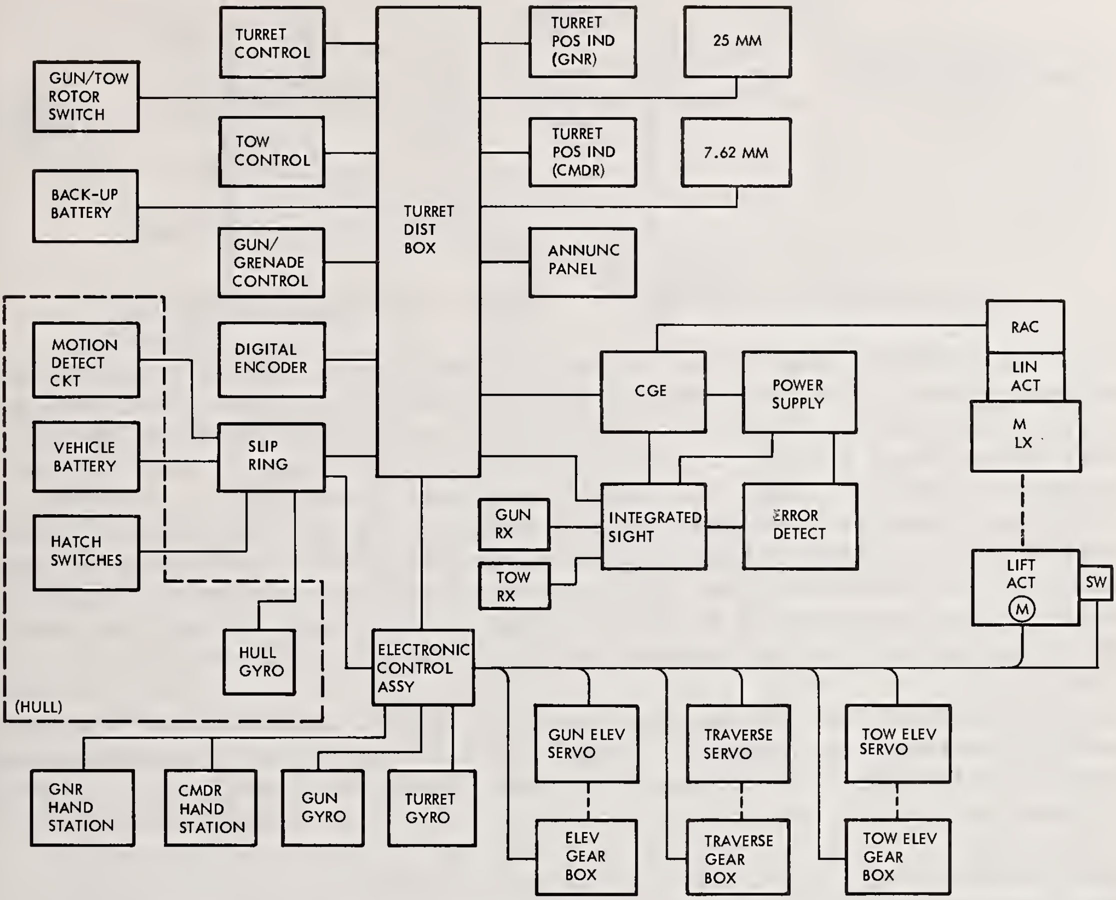

Figure 3. IFV Turret Components

The extension of the STE/ICE test and measurement capability to include complete turret testing was effected through changes internal and external to the standard STE/ICE set. Internal changes are primarily in microprocessor program memory. External changes are concentrated in a Controllable Interface Box (CIB) that expands the normal STE/ICE measurement capability to 291 channels with full scale capabilities ranging from ±5 to ±187 volts, some single ended, some differential, some shielded, and some with special overvoltage protection. The interface between the turret and the test equipment is through 3 standardized 128 pin test connectors and a power connector as shown in Figure 4.

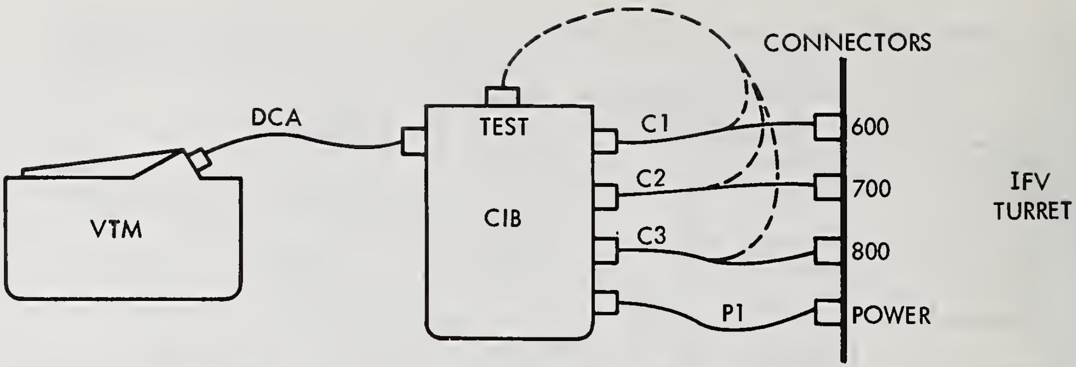

Figure 4. STE/FVS - Turret Test Configuration

The simplicity of the system is best illustrated by describing its operational characteristics. Recommended procedure for use of the system is: connect all cables (P1, C1, C2, C3, DCA), turn system on with Vehicle Test Meter power switch, select appropriate test numbers, and observe displayed results. Once all cables have been connected, full turret test capability is available at the standard soldier-tested (and accepted) VTM man-machine interface. The CIB has no control or display functions on it. Designing the system so that all test points can be connected simultaneously (3 cables) permits the mechanic to use the same set up procedure for turret testing regardless of fault symptoms.

The operation of the VTM in its Turret Test mode makes use of 600, 700, and 800 series test numbers. Normal vehicle testing uses test numbers less than 100 (only two digiswitches available for input). To use the systems for turret testing, the mechanic must first enter a "number series indicator" (06 for 600, 07 for 700, 08 for 800) and then enter other test numbers within the series. The "number series indicator" need be entered only once for a whole group of tests within a series. Entering a "99" returns the VTM to its normal Vehicle Test Meter mode of operation where it is possible to enter another number series. All 600 series test parameters come through a common test connector and the same is true for 700 and 800 series parameters. Table 3 shows the distribution of turret system parameters within test and connector number series.

Table 3. Turret Systems Test Points

Turret Systems	Number of Test Points per Test and Connector Number Series		
	600	700	800
Turret Power Control, and Interlock Distribution Systems	80	15	
Turret Electric Drive and Stabilization Systems		69	
Integrated Sight and Fire Control Electronic Systems			77

This distribution of systems within the number series permits much of the testing to be confined to a single number series. Thus, the mechanic is only required to make a single entry for most tests.

The types of measurements called for are DC voltage, AC/RMS voltage, peak voltage, and peak-to-peak voltage. Table 4 shows the distribution of these types of tests.

Table 4. STE/FVS Test Capability

Measurement Type	600	Test Number Series 700	800	Total
Volts DC	79	82	58	219
Volts AC/RMS			15	15
Volts Peak	1	2	1	4
Volts Peak-to-Peak			3	3
				241

Standardization of the test connectors and their interface made several desirable features possible including operational simplicity, redundant parts, and a complete system self test. The turret test and self test connectors are all coded; the three test cables and three CIB multiplexing interfaces are all identical. Thus, it was possible to include a connector search routine in the software so that it does not matter how the using mechanic connects the cables. The microprocessor determines which turret test connector is connected to which CIB connector and then addresses the appropriate input channel. There is no wrong way to hook up the three cables.

The CIB contains seven boards as shown in Figure 5. All six of the input multiplexer boards are identical and completely interchangeable. In normal operation, there are three identical sets of hardware (cables, connectors, boards, and wires) connecting the three turret test connectors to the CIB Receiver/Interface Board. Given this redundancy, the mechanic could have two faulty cables and four faulty Mux Boards but as long as one of the CIB Test Connectors was fully operational, he could still perform all vehicle tests with the only penalty being the required movement of the remaining cable each time the number series was switched. Should he connect the one cable to the wrong connector, the VTM would so indicate by an error message.

The CIB self test is a full compensated system test which includes a test of its own cables. Any one of the three test cables can be mated to the self test connector. The self-test then checks out all input channels and indicates either PASS or how many bad channels were found and which ones they were. By simply interchanging cables, the support mechanic can then fault isolate to a single board or cable. If necessary, the same information will often allow isolation of the fault to a single chip or few chips. Thus, no new support equipment is required to support the test system itself.

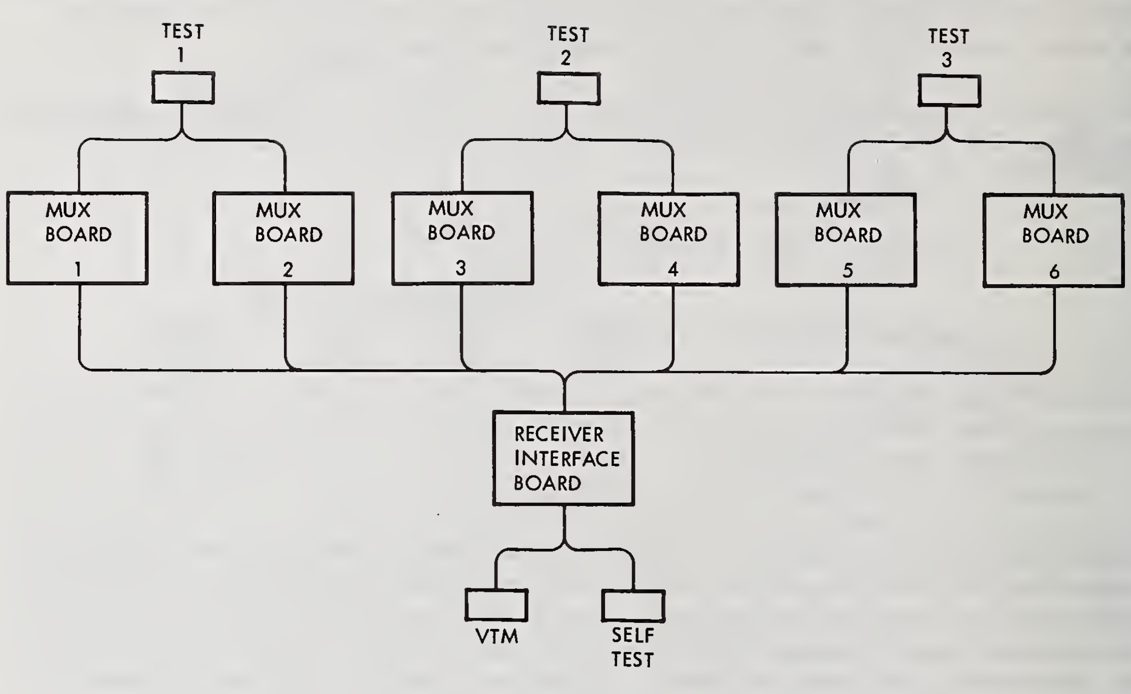

Figure 5. Simplified CIB Block Diagram

CONCLUSIONS. The progress in extending STE/ICE application and applicability as described here-in are most significant when viewed in conceptual terms. STE/ICE applications (TK mode) now encompass power pack support for virtually all of the U.S. Army Combat Vehicle Fleet. In addition this simplified test system has been demonstrated to be capable of providing all required organizational or "on-vehicle" test capability for a modern, sophisticated combat vehicle. Among the benefits expected from the FVS test system approach are the following:

- Reduced vehicle logistics support costs from multiple use of a single organizational level test system.
- Hull systems mechanics will be trained in the use of STE/ICE in the course of normal MOS training. The FVS will impose no additional test equipment interface training on the Army Mechanic.
- The interface between Simplified Test Equipment and the mechanic initially designed for automotive mechanics will now be available to turret mechanics.
- The task of maintaining an inoperable vehicle in the field is made manageable by the ability to bring only one test system to the vehicle.

In the process of this demonstration, the STE/ICE application to FVS hull systems has confirmed the validity of the STE/ICE Generic DCA concept. It is possible to field STE/ICE in support of the existing Army vehicle fleet while anticipating the future vehicle fleet in generic terms such that future DCA equipped vehicles can be accommodated without change to the test system.

From the perspective afforded by this demonstration, it is possible to visualize additional characteristics of the test system that are desirable and achievable without significant additional test system complexity.

The next desirable test system feature is selective automation of turret diagnostics. The microprocessor resident in the STE/ICE VTM provides the potential to automate turret test sequences to simplify the turret mechanic's task by making him significantly less dependent on technical manuals. This automation should increase diagnostic accuracy while decreasing test time. The STE/ICE-CIB system now executes tests on a "one-at-a-time" basis. The turret mechanic depends on a technical manual diagnostic procedure to link test results to form diagnostic conclusions. One way to automate this diagnostic process is to validate the manual diagnostics contained in technical manuals, await the "frozen" production vehicle configurations and convert technical manual diagnostic procedures to test system program memory. In this way, a well validated diagnostic procedure can be obtained for the proper vehicle configuration while minimizing the cost associated with software maintenance.

It seems clear that the extended FVS test system approach described herein may have application to other combat vehicles; some of which are now supported in part by STE/ICE. In the absence of direct applicability, it may be concluded that two project concepts apply:

- It is possible for a single simplified test system to perform all organizational level on-vehicle tests for a combat vehicle.

- It is possible for a test system to be developed, or applied, in parallel with the development of the prime weapon system.

Given some standardization of diagnostic connector interfaces in turret systems (perhaps employing a generic interface concept) it seems practical to configure a single simplified test system for on-vehicle test of the entire combat vehicle fleet.

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AUTOMATED VEHICULAR TEST EQUIPMENT

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Abstract: Motor vehicles are becoming increasingly more complex as radically new vehicle systems are being incorporated as standard equipment with each new model year. Government regulation of vehicle performance is having a significant impact upon the design and maintenance of these vehicles. Ever-increasing fuel costs are becoming a tremendous incentive to keep vehicles in an optimum state of tune to reduce fuel consumption and minimize pollution. These situations have combined to form a formidable challenge to the automotive repair industry. To meet this challenge, the automotive repair industry will have to define a revised approach to vehicle test and diagnostics. Any new approach must be cost effective, minimize dependence on mechanic's skill and experience while increasing the quality of diagnosis and subsequent repair; it must be adaptable to new vehicle systems with minimum test equipment obsolescence; and it must be compatible with Government regulations and provide acceptable service to the customer. One such approach to vehicle test and diagnosis, which is described in this paper, involves one piece of self-contained computerized test equipment - Autosense® - which performs both the test and diagnosis.

Key Words: Automotive test and diagnostics; vehicle test and diagnostics; automated test and diagnostics.

INTRODUCTION

The present day automotive repair industry is faced with a number of significant problems. Motor vehicles are becoming increasingly complex. Radically new vehicle systems are being incorporated as standard equipment with each new model year. These new systems, such as HEI, Lean-Burn, EFI, etc., accelerate test equipment obsolescence and worsen the shortage of skilled mechanics. The availability of skilled mechanics is also limited by promotion to levels of supervision and lack of adequate training from the industry.

Government regulation of vehicle performance is also having an impact on the repair industry. The Federal Government is involved in establishing fuel efficiency requirements for vehicles. When these requirements are generated, they will require the industry to design and maintain vehicles specified performance tolerances. Many state governments are already incorporating mandatory vehicle emission and safety inspections and require that vehicle test equipment itself be designed and certified in accordance with state law. Some states have imposed requirements for written records of work carried out during repair of vehicles as a further step to protect the public and improve the quality of vehicle repair work. In addition, ever-increasing fuel cost is a tremendous incentive to keep vehicles in an optimum state of tune to reduce fuel consumption and minimize air pollution. Manufacturing problems, which result in more recalls and subsequent apprehension by the public toward vehicle safety and performance, also add to the repair problem.

The new vehicle systems and a trend toward increased maintenance to obtain better fuel economy and to meet warranty obligations have forced the repair industry to rely more heavily on the professional mechanic. The repair industry, in turn, is short of the skilled personnel and equipment necessary to maintain service quality on the ever-increasing quantity of new and used vehicles. The result is an increase in come-back problems and a reduction in vehicle availability.

A NEW APPROACH TO VEHICLE TEST & DIAGNOSIS

One solution to the problems faced by the automotive repair industry is to define a revised approach to vehicle test and diagnosis. Any new approach must be cost effective (i.e., lower total time for vehicle service), minimize dependence on mechanic's skill and experience while increasing the quality of diagnosis and subsequent repair. It must be adaptable to new vehicle systems with minimum test equipment obsolescence. It must be compatible with Government regulations and provide acceptable service to the customer.

Conventional methods of vehicle problem diagnosis rely on the mechanic's automotive experience and his skill to operate and interpret various pieces of test equipment. The vehicle is tested by the equipment but it is diagnosed by the mechanic.

The new approach to vehicle test and diagnosis, which is described in this paper, involves only one piece of self-contained computerized test equipment - Autosense - which performs both the test and diagnosis. The Autosense system is the first fully computerized digital automotive test and diagnostic system. The interaction of mechanic and machine is simply this:

* Hook Up - The mechanic makes the simple connections to the vehicle.

* Test - The Autosense system guides the mechanic through a number of tests and collects and prints the results of each test.

* Diagnosis - The Autosense system interprets the results and recommends the necessary repairs.

* Repairs - The mechanic repairs the vehicle and uses the Autosense system to help make any required adjustments.

* Quality Check - The mechanic uses the Autosense system to test the quality of his work and the Autosense unit prints the results of this check for vehicle records.

The vehicle user will then have a computer printout showing the actual test results and specification range for all the tests carried out on the vehicle, the recommended repair and the final test results following repair.

The equipment can be readily adapted to interface with new car and truck systems at the user location. Most new vehicle systems and model year changes can be accommodated by modifying the computer software. These changes are accomplished by mailing a new cassette tape to the user location. This tape, when installed in the machine, will modify the computer program to enable the Autosense system to test the new model year vehicles. This ability to reprogram the Autosense computer by simply inserting a new cassette allows the machine to be easily updated to take advantage of new diagnostic methodology as it develops.

AUTOSENSE SYSTEM DESCRIPTION

The Hamilton Test System's Autosense system brings to the repair industry a new system designed for rapid and efficient testing of automotive engine and vehicle systems. It provides for accurate test and diagnostic capability, thus resulting in an increase in customer satisfaction, and fewer "come backs". The Autosense unit systematically evaluates problems and identifies repair needs with minimum operator interpretation. The system offers the repairman an efficient, reliable tool, and the vehicle owner an accurate, printed test report on the vehicle.

The Autosense system utilizes the latest in solid state electronics for high reliability and it consists of the following subassemblies.

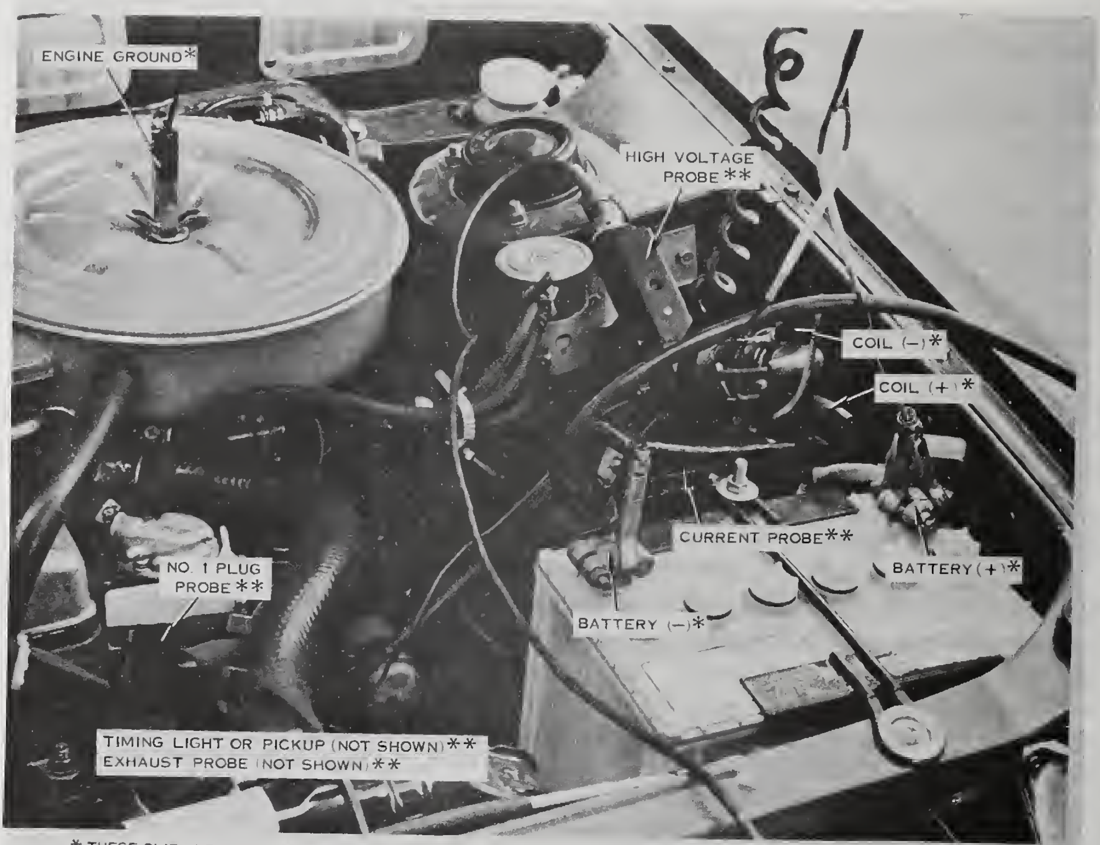
1. Vehicle Instrumentation Harness

2. Autosense Console

3. Hand Held Controller

4. HC/CO Infrared Emissions Analyzer

Vehicle Instrumentation Harness - The connections to the vehicle are made via the Vehicle Instrumentation Harness. This harness consists of the basic electrical harness which quickly attaches to 5 points in the engine compartment and the 4 sensors used to measure current, secondary voltages and timing. Additional connections and probes are available



* THESE CLIP LEADS MAKE UP THE BASIC HOOKUP USED IN ALL TESTS.

** 94% OF THE AUTOSENSE INDIVIDUAL TESTS ARE PERFORMED USING THE BASIC HOOKUP PLUS THESE PROBES AND LEADS.

ADDITIONAL CONNECTORS (USED AS REQUIRED)

- STARTER HARNESS (3 CLIP LEADS)
- ALTERNATOR/VOLTAGE REGULATOR HARNESS (1 CONNECTOR AND 1 CLIP LEAD)
- MANIFOLD VACUUM HOSE

FIGURE 1. VEHICLE HARNESS CONNECTIONS

for specific tests or diagnostic purposes: e.g., Manifold vacuum, alternators, starters, emissions, etc. The Vehicle Harness Connections are shown in Figure 1.

The complete hook up is normally made only when a total vehicle health check is being run. The basic hook up used for normal problem diagnosis or post-tune up and quality checks can be made in 1 to 2 minutes.

One of the unique features of the Autosense unit is the current sensor. It is an easy-to-connect "clamp-around" instrument which senses current flowing through the wire to which it is attached. It has a computer selectable range from 0 to 50 amps or 0 to 200 amps. It has a computer used for measuring low current flows such as lamp circuits or to check for leakage current which can inadvertently drain the vehicle battery over a period of hours.

Autosense Console - The Autosense Console is a metal enclosure for the printer, the integrated diagnostic computer unit and the Exhaust Gas (HC/CO) infrared gas analyzer. It is depicted in Figure 2.

The printer consists of a Teletype Model 33 typing unit and a call unit. It receives communication signals from the diagnostic unit and prints the identification codes and messages on a Vehicle Test Report as shown in Figure 3. The printout shows the vehicle identification, the test number, the vehicle specifications and the actual test results. Repair codes are referenced which indicate the necessary corrective action that should be taken.

The integrated diagnostic unit is a three-bay chassis into which the system power supply, automatic ignition defeat module, tape cassette drive module, and printed circuit board assemblies are installed. An eight thousand word random access memory provides the computer with the necessary capacity to perform its tests, computation and diagnosis. Analog signals are received by the integrated diagnostic unit from the sensors and converted to digital signals prior to processing by the computer while the digital signals are processed directly. The signals are compared with the vehicle's specifications, the results displayed on the operator's hand held control unit and printed upon request. All engine data and vehicle specifications for the over 2000 domestic vehicles manufactured in the U.S.A. in the last five years are stored on a single tape cassette. Tape Cassettes are also available for domestic light trucks and over 25 different makes of imported automobiles. Tape cassettes are available for domestic vehicles dating back to 1966 and for trucks and imported vehicles back to 1970. This data is available to the operator from the computer's memory after he has entered the Automobile Identification Number (AIDN). The AIDN is obtained from the Hamilton Test Systems supplied AIDN manual which is categorized by year, make and model of vehicle.

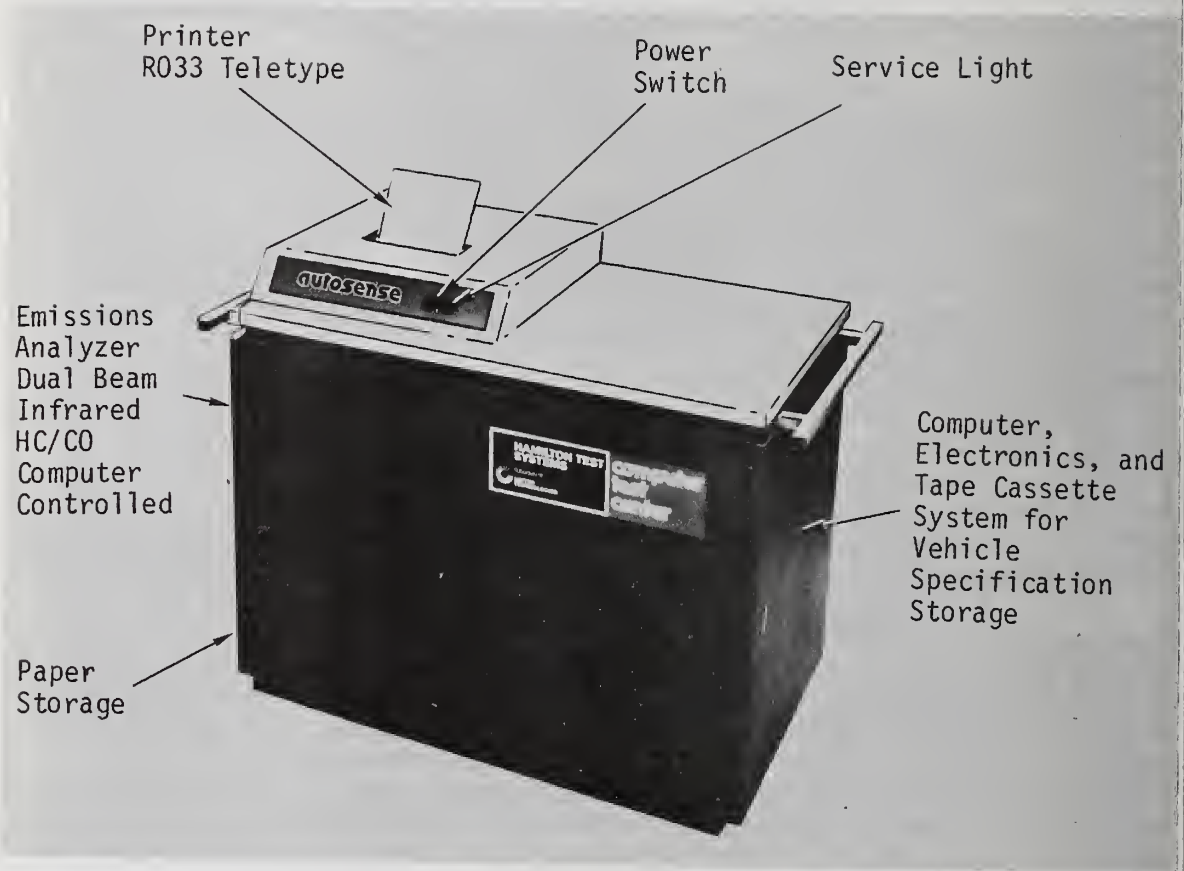


FIGURE 2. AUTOSENSE® CONSOLE

autosense®

COMPUTER REPORT

TEST RUN ON YOUR VEHICLE

AIDN-3010 CH 250A,S6

904 GENERAL HEALTH CHECK

TEST NUMBER	ACCEPTABLE LOW LIMIT	YOUR VEHICLE	ACCEPTABLE HIGH LIMIT
1	12.1	12.6	----
14	9.0	10.5	----
31	75	74*	100
32	75	86	100
33	75	65*	100
34	75	78	100
35	75	100	100
36	75	86	100
40	540	610	660
51	7.0	14.2	16.0
52	7.0	17.3*	16.0
53	7.0	15.0	16.0
54	7.0	15.6	16.0
55	7.0	16.7*	16.0
56	7.0	16.8*	16.0
67	----	780*	280
68	----	6.45*	2.50
50	5.0	11.0*	7.0
90	40.0	47.5	48.0
95	12.7	12.6*	15.0
71	----	3.1	8.0
72	----	4.1	8.0
73	----	3.6	8.0
74	----	4.5	8.0
75	----	3.5	8.0
76	----	3.0	8.0

0 R/C - BATTERY/STARTER
114 R/C - TIMING
122 R/C - IGNITION
131 R/C - ENGINE
145 R/C - IGNITION/CARB
155 R/C - CHARGING

TEST NUMBER	TEST DESCRIPTION
IGNITION OFF	
1	Battery Voltage - Preconditioned (Volts)
2	Battery Current Leakage (Amps)
KEY ON, ENGINE OFF POINTS CLOSED	
3	Primary Ignition Current (Amps)
4	Battery to Ignition Switch - Voltage Drop (Volts)
5	Coil Primary Voltage (Volts)
6	Distributor Point Voltage Drop (Volts) (Electronic Ignition Coil Negative Voltage)
7	Ignition Switch Voltage Drop (Volts)
ENGINE CRANKING OR ATTEMPT CRANKING	
8	Starter Solenoid/Relay Current (Amps)
9	Starter Cranking Current (Low Limit) (Amps)
10	Starter Cranking Current (High Limit) (Amps)
11	Voltage Drop - Battery to Starter (Volts)
12	Voltage Drop - Battery to Starter Solenoid (Volts)
13	Starter Solenoid Voltage (Volts)
14	Battery Cranking Voltage (Volts)
15	Battery to Coil Voltage Drop (Volts
16	Cranking RPM (RPM)
17	Engine Rotation (RPM)
STABILIZED ENGINE CRANKING	
18	Coil Output Voltage at Coil (Kilovolts)
19	Coil Output Voltage at Distributor (Kilovolts)
20	Distributor Rotor to Cap Voltage Drop (Kilovolts)
21-28	Spark Plug Firing Voltage (Kilovolts)
29	Distributor Point Dwell (Degrees)
30	Basic Timing-Vacuum Disconnected (Degrees)
31-38	Relative Cylinder Compression (Percent)
39	Ignition Switch Voltage Drop (Volts)
ENGINE AT IDLE, ACCESSORIES OFF	
40	Curb Idle (RPM)
41-48	Cylinder Power Contribution - Fast Idle (Percent)
49	Distributor Point Dwell (Degrees)
50	Basic Timing - Vacuum Disconnected (Degrees)
51-58	Spark Plug Firing Voltage (Kilovolts)
59	Coil Output Voltage at Coil (Kilovolts)
60	Coil Output Voltage at Distributor (Kilovolts)
61	Distributor Rotor to Cap Voltage Drop (Kilovolts)
62	Distributor Condenser Test (Counts)
63	Coil Test (Level)
64	Fast Idle (RPM)
65	Low Curb Idle (RPM)
66	Manifold Vacuum (IN HG)
67	Hydrocarbon Content (PPM)
68	Carbon Monoxide Content (Percent)
69	Headlight Switch Voltage - Any RPM (Volts)
70	Battery to Coil Voltage Drop (Volts)
SNAP ENGINE ACCELERATION	
71-78	Spark Plug Load Test (Kilovolts)
ENGINE AT 2500 RPM ACCESSORIES OFF	
80	Timing - Any RPM (Degrees)
86	Hydrocarbon Content (PPM)
87	Carbon Monoxide Content (Percent)
88	Distributor Point Dwell - Any RPM (Degrees)
89	Basic Timing with Mechanical Advance (Degrees)
90	Total Timing - Basic + Mech + Vacuum Adv (Degrees)
93	Coil Output Voltage (Kilovolts)
ENGINE AT 2500 RPM ACCESSORIES ON	
95	Battery Voltage (Volts)
96	Regulator Battery Voltage (Volts)
98	Alternator Output Voltage (Volts)
99	Alternator Output Current - Any RPM (Amps)

R O #________ Owner ____________________

Mileage ________ Plate # ________ Phone # ________

V I N # ____________ Operator ________ Date ________

* INDICATES OUT OF LIMIT CONDITION
M INDICATES DATA ENTERED BY OPERATOR

HAMILTON TEST SYSTEMS UNITED TECHNOLOGIES

FIGURE 3. TEST REPORT PRINTOUT

Hand Held Controller - The hand held controller consists of a lightweight plastic housing which contains the displays and keyboard. This controller is the means by which the operator and the system communicate with each other. It is connected to the Autosense console by a 17-foot cable.

This arrangement makes it possible for the operator to conduct tests from inside or outside the vehicle. The hand held control provides the operator with a portable meter capable of reading all engine parameters. The information is displayed in three, 4-digit alphanumeric displays. Using the hand held controller, the operator is able to call up the vehicle specification and compare these to the actual test results. The unit has 8 light emitting diode (LED) "Status Indicators" which are computer driven to automatically step the operator through a sequence of tests. The Hand Held Controller is shown in Figure 4.

Exhaust Emissions Analyzer - The exhaust emissions analyzer is a nondispersive infrared gas analyzer that measures the hydrocarbon and carbon monoxide content of the automobile's exhaust gases. The response time of this analyzer is less than 10 seconds to 90% of full scale (FS) reading. This response time provides rapid and accurate indication of overall power plant efficiency and makes this system ideal for a quick vehicle check to identify the need for further testing or adjustment and service. The computer provides the analyzer with automatic zero and span calibration as well as automatic temperature and pressure compensation. It ensures easier and more accurate operation by the mechanic because the computer obviates the need for manual "span" and "zero" adjustments.

AUTOSENSE SYSTEM OPERATION

The operation of the Autosense system is simple and is outlined as follows:

1. Turn On Power - Initial power turn on causes the computer to read its operating program from the cassette memory tape, and carry out the internal self-checking routines to ensure the Autosense unit is ready for operation. This cycle of tape read, program load and check takes about 30 seconds and, when completed, the computer lights the appropriate cue light on the hand held control.

2. Identify Vehicle - To ensure that the correct vehicle specifications are instantly available to the computer, a four-digit AIDN is entered by the operator to tell the computer to search the data stored on the cassette tape and load a specific group of specifications into memory. When the desired specifications are in memory, the computer types out the vehicle identification and signifies to the operator it is ready to proceed by lighting the appropriate cue light on the hand held control.

FIGURE 4. HAND HELD CONTROLLER

3. Vehicle Hook Up - The connections to the vehicle specified in the manual for the particular test sequence are made. The connections are typically clips to the vehicle coil and battery, current probe, secondary voltage sensor, timing sensor, and exhaust probe. The vehicle hook up takes typically 1 to 2 minutes.

4. Test Sequence - The operator enters the test sequence appropriate to the problem to be diagnosed. The computer will then sequence the individual tests which it requires the operator to carry out. As each test is completed, the operator presses the "print" key on the hand held control unit. The data is stored in the computer's memory and also printed along with the high and low specification limits on the Vehicle Test Report.

5. Diagnosis - Upon completion of the printing of the last test results in the selected sequence, the computer lights the appropriate cue light and displays the first repair code in the center display of the hand held control. The operator presses the "Print" key and prints out all the remaining repair codes.

6. Repair - The mechanic obtains the parts and carries out the repairs to the vehicle recommended by the Autosense system. He then uses the machine to set up the vehicle and make the necessary post-repair adjustments.

7. Quality Check - After the repairs and adjustments have been made, the mechanic re-enters the automatic sequence number and the Autosense unit guides him through the appropriate tests and prints out the results to verify that the repair has indeed corrected the vehicle's problems. This automatic sequence feature of the Autosense system ensures a uniform high quality of testing and diagnosis and removes the variations that can occur with different operators. The Autosense unit rapidly trains and improves the discipline of the mechanics. It increases the rate at which a skilled mechanic can diagnose and repair vehicles. It further has the advantage of providing a hard copy of the result of the tests conducted on the vehicle and evidence of it being within recommended performance levels after the repair work is completed. This feature is significant in preparing shops to comply with legislation which requires written evidence of work carried out and improving their vehicle maintenance record keeping.

TABLE 1

USES OF THE AUTOSENSE SYSTEM

* TUNE UPS
* PERIODIC ROUTINE MAINTENANCE
* CUSTOMER COMPLAINTS
* PRE-DELIVERY VEHICLE PREPARATION
* USED CAR PRE-SALE PREPARATION
* SELECTIVE MAINTENANCE
* INVENTORY & COST CONTROL
* FUEL ECONOMY ADJUSTMENTS

USES OF THE AUTOSENSE SYSTEM

The typical ways in which the Autosense system is being used are listed in Table 1. The use of the Autosense system for tune up or regular maintenance checks in a typical 2 or 3 bay garage or specialty shop ensures that rapid, accurate tune ups are completed and enables the vehicle to be returned to the owner with the assurance that the work has been correctly done. It further provides a printout of the data which the owner can review.

When used as a troubleshooting device to attack specific complaints, the Autosense unit ensures rapid identification of the vehicle problem and the necessary repair, and can provide hard copy proof of the vehicle condition after the repair has been carried out. This ensures fewer comebacks for unsatisfactory service as it provides evidence at the time of vehicle pick up of satisfactory completion of work.

The use of the Autosense system as a predelivery vehicle checking system by both dealerships and fleet or rental companies to ensure the satisfactory condition of a vehicle before the new owner or renter picks it up is expected to increase sharply in the next year. Already many Autosense users are taking advantage of the ability to completely check out a used vehicle and provide hard copy evidence which is displayed in the vehicle on the sales lot to show that it has been properly serviced and meets recommended specifications. This gives the prospective purchaser confidence that the vehicle he or she may be considering buying is in satisfactory condition.

Because the Autosense system also indicates which parts are good, arbitrary parts replacement is eliminated. The use of the Autosense system for selective maintenance, therefore, reduces parts usage and labor hours because you replace only those parts that need to be replaced.

The Autosense printout becomes a valuable tool not only in quality control but also for the monitoring of parts and labor hours for maintenance managers.

In addition, many vehicle owners are losing money due to unnecessary, poor fuel consumption. The Autosense system acts as a unique qualifier in that its regimented nature allows for detection of problems normally missed by mechanics using conventional equipment. Even as low as a 5% fuel consumption improvement can mean savings of thousands of dollars per year to fleet operators.

There are now many Autosense units in the field both in the United States as well as many other parts of the world. Dealerships, Service Stations, Repair Garages, Diagnostic Tune Up Centers, Specialty Shops (tires, mufflers, etc.), National Corporations/Fleets, State/Municipalities, Federal/Military, Universities and others are the categories of users that have put the Autosense system to profitable use in their operation.

AUTOSENSE SYSTEM USERS

One of the major Autosense system users in the United States is Avis Rent A Car. Since last June, Avis has been using 30 Autosense systems at 21 of its service centers across the United States. As stated in an article which appeared in the June, 1978 edition of Automotive Fleet Magazine, the results after less than a year point to substantial reductions in maintenance costs and customer complaints.

At the maintenance centers where Autosense units have been installed, Avis uses them chiefly to evaluate new cars being delivered by dealers and manufacturers. From this experience, Avis has learned that no less than 40-percent of its new cars fail to meet specified requirements. The Autosense system allows Avis to get their new cars fixed before they send them out on the road, and it also has given them leverage in going back to the dealers to point out what's wrong with the cars.

Periodic maintenance is Avis' second priority in its use of the Autosense system. Using figures from the company's Chicago service center, 85-percent of the cars that received an Autosense evaluation when they were new were able to pass a mandatory 7,000-mile maintenance check. Previously, only 30-percent of the Chicago Fleet could pass the test. To the fleet owner this, quite simply, means more cars on the road generating more revenue.

Besides using Autosense units for periodic maintenance, Avis has also instructed its mechanics to use the system as often as they can for unscheduled curative maintenance.

Finally, Avis uses the Autosense system in evaluating vehicles being sold to the general public under its "Young Used Car" program. Avis currently sells about 50-percent of its domestic auto rental fleet as part of a fleet recycling program. On the cars being inspected, the Autosense system helps them guarantee that the used cars they are selling are in excellent mechanical condition.

Initially, Avis field-tested five Autosense units at service centers in four cities: New York, Philadelphia, Chicago and San Francisco. The three-month evaluation was completed successfully, and the additional units were delivered to maintenance centers throughout the country and integrated into the Avis Car Care program.

In New York, Avis also has an Autosense unit in a small van that moves among several area service centers that don't have Autosense units of their own. In that way, service personnel aren't forced to waste time driving to Avis' main service center in Queens for a diagnostic test. The van also exposes more mechanics to the Autosense system, which Avis considers to be an effective training and motivational tool.

Cost-effectiveness and improved fleet utilization continue to be Avis' prime considerations.

Figure 5 depicts a mechanic using an Autosense unit to check out a car at one of Avis' fleet maintenance centers.

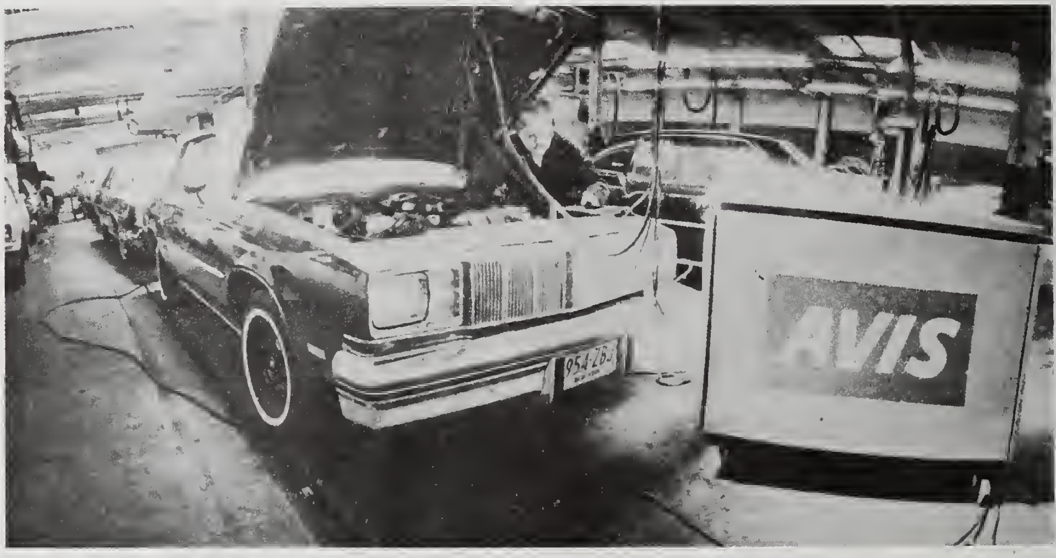


FIGURE 5. AVIS FLEET MAINTENANCE CENTER

Another major Autosense user is the Canadian Armed Forces (CAF). CAF procured commercial 1-1/4 ton trucks for their fleet in late 1974. These vehicles incorporated a High Energy Ignition (HEI) system as well as some military options. Several unforeseen maintenance problems occurred with these vehicles. An in-depth study of in-house CAF test equipment indicated that the CAF test equipment inventory was obsolete insofar as HEI systems were concerned. An evaluation of commercially available test equipment was conducted and all except the Autosense system fell short in the areas of prime importance to the CAF. A field trial was authorized to determine the applicability of Autosense to other vehicles in the CAF inventory and to determine the best method of employing the Autosense unit in the field and base environment. As a result of the favorable field evaluation, a contract was signed for procurement of 58 Autosense systems in early 1978 with delivery of systems to commence in March, 1978, training to commence in April 1978 and initiation of fielding the Autosense systems in May 1978.

At the time of this writing, the fielding of Autosense units is about 90% complete. The CAF, as stated in a technical paper entitled "Vehicular Automatic Test Equipment for the CAF" and presented at the AUTOTESTCON '78 meeting, believes that a comprehensive and valid assessment of the introduction and employment of the Autosense system can be made only after at least two years of use. However, some positive trends are already starting to develop and were reported in that paper as follows:

a. Parts Savings - The time honored use of parts to diagnose faults has been largely stopped where the Autosense system is employed. Parts replacement is expected to rise initially as the machine diagnosis identifies unsatisfactory parts that could not otherwise be detected. However, after all vehicles have been initially checked and brought back to recommended specifications, the rate of parts replacement is expected to drop and fuel consumption reduced.

b. Labor Saving - The accurate and very quick diagnostic action of the Autosense system was immediately obvious to all who saw and used it. The machine has yet to be proven wrong in any of the operations witnessed by the fielding team or any of the base maintenance supervisors with whom results have been discussed. Each base had vehicles which did not run well or had a peculiar failure that defied diagnosis. Some of these cases had been present for several years. In every case, the machine diagnosed the problem within twenty minutes of start and the problem was resolved by either an adjustment or replacement of a small part.

c. New Tools - The Autosense system has an inherent ability to correlate engine subassembly functions that cannot be demonstrated by any other means. In particular, the relationship of carburetor balance, exhaust emissions and fuel consumption cannot be grasped much less controlled without this equipment. Mechanics have not had a tool that diagnosed engine functions when the motor is running at high RPM or the engine is hot. Senior technicians have come to realize that they have a new tool for better performance, while it serves as a very useful training instrument for junior tradesmen.

d. Acceptance - The Autosense system has been received very well in all but isolated instances. All service personnel and civilians employed by the Department of National Defense (DND) maintenance system who are forward thinking and confident about their trade are delighted to have a new and sophisticated piece of equipment that moves auto mechanics into the "twentieth century" as one senior foreman exclaimed. This attitude runs right through the rank structure from Corporal to Colonel and includes the conversion of many skeptics.

FUTURE DEVELOPMENTS

The basic design philosophy of the Autosense system was to construct a basic unit which is capable of being expanded by the addition of both software and hardware packages to interface with new vehicle systems and different types of vehicles. New software packages are available annually to update the machine to interface with the new model year vehicles. These packages are in the form of cassette tapes and amendments to the Operator Manual. They are mailed to the user facility for the user to install in the Autosense console. New hardware features are also being made available to take advantage of improvements in diagnostic information available from on-board sensors. These features speed up the operation of vehicle diagnosis and simplify the mechanic's task of connecting to the vehicle.

With the ease of expansion provided by the basic Autosense system construction, we have also easily provided custom systems to meet particular customer requirements. These custom systems have improved operational characteristics which tend to maximize the economic return to their users.

SESSION III

MARINE APPLICATIONS

Chairman: Raymond A. Coulombe
Naval Ship Engineering Center
Co-Chairman: Rudie Hohenberg
Mechanical Technology, Inc.

THE ACOUSTIC VALVE LEAK DETECTOR
A NEW TOOL FOR FLUID SYSTEMS MAINTENANCE

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Abstract: The operations, limitations and successful applications of a portable, non-intrusive instrument currently in use by the U.S. Navy to detect internal leakage through shipboard steam, water, hydraulic and high-pressure air valves are described. The Acoustic Valve Leak Detector (AVLD), developed by the David W. Taylor Naval Ship R&D Center, listens for the ultrasonic emissions characteristic of internal valve leakage. The AVLD is being used for troubleshooting, for overhaul planning, and in a systematic preventive maintenance monitoring program.

Key words: Preventive maintenance, Failure detection, Acoustic emission

Introduction: Work on the Acoustic Valve Leak Detector (AVLD) began in November 1973. One year later, the first prototype was delivered to a repair ship for field evaluation. Following the success of the first instrument, several more were built and delivered to other repair ships. Later models incorporated evolutionary changes developed on the basis of practical experience. Originally developed to detect leakage through large seawater ball valves, the AVLD has been successfully used to detect leakage through valves in a variety of fluids in shipboard and shore installation piping systems. Additional research and development are being conducted to extend the concept to include measuring as well as detecting internal valve leakage.

The Acoustic Valve Leak Detector is a portable, non intrusive instrument developed by the David W. Taylor Naval Ship R&D Center in response to a requirement for an instrument which would reduce the need for opening piping systems to inspect valves. Applied in a systematic preventive maintenance program, the AVLD has begun to reduce the number of costly and time-consuming inspections previously required. Savings have also resulted from its ability to detect small leaks before they become large enough to necessitate more expensive repair procedures. The AVLD has proven effective for troubleshooting by identifying the leaking valves in parallel arrangements where it is not normally possible to determine which valve is leaking. It has also been used by naval shipyards to identify ship valves requiring repair during scheduled overhauls.

The AVLD listens for the ultrasonic acoustic emissions characteristic of internal valve leakage. Transducers are attached to the valve and connected to the AVLD. Types of fluids to which the instrument has been successfully applied include steam, water, hydraulic oil and high-pressure air. Since the transducers are attached to the outside of the valves, the time and expense of dismantling the valves or removing them from the systems are eliminated.

The purpose of this paper is to introduce the Acoustic Valve Leak Detector to potential industrial users. The underlying theory, principles of operation and circuit design are briefly described. Specific examples of some successful applications of the instrument are described in detail, including performance limitations. The preliminary results of some current research and development are summarized. Conclusions and recommendations with regard to performance and industrial applications are presented.

Background: The U.S. Navy is attempting to extend the time between major overhauls of ships, while simultaneously reducing repair costs and improving the material condition of operating ships. To achieve this objective, there must be instruments and procedures available which are able to identify maintenance problems in their incipient stages and to establish a record from which it may be concluded confidently that a ship should be continued in service beyond its formerly scheduled overhaul date. By following a similar program, aircraft industries have increased the interval between scheduled disassembly, inspection and remanufacture of commercial airline engines from a few hundred to several thousand operating hours.

"Open-and-inspect" procedures are expensive and time-consuming, especially if the equipment is complex or relatively inaccessible. There is also the risk of damage or of introduction of contamination. Another disadvantage is the fact that equipment or systems must be taken out of service for the duration of the inspection. High standards of quality assurance add to the cost and duration of such procedures. Opening and reclosing are often the major time and cost factors, and these factors are wasted if it is found that no repairs are required.

Ships operate at sea for several months, followed by an upkeep period of a few weeks. During the upkeep period, inspection, repair, reprovisioning, and post-upkeep sea trials take place, followed by another period at sea. Since there is a limit to the amount of work that can be done during the upkeep period, it is important to concentrate the limited repair resources on those systems and equipment that actually need repair. Equally important is the ability to conclude that the other equipment is not in need of repair before the ship returns to sea.

A typical ship has several hundred valves, holding various fluids at pressures up to several thousand pounds per square inch. Many are welded in place, and most are difficult to remove because of the cramped quarters. There are many valves for which the removal, inspection, replacement and quality assurance costs exceed $50,000 per valve. Although most valves are not in that category, large savings are realized each time it is determined that a valve does not require repair, or leakage is detected while it is still possible to repair the valve in place.

Major shipyard overhauls present another opportunity for savings. They are performed at intervals of several years and require a year or more to accomplish. Shipboard surveys that identify leaking and non-leaking valves prior to the scheduled overhaul provide a rational basis for scheduling and budgeting. The surveys also ensure that repair time, labor and parts are not wasted on valves that are already in working order.

Thus, the decision to develop the Acoustic Valve Leak Detector was made on the basis of a need for a non-intrusive, portable instrument to support a systematic preventive maintenance monitoring program for fluid valves.

Sources and Distribution of Sound in a Piping System: Sound source mechanisms in a leaking valve and piping system may be classified as follows:

- Unsteady flow (turbulence)
- Cavitation
- Flashing of liquid to vapor
- Mechanical movement of parts

Although each source mechanism is treated separately, it must be understood that the generating mechanisms themselves interact and that the total acoustic emission generated is therefore a sum from all sources.

In addition to the noise source itself, the amplitude and spectral distribution of the acoustic emission signal are further influenced by: (1) the transducer's sensitivity and spectral response; and by (2) cavity and mechanical resonances in the valve and its associated piping.

The various source mechanisms are not well covered in the literature and there has been little reported work analyzing the effects of temperature, vapor pressure or other physical characteristics which have been found important to some aspects of this work. Although the following discussion of leakage sound sources are necessarily brief, the attention of the interested reader is invited to reference [1], wherein the theory is treated in greater detail.

Fluid Dynamic Sources: Sounds are end products of the decay of turbulent eddies created just downstream from the orifice which is causing the leak. The acoustic power generated by turbulence in a fluid is given by the following equation. [2]

$$\text{Acoustic Power} = \rho \frac{\upsilon^8 \ell^2}{c^5} \tag{1}$$

where ρ is the fluid density, c the sound velocity in the fluid and ℓ is a characteristic length of the system bounded by the orifice size and the downstream pipe diameter.

Since the extreme values for ℓ are unchanged with pressure, a lower limit to the frequency spectrum expected from fluid dynamic noise can be estimated by taking ℓ to be the downstream pipe diameter and using the following values for the frequency:

$$\text{frequency} = \frac{c}{\ell} \qquad \begin{array}{l} 3 \text{ kHz for gas} \\ 15 \text{ kHz for water} \\ 12 \text{ kHz for oil} \end{array} \tag{2}$$

Cavitation Sources: Cavitation in a liquid will occur whenever the local pressure drops below the vapor pressure for the liquid or for any dissolved gas in that liquid. The degree to which cavitation occurs in leakage through an orifice is directly proportional to the pressure across the orifice and inversely proportional to the difference between the local static pressure and the sum of the partial pressures of vapors and dissolved gases. The acoustic power radiated by cavitation resulting from flow through orifices is generally taken to be proportional to the square of the pressure drop across the orifice. [3]

For both water and hydraulic fluid, there is experimental evidence [1] to show that cavitation often occurs under the fluid conditions found in many piping systems. There are very little data on the dissolved gas content or vapor pressure of water or hydraulic fluid at a valve. This, coupled with the fact that the theory cannot handle real (impure) liquids such as tapwater, seawater and hydraulic fluid, suggests that the previously reported [1] observations be accepted. It was observed that cavitation occurs very irregularly in the seawater valves at 7 psi and leaking to atmosphere; and that cavitation usually does occur for hydraulic valves leaking to pressures which are lower than system backpressure (the pressure at which the fluid has been stored in the sump, normally above atmospheric pressure). However, it was observed that cavitation usually does not occur for hydraulic valves leaking to pressures substantially above the system backpressure. At system backpressure, cavitation in hydraulic valves is very erratic.

Flashing Sources: The flashing of pressurized water to steam as it leaks through a valve is known to be a very noisy process, but no information has been found regarding the intensity or frequency distribution from this source, nor has it been experimentally observed in this work. It is expected to be broadband and very intense since the energy associated with the phase transition is many (about eight) orders of magnitude greater than that of turbulence under typical steam plant conditions.

Mechanical Sources: Mechanical sources in leaking valves arise from pressure fluctuations that pass from the fluid to the valve, rattles of loose parts of the valve, and modification of the sound field due to cavity resonances. Valve rattle has not been observed, but occasional inadvertent metal-to-metal external contacts are easily identified, indicating that rattles would be easily detected by the AVLD.

Equipment Description: The Acoustic Valve Leak Detector monitors leak-associated acoustic energy in the frequency range of 10 kHz to 100 kHz. This frequency range was chosen because there is significant energy emitted by leaky valves in this range and because acoustic energy in this range is strongly attenuated with increasing distance from the source. Therefore, background noise often can be electronically separated from the signal. The detector permits the operator to observe the acoustic energy density as an analog meter reading or to listen to it on headphones. The audio output is derived from the ultrasonic frequencies by beating the input with a controlled frequency oscillator and amplifying the resulting beat frequencies for the headphones. The internal reference oscillator may be swept automatically or held at a fixed center frequency of 25 kHz. Two outputs are provided to permit recording the acoustic amplitude versus frequency on a standard X-Y plotter.

The acoustic signals are obtained by temporarily attaching commercially available piezoelectric transducers to the valve or nearby piping. Since the transducers are attached to the outside of the valves, the time and expense of dismantling the valves or removing them from the systems are eliminated.

The detector unit is of all solid-state construction and fits in a small case about 18 cm (7 inches) high by 23 cm (9 inches) wide by 25 cm (10 inches) long. The entire instrument, with all accessories stored in the case cover, weighs less than 7 kg (15 lb). Two transducers, a set of headphones and a detector unit are shown in Figure 1. Other accessories, which will be described separately, include transducer holders, transducer standoffs, mounting discs, and a hand-held probe. The case, when closed, is watertight and buoyant. Power is supplied by rechargeable 6-volt batteries.

Figure 1 - Acoustic Valve Leak Detector, Model C

Electronic Construction: The detector unit, which is mounted in the bottom half of the case, is covered by the controls and displays on the front panel. A functional block diagram of the detector unit is shown in Figure 2. Electrical signals from each transducer are fed to preamplifiers through coaxial cables. Signals from a local oscillator and from one of the preamplifiers are then fed to a mixer stage via a high-pass filter which eliminates low-frequency structureborne noise. The mixer stage outputs, which are the differences between the amplified transducer signals and the local oscillator signal, are in the audio spectrum. This heterodyne technique allows the operator to hear a representation of the ultrasonic acoustic emissions on the earphones. The amplitude of the audio signal is also displayed on the analog acoustic amplifier meter located on the front panel.

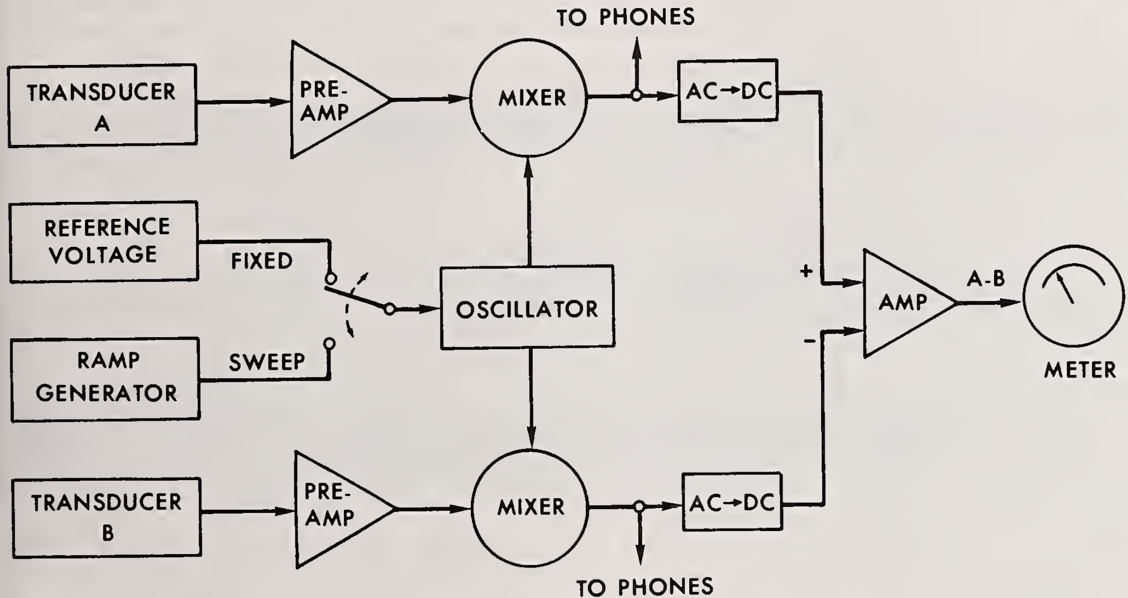

Figure 2 - Acoustic Valve Leak Detector Block Diagram

An amplitude output is provided to drive an X-Y plotter with a d-c voltage proportional to the average rms value of the input energy in a selectable bandwidth of ±3 kHz or ±10 kHz, with a center frequency selectable from 10 kHz to 100 kHz or from 20 kHz to 200 kHz. The frequency output provides a d-c voltage proportional to the center frequency of the amplitude output. In the sweep mode, a voltage ramp drives the variable control local oscillator over the required 10:1 range in approximately 30 seconds.

Power is supplied at ±12 volts from four series-connected, sealed, 6-volt, lead-acid storage batteries. The detector unit draws 60 ma and will operate continuously for 8 hours on a 16-hour charge.

The electronics are mounted on two printed-circuit boards located in the bottom half of the case along with the batteries and charging transformer. Rectifiers and the battery charging control circuits are mounted on the power board. The preamplifiers, ramp circuit, local oscillator, mixers and the audio amplifier are mounted on the main printed circuit board.

Front Panel: All of the controls, connectors and displays required to operate the detector unit are mounted on the front panel. Two input attenuators, one for each channel, each with 12 fixed steps of 5 dB per step provide a maximum of 60 dB attenuation to allow adjustment to the noise levels present. The function selector is a rotary switch which selects the input to the local oscillator. The sweep/reset toggle switch starts and resets the voltage ramp to the local oscillator when the sweep mode is selected. Either channel may be monitored on the headphones. The volume control adjusts the amplitude of the signal to the headphones. The on/off power switch must be in the off position to allow battery charging with the a-c power cord connected. The battery test toggle switch allows the front panel meter to momentarily monitor the battery condition. The test switch applies power to an internal noise generator for a complete system self-test without any additional test equipment.

Accessories: The transducer used with the AVLD is an Endevco Model 2217E, and suitable headphones are available from numerous manufacturers. Several unique accessories have been designed to improve the means of acoustically coupling the transducer to the pipes or valves. The devices include a clamp for hands-free operation, a standoff for thermal protection of the transducer, and a hand-held probe. Basic to all is a ball-and-socket connection which allows repeatable acoustic coupling to be obtained reliably without requiring accurate or even steady alignment.

Figure 3 shows a socket and a transducer attached to a standoff. The end of the standoff is a half-inch diameter ball which fits the spherical indentation in the socket disc. The standoff, which is a 3/8-inch drill rod with a 1/2-inch ball bearing welded to one end, is attached to the transducer by a threaded mounting stud. The socket disc may be epoxy-bonded to the valve to be tested, or it may be held by a spring to the ball end of the standoff, forming a hand-held probe, as shown in Figure 4. Note also the threaded mounting stud for attaching the transducer.

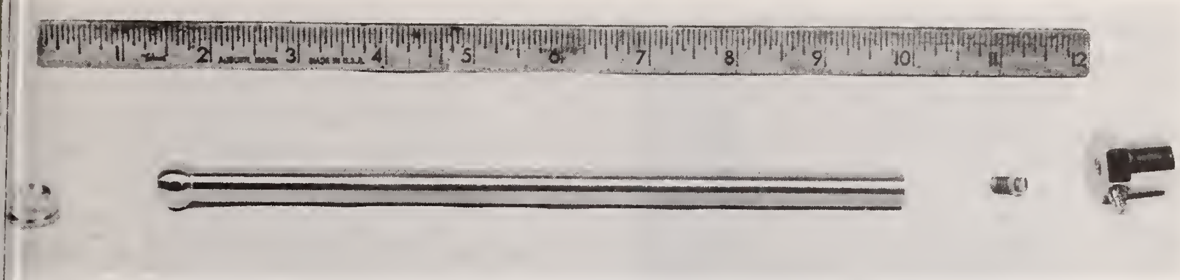

Figure 3 - Mounting Disc, Standoff and Transducer

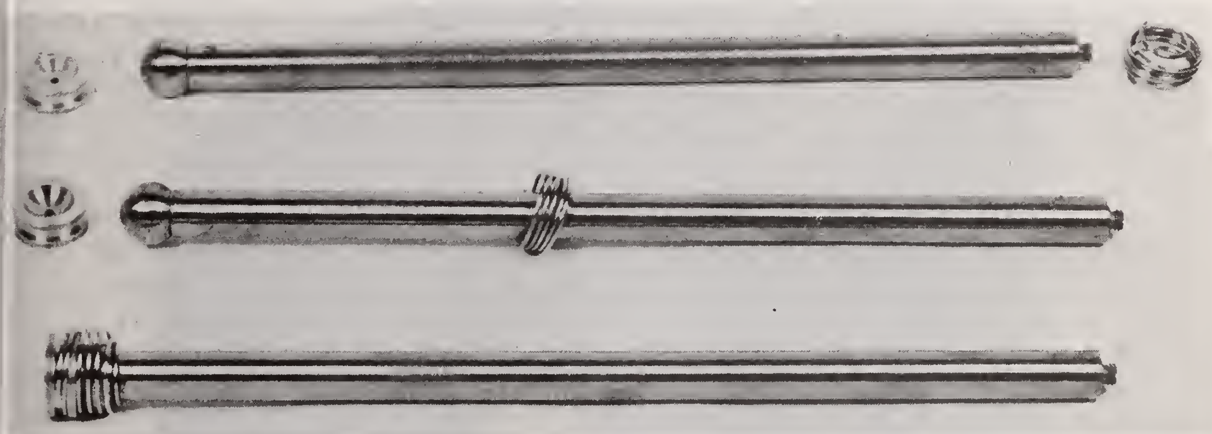

Figure 4 - Hand-Held Probe Parts

The circumferential groove around the socket disc is for holding the disc to the standoff rod by means of the spring shown in Figure 4, or for clamping the transducer to the epoxy-bonded socket disc shown in Figure 5. The transducer holder shown in Figure 5 uses a coil spring to clamp the transducer to a socket disc which has been epoxy-bonded to the test piece. When used as shown in Figure 5, a sector of a 1/2-inch sphere is bolted into the face of the transducer to provide the ball portion of the connection. In all cases, a small amount of acoustic coupling compound is applied between mating metal surfaces.

Figure 5 - Transducer Clamped
to Mounting Disc

Operation: Due to the large variety of fluids, valves and fluid conditions, it is considered important, at this point in the program, to have trained operators conduct leak checks. In some Navy applications where a large number of identical valves are to be checked, the breadth of experience required to interpret properly the results is much less. Most of the leakage detection programs are still in the stage where baseline data for specific valve and fluid types are still being gathered and plots of acoustic amplitude versus frequency are still being correlated with independent leakage rate measurements where possible.

Basis for Detection: Useful frequency ranges for leakage measurement were determined from measuring the acoustic emissions of various valve and fluid combinations at ultrasonic frequencies up to 1 megahertz. It has been found that leakage noise is generated from audio frequencies up to several hundred kilohertz. The signature depends on fluid type and pressure, leakage rate, and valve type and condition. The AVLD was designed to reject frequencies below 10 kHz because high levels of structureborne noise in most systems gave a poor signal-to-noise ratio there, and to reject signals above 200 kHz because in most systems the signal levels in this range became quite small.

Normally, two transducers are employed for detection. One is placed on the valve or adjacent piping to pick up leakage-generated noise which will be mixed with structureborne background noise and the second is located either upstream or downstream of the valve to pick up structureborne noise only. This process is illustrated by Figure 6, which shows typical signatures obtained from a leaking seawater ball valve. To the extent that the leakage generated noise is attenuated by the time it reaches the background transducer, and the structureborne background noise is the same at the two transducer locations, the subtraction of the two signals will result in the leakage noise only.

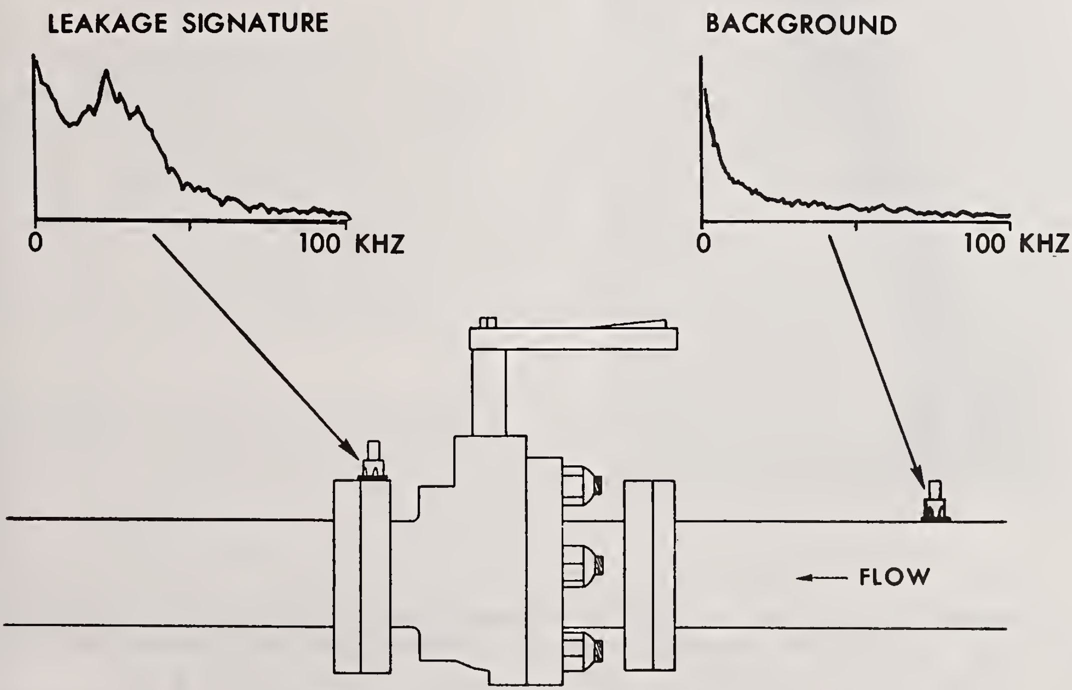

Figure 6 - Basis for Detection

Attaching Transducers: The location and method of attachment of transducers depends on the nature of the application. If the surface of the pipe or valve is hot (above 177° C), as is the case with steam valves, the standoff must be used. The hand-held probe with attached socket disc is especially helpful for determining the most sensitive location for attachment of epoxy-bonded discs. Its use is illustrated by Figure 7.

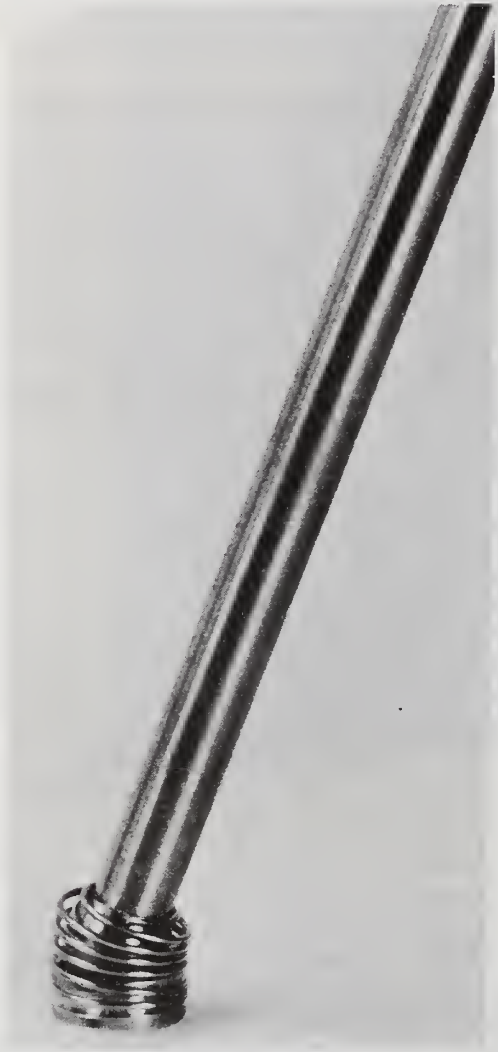

Figure 7 - Use of Hand-Held Probe

To detect leaks in a typical seawater ball valve, a mounting disc should be epoxy-bonded to the downstream side of the valve to be checked. Additional discs should be attached, one each, approximately 30 cm upstream and downstream of the respective flanges, as illustrated by Figure 8, when noise is present. As with any bonding process, it is necessary to have the surfaces clean and free of any lagging, dirt or grease. The epoxy should be applied smoothly and evenly to the disc to eliminate air gaps. The epoxy should then be squeezed as thin as possible to assure metal-to-metal contact at the center of the disc for good acoustical coupling. Take care that the epoxy does not enter the groove on the side of the disc.

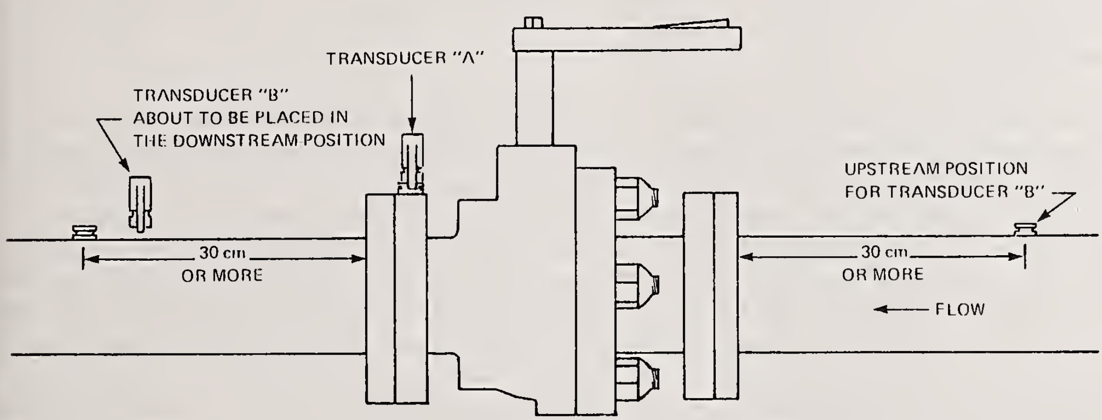

Figure 8 - Typical Transducer Locations

With the mounting discs in place, the transducers may be clamped to the disc as shown in Figure 5, or the ball end of the standoff shown in Figure 3 may be hand-held against the socket in the mounting disc. The ball-and-socket connection between the rod and the disc makes the acoustic measurement independent of the angle between the rod and the disc. In all cases, small amounts of coupling compound should be applied to the transducer-rod, rod-disc, or transducer-disc interfaces as appropriate to insure good acoustical coupling.

Interpreting Results: A complete system self-test, which includes cables, transducers, detector unit and X-Y plotter should be conducted at the beginning of each day's work, using the internal noise source. Each test begins with a determination of the transducer sensitivity (a partial self-test), followed by a measurement of the meter offset. The transducer test uses the internal noise generator. Meter offset at zero input attenuation with no signal present is then recorded for comparison with later readings.

The next step is to determine if significant background noise is present. This is done by attaching transducer A, as shown in Figure 8, and decreasing the attenuation until mid-scale meter deflection occurs with zero differential pressure across the valve. The attenuation and meter reading are then recorded for comparison with readings to be taken with normal differential pressure across the valve. If, with normal differential pressure across the valve, the meter reading and attenuation setting indicate a signal above the background noise level, it may be concluded that the valve is leaking. If the results of the single-transducer procedure are inconclusive, both transducers and possibly the X-Y plotter will have to be used to determine if the valve is leaking.

The next step is to attempt to electronically separate the background noise from the leakage signal, using the differential (A-B) function of the detector unit. Transducer B is first tested in the same manner as described for transducer A. Then, transducer A is moved to the upstream mounting disc, and then to the downstream mounting disc, recording the signal levels observed, to determine which mounting disc is nearest the dominant background noise source. Using the attenuator controls and the panel meter, the signal levels from both transducers successively placed at the mounting disc nearest the dominant background noise source are matched to compensate for differences in transducer sensitivity. With the input selector in the "A-B" position, the A transducer is placed on the valve flange, and the panel meter levels are recorded with the B transducer placed first upstream and then downstream. If a positive meter deflection is observed at both the upstream and downstream locations for the B transducer, or if there is a positive deflection at one location and zero at the other, it may be concluded that the valve is leaking. If zero deflection occurs at both locations, it may be concluded that the valve is not leaking. If a negative deflection (meter pegged below zero) is observed at either location of the B transducer, the situation is still ambiguous and a spectral plot must be made.

If, having recorded the amplitude versus frequency spectra with the X-Y plotter, it is observed that the signals are higher with normal differential pressure applied than with zero differential pressure, it may be concluded that the valve is leaking. If no differences are observed the results remain inconclusive unless some way can be found to reduce the background noise level to obtain a more positive indication. However, experience with shipboard systems indicates that inconclusive results are rare.

Application Experience: U. S. Navy experience with the Acoustic Valve Leak Detector has been of three distinct types:

- Monitoring programs for preventive maintenance
- Laboratory work
- Emergent applications

The AVLD is in general use by trained survey teams at several shipyards and onboard submarine tenders, on both coasts and at overseas bases. It is being used to detect leaky valves as part of systematic preventive maintenance monitoring programs and for overhaul planning, scheduling and budgeting. The survey teams are often called upon to determine which of two or more parallel-connected valves are leaking, to save the time and expense of removing or dismantling all of the suspected valves. Although most experience in this category has been limited to valves for water and steam, it is planned to expand the systematic survey programs to hydraulic and compressed gas valves also.

Experience has been gained under controlled laboratory conditions with water, steam, hydraulic and compressed air valves. Most of the laboratory work has been done in connection with a research and development program to extend existing detection technology to provide a leakage rate measurement capability. With a leakage rate measurement capability, it will be possible to establish repair priorities and to support long-term trend monitoring programs.

As a result of the increasing availability and acceptance of the AVLD, several requests have been received to explore other applications. Laboratory work has been found necessary to confirm field results in some cases, but initial results have often been good enough to support expansion of existing systematic survey programs to include additional valves and fluids.

Water Valve Experience: The original purpose for the Acoustic Valve Leak Detector was to detect leaks in seawater ball valves of 4- to 12-inch diameters. In this application, the differential pressures across the valves to be leak-checked are in the 5-7 psi range. Leaks are caused by marine fouling on the ball, by wear of the resilient seats and by a combination of corrosion and erosion between the seats and the valve body. Small leaks tend to remain small for long periods, but there is a threshold in the range of several hundred milliliters per minute per inch of pipe size, beyond which leakage rates tend to increase rapidly. The AVLD is not normally capable of differentiating between ball-seal or seal-body leaks.

Since the AVLD can detect leaks of a few hundred milliliters per minute consistently, periodic leak checks have made it possible to identify leakers while it is still easy to repair them by simple replacement of seats. Time and budget constraints make it impossible to repair all of the valves in a ship at one time except during a regular shipyard overhaul. Use of the AVLD makes it possible to maintain the piping systems in a high state of readiness by concentrating the limited repair resources on the few valves that actually need repair at a given time. The systematic monitoring and preventive maintenance program is resulting in a yearly maintenance savings of tens of thousands of dollars per ship.

A typical troubleshooting application of the AVLD is illustrated by Figure 9. Without the AVLD, it might have been necessary to dismantle and inspect nine large valves. In the example shown, a few minutes work with the AVLD eliminated two-thirds of the time and labor which would otherwise have been required.

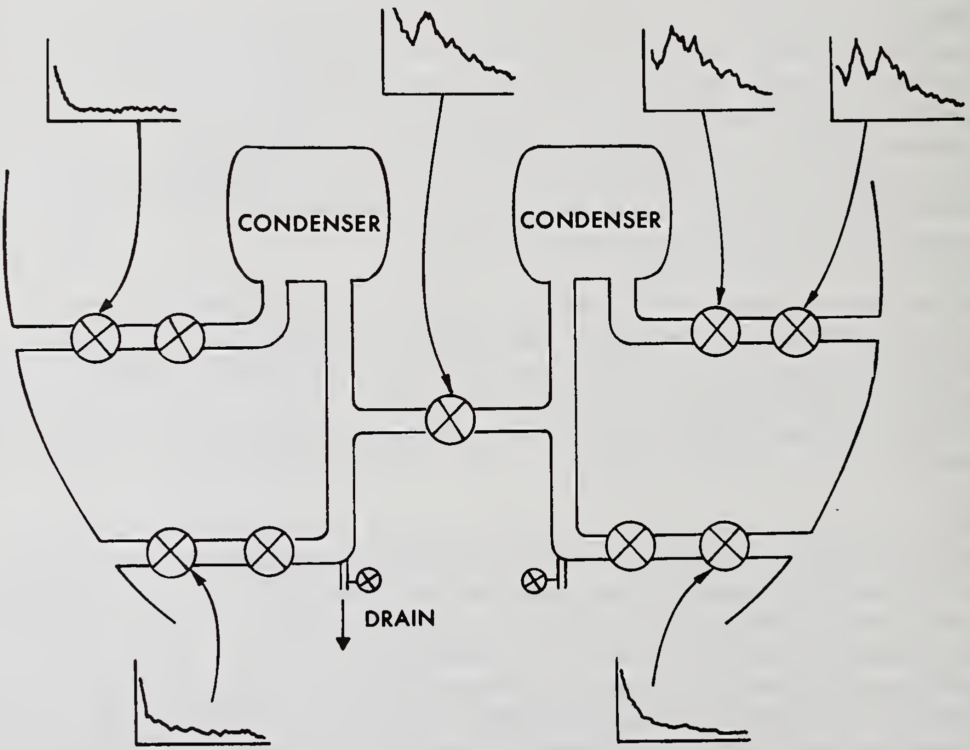

Figure 9 - Example of Leak Detector Application on Ship

With the epoxy-bonded discs in place, it takes less than 2 minutes to determine if a valve is leaking, even if it is necessary to make a spectral plot. In this application, spectral plots are seldom required. A comparison of meter readings at a center frequency of 25 kHz is usually sufficient for leak detection.

In the course of laboratory experiments [1] undertaken to determine what characteristics of the acoustic emission were related to leak rate, large variations were observed in the amplitude of the acoustic emissions of leaking seawater ball valves. No means were found to measure by acoustic emissions the leakage rate through the seawater ball valves at constant differential pressures in the 5-7 psi range because the variations in the acoustic amplitude were so large, but leakage rates of a few hundred milliliters per minute were consistently detectable.

It was observed that the large variations in acoustic amplitude were caused by several phenomena loosely related to air coming out of solution from water that had become supersaturated with dissolved air due to the pressure drop across the leaking valve. It was concluded that means must be found to predict, measure or control those phenomena before leakage through seawater ball valves can be measured acoustically at differential pressures of 5-7 psi. [1]

On the basis of the experiments at low differential pressures, it has been hypothesized that the 5-7 psi range is at or near the lower limit of detectable differential pressures and that higher differential pressures may produce acoustic emissions more consistently related to leakage rates. Experiments to test this hypothesis, using differential pressures up to 200 psi, are still in progress.

Shipboard surveys of water valves at even higher differential pressures are also in progress. Although there is good confidence in the initial results, the valves suspected to be leaking have not been examined internally and there are no other means to detect leakage while the valves remain in place.

Steam Valve Experience: Shipboard and laboratory experience indicates that steam valve leaks are easier to detect than water valve leaks. There are at least three factors which contribute to the ease of detecting steam valve leaks:

- High pressures
- All-metal construction
- Low background noise

The relatively high differential pressures across a typical leaking steam valve increases the acoustic power and frequency range of the noise source. The all-metal construction (no resilient seats) results in low transmission losses between the noise source and the point of transducer attachment on the valve body or valve stem. Background noise is seldom a problem with steam piping systems. The signal-to-(background) noise ratio for steam valves is further increased by lagging which tends to damp structureborne noise from other sources.

Another important consideration is that many shipboard steam systems are at least doubly redundant. This means that in case of doubt, it is often possible to compare the acoustic signatures of two ostensibly identical valves in identical service.

Because of redundancy requirements and other reasons, shipboard steam valves are often connected in parallel. Before the introduction of the AVLD, steam leaks detected or suspected through other means were often impossible to attribute to a single valve. The AVLD is usually capable of determining which valve is not leaking, thereby saving the time and expense of removing or dismantling it. In the case of large stop valves paralleled by much smaller warmup valves, valve size must be considered in drawing conclusions. The signatures of the large valves must be compared with the signatures of the bypass valves and other large valves. If the large valve signature is greater than the small valve signature, it is reasonable to conclude that the large valve is leaking. However, if the small valve is leaking also, its signature will often be greater than the signature of the large valve. In general, very large signatures from large valves indicate large leaks, and very small signatures from small valves indicate no leakage.

In attaching the transducer, it is sometimes necessary to remove a small amount of lagging; however, in valves where the stem connects directly with the noise source the exposed valve stem is often a good point of attachment. Because steam and piping temperatures exceed the temperature limits of the transducer, it is necessary to use the standoff, usually as a hand-held probe, as illustrated by Figure 7. Once the best locations for the transducers have been identified, it is possible to leak-check steam valves, including poppet-type turbine throttles at the rate of about one valve per minute.

The original purpose of systematic valve surveys was to increase overall system operating life, reliability and availability by determining where to concentrate limited maintenance resources. Subsequently, requirements for reduction of energy consumption have led to proposals to use the AVLD to minimize energy losses.

Laboratory experience with the AVLD indicates that it is feasible to measure leakage rate through steam valves. However, since there is evidence that small steam leaks grow rapidly, a decision was made to abandon that effort in favor of development of a simpler instrument capitalizing on the high signal-to-noise ratios present in steam piping systems, but capable of detection only. It is hoped that increased use of the less expensive instrument will enable small leaks to be identified and repaired before they become so large as to require more expensive repair procedures.

A prototype of the simplified steam leak detector instrument is currently being evaluated aboard ship. It is basically an rms acoustic amplitude meter, operating in the 20 kHz to 80 kHz range and capable of an extremely large dynamic range.

In addition to the basic conclusion that steam valve leakage rate measurement by analysis of ultrasonic emissions is feasible, some other useful information was developed. With a 3 1/2 inch globe valve mounted in a test stand and pressurized about 600 psi, it was possible to measure acoustically leakage rates as low as 0.2 ml/min of condensate, which was collected at the valve discharge. Since a steam loss of 0.2 ml/min corresponds roughly to a fuel waste of about 0.002 pounds per hour, it is obvious that leaks causing significant energy losses are easily detectable. Several spontaneous changes in leakage rate were observed. It is suspected they were caused by differential thermal expansion of the parts, implying that acoustic measurements made for trend analyses should be taken after the valve is thoroughly warmed up.

Compressed Gas Valve Experience: Shipboard applications of the Acoustic Valve Leak Detector to 4000 psi compressed air valves have been hindered by the high levels of background noise typically present. The pipes and valves are so well coupled acoustically that leakage noise and other noise picked up from external sources tend to spread throughout the system. The valves which have been of primary interest in the program so far are 2-inch ball valves with resilient seats, connected by steel pipe. No lagging is present. There is very little transmission loss of the ultrasonic acoustic energy. The result is that with the presently operational instrument, it is always difficult and sometimes impossible to determine which of several valves is leaking.

Laboratory work is currently in progress to determine which of several candidate signal processing schemes will permit the AVLD or new techniques to work better in the high noise environment.

Experience in the laboratory with the 2-inch ball valves and aboard ship with smaller valves has been much more successful. Leaks in smaller valves are more easily detected. For instance, the AVLD was recently used to locate a leak in a shipboard oxygen generator system. A 1/2-inch valve pressurized at 1800 psi was cracked open to leak at a measured rate of about 1 ml/min (at atmospheric pressure). It was also monitored by bleeding the leakage through a piece of flexible tubing into a beaker of water. The leaking valve was easily found by the AVLD from among several dozen other valves in less than 2 minutes. Prior to the introduction of the AVLD, troubleshooting the system for a leak of that size took an average of 20 man-hours, and occasionally took 100 man-hours or more. Signfiicant leaks which are initially detected by monitoring system pressure losses over time, occur about four times a year per system.

Leaks smaller than the 1 ml/min rate were also detected. There was an interesting phenomenon observed with very small leakage rates. From monitoring the leakage noise on the AVLD audio output, it was observed that the acoustic emission was intermittent. This phenomenon had been observed previously in hydraulic and high-pressure water leaks. If the leaks are as intermittent as their acoustic emission, that could explain why some leaks in this system are very elusive to traditional leak-finding procedures involving water and soap.

Laboratory work with the 2-inch ball valve at 4000 psi has shown that in the absence of high levels of background noise, leakage rates as small as 100 ml/min can be detected reliably on the basis of ultrasonic acoustic emissions, and that the signals increase with increasing leakage rate. As a result of this finding, work is in progress to develop an operational instrument capable of measuring high-pressure air valve leakage rates by analysis of ultrasonic acoustic emissions.

Since the background noise levels in shipboard high-pressure air systems are high, a successful instrument must incorporate noise rejection features. At least three techniques to reduce the effects of background noise are being considered. Because detectable ultrasonic signals from leaking high-pressure air valves have been observed at frequencies as high as 400 kHz, and because there is a theoretical increase in transmission attenuation with increasing frequency, surveys will be conducted to determine the extent to which shipboard background noise is attenuated at higher frequencies. A technique being investigated with some success in the laboratory is to damp the ultrasonic acoustic emissions in the vicinity of a valve being leak-checked by attaching sound-absorbing materials to nearby pipes.

A third approach being developed uses the cross-correlated signal between two transducers mounted at different distances along the pipe. The signal is different depending on the direction of the noise and this difference is sensed to indicate the direction from which the dominant noise is coming.

The objective of this development effort is to produce an instrument which can detect a leak, isolate it to a single source, and then measure the leakage rate; all by analysis of ultrasonic acoustic emissions. The leakage rate information will then be used for trend analysis and for establishment of repair priorities and criteria.

Hydraulic Valve Experience: The Acoustic Valve Leak Detector is currently being used to identify leaking hydraulic valves on a troubleshooting basis if leakage is detected or suspected as a result of other evidence. Laboratory experiments have determined that the minimum detectable leakage rate is about 10 ml/min at 2800 psi, and have established the feasibility of measuring hydraulic valve leakage rates by analysis of the ultrasonic acoustic emissions.

Laboratory work to date has the objective of developing an operational instrument capable of measuring, as well as detecting, internal leakage rates of hydraulic valves by analysis of ultrasonic acoustic emissions. It has been determined that there are detectable ultrasonic signals associated with hydraulic valve leakage and that the signal amplitudes increase with increasing leakage rate.[1] On the basis of this finding, it was concluded that a quantitative instrument is feasible. A capability to differentiate one leaking manifold valve from the non-leaking valves was also demonstrated. [1]

Despite the progress made in the laboratory and aboard ship, some important aspects of the acoustic emissions of leaking hydraulic valves remain incompletely understood and are currently being investigated. In particular, signature amplitude was observed to increase with decreasing valve backpressure. [1] Another important factor is the sump pressure, usually above atmospheric pressure, at which the hydraulic oil is stored for long periods in contact with air. In some instances, large acoustic signature amplitude variations were observed at backpressures near the sump pressure.[1]

Future Developments: Improvements to the existing Acoustic Valve Leak Detector are being developed in four major areas:

- Leakage rate measurement (as opposed to direction)
- Background noise rejection
- Accessories for ease of operation
- Design simplification

Leakage rate measurement as an extension of the existing technology will permit a trend-monitoring program to be established. This capability will be especially important when applied to valves and fluids with a leakage rate threshold, above which valve damage and leakage rates increase rapidly. Experimental data reported elsewhere [1] show that there are detectable ultrasonic acoustic signals associated with hydraulic, steam and high-pressure air valve leakage, and that the signals increase with increasing leakage rate. The known ranges of acoustically measurable leakage rates for the three fluids are tabulated in Table 1. Note that the greater of the leakage rates listed are not necessarily upper limits. They are simply the greatest leakage rates observed in the laboratory experiments which were the basis for the data shown.

Table 1 - Known Range of Acoustically Measurable Leakage Rates

Fluid	Valve Type	Valve Size	Differential Pressure	Acoustically Measurable Leakage Rate (ml/min)
Hydraulic	Spool	1/2-1 in.	2800 psi	10.0-1000
Steam	Globe	3-1/2 in.	600 psi	0.2- 30 (condensate)
Air	Ball	2 in.	4000 psi	100.0-3000 (measured at atmospheric pressure)

Despite the progress reported, many factors affecting the relationship of acoustic signatures to leakage rates remain incompletely understood. These factors are related to valve size, background noise, and fluid characteristics such as pressure, temperature and dissolved gas content. Current development work is directed toward obtaining a better understanding of these factors and toward developing instruments capable of measuring leakage through 2-inch ball valves for high-pressure air and through hydraulic directional control spool valves.

Background noise rejection improvements are being developed for shipboard high-pressure air systems. Methods being developed for rejection of excessive structureborne noise include local damping, electronic signal processing and the use of higher frequency signals.

Accessories which make the AVLD easier to operate have been developed as the need arose. A current example is a transducer clamp which will not require mounting discs to be epoxy-bonded to the pipe or valve surface, but will still permit hands-free operation.

Design simplification is a normal evolutionary process for any new development. The existing AVLD is a very versatile instrument which can be used for a variety of valves and fluids. By including only the features needed for a particular application, it is possible to make a simpler, but less versatile instrument. An example of this is the prototype steam valve leak detector which was recently completed.

Summary: Detection and measurement of the internal leakage of fluid valves by analysis of ultrasonic acoustic emissions are rapidly expanding technologies within the U. S. Navy. The Acoustic Valve Leak Detector, when applied in a systematic program of preventive maintenance monitoring, can eliminate most of the cost and downtime associated with determining the internal condition of valves by traditional methods of removal, disassembly and inspection. In troubleshooting applications, it enables repair efforts to be concentrated quickly on the actual cause of the problem, rather than wasted in a long search for the leaking valves. In some applications, the AVLD can be used to detect small leaks before they become too large to repair by simple methods.

The Acoustic Valve Leak Detector also has great potential for energy savings when applied in a preventive maintenance program aimed at detecting and eliminating leakage losses, particularly in steam systems and other piping systems which use fluids to transport heat.

Research and development efforts are continuing to expand the capabilities of fluids, pressures, temperatures, valve types and valve sizes. Since none of the fluids or valves are particularly unique to the Navy, it is expected that the instrument will find even wider commercial and industrial applications.

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PIELSTICK ENGINE DIAGNOSTICS

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Abstract: In order to improve engine reliability and reduce maintenance expenses on ships, S.E.M.T. has developed a monitoring and diagnostic system for medium speed diesel engines used in marine propulsion. The system was designed to monitor ship's engines automatically, and without manual intervention, while underway. The aim was both to prevent failures and to perform maintenance only when necessary. The Pielstick Engine Diagnostic system automatically monitors wear of the piston top ring, main bearing alignment and shell wear, pressure charging circuit fouling condition, and exhaust gas temperatures. The use of the system will result in the extension of piston on-line time between inspections, in the elimination of alongside monitoring of the shafting, and in the improvement of the operating environment of the engine. The economical justification will be extended engine life while eliminating unnecessary labor and engine outages.

This paper describes the monitoring arrangement, including data acquisition and processing, with results from both land tests and a sea-going vessel.

Key Words: Crankshaft displacement; medium speed diesel engine, piston ring wear; turbocharging monitoring.

Introduction

The Pielstick Engine Diagnostic system (P.E.D.) monitors the on-line condition of certain components of medium speed diesel engines with outputs ranging from 480 to 1100 kW per cylinder. The system uses pickups, "AND" circuits, and a data microprocessor to supply users with information about piston ring wear, crankshaft bearing alignment and wear, turbocharger fouling, and exhaust gas temperatures (fig. 1).

Some of the benefits of this system are: (1) automatic monitoring of engine conditions which eliminates several hours of labor and engine outages that are required for manual inspections; (2) helping to prevent failures which would have serious consequences to ship operations; and (3) permitting corrective actions to be taken only when actual wear damage has occurred.

Research on the P.E.D. system started in May 1977 using a 12 cylinder power station engine for the development of the system software. At the end of December 1977, a first prototype system was fitted onto an 18 cylinder propulsion engine of the container ship M/V "RENOIR" which was commissioned in January 1978. A second prototype system has been fitted onto a test engine in S.E.M.T.'s laboratory.

Piston Ring Wear Monitoring

Two cylinders from every Pielstick engine are inspected at 6000 hour intervals for piston ring wear; all engine cylinders are inspected after 12000 hours of operation. The main purpose of these inspections is to check the amount of wear in the chromium layer covering the top ring face. Chromium plating wear depends to a large extent on the engine working conditions such as rotation speed, lube oil nature, cooling water temperature, on/off cycles, etc.

The dismantling of a piston and con-rod assembly for checking piston ring wear is a long and tiresome operation and therefore it is very desirable to extend the inspection interval. In a great number of cases, after dismantling, inspection shows that the interval could have been extended without detrimental effects. But, once the top ring protective chromium layer is worn, the cast iron ring rapidly deteriorates necessitating the replacement of the piston ring set. Therefore, the intervals between inspections cannot be extended without some kind of monitoring system such as the Pielstick Engine Diagnostic system. This system continually measures the top ring chromium ring plating thickness. The expected cost of the system will be recovered if the piston ring service life can be increased by 1000 hours per set, based on the smallest PC engine and monitoring one cylinder out of 3 or 4.

Inductive sensors are used in the P.E.D. system to measure the thickness of the chromium plating on the piston rings. These sensors produce a signal whose amplitude varies with both the thickness and the magnetic properties of the coating material (fig. 2).

These sensors are placed in the cylinder liner of the engine flush with the cylinder liner wall (fig. 3). The sensor is placed in such a way that all the piston rings pass successively in front of the sensor. This allows the sensor to scan each ring and generate an appropriate output signal. If one of the piston rings is pure cast iron (no coating), then it is possible to measure the thickness of the coatings by comparing the amplitude of the signals given by the passage of each ring. The accuracy of this technique is such that it has been possible to compute a 0.044 mm reduction in coating thickness compared with an actual wear reduction measurement of 0.047 mm.

Figure 4 shows the signal from the piston rings transducer as displayed by the data microprocessor. The computer is programmed to eliminate abnormal values resulting from the passage of ring gaps before the sensor. The signal is analyzed vs time and the wear rate of the piston ring is computed to help determine the next scheduled overhaul.

Measurements from the system installed on the M/V "RENOIR" reveal a slight chromium wear on the piston rings after 3400 operational hours. No dismantling has taken place since the installation of the P.E.D. system. Therefore, no direct measurements are available for comparison.

Crankshaft Monitoring

At the present time, crankshaft alignment and wear inspections are achieved by measuring crank deflections and under journal clearances. This inspection is performed after every 3000 operational hours, and while this is adequate for proper engine operation, it does not predict or prevent failures such as delamination of anti-friction metal, faulty tightening, poor lubrication, faulty filtering, etc. Furthermore, these scheduled inspections require relatively long downtimes which often are unnecessary because no anomalies are found.

From the economical standpoint, the new P.E.D. monitoring system eliminates time consuming inspection and reduces outages due to component failure. Its chief value may be its ability to detect imminent failures because a shafting breakdown could stop the engine, and thereby put the ship out of service for a long time.

Monitoring of the crankshaft is based on the analysis of the vertical component of the crankshaft motion in the bearings. A contact free displacement transducer is fitted in each main bearing on the engine vee axis (fig. 5). From the signals emitted by the transducers, the following parameters are computed: the total amplitude of the displacement (a) from peak to peak during a cycle (two engine revolutions); the mean position of the crankshaft (b) during these same revolutions; and the minimum lift (c) of the crankshaft in the bearing. These three parameters differ from one bearing to another and vary with the engine speed (fig. 6).

Results from the M/V "RENOIR" show that for a given rotation speed, amplitude "a" decreases slightly when the engine power demand increases; this amplitude also decreases by 3/100 when the ship's displacement increases from 16000 to 29600 tons. The ship's cargo seems to have no effect on "b" and "c" values.

In order to ascertain that the signal indicating crankshaft journal movement in its bearing was affected by wear of the bearing anti-friction metal, we recorded the signals given by a transducer installed on the bearings of a 12 cylinder engine operating under normal conditions and after having removed the bearing shell of one of the bearings. It was observed that the signal amplitude doubled for the bearing with the shell removed. Figure 6 shows that an increase in the rotation speed results in an increase in the journal movement amplitude. As a result, crankshaft monitoring is only done while the ship is at "full speed". At "full speed", the engine rotates between 475 and 500 rpm depending on the wind, the load, and hull fouling leading to a variation in parameter "a" of about 0.03 mm or 10 percent.

Analyses of "b" and "c" values are used to monitor main bearing alignment by comparing the mean position "b" of a bearing with that of the neighboring ones. The values of parameters "b" and "c" are not affected by the roughness of the ocean over the range from a calm sea to a Beaufort number of 9. The value of "a" is not affected since it is measured over two crankshaft revolutions which is a much shorter period than one swell.

Exhaust Gas Temperatures

Monitoring of exhaust gas temperature is an usual practice aboard ships. We have found it to be practicable, both technically and economically, to replace the analog equipment with a simple indicator and to perform monitoring and analysis using the computer provided for the crankshaft and piston ring monitoring. The exhaust gas temperature is measured at each cylinder outlet. The readings are averaged and the individual deviations with respect to the mean value are computed. The computer verifies that each temperature does not deviate from the control values established for a new engine, taking the control rack position into consideration. The computing program also takes into account the systematic deviation among the cylinders which is specific to each engine. Practical experience indicates that with a fixed-pitch propeller the rotation speed should also be taken into account in addition to the control rack position.

The alarm threshold varies as the temperature average with the permissible deviation being larger for the low averages. Figure 7 shows the influence of the after-cooler air temperature. Both experimental curves plotted for 31 and 39°C air temperatures bracket the ideal curve.

Survey of the Supercharging System

The aim of this survey is to determine fouling of the supercharging system and to predict the evolution of this fouling. The survey system applies to the air-cooler, the turbine and the compressor. The economical advantage of the system rests on the fact that any anomaly in the pressure charging entails a loss of engine efficiency and, in extreme cases, damage to the valves.

The survey system measures the following parameters:

- air temperature after cooler

- water temperature at cooler inlet
- air pressure after cooler
- difference in air pressure, before and after cooler
- fuel rack position
- revolutions of the turbo-blower.

Fouling of the air cooler will be determined by the difference between the water temperature and the air temperature, and by pressure loss at air side. These readings are subject to trend analysis in order to warn the servicing staff that corrective measures must be undertaken.

Air filter or compressor fouling may be found by comparing the air pressure value read before the compressor and that found by application of the law giving that pressure in terms of turbocharger rotation speed. Figure 8 shows the experimental results and also that the linear function first adopted as the pressure - rotation speed relation was over-simplified, as the difference between the measured and computed pressures may exceed the alarm threshold fixed at 0.13 bar. The linear function will be superseded by two straight line segments. The exhaust gas side of the turbocharging system is monitored by comparing charge air pressure at the compressor outlet with the theoretical pressure given by the law relating the air pressure to the engine speed multiplied by the control rack stroke. The product of the control rack stroke and rotation speed is sufficiently accurate to be used for the power developed by the engine. Insofar as their installation has been anticipated by the builders, the system may be completed with accelerometers to monitor turbocharger bearings. These accelerometers may either trip an alarm for too severe vibrations or be used, with a particular routine, to determine the time when the rolling bearing should be replaced.

Computation Means

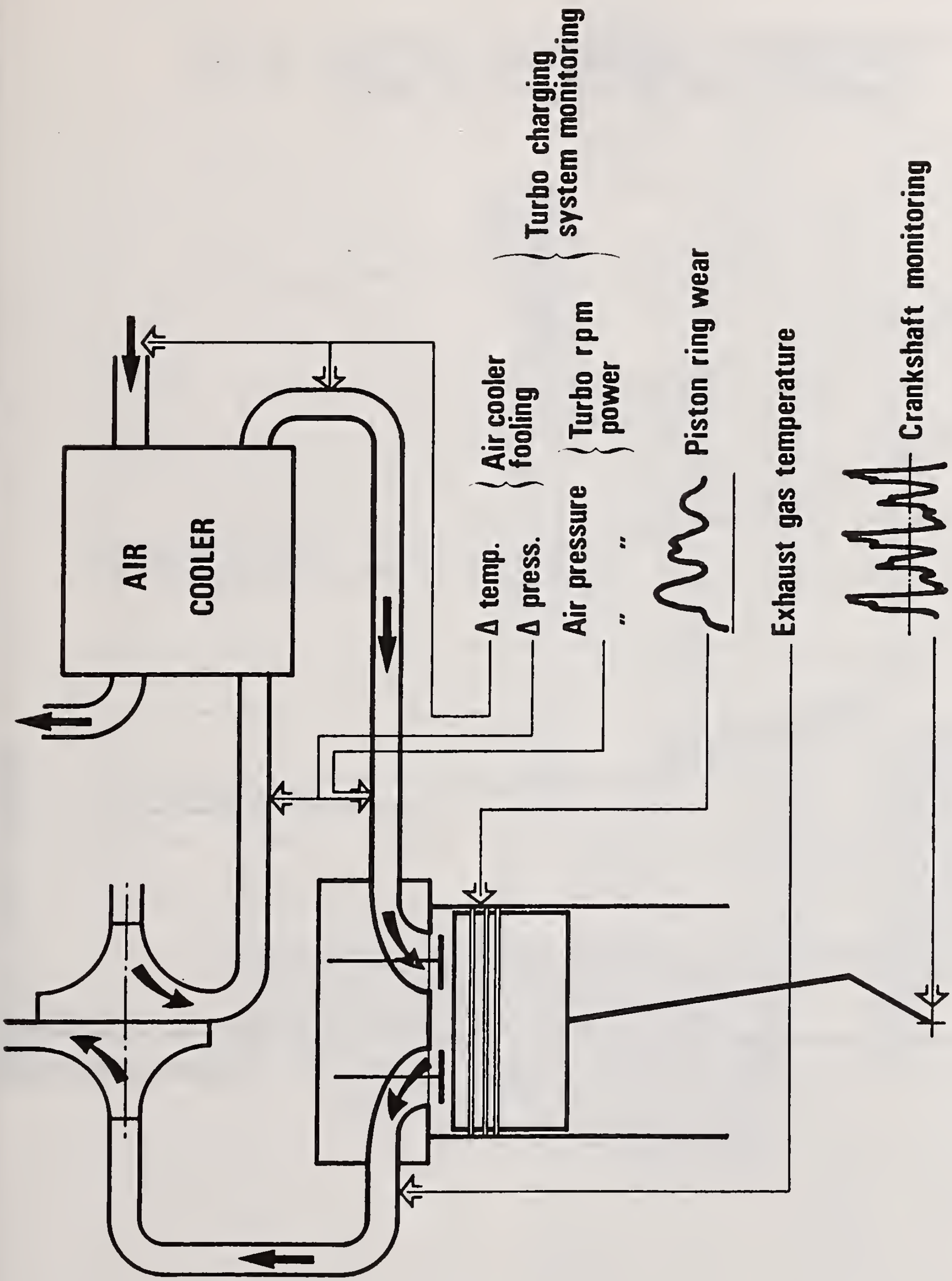
The microprocessor is located in the control room a few meters distance from the engine. It receives analog signals from the various sensors, handles the data according to computation programs, compares the obtained values with the reference values stored, commands sound and light alarms, and prints instructions for the servicing staff. Computer storage facilities are either unalterable ones or active ones fed by batteries or the ship's electric circuit, depending on the importance of the data to be stored and on the consequences of their being erased.

Hardware Problems

The first objection raised by the shipowners regarding monitoring systems is the problem of the maintenance of these systems. It is therefore necessary to search for sensors that are more rugged than precise and to provide for easy access to the sensors. Wires should be easily accessible and well protected against the shocks they might suffer during dismantling of engine components. Since the system was put into service, we have recorded the destruction of one air temperature sensor, the drift of an "AND" circuit for a main bearing sensor, and the shut off of the microprocessor electric supply due to vibrations. These failures show that great care must be taken, especially from the vibration standpoint, when fitting electronic equipment into a medium speed diesel engine machine room.

Conclusion

The results of the P.E.D. prototype system being tested aboard the M/V "RENOIR" are promising. They show that the monitoring of a medium speed diesel engine used for marine propulsion is possible. It was necessary to try it at sea so that the system prototype would be subjected to a machine room environment. It is too soon to reach a conclusion about piston ring wear reading accuracy and long term sensitivity of shafting monitoring. The economical advantage of the P.E.D. system is not yet established, but the system is a sound base for further research and development.



AIR
COOLER
Δ temp.
Δ press.
Air cooler fooling
Air pressure
"
Turbo r p m
power
Turbo charging system monitoring
Piston ring wear
Exhaust gas temperature
Crankshaft monitoring

Figure 1.

INFLUENCE OF THE COATING THICKNESS ON THE SIGNAL GIVEN BY THE PISTON RING

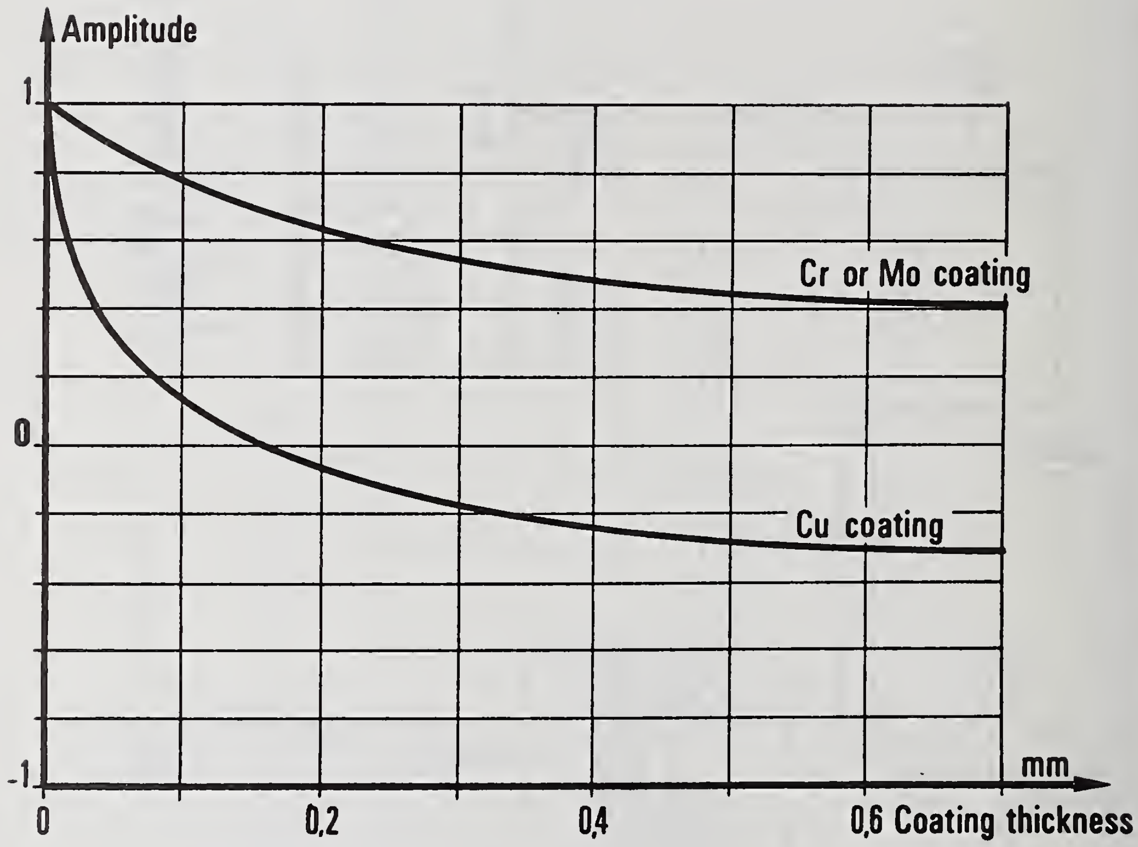


Figure 2.

PISTON RINGS SENSOR

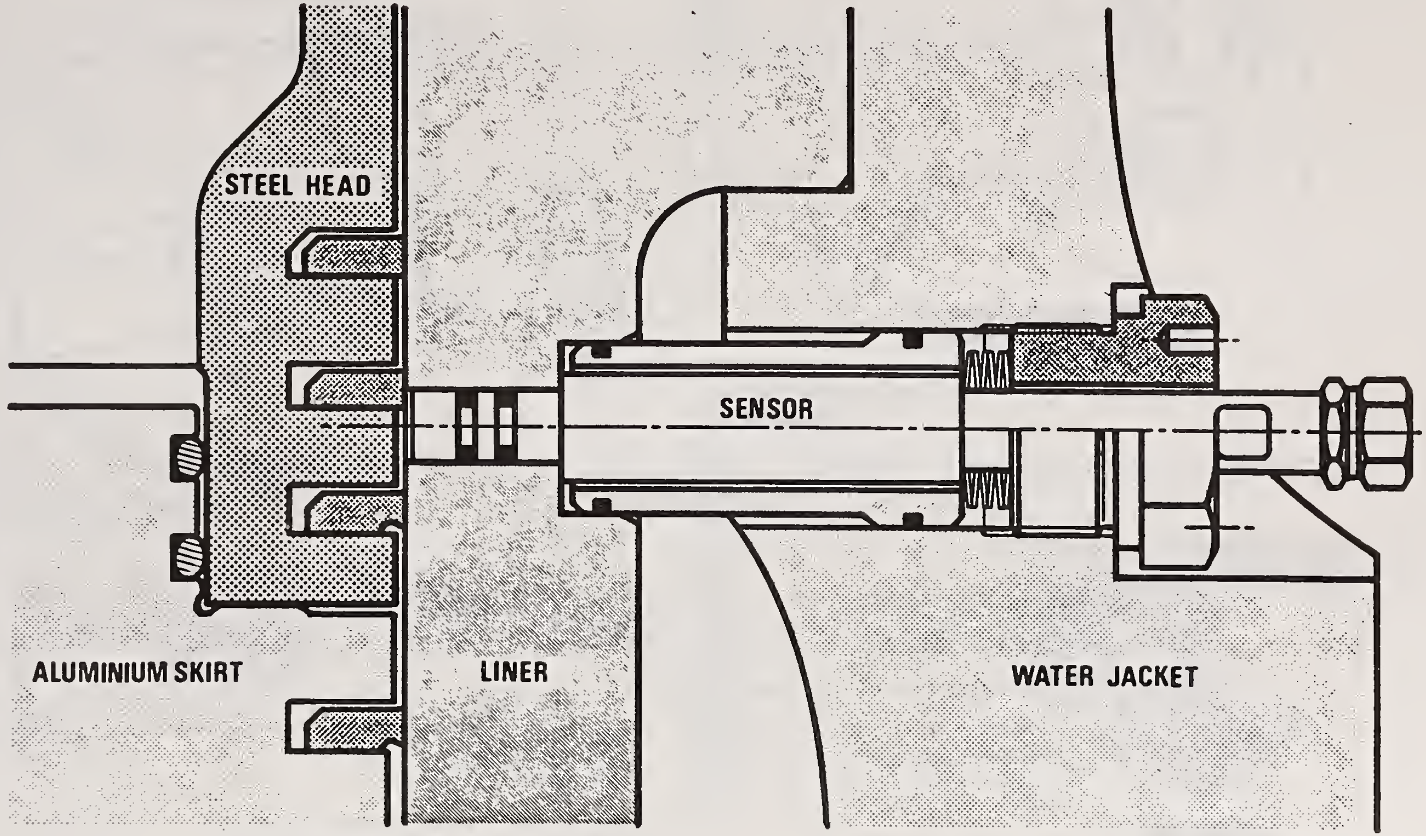
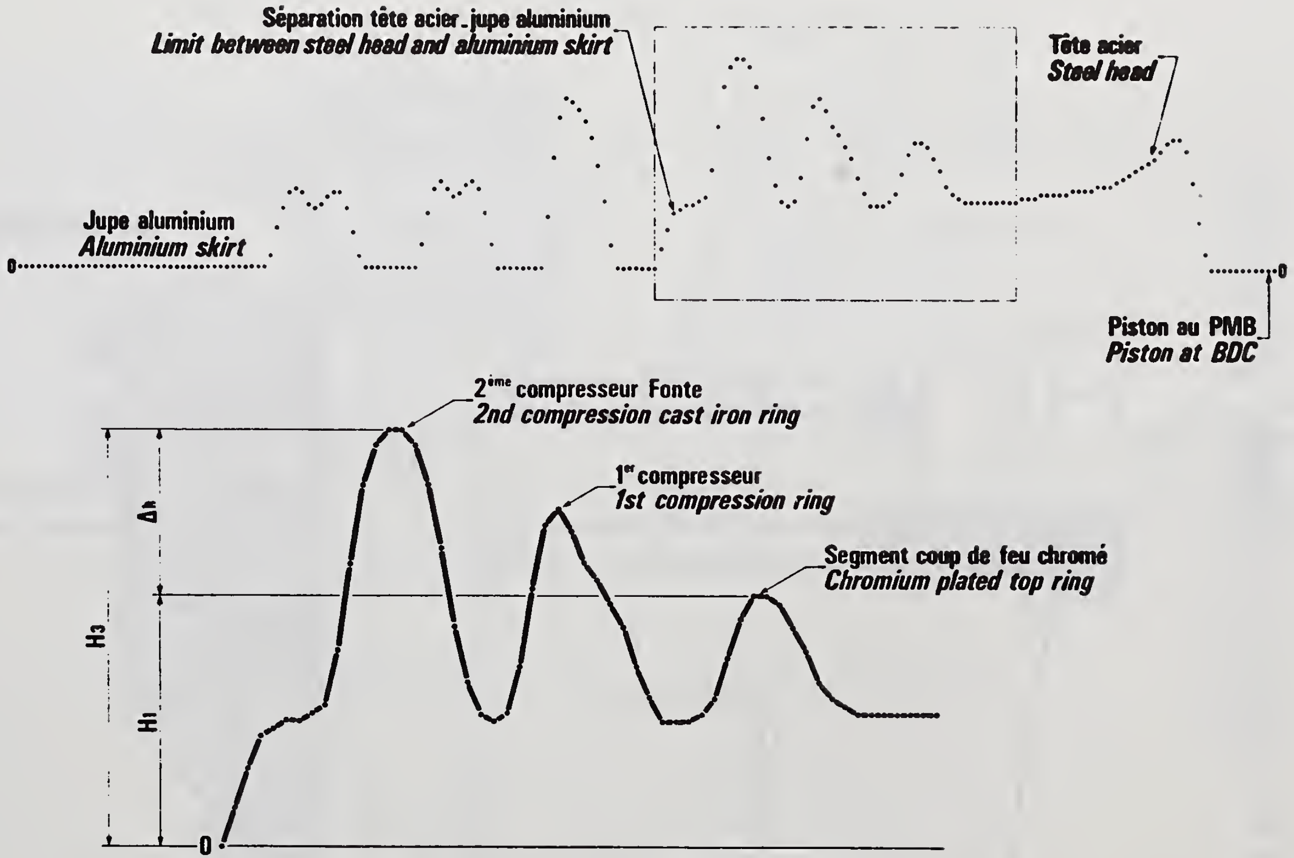


Figure 3.



SIGNAL DU CAPTEUR DE SEGMENTS VU PAR L'ORDINATEUR.
SIGNATURE FROM THE PISTON RINGS TRANSDUCER AS SEEN BY THE COMPUTER.

Figure 4.

CRANKSHAFT SENSOR

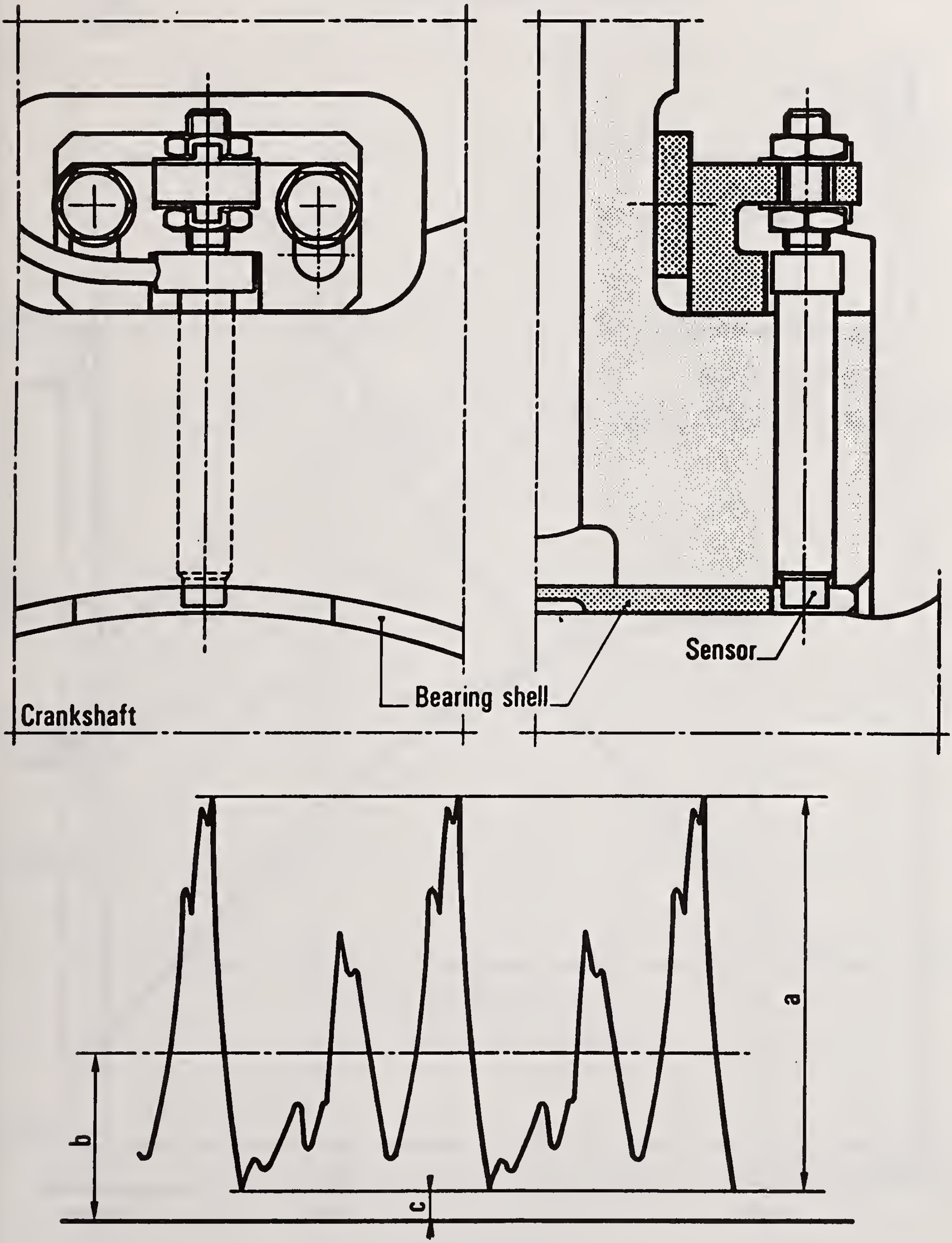


Figure 5.

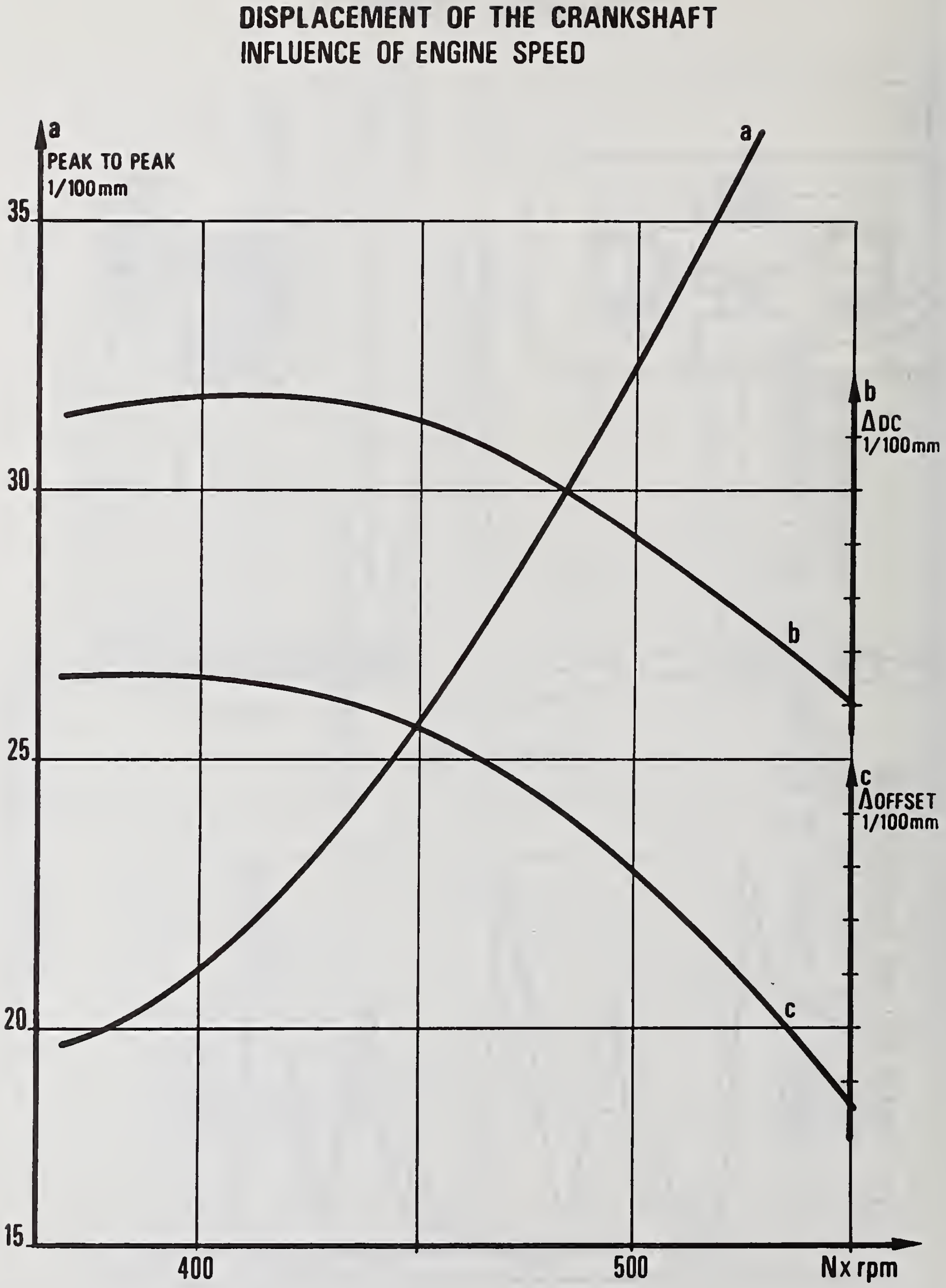
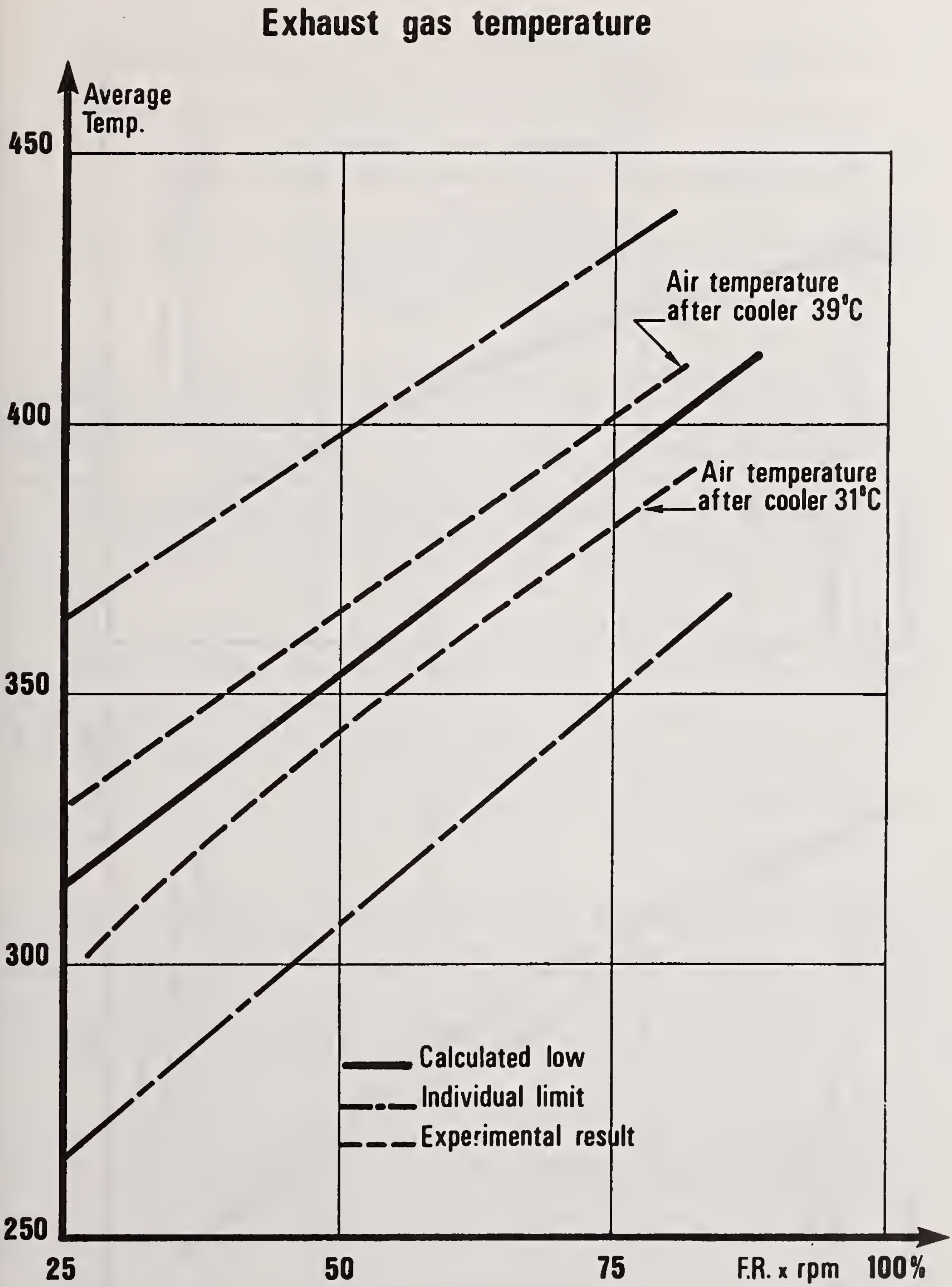
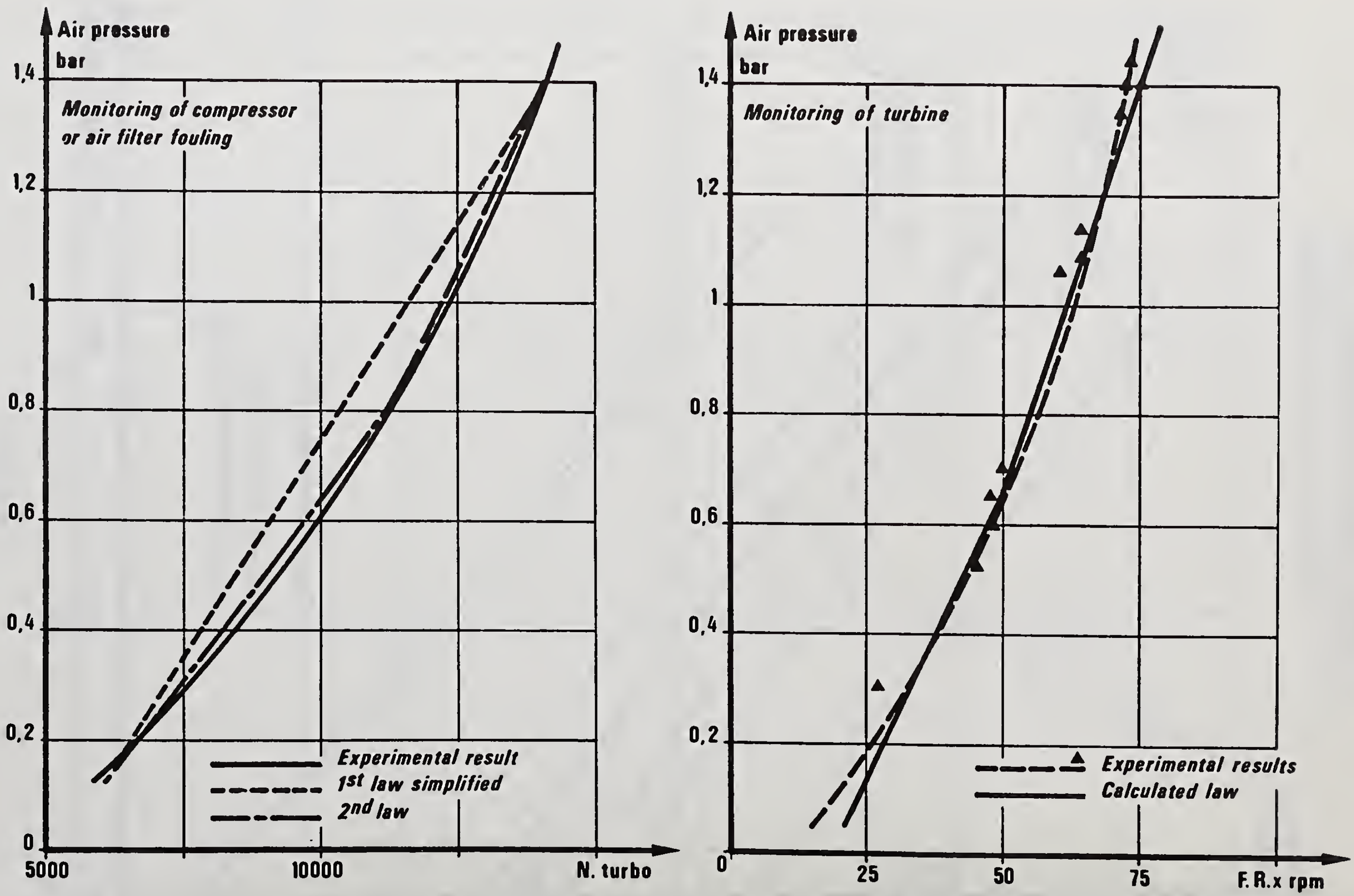

DISPLACEMENT OF THE CRANKSHAFT
INFLUENCE OF ENGINE SPEED
a
PEAK TO PEAK
1/100mm
35
30
25
20
15
400
500
N x rpm
a
b
c
b
ΔDC
1/100mm
c
ΔOFFSET
1/100mm

Figure 6.



Exhaust gas temperature
Average Temp.
450
400
350
300
250
25
50
75
F.R. x rpm
100%
Air temperature after cooler 39°C
Air temperature after cooler 31°C
Calculated low
Individual limit
Experimental result

Figure 7.



Air pressure
bar
1,4
1,2
1
0,8
0,6
0,4
0,2
0
5000
10000
N. turbo
Monitoring of compressor
or air filter fouling
Experimental result
1st law simplified
2nd law
Air pressure
bar
1,4
1,2
1
0,8
0,6
0,4
0,2
0
25
50
75
F.R.x rpm
Monitoring of turbine
Experimental results
Calculated law

Figure 8.

MACHINERY CONDITION ANALYSIS FOR MAINTENANCE PLANNING--THE AIRCRAFT CARRIER EXPERIENCE

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Abstract: In 1970, Machinery Condition Analysis (MCA) began to replace the more traditional methods of planning the overhaul of aircraft carrier machinery. These traditional methods included overhauling all machines, opening each machine up and inspecting to see what was wrong, or running until failure. None of these methods, however, was particularly conservative in either money or time, and MCA was intended to take a more objective look at high cost, mission critical machines, and identify which ones were most in need of overhaul.

This paper addresses the evolution of MCA at PERA (CV), the process as it is conducted today, and the varied uses of its results. Particularly addressed are the benefits derived from the program and the possible expansion of the program in the future.

Key words: Aircraft carrier; condition analysis; machinery; maintenance; monitoring; repairs; vibration.

WHY PLAN MAINTENANCE? The Navy, like every major firm that relies on machinery for production, processing or services, spends a considerable amount of time, effort and money keeping them operational. From the maintenance done by the operators on the ships, to the complete overhauls done in public and private shipyards, $2.5 billion will be spent this year keeping the ships operational.

All of the planning that goes into the maintenance of ships is done for one reason - neither the Navy nor the taxpayers can afford the alternative of no planning. Ships have become too complex, materials and parts take too long to buy, and the money is not available, for ships to simply come into a shipyard without tremendous preparation, and the Navy is the first to recognize this.

In 1967, the office for Planning and Engineering for Repairs and Alterations of Aircraft Carriers (PERA (CV)) was established at Puget Sound Naval Shipyard in Bremerton, Washington. The purpose of this organization was to do the advanced planning for all Aircraft Carrier Industrial availabilities, both for maintenance of equipment and modernization.

EARLY MAINTENANCE PLANNING FOR AIRCRAFT CARRIERS.
Whether intuitively or analytically, it is fairly well known that machine failures occur in a manner similar to the "bathtub" curve (FIG. 1). Most failures occur when a machine is new or recently worked on (break in), or when it has run for a considerable length of time (wear out). The challenge of maintenance planning is to determine when to overhaul a particular machine. Some give you clear signals, such as poor performance, high vibration, or strange noises. But others give no indication that is obvious or apparent prior to failure.

Early maintenance planning at PERA (CV), and much of the present planning also, took one of the following directions depending on the criticality of the equipment, the length of overhaul, and the amount of funds available.

1. Overhaul all machines of a certain type on a fixed schedule (i.e., every major overhaul).

2. Select a certain number of machines to be overhauled (i.e., 4 of 12 Main Feed Pumps) and allow Shipyard inspectors or Ship's Force to select the specific units.

3. Open and inspect machines when they arrived in the Shipyard.

4. Fix at failure.

With the exceptions of nos. 1 and 4, there was little objective data on which to base the actions taken on a particular machine, and often the complaint arose from the operator, "My machines were in better shape before I came into the overhaul," and possibly he was correct. At a minimum, the failure rate of the machines overhauled will be greater than upon arrival, and, until the breakin time is over, the failure rate will not be at its previous level.

MACHINERY CONDITION ANALYSIS (MCA) BEGINS.
In 1970, it was proposed that Machinery Condition Analysis (MCA) be used to determine which high-cost, mission-critical machines required overhaul. Vibration Analysis was chosen as the prime element in this program for several reasons.

1. Vibration Analysis had been used since 1939 for detecting problems with rotating machinery in petrochemical plants.

2. It had been very successful in the submarine noise reduction program.

3. It could be done without taking the machine off the line or interrupting ship's operation.

In January of 1971, the first MCA survey was conducted on 40 machines in the USS FORRESTAL (CV 59) in support of its FY 1972 Regular Overhaul. The report was basically a priority listing of machines by need for overhaul, and a simple OVERHAUL/DON'T OVERHAUL recommendation on each machine. Since 1971, 84 MCA surveys have been conducted on Aircraft Carriers - 72 prior to availabilities and 12 immediately after availabilities.

MCA IN SUPPORT OF MAINTENANCE PLANNING TODAY.
To support Maintenance Planning today, two surveys are conducted between each availability - one 30-60 days after the completion of an availability, and one five to six months before the next (FIG. 2). This allows some trend analysis and provides quality assurance for the past availability. During these surveys, between 150-250 machines are tested. Accelerometers are attached to welded or glued blocks on each machine and vibration signatures are recorded on magnetic tape. In conjunction with vibration, visual inspections and discussions with the operators are held during the survey, and all the data gathered goes on a single report. The survey itself takes from 4-8 days depending on the number of machines, the ship's operations, and the number of compartments the machines are in.

The vibration data is then transferred to hard copy for analysis. A typical survey will result in 2000-3000 vibration signatures (FIG. 3). Each signature is: (1) analyzed for high vibration, (2) compared to similar machines, and (3) compared to its previous signatures. Significant increases in vibration, or high peaks, are analyzed and recommendations are made for correction.

Within thirty days of the completion of a survey, a final report is forwarded to PERA (CV). This report is then provided to the maintenance planner, the Navy customer and ship for use at the pre-arrival conference where machines are selected for overhaul.

The final report contains analyzed vibration information, visual inspection and historical data, and detailed recommendations for repair. This allows the flexibility to do selected repairs, such as changing bearings or aligning machines, rather than complete overhauls only. In many cases, overhauls have been deferred and minor repairs have been assigned to Ship's Force.

WHAT BENEFITS HAVE BEEN SEEN? The primary benefits of MCA can be best seen in conjunction with the rest of maintenance planning. A repair profile is used to order material for machine overhauls 1½ years ahead of the availability. During the pre-arrival conference, the customer decides the specific machines to repair, and MCA allows the latitude to do less than the number scheduled by the profile, and put the money and mandays where it can do the most good. Since MCA began in 1970, the entire program has cost approximately $3.5 million. This includes all development and the conduct of 84 surveys. However, the funds reallocated thru the use of MCA for 14 availabilities over the past 4 years have totaled $10.3 million. This represents a return of $18.84 for every $1 spent on the 14 surveys.

In August of this year, the long range maintenance plans officer for the Naval·Air Force, Atlantic (AIRLANT) stated that two years ago, when he began to keep a list of the top 10 areas of casualties onboard AIRLANT ships, Main Feed Pumps and Forced Draft Blowers were near the top. Since that time, they have disappeared from the list, and he attributes this to the success of the MCA program for detecting problems before casualties occur.

MCA IN THE FUTURE. MCA has become more accepted by the Navy customers in the past few years, as evidenced by the increase in the number of machines requested for survey, the addition of post-overhaul surveys to the program, and the increased use of the reports. MCA identifies problems in machines, but, more importantly, it identifies the cause of the problems, and this is the area to direct our attention. Ninety percent of the problems we see in rotating machinery begins with either imbalance or misalignment, both of which can be corrected if caught soon enough. Programs to improve the balance and alignment of machinery immediately after overhaul are in the early development stages.

Automatic processing of the enormous volume of vibration data gathered in each survey is also in the development stages. Up to this point, every graph had to be physically screened by the analyst for significant anomolies and obvious problems. These were then compared to similar machines and previous survey of the machines in question. At best, the task is formatible, at worst, impossible. By using a computer to do the initial screening and provide only the large deviations for analysis, the analyst is free to do more investigation. This will also identify low level vibration problems that the analyst cannot see under the present system.

CONCLUSIONS. Machinery Condition Analysis as used by PERA (CV), has proven itself to be an extremely cost effective maintenance planning tool over the past 8 years. With returns in excess of 18:1 the program has been well accepted and used by both the Navy customers and the carrier fleet. With modification, the program could easily be adapted to any ship, manufacturing plant, or processing facility with similar success.

PRODUCT FAILURE RATE "BATHTUB CURVE"

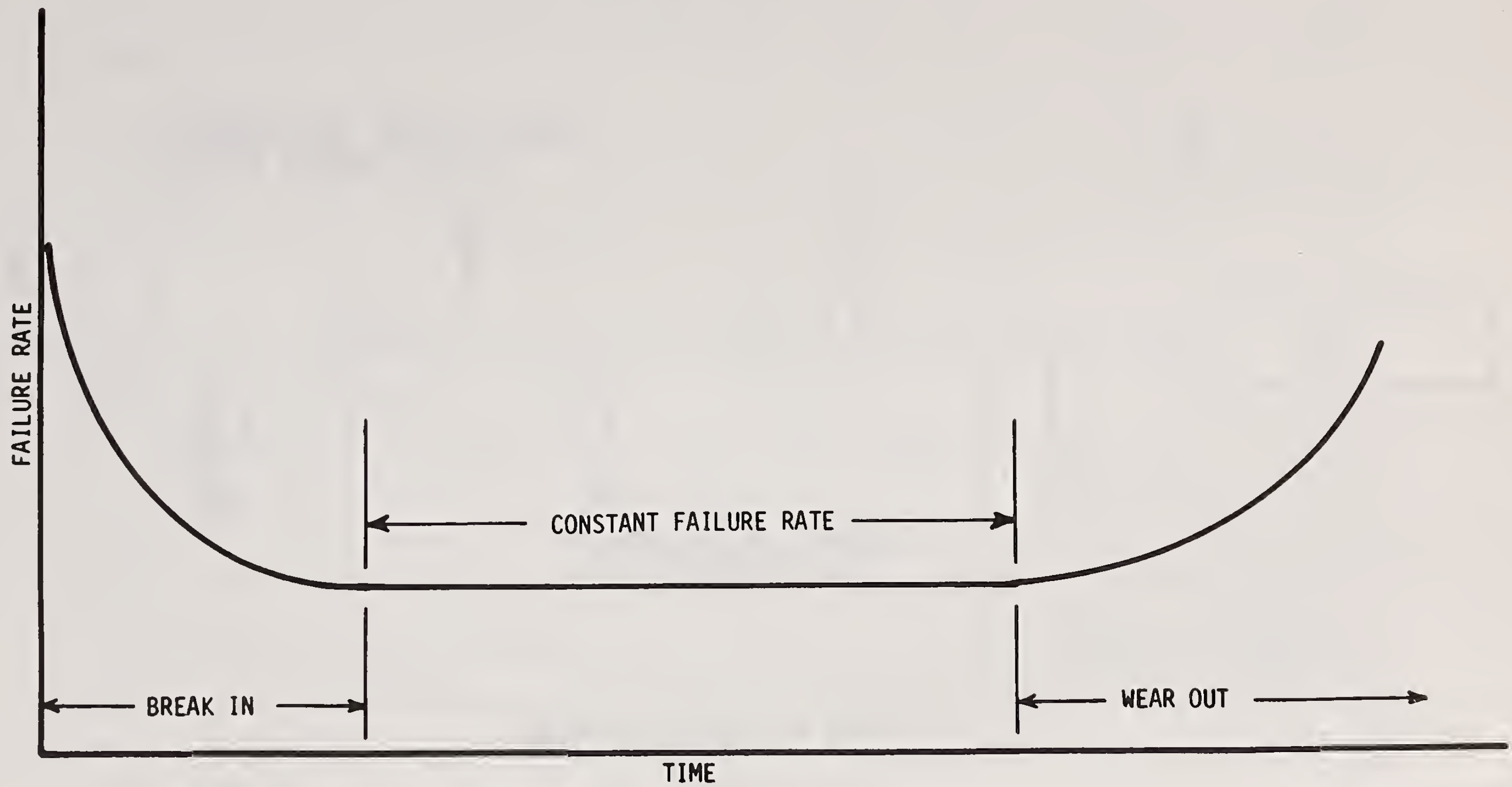


Figure 1.

MACHINERY CONDITION ANALYSIS

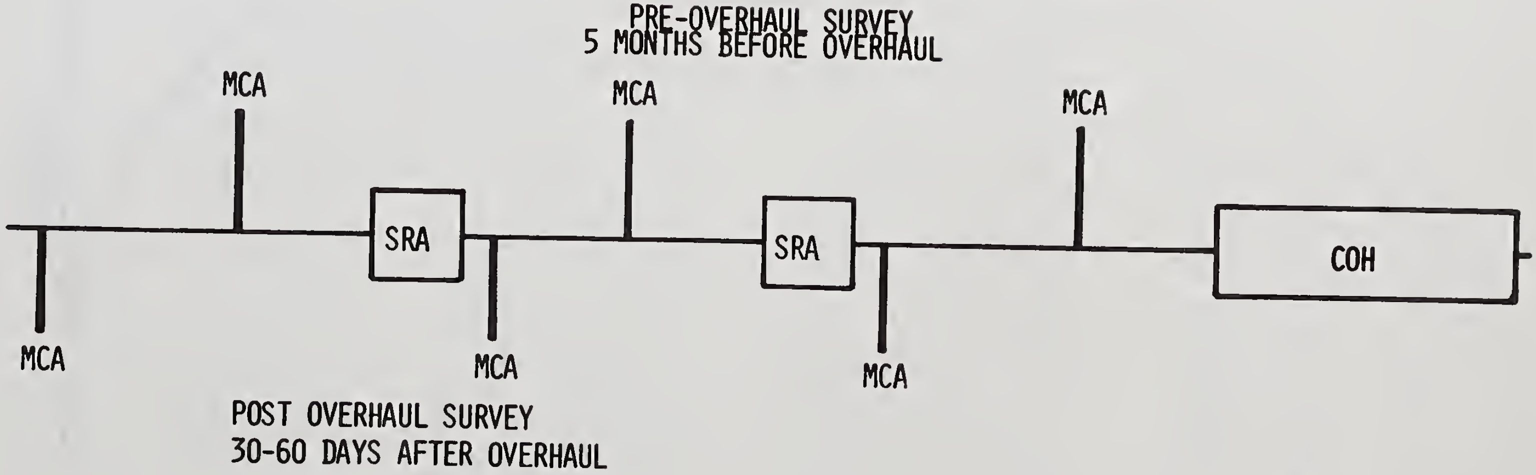
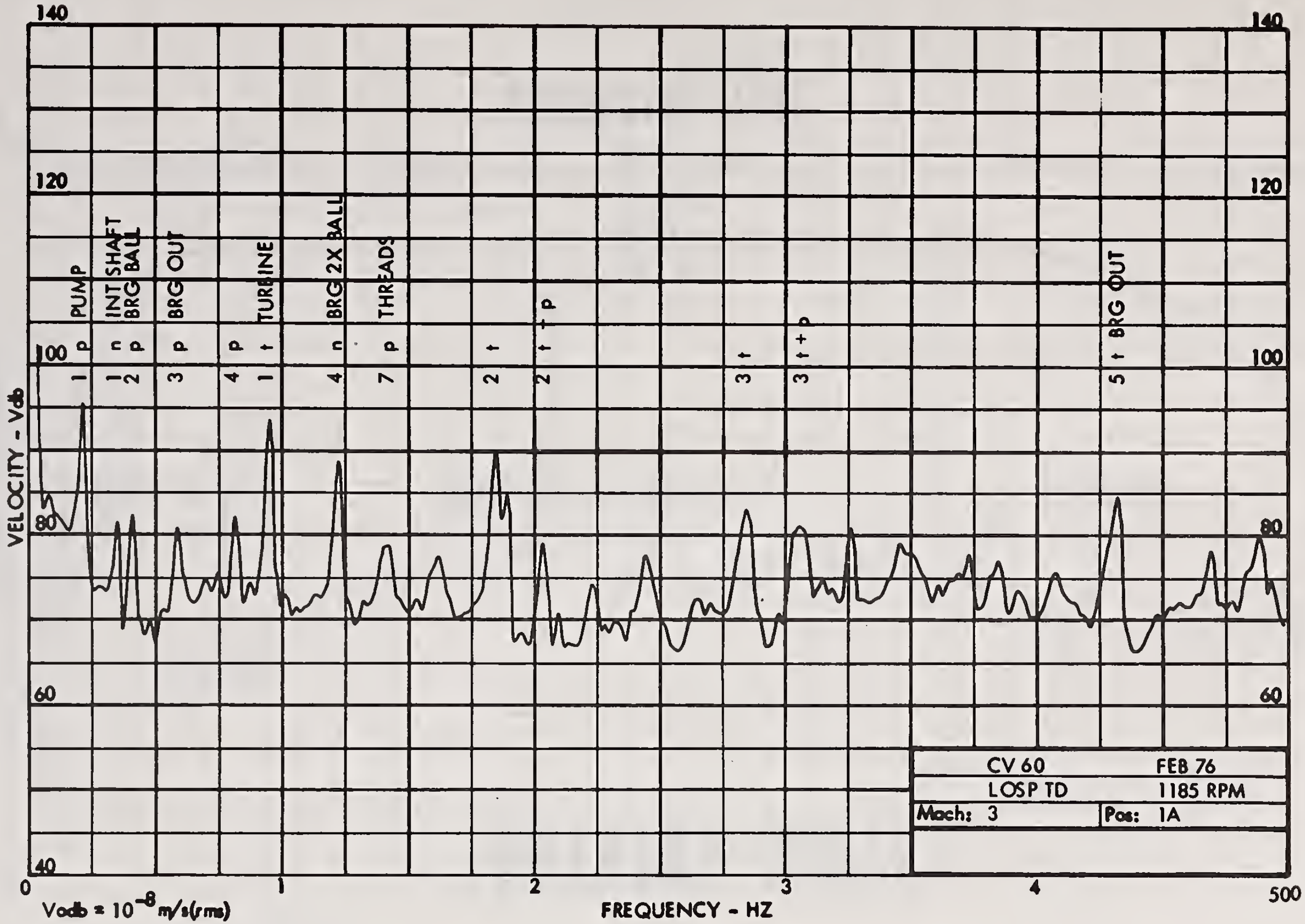


Figure 2.



VELOCITY - Vdb
140
120
100
80
60
40
0
1
2
3
4
500
Vodb = 10^-8 m/s(rms)
FREQUENCY - HZ
1 p PUMP
1 n INT SHAFT
2 p BRG BALL
3 p BRG OUT
4 p
1 t TURBINE
4 n BRG 2X BALL
7 p THREADS
2 t
2 t + p
3 t
3 t + p
5 t BRG OUT
CV 60
FEB 76
LOSP TD
1185 RPM
Mach: 3
Pos: 1A

Figure 3.

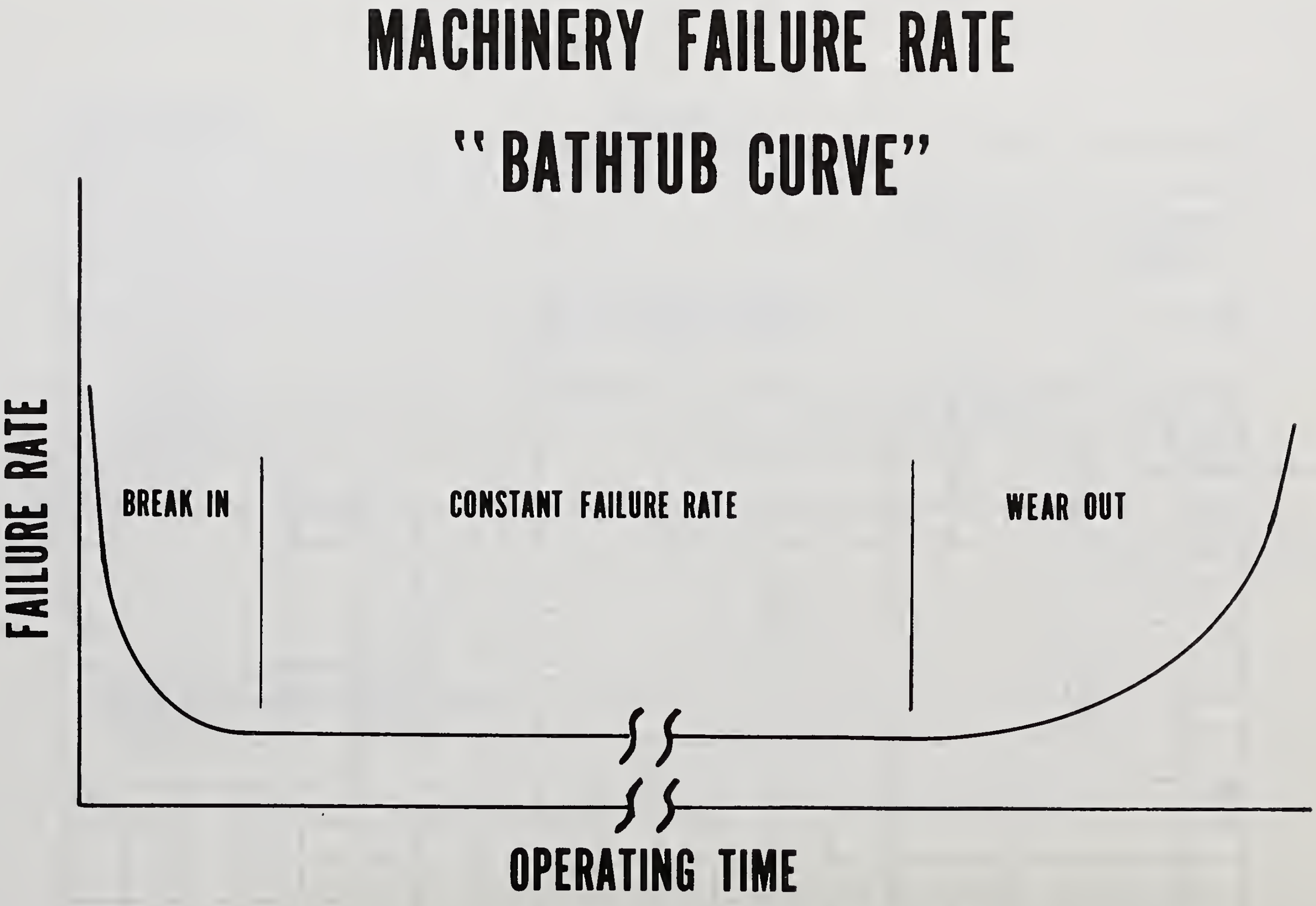

MACHINERY FAILURE RATE
"BATHTUB CURVE"
FAILURE RATE
BREAK IN
CONSTANT FAILURE RATE
WEAR OUT
OPERATING TIME

Figure 4.

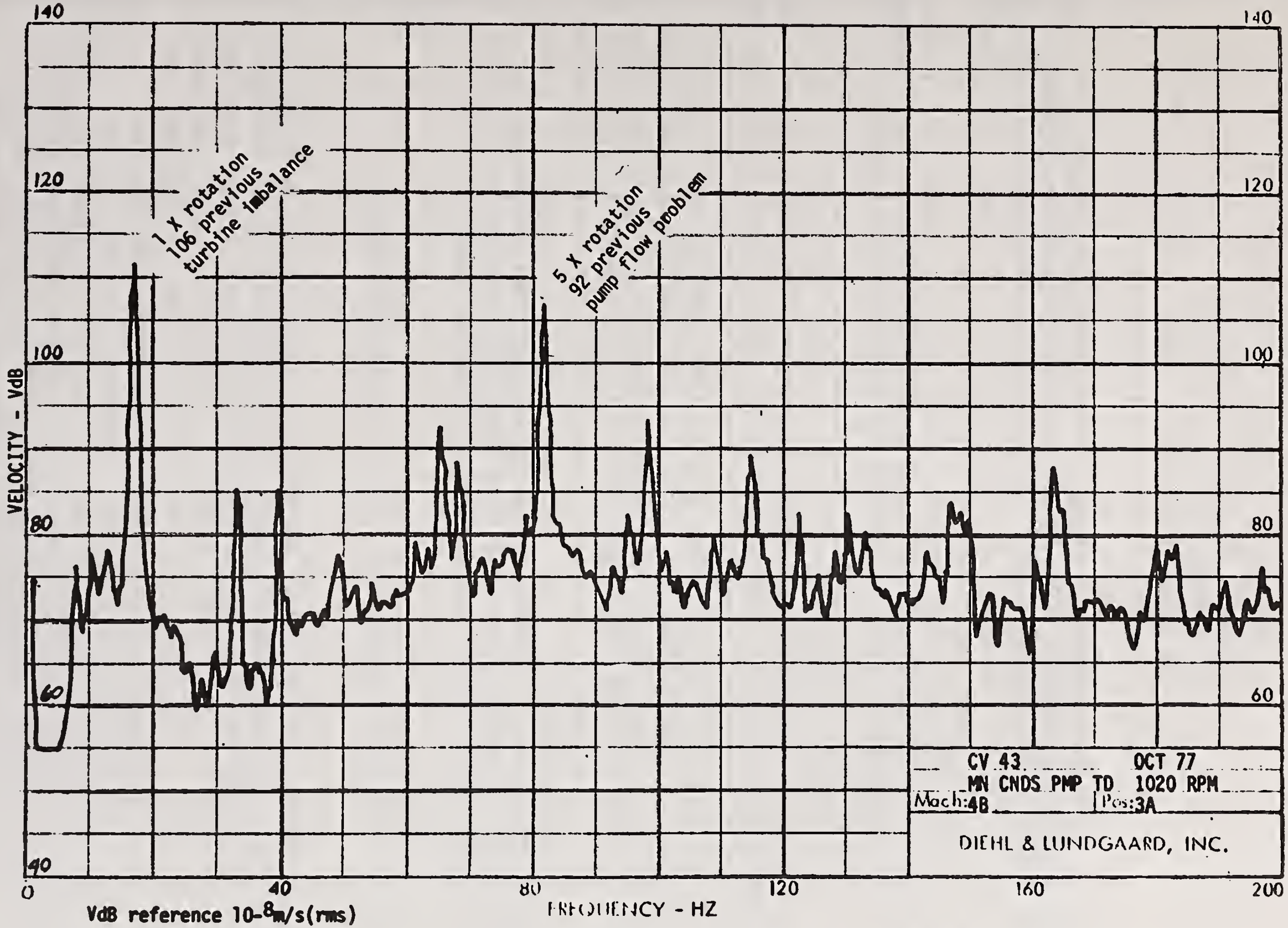

1 X rotation
106 previous
turbine imbalance
5 X rotation
92 previous
pump flow problem
140
120
100
80
60
40
VELOCITY - VdB
0
40
80
120
160
200
VdB reference 10-8m/s(rms)
FREQUENCY - HZ
CV 43
OCT 77
MN CNDS PMP TD
1020 RPM
Mach:4B
Pos:3A
DIEHL & LUNDGAARD, INC.

Figure 5.

DIESEL ENGINE ANALYZER: PAST EXPERIENCE AND FUTURE PLANS

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Abstract: A computer-automated diesel engine analyzer system with four test cells was developed in 1973-74 for use at the Long Beach Naval Shipyard. As originally designed, the system performed fully automatic final testing of nine specific type diesel engines or manual testing of any diesel engines which could be fit into one of the four test cells. The nearly four years of operation has proven many of the original design concepts, as well as revealed some areas where changes were needed if the full potential of the system was to be realized. Operation of the automated diesel engine analyzer has also stirred the imaginations of both the original designers and the test system operators as to how the existing system might be augmented to perform final test after overhaul on equipments other than diesel engines. This paper gives a brief description of the system as originally constructed and implemented. It points out those facets of original design that have proven to be helpful in updating and modifying the system to perform the task at hand. It also points out areas where major changes will be made both in hardware and software to take advantage of the experience gained over the several years of testing, as well as those required to cope with changing Navy test requirements. The final portion of the paper deals with augmentations that will be made to the system to test shipboard air compressors. The description of a proposed fifth engine test cell for testing large diesel engine subsystems is also included.

Key words: Automatic test system; Diesel Engine Analyzer.

The Diesel Engine Analyzer (DEA) to be discussed in this paper was installed at the Long Beach Naval Shipyard in 1975 as part of the Navy's modernization program. The technical aspects of this system have been covered in detail in other publications (references 1 and 2) and will not be repeated here. A brief description of the system is included for those who might not have had access to the earlier publications.

The purpose of the DEA, as spelled out in the LBNSY Request for Technical Proposal, is to evaluate the quality of repair of diesel engines under test in terms of (1) satisfactory performance within specifications and (2) reliable operation with respect to run in test data. Another feature of the DEA is to shut down an engine test when unreliable operation is detected prior to a catastrophic failure of the engine.

The system was originally designed to conduct automatic tests on the following types of engines.

1. Cummins VT-12
2. Fairbanks Morse 38D8
3. GM 6-71
4. Packard V-12
5. Waukesha L1616

Figures 1-6 provide an overview of the system as installed.

Figure 1 is a diagram of the entire DEA area. The four test cells are placed around the control area on three sides. Not shown are the cooling water towers and fuel storage facilities which are outside the buildings near cell 2.

Figure 2 is a block diagram of the entire DEA system. The basic computer equipment is connected directly to the control consoles which are in turn connected through the junction box to the engine/dynamometer combination for a particular cell.

Figure 3 shows the insides of the engine junction box. The large box at the top is a 24-well, 150^{O}F reference junction for the thermocouple temperature probes. The smaller box and heat sink device are a 40 amp solid state contactor and rectifier for providing pulsed DC to load the eddy current dynamometer. The tank and piping at the bottom form a pneumatic shut down system that sequences the engine to a minimum throttle minimum load condition with timed cool down in case of electrical power failure.

Figure No. 4 shows the test console arrangement in the control room while Figure No. 5 is an enlarged view of one of the test consoles. The test consoles are used primarily in the manual mode. The direct view gauges across the top row display crankcase pressure, turbocharger pressure, exhaust back pressure, oil pressure, dyno water pressure, and water pump pressure. Twenty-four separate temperatures can be read on the digital read out at the left side of the console. Engine RPM is shown both digitally and in analog form near the center of the console. Exhaust smoke opacity is measured by the device at the lower left side of the panel. The two large round controls are for manual adjustments of speed and load. The remaining push button controls perform various housekeeping functions.

Figure 6 is the associated computer equipment. Rack No. 1 at the left contains the HP 2100S minicomputer, associated disc storage unit and paper tape equipment. The rack at the right contains the calibration relay/line driver/line receiver equipment, low level multiplexer/A-D system and the multiprogrammer. All of this equipment, except the calibration relay section are standard off-the-shelf Hewlett-Packard items.

Interconnection of the three main equipment locations is by means of multiple twisted shielded pair lines with hermaphrodite (Elco varicon) multi-contact connectors. There are also some pressure tubes (PVC or nylon depending on pressures involved) which run from the junction boxes to their associated control console.

As originally configured, cells 1 and 2 were equipped with eddy current dynamometers while water brake dynamometers were installed in cells 3 and 4.

Operation of the equipment is possible in either the full automatic mode or in a manual mode. Each test cell function is entirely independent of the other three cells with one minor exception. Test area barometric pressure is provided for all cells by a pressure transducer in test cell 2.

The preceding overview has, I hope, given you a small insight into the DEA system as it was originally constructed.

Now, after several years of operation, what have we learned about automatic testing of diesel engines, and where do we go from here?

First, and I'm sure foremost, we have learned that automatic testing, properly conducted, can be a cost effective way to test overhauled diesel engines. A study performed for the Long Beach Naval Shipyard in October 1972 to determine the requirements for a diesel engine analysis system reveals that during the years 1971 and 72, seven rebuilt engines suffered catastrophic failure while on the shipyard engine test stands. These were all engines of a type that are now tested on the DEA. It is not possible to say positively that all of these failures would have been detected and precluded by the DEA, but we do know that since the DEA has been installed, there have been no cases of catastrophic failure while engines were being tested in the automatic mode. At least two engines have been saved from catastrophic failure. The total value of saving thus realized from this one facet can only be estimated, but has to be significant.

Now let me discuss some specific items that we think are significant. Let me comment first about the automatic test scenario.

As originally designed, the system software program left little latitude for the equipment operator to make decisions and minor modifications to the test as it progressed. This type of program did not evolve by accident. During the design stage, the LBNSY project technical monitor personnel were advised of the various scenarios that could be built into the software. They preferred a system with only a minimum of operator participation possible.

To complement this decision we chose a simple 8-hour test profile that we felt would provide an adequate test that could be easily completed by an engine that met the overhaul specifications. If during this test, any of the approximately 40 parameters exceeded a specified bounds, the test was automatically terminated and had to be restarted at the beginning after the indicated fix had been made.

In our test profile the engine was started and run at idle until certain key temperatures had stabilized. The test then proceeded through a set number of phases of increased speed and load until the full load condition was reached. The full load condition was maintained for a specified time after which the load was slowly decreased to zero, then the RPM was reduced to idle and the engine allowed to cool down. A "good" engine could normally complete the test without exceeding any of the established test parameters. This meant that the requirement to restart a failed test did not result in excessive delays in completing the engines required tests.

Subsequently a more detailed test procedure was superimposed by NAVSEC. This included a much longer test period (28 hours) with several cycles of load and speed variations both up and down. This resulted in combinations of load and RPM that were not originally contemplated, as well as excursions of temperatures and pressures that were not within the previously established limits. As a result, we have encountered numerous test interruptions for seemingly inconsequential reasons.

Although it is a simple matter to change a particular limit in the computer program, it is not an easy matter to assure a completely adequate test using a patched up program which has been modified to fit a different test profile. More about this later when we get around to future plans.

Some of the diagnostic aids that we included in our original test scenario have failed to live up to our expectations.

Instantaneous crankshaft angular velocity (ICAV) is one of the areas where we feel more work must be done. In this test we detect top dead center, then measure variations in rotational speed of the crankshaft as the individual pistons progress through the various strokes. The test can be performed either in the cranking mode or while the engine is idling. Ideally the test can detect loss of compression in a particular piston/cylinder pair or faulty fuel delivery to a particular cylinder or group of cylinders. These measurements appear to have considerable diagnostic potential but presently there are no set standards that can be used to determine when an engine is "bad". We feel that this technique can and should be further developed.

Smoke measurements have been a disappointment. Consider steady state smoke. We had hoped to be able to measure total energy into the engine in the form of fuel and compare that with total energy out in the form of torque, heat, and unburned fuel (black carbon smoke). So far we have been unable to do this because the installed opacity meter cannot tell the difference between black carbon smoke and blue smoke caused by burning oil in the exhaust system. This further complicates the problem because oil smoke can show up at times that are not directly related to the engine performance at that particular instance. The location and complexity of the smoke meter stack unit makes it almost impossible to keep the optical system free of the foreign matter. Naturally, this creates errors in the readings. We feel that steady state black smoke measurements can contain significant information but so far we feel there is a way to go to before we can reliably get this information in an automatic test. Dynamic smoke measurements have also proven to be disappointing. As stated before, oil deposits in the exhaust system tend to create smoke that is not directly related to the instantaneous operating conditions within the engine.

A diagnostic phase was provided in the original test program. This procedure could be called for when an engine failed to achieve rated horsepower. The diagnostic phase included a post test idling ICAV, a dynamic crankcase pressure measurement and a print-out of all those parameters which were within 10% of their limits when the rated horsepower failure occurred. Dissatisfaction with the current ICAV test seriously weakens the diagnostic phase.

Other minor items such as an automated cooling system pressure test and an automated rack and fuel cut off cylinder adjustment are in the process of being eliminated. It was found that it was much simpler to do these items manually than try to include them in the automatic test. Long pressure tubes from the engine into the test console have also resulted in some problems. Delays can be created in important parameters like oil pressure. Low pressures such as crankcase pressure (1-2 inches of water) can be completely negated by a drop of oil in the line. Plastic pressure tubes are also subject to breakage.

So far I have only mentioned those items that we have found to be in need of change. Let me now tell you about some of the things that we found worked very successfully. The general manner in which the system was constructed has, we think, served well in keeping the system not only functioning, but developing as well. As you may know, the DEA, as developed at SwRI, is a one-of-a-kind item. This required that the construction technique lend itself to ease of maintenance and expected modification. To support this requirement we installed a large number (20-25%) of spare cable runs between the three major locations (junction box, console and computer) affecting each test cell. All interconnecting lines for a particular cell were passed through a cross connect board in the console (see Figure 7) so that they were readily available. To make maintenance of the system as simple as possible, we kept the table of differences between the four cells at an absolute minimum. In essence all four cells were fabricated identically. Since there were two types of dynamometers to operate (eddy current and water brake), all four cells were designed to be capable of operation with either type of unit. We deviated from this practice only where unused high value items would have been included, but even then the mechanical layouts were the same with the unneeded parts merely left out.

The same techniques were used in the computer program. Look-up tables were used wherever possible to catalog test cell particulars. When a test is initiated, the engine type and cell number are both entered. The engine type selects the proper test parameters and limits while the cell number selects the dynamometer type and establishes the correct dynamometer constants so that load can be read properly. This procedure made it possible to test some engines in more than one particular cell.

This system of construction and programming greatly simplified the recent conversion of the two water brake test cells to eddy current dynamometers. The mechanical modification was limited to adding the few required high value parts (D/A converter in multiprogrammer, rectifier and contactor in J-box), modifying the control console to accommodate the additional LOAD control and removing a few grounds in the console logic. Equally simple changes in software were required. The look-up table for these cells now references the eddy current subroutines, and the new dynamometer factors replace the old water brake factors.

Successful operation in a heavy industrial area is another area where I feel we were successful. As everyone knows, in an industrial area you must anticipate electrical noise problems. To counter this we used twisted shielded pair wiring and filtered differential inputs for all low level signals. We religiously kept track of our signal grounds, and optically isolated our logic signals. To date we have had no problems that we could trace to electromagnetic or conducted interference. The system has continued to operate for approximately four years with a minimum of maintenance. Dirt, grease, diesel fuel, etc. are all items that must continually be controlled though if successful operation is to continue.

So much for past experiences, now to the "future plans" portion of the presentation. This will be further subdivided into two portions: future plans that are directly related to the analyzing of diesel engines and future plans that relate only to the utilization of the DEA hardware.

First, as applies to analyzing diesel engines.

We are currently in the midst of a major rework of the entire computer program. Under this program, which we refer to as "fast restart", we plan to revise the software to simplify and speed up the completion of a given test. A major part of this rework involves the function of limit setting. We currently have an upper and a lower limit on most parameters. If either of these are exceeded, the test is automatically halted and must be started again from scratch. Under the new program we will still have an upper and a lower absolute limit, but within these limits will be an upper and lower warning limit. When any parameter exceeds the warning limit, a flashing yellow light will be lighted on the particular console and a flashing asterisk will identify the offending limit on the CRT read out. The operator can then analyze the situation. He will have the option of making running adjustments, taking other action that seems appropriate, or just watching the particular parameter. We feel that this warning will help us to counter those simple problems which can be corrected before they can interrupt an otherwise satisfactory test. Things such as loose thermocouples, leaky pressure fittings, improperly set valves, etc.

The second major change in software will allow the immediate restart of a test that has been halted for a non-debilitating reason. For example: when changing from one test phase to another, we have occasionally experienced conditions where the speed and load combination resulted in horsepower, pressure or temperature readings that were momentarily outside the desired limits. Should a situation such as this occur in the future, the operator will be able to immediately resume the test where the interruption occurred and continue on through the run as soon as certain key temperatures stabilize. We feel that with the lengthy tests specified by NAVSEC that a system such as this will greatly speed up testing without endangering the engine or the quality of the test.

Another feature of our redesigned software will permit a more thorough calibration of the DEA system. Calibration so far has been carried out only on the console gauges which are used primarily in manual operation. In the future a software change will allow calibration of the computer read values to be conducted simultaneously with the console gauges.

A fifth engine test cell is also on the horizon. This cell will be dedicated exclusively to the testing of GM 149 series 16 cylinder engine subsystems. The cell will be equipped with a complete GM Detroit Diesel 16V-149TI engine extensively modified by Stewart Stevenson to serve as a 1000 kw generator on the Navy FFG-7 series ships. The engine will be used as a test bed for hot checking the various subsystems utilized on this series equipment. The hardware used in this cell will be much the same as the other four cells with one major exception. In this cell we will be equipped to measure air intake volume on each of the four turbocharger inputs. Also, on the Control Console we plan to read all pressures on remote digital panel meters when in manual mode. We will not run pressure tubes into the control room for the reasons previously stated.

To handle the increase in memory requirements for this fifth cell (and for some other requirements which I will mention in a minute) we are also changing out the HP 2100S computer and replacing it with an HP 21MX with a much larger memory capacity. In this same modernization program we are also replacing the 2.5 M byte disc recording system with 4.9 M byte device.

There are also future plans that apply to the DEA equipment but are not concerned with testing diesel engines.

At the request of LBNSY a study was performed to see if it would be possible and economically feasible to use the DEA computer equipment to conduct automated test after overhaul on devices other than diesel engines. Specifically, could the system be augmented to test multi-stage air compressors, sealed hydraulic transmissions, and cryogenic generators. The study revealed that while testing all of these items was possible with certain hardware additions to the computer, only the air compressor and cryogenic generator testing appeared to be economically feasible. As a result of this study, the LBNSY has contracted to enlarge the system to encompass the air compressor testing.

The manner in which the software was originally written (with maximum use of look-up tables) lends itself well to this addition. Although the air compressor test will be different than a diesel engine test, the air compressor cell will be generally treated as just another test cell with periodic servicing by the computer. This cell will feature both manual and automatic operations just as the engine cells do. All parameters will be available for display on digital meters on the console during manual operation and additionally on an associated CRT read-out during automatic operation.

This concludes our look at where we are in the automatic testing of diesel engines and other pieces of Navy gear. Before closing though, I would be remiss if I did not say a few kind words about the people who have operated the equipment over the past four years. Any system such as this will not operate efficiently unless the people operating it believe in it and want it to work. We have been very fortunate in this respect, and look forward to many more years of friendly cooperation.

ACKNOWLEDGEMENT

The author expresses his appreciation to Mr. R.B. Curtin and Mr. V.R. Sturdivant of Southwest Research Institute for their contributions in the preparation of this paper.

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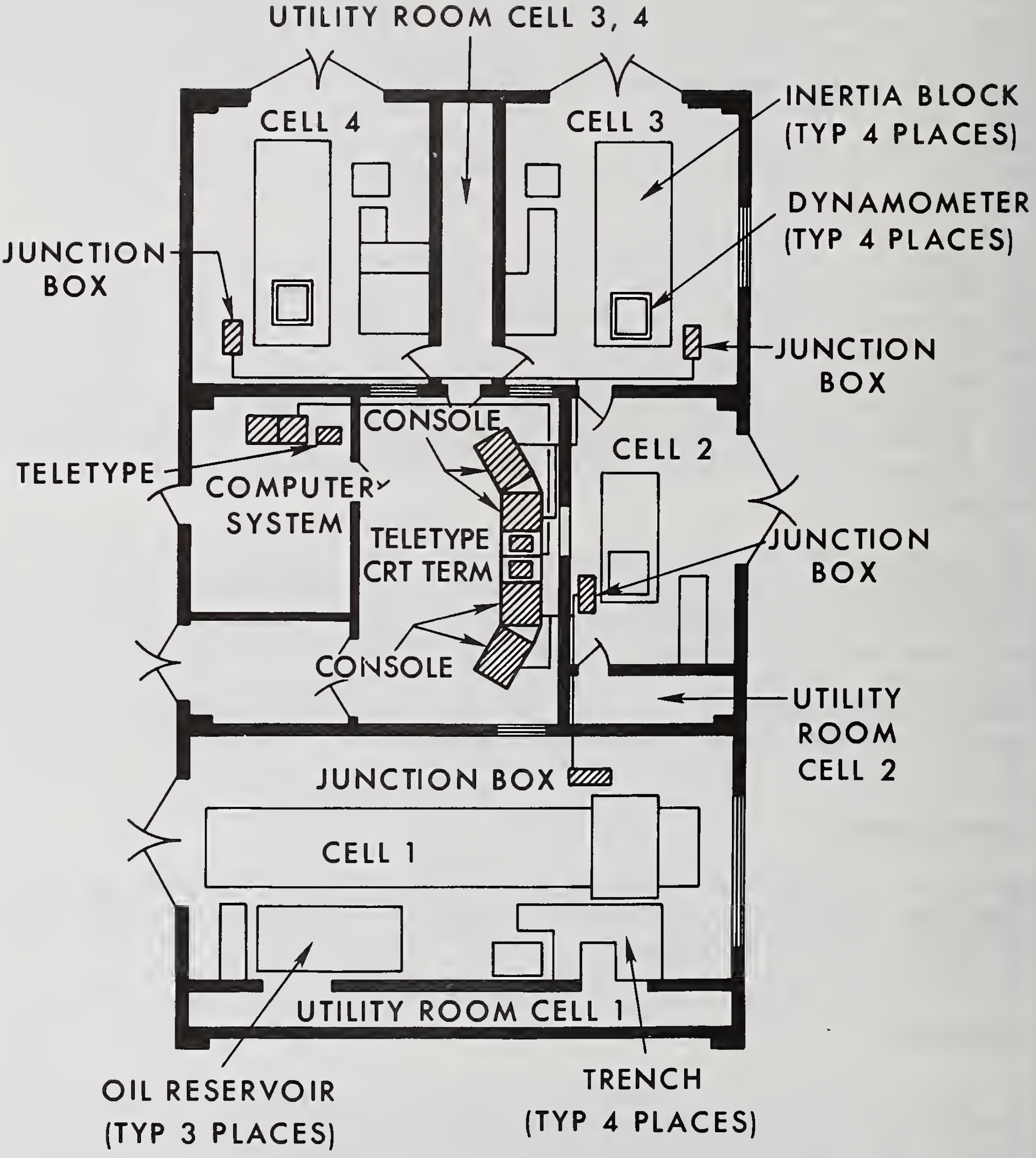

FIGURE 1 - THE DEA TEST FACILITY

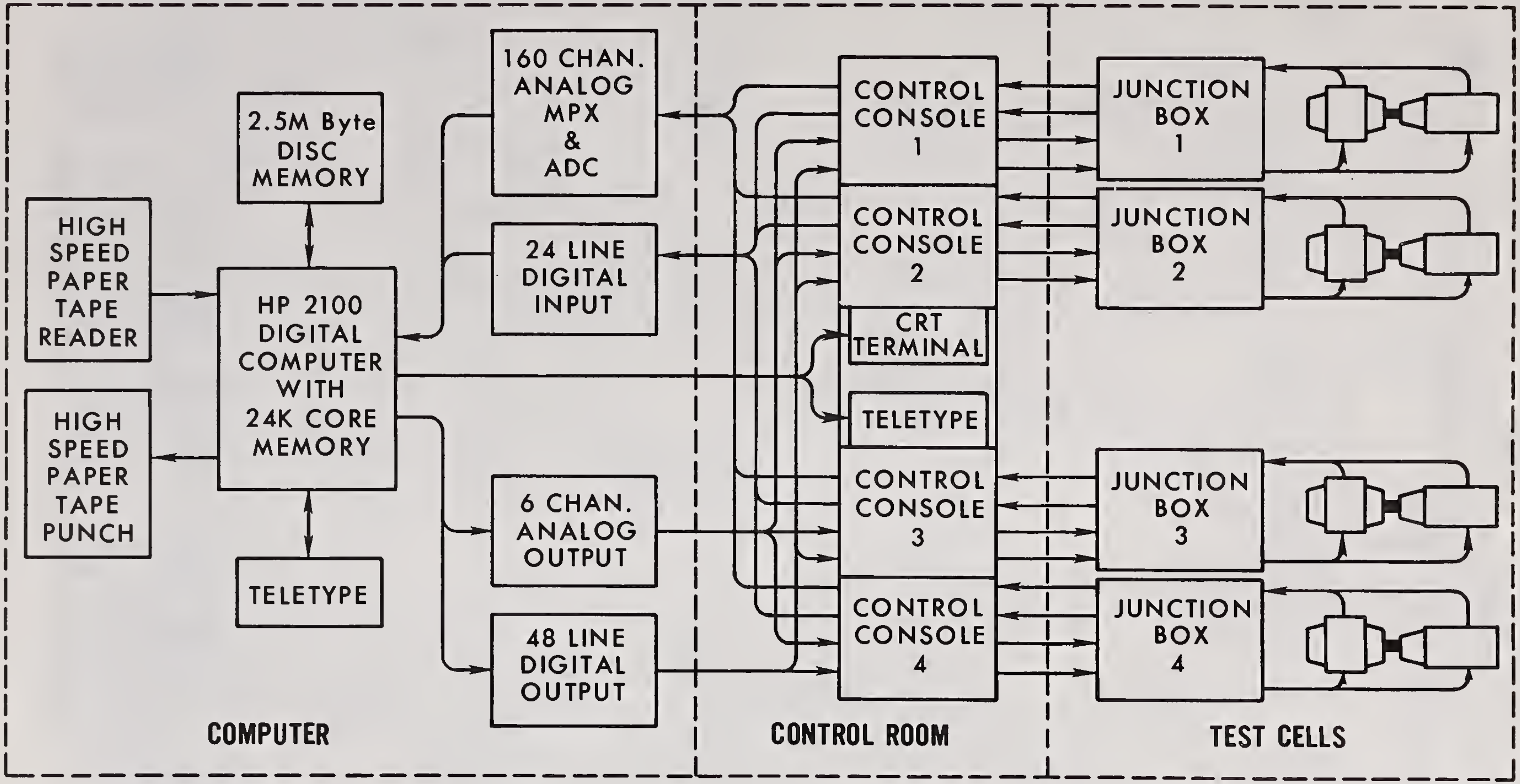

FIGURE 2 – DEA BLOCK DIAGRAM

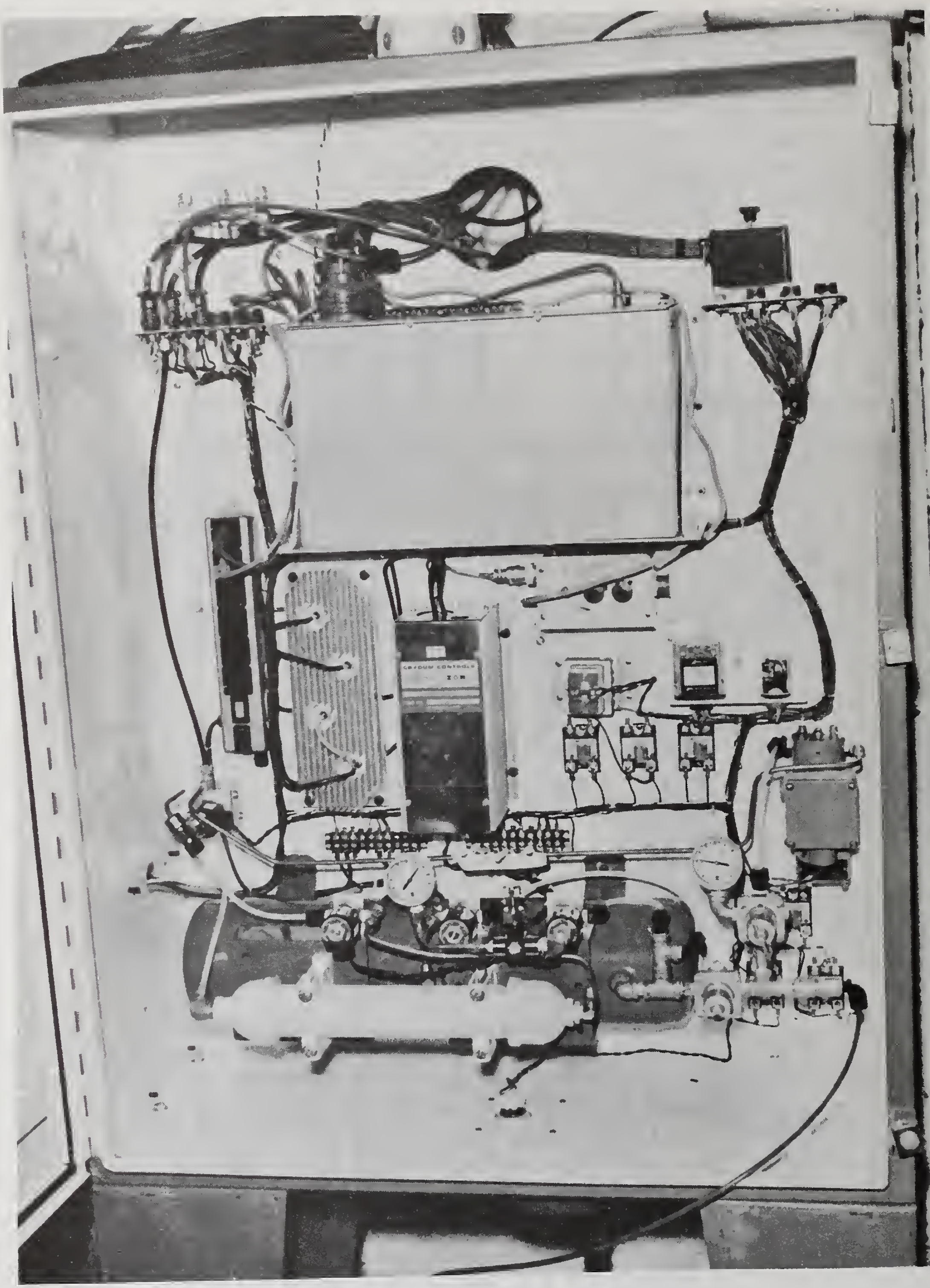

FIGURE 3 – ENGINE JUNCTION BOX

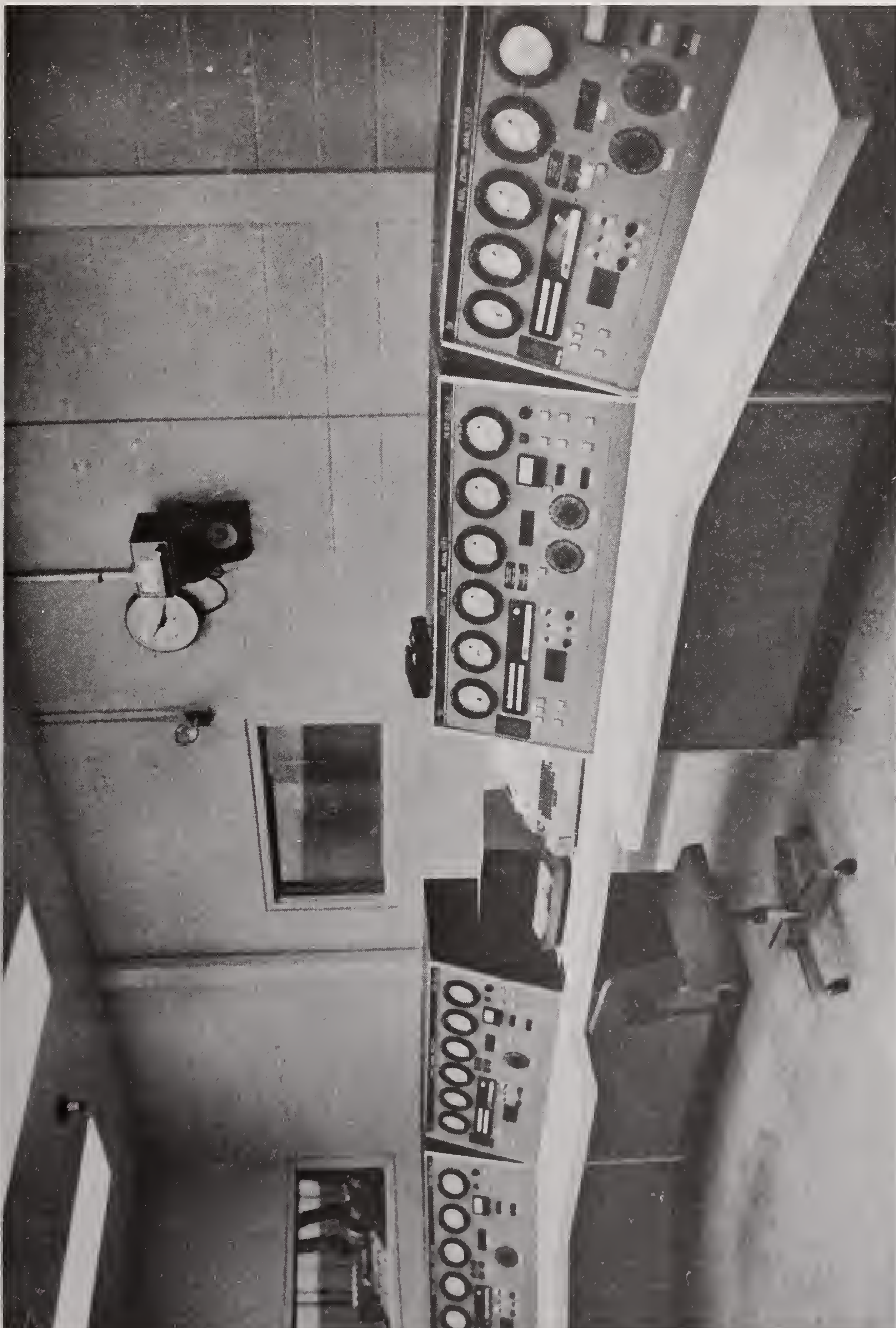

FIGURE 4 – TEST CONSOLE ARRANGEMENT

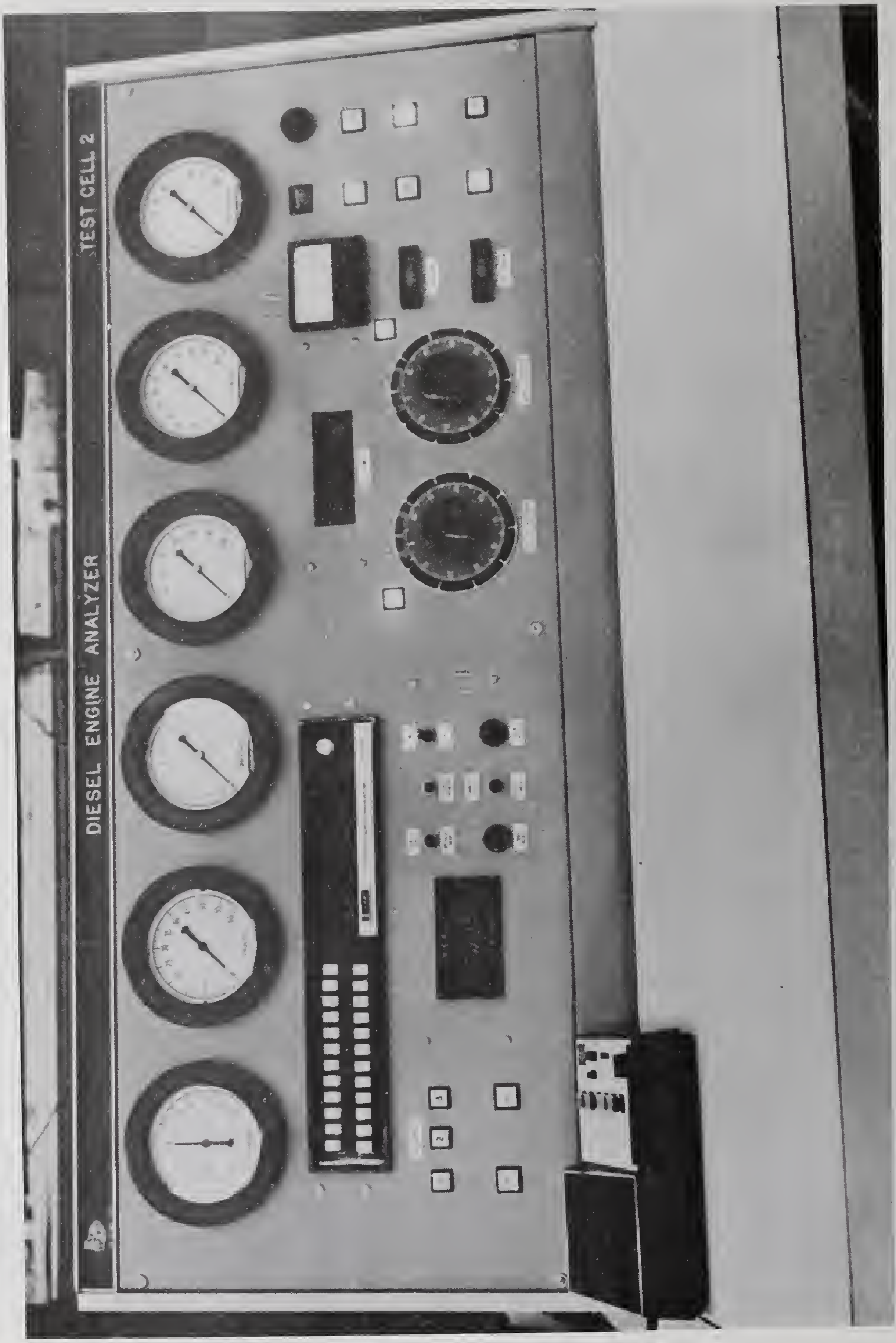

FIGURE 5 – CONSOLE FRONT PANEL

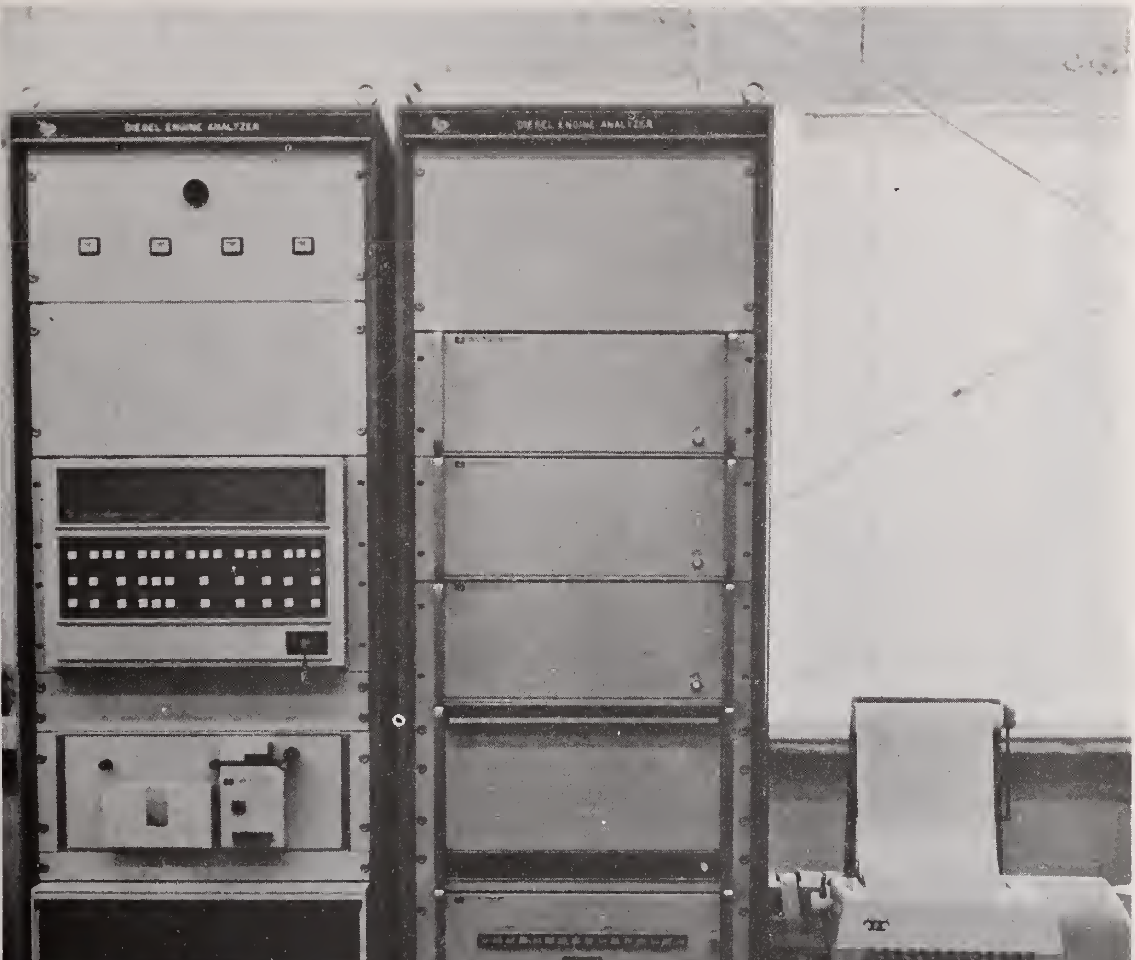

FIGURE 6 – COMPUTER EQUIPMENT

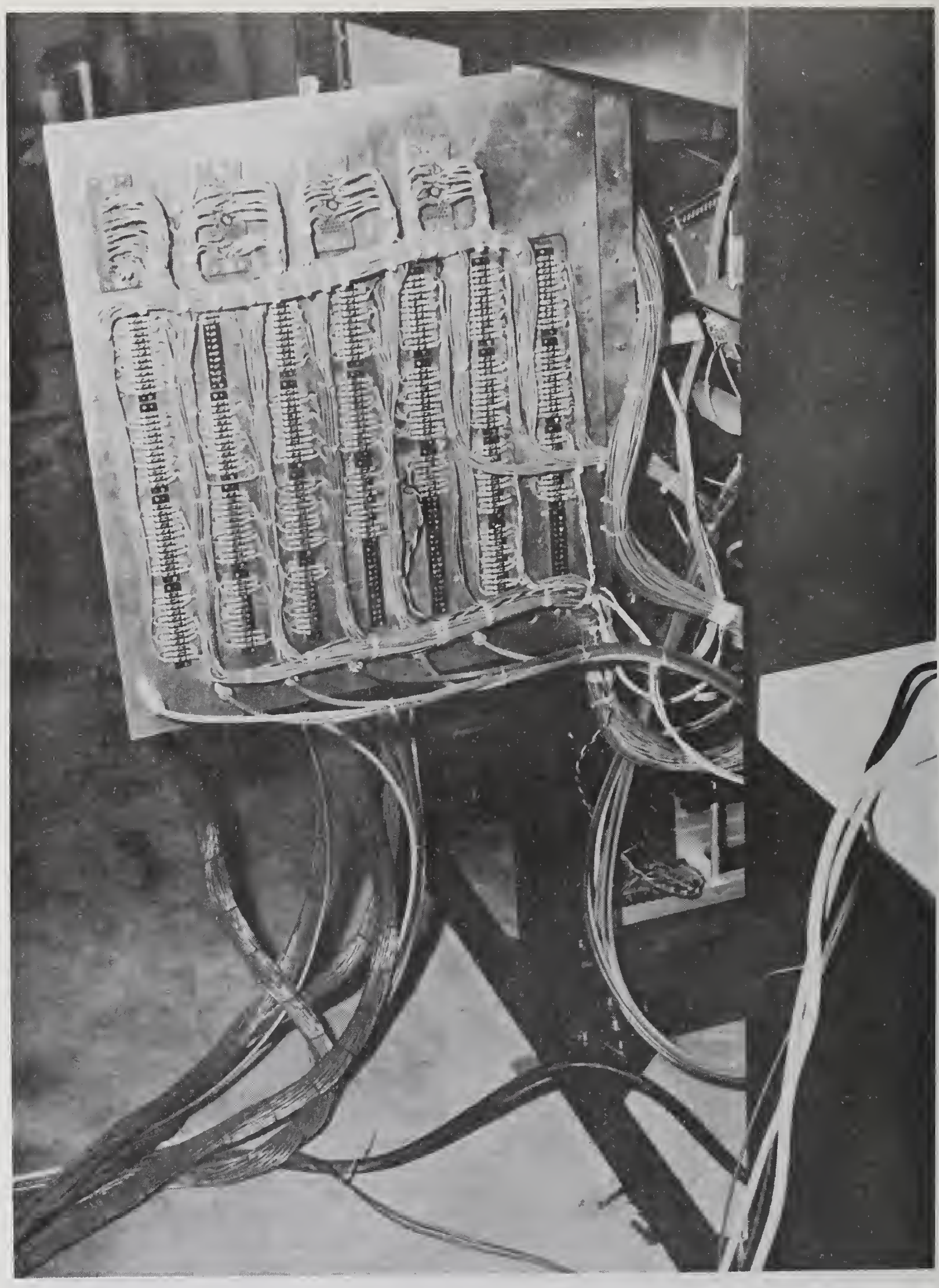

FIGURE 7 – CONSOLE CROSS CONNECT

FIBER OPTICS FOR BEARING PERFORMANCE MONITORING

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Rolling element bearings are used in rotating machinery to separate stationary and rotating components. Commercial and military organizations have sought to improve the reliability of such machinery through the detection and diagnosis of bearing problems and hopefully through the prognosis of impending bearing failures. Traditional methods of bearing performance monitoring employ accelerometers mounted somewhere on the machine's external surface. The fiber optic method employs proximity sensors that are mounted in the bearing housing, as shown in figure 1. Data retrieved by such fiber optic sensors are not confounded by the resonances and vibrations of the surrounding structure. The signal obtained directly from the bearing is found to be relatively simple and easy to analyze. For example, an unfiltered bearing signal is shown in figure 2, wherein pattern recognition of the oscilloscope trace indicates the bearing contains a defective ball. Each wave represents the deflection of the bearing outer race as a ball passed by the fiber optic sensor. Discontinuities of the otherwise smooth waveform are clustered about one wave or ball and repeat every eighth wave (there are eight balls in the bearing). The unfiltered signal of an 11-ball bearing is shown in the top half of figure 3. Discontinuities were found at each eleventh wave, which again is indicative of a defective ball. When viewing the signal through a 1,000 - 10,000 Hz window, the defect is more clearly discernible, as can be seen in the bottom portion of the figure.

Through pattern recognition it is possible to identify the defect location, whether it be on a ball, the inner race, or the outer race. However, it is usually academic where a defect is and more important to accurately detect the existence of the defect and predict its effect on the remaining life of the bearing. Towards that end, the pk/rms ratio of the filtered signal can be measured to indicate the relative magnitude of the defect. Figure 4 shows the signals from three bearings: one good, one marginal, and one obviously bad. One problem currently under study is the establishment of a fiber-optic pass/fail criteria for bearings. That will be the pk/rms ratio at which a bearing should be removed from service.

Obtaining a measure of the functional integrity of bearings (pk/rms) is but one of the uses of the fiber optic sensors. Band-pass filtering in the low frequency end provides important information regarding the mechanical performance of the bearings and the machines in which they are installed. As applied to a typical electric motor, two proximity probes are used to measure the vibration on the outer races of each of the two ball bearings and another sensor is used to measure the rotational speed of the motor's shaft. Two of the principal components of the signal produced by the bearing probes are the rate of rotation of the shaft and the frequency at which balls in the bearing pass by the probe. A measure of ball bearing operation is the bearing speed ratio which is the ratio of the ball passing frequency to the shaft rotation frequency. The value of the bearing speed ratio indicates the amount of axial load on the bearing, the extent to which the bearing is installed too loosely or too tightly within the bearing housing, as well as the condition of the lubricant. Speed ratio limits such as shown in figure 5 based on normal variations of operating loads and clearances, can be calculated and used as an overhaul criteria. Too much grease is just as bad as too little grease in a bearing. Figure 6 illustrates that extreme deviations from calculated speed ratio performance is encountered for improperly lubricated bearings.

When the rotor of a machine is not perfectly balanced, it will produce vibrations at its frequency of rotation. These vibrations are detected by the proximity sensors. The angular position of the unbalanced weight on the rotor is determined by comparing the phase of the signal with that from the shaft sensor. This can be done simply on an oscilloscope screen as illustrated in figure 7. By setting the shaft timing pulse to exactly six screen divisions, the peak amplitude of the unbalance signal can be read directly from the oscilloscope. This method has been found to be of value for in-place balancing of rotating equipment. Compared to a standard method utilizing externally mounted accelerometers, the fiber optic method is faster and can result in a lower residual unbalance level.

Traditional bearing performance monitoring methods normally employ externally mounted sensors. These sensors are fastened to the machine in various ways such as with epoxy, dental cement, magnets, or hand pressure. The fiber optic method sacrifices ease of installation but delivers much more useful information to the bearing engineer. Some applications of the fiber optic method are in new bearing inspection, machinery balancing, the detection of ball skidding, bearing loads, and shaft and housing fits. Therefore, with the fiber optic method it is not only possible to determine the condition of bearing surfaces, but also to determine if bearings have been properly installed in machines and therefore given the best chance to survive to their fatigue lives.

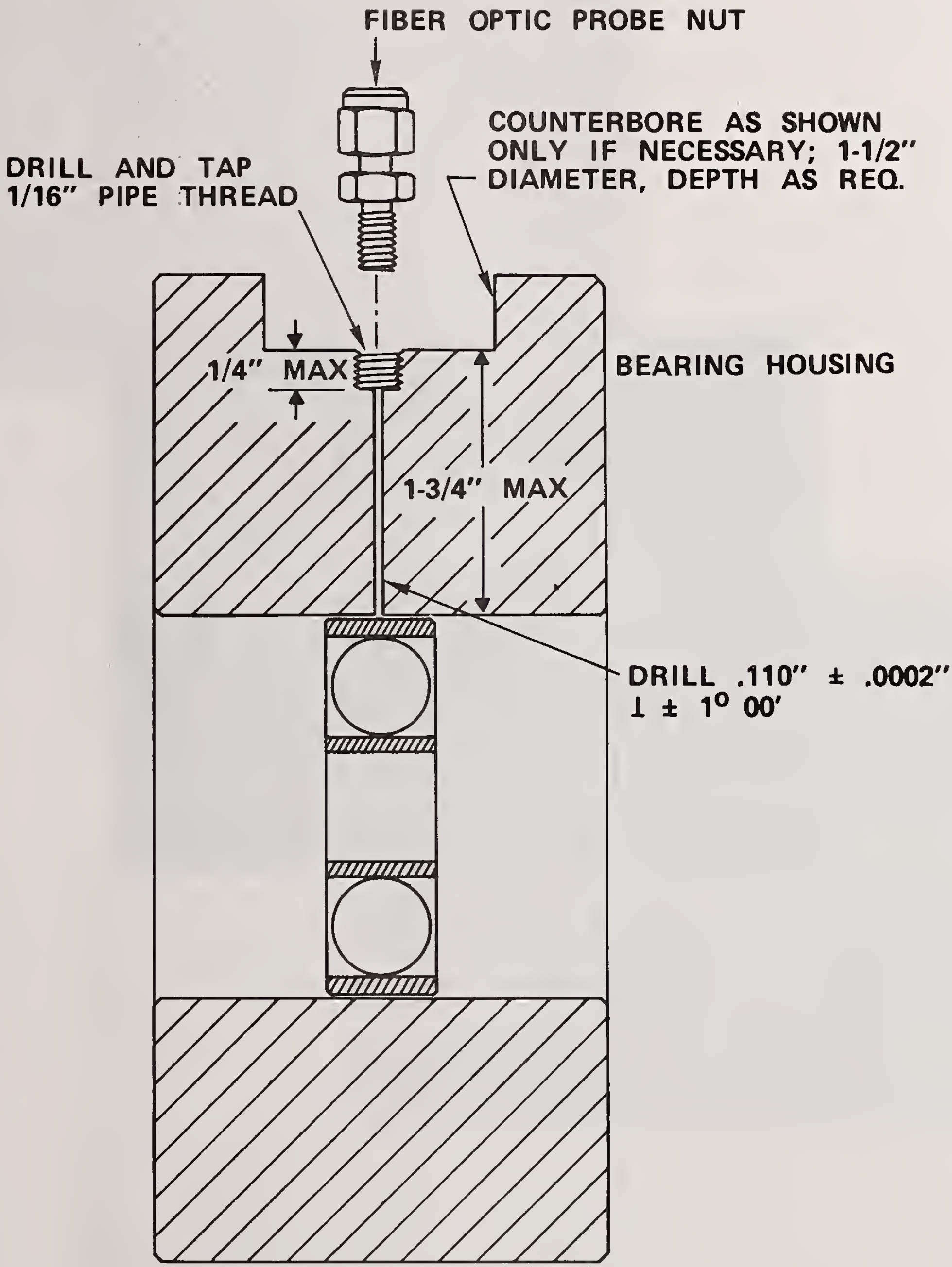

FIBER OPTIC PROBE NUT
COUNTERBORE AS SHOWN ONLY IF NECESSARY; 1-1/2" DIAMETER, DEPTH AS REQ.
DRILL AND TAP 1/16" PIPE THREAD
1/4" MAX
BEARING HOUSING
1-3/4" MAX
DRILL .110" ± .0002" ⊥ ± 1° 00′

Figure 1.

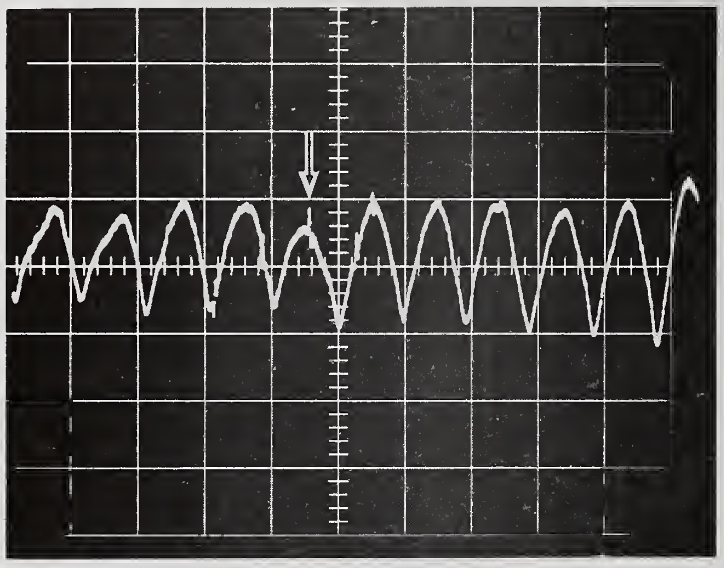
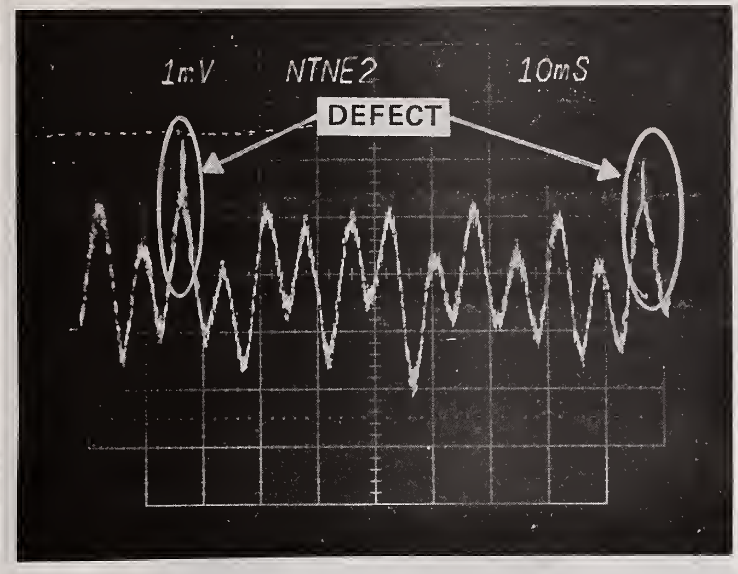
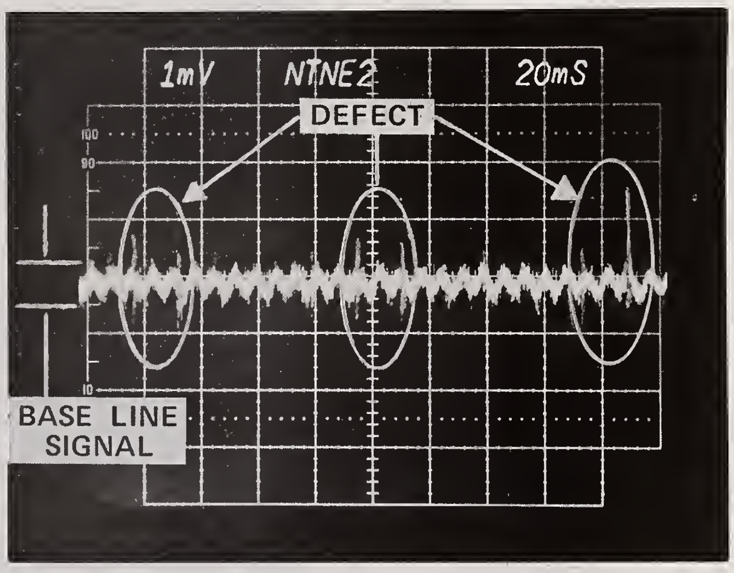


Figure 2 - Bearing Wave Form Showing
Presence of One Defective Ball



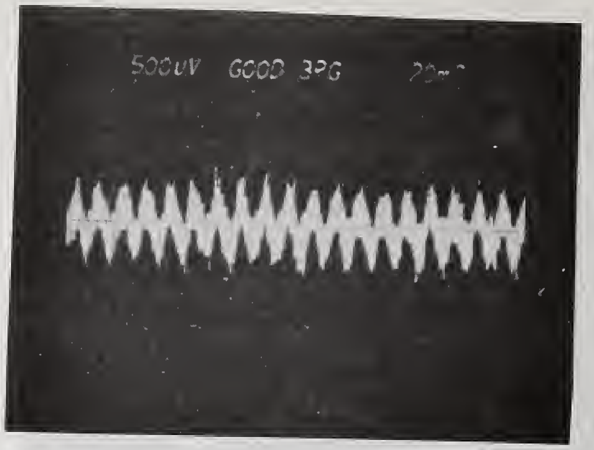
DC-10,000 Hz



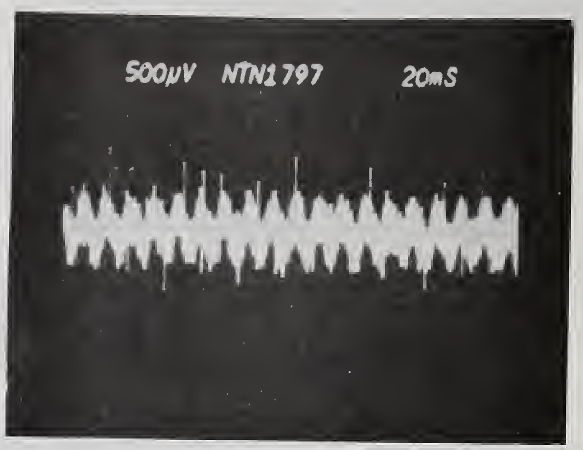
1,000-10,000 Hz

Figure 3 - Effect of Filtering Illustrated

Good Bearing
Pk/rms = 1.2



Rejected Bearing
Pk/rms = 1.6



Rejected Bearing
Pk/rms = 3.0

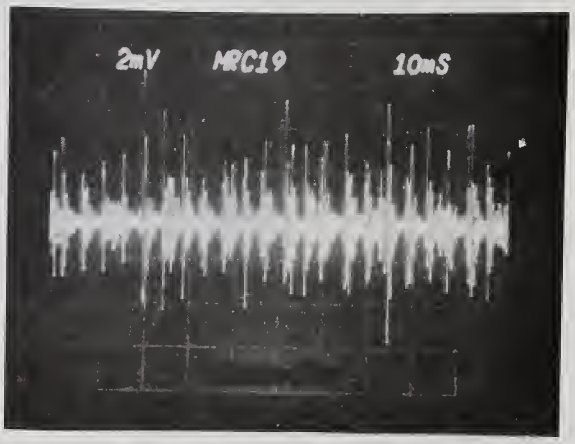


Figure 4 - Filtered Signals from Three Bearings

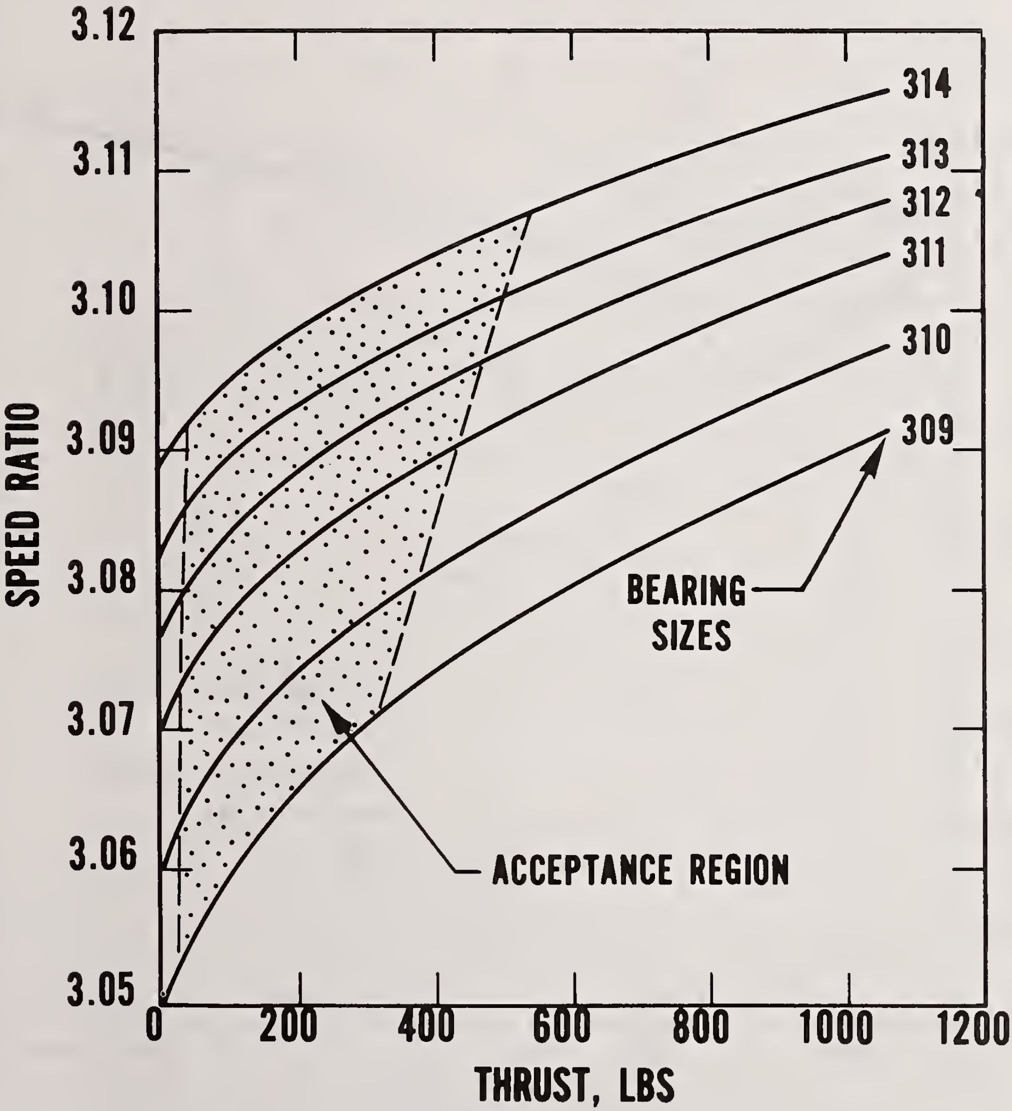


Figure 5 - Speed Ratio Overhaul Criteria

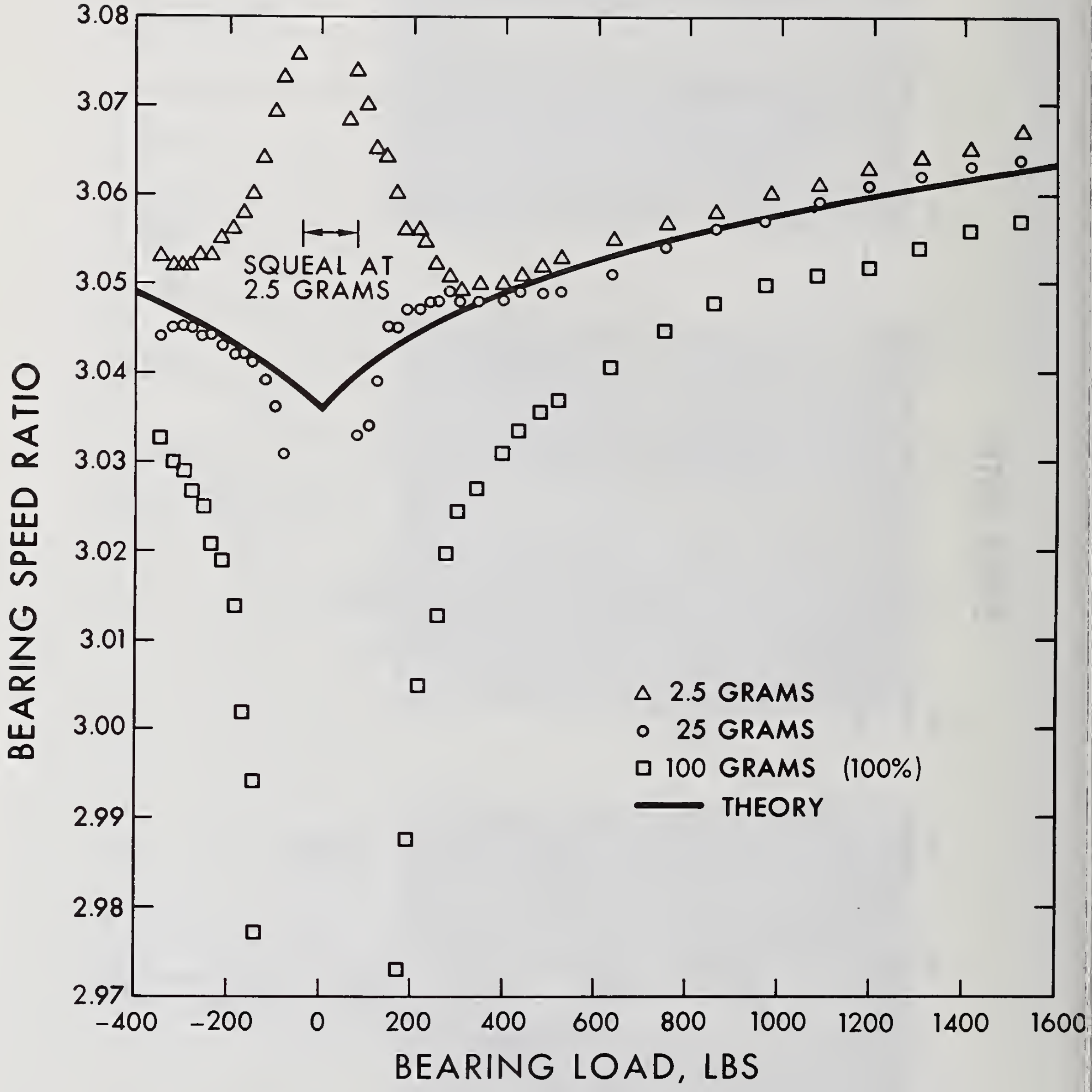


Figure 6 - Bearing Speed Ratio Performance at Three Levels of Grease Pack

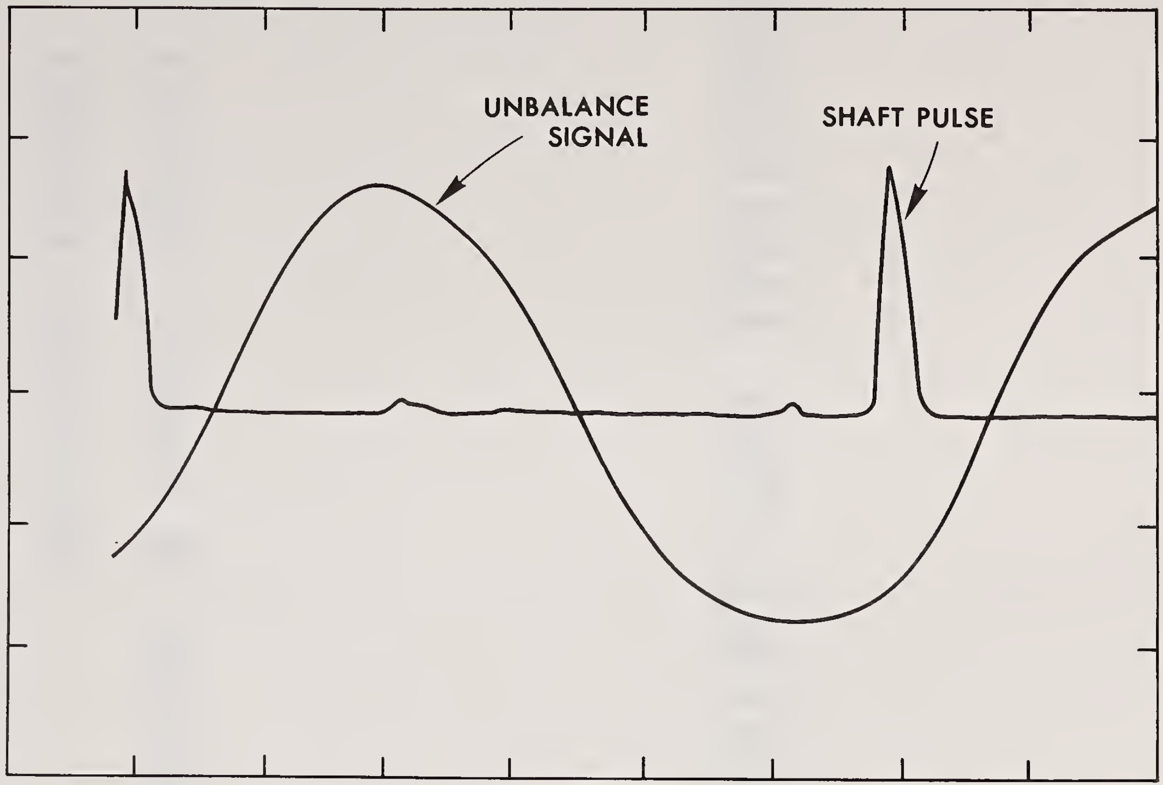


Figure 7 - Machinery Balance

SESSION IV

INDUSTRIAL APPLICATIONS

Chairman: Robert M. Whittier
Endevco Corporation
Co-Chairman: Robert Leon
Franklin Institute Research Labs

STATISTICAL TECHNIQUES FOR AUTOMATING THE DETECTION OF ANOMALOUS PERFORMANCE IN ROTATING MACHINERY

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Abstract

We have assessed the level of technology utilized in automated systems that monitor industrial rotating equipment and the potential of alternative surveillance methods. We conclude that changes in surveillance methodology would upgrade ongoing programs and yet still be practical for implementation. We formulated an improved anomaly recognition methodology and implemented these methods on a minicomputer system. The effectiveness of our monitoring system was evaluated in laboratory tests on a small rotor assembly, using vibrational signals from both displacement probes and accelerometers. Time and frequency domain descriptors are selected to compose an overall signature that characterizes the monitored equipment. Limits for normal operation of the rotor assembly are established automatically during an initial learning period. Thereafter, anomaly detection is accomplished by applying an approximate statistical test to each signature descriptor. As demonstrated over months of testing, this monitoring system is capable of detecting anomalous conditions while exhibiting a false alarm rate below 0.5%.

Key words: Automated surveillance; rotating machinery monitoring; statistical detection algorithm; vibrational signatures.

Introduction

Scope of the work: The purpose of this work is the demonstration of surveillance techniques that can extend the performance capabilities of automated systems for monitoring industrial rotating equipment. In preparation for this work we have assessed the effectiveness of ongoing monitoring programs and the potential improvements offered by alternative programs. Based on our evaluation of the merits and deficiencies in existing and proposed surveillance systems, we formulated an improved anomaly recognition methodology. The monitoring system implemented and tested at ORNL offers improved monitoring performance, utilizing methods that are practical for even large industrial applications.

Background: The practice of monitoring gross vibrational levels as an indication of machinery health began more than 150 years ago. However, it was not until 1939 that vibration sensors and rudimentary signal analysis techniques enabled the compilation of empirical vibrational severity criteria (1-3). Only in the past 25 years have advancements in data processing techniques and computer hardware allowed machinery health to be evaluated using signatures derived from the detailed structure of vibrational signals (4,5).

Although the advantages of signature analysis techniques are widely acknowledged, the demands such analytical methods place on plant personnel limit the use of such techniques for general surveillance tasks (5,6). Computer automation of these monitoring requirements alleviates this drawback and allows maintenance personnel to direct their efforts towards equipment most in need of attention. Additionally, a computerized surveillance system should provide sufficient sensitivity to give early warning of incipient failures, thus enhancing diagnostic capabilities and allowing better scheduling of maintenance. However, while monitoring of machinery to detect excessive vibration is a well-established practice, a best approach for automating such monitoring activities has not gained general acceptance.

Limitations of monitoring systems: There are certain drawbacks associated with all systems presently used for on-line surveillance of rotating equipment. The most basic of such systems are those which derive a set of parameters characterizing the vibration signal (such as its peak-to-peak amplitude, RMS power, or power at the rotational frequency) for comparison with absolute limits (7-9). To set such limits one must resort to a vibration severity chart, perform analytical calculations for the equipment to be monitored, or accumulate the necessary information from testing. Since fixed limits must encompass the "worst-case" conditions over the entire range of normal operations, sensitivity to anomalous performance at any given operational state is reduced (9,10). Another disadvantage frequently associated with this approach is a lack of information on which to base diagnostic decisions (9,11) once an anomaly has been detected.

To compensate for this deficiency some monitoring systems add trending capabilities or utilize the detail available with complete spectral analysis (12-16). Unfortunately, due to the storage limitations which exist in systems monitoring several hundred data channels, trending the entire power spectrum is typically not practical. The storage problems associated with maintaining full spectral detail are further compounded if baseline signatures and limiting criteria are to be saved as a function of operational conditions. A common compromise is to trend only gross vibrational levels and to alarm if these parameters exceed acceptable limits. The complete power spectra of the vibrational signals are saved only at baseload conditions at the outset of monitoring, with further spectral analysis performed only upon operator request, at widely spaced intervals, or under alarm conditions. A decision to monitor only gross vibrational level sacrifices sensitivity (6,11,17). However, the decision to monitor a larger set of detailed descriptors makes it difficult to establish meaningful detection criteria (particularly as a function of operational conditions) and has, in some cases, exhausted the patience of operations personnel (7).

Another approach taken by some researchers is the implementation of statistical algorithms as a basis for anomaly detection (17-19). Both the experience and success in applying these techniques have been limited. Our own previous efforts with a strictly statistical approach revealed that the rotating equipment being monitored was nonstationary. Even at fixed conditions, the equipment would operate for indefinite periods described by one set of statistical parameters and then would randomly change to other equally normal conditions with different statistics. Data taken under such conditions results in biased samples of the statistical populations, thereby destroying the rigor of statistical tests (19). Statistical techniques can also be data intensive and thus become unmanageable with the added complication of varying operational conditions.

The most mathematically complex techniques envisioned for automated surveillance systems may be generally referred to as pattern recognition methods (17, 20-22). Implementation of these methods typically requires the accumulation of signatures for abnormal conditions in addition to those for normal conditions. Such comprehensive data requirements cannot normally be satisfied, particularly at the onset of surveillance activities. In addition, since pattern recognition methods have characteristically been developed for other applications, they rarely incorporate -- and then only indirectly -- engineering knowledge pertinent to specific surveillance tasks. Nonetheless, it would appear that some of these methods do show promise as diagnostic algorithms once the required data is obtained.

The ORNL surveillance system

Overview: This monitoring system is the result of applying engineering judgment to the specific task of automating machinery surveillance. To maintain high sensitivity to anomalies, vibrational signatures are catalogued as a function of operational conditions, and detection decisions are based on simple statistical tests. The determination of alarm criteria is accomplished automatically, based upon normal data obtained during a learning period. Judicious feature selection is incorporated to reduce storage requirements; however, data logging adequate for diagnostic investigations is provided. False alarms are reduced by implementing processing logic that compensates for normal data variations.

Feature selection: A vibration signature is obtained by selecting only a subset of the various signal descriptors that might be derived from the measured data. This selection process introduces available engineering knowledge related to individual equipment, critical fault events, or the signal character into the monitoring system. For example, the power in the fifth order (five times the rotational speed) would logically be included as a feature describing a fan with five blades. Obviously, the specific set of parameters comprising a signature will vary for dissimilar applications. Discarding or combining redundant descriptors should result in a reduced set of descriptors which enhance the information content of the measured data. For our test purposes we chose 48 parameters per signal which define the phase, size, and shape of the time-averaged waveform, the total power of the signal, the harmonic and nonharmonic power, the power and phase of the first three orders of rotation, the spectrum-weighted order, and the average harmonic and nonharmonic order. A detailed explanation of these descriptors is given in the appendix. Although these features are not proposed as an optimum set for other monitoring applications, many descriptors in widespread use are included, and the ability to compare the performance of descriptors with different levels of detail is provided.

Reference catalogue of baseline data: Baseline signatures are catalogued as a function of operational conditions. This procedure necessitates access to variables that define the operational state, for example, speed, load, or flow. Discrete intervals are chosen to span the full range available to controlling variables; once specified, the interval structure determines the maximum number of entries required in the reference catalogue. Since it has been demonstrated that variations in speed and load can introduce changes in vibration exceeding those associated with anomalies (10), compensation for such changes stimulated by control variables is necessary for maintaining sensitivity for anomaly detection and for reducing false alarms. Although most investigations support this conclusion (7-10), few monitoring systems implement capabilities for handling this complication. We chose the direct cataloguing approach after reviewing various mathematical alternatives and experimenting with techniques based on principal components analysis and regression analysis.

Establishing limiting criteria: Baseline signatures and their normal interval of variation are established automatically by observing equipment operation during an initial learning period. During this period, the equipment must be operated at or near all conditions for which monitoring capability will be needed. The learning period should be of sufficient duration to include a representative sample of normal variations. This period was 2-4 days in our investigations. The adequacy of learning appears to be more closely related to elapsed clock time than to the number of signatures measured, because of the biased sampling previously cited (19). Several checks are available to ascertain if the learning period has been adequate. These include counters which conservatively estimate the proportion of the learning signatures considered normal and the number of learning signatures since the last abnormal classification, as well as the ability to switch to the monitoring mode for a defined period during which a detailed monitoring summary is automatically obtained. If necessary, additional learning can be initiated at any time. Since the system detects deviations from whatever baselines are established, sensitivity to further degradation is maintained whether or not equipment was operating normally during the learning period.

Detection logic: During monitoring, each vibration signature is measured under steady operating conditions and tested to determine if its deviations from the baseline signatures are statistically significant. While the application of classical statistics is invalidated by biased sampling and by lumping differing operations into coarse intervals, the deviations calculated in approximate standard deviation units do provide a quantitative measure of problem severity. Approximate methods of calculating signature deviations, although lacking in mathematical elegance, are incorporated because they have proven to reduce the incidence of false alarms.

During learning, the maximum and minimum values encountered for every feature are stored for each operational interval. When a signature at a given operational state is tested, the extreme values normal to that operational interval and those values from its nearest neighbors are combined to obtain a smeared interval that encloses all extremes. From this interval, a pseudo mean, m, and a pseudo standard deviation, σ, are calculated as follows:

$$m = \frac{\text{Max} + \text{Min}}{2}$$

$$\sigma = \frac{\text{Max} - \text{Min}}{6}$$

The absolute deviations calculated using these quantities are compared against a confidence limit which decreases from C + 3 to C (an input parameter) as the number of measurements, M, upon which m and σ are based, increases from 0 to 500:

$$\left|\frac{x - m}{\sigma}\right| \leqslant C + 3\left(\frac{500 - M}{500}\right)$$

Statistical intuition and experience indicate that a value of $C\approx 7$ is most appropriate. For industrial surveillance applications, testing the gross vibration levels against established severity criteria (1-4) is also recommended. This additional detection capability would provide limited protection during learning when no other performance monitoring is in force and would inherently set an upper limit on the statistically derived criteria.

Comprehensive data logging for diagnosis: No automatic diagnostic logic is implemented in this system. However, the detection of anomalous events does automatically initiate procedures that log data to assist in diagnosis. If a signature is encountered that exceeds normal bounds, an anomaly signature catalogue is begun for all signals from the suspect machine. The anomaly catalogue allows detailed comparison between data accumulated following the suspect event with that in the baseline reference catalogue obtained during learning. Additionally, a detection summary which tallies suspect events for each signature component and computes the average deviation is collected and available on request. Also upon demand, a variety of visual displays from standard signal processing algorithms (orbits and detailed power spectra) can be obtained, although data from these analysis capabilities are not automatically retained. It is expected that the data collected for diagnostic purposes will allow the development of algorithms to diagnose the most probable faults.

Results

Software implementation: The surveillance software has been implemented on a Digital Equipment Corp., PDP 11/34 minicomputer with 28K words of memory. Mass storage capability is provided by two disks, each with a 1.2M word capacity. All programs are written in FORTRAN except for the peripheral handler routines that require assembly language.

A small portion of the disk storage is required for the software system; the remaining portion, ~2M words, is available for data storage. The burden of the data storage is associated with cataloguing baseline data. The total storage requirement, R, for this reference catalogue is given by

$$R = 4 \sum_{i=1}^{M} O_i \sum_{j=1}^{S_i} D_{ij} ,$$

where M is the number of machines to be monitored; O_i, the number of lumped operational states allowed for the ith machine; S_i, the number of sensors on the ith machine; and D_{ij}, the number of descriptors used to describe the information from the jth sensor on the ith machine.

The mass storage requirements for the monitoring system are within reason for even large-scale industrial applications. Assume, for example, that one desired to monitor 100 machines, each equipped with eight sensors. An analysis that assigns 20 lumped operational states to each machine and characterizes each signal with 25 descriptors would require 1.6M words of storage. This allows one to describe each piece of equipment with 200 descriptors and still reserve some storage area for logging diagnostic data.

Evaluation of monitoring system: A laboratory evaluation of the monitoring software has been accomplished using a small rotor assembly driven by a fractional horsepower motor.* Three displacement probes and two accelerometers are installed on the rotor as shown in Fig. 1. One probe ("keyphasor") provides a tach signal and, through supplementary electronics, generates a rotationally synchronized sampling pulse to trigger the analog-to-digital converter. Two other probes, placed at 90° to each other, measure the radial vibration of the shaft. In addition, two accelerometers are installed on the inboard bearing housing to measure the orthogonal components of radial vibration. In our tests, two signatures describing rotor operation are actually calculated, one for the displacement probes and the other for the accelerometers. Each signature is composed from descriptors for both the horizontal and vertical directions.

The rotor can attain speeds from 0 to 200 revolutions per second (rps); this was the only control variable altered during our tests. Lumped operational states were defined in 1-rps intervals. This speed resolution was a convenient choice which offered reasonable detail.

In our previous work (19), the monitoring system was unable to maintain a low false alarm rate over extended periods of testing using the limiting criteria which were automatically established. This difficulty was overcome by modifying the detection logic and by extending the learning period. We have, in fact, demonstrated that a learning file composed in a few days can be used to monitor normal operation for periods of several months without false alarms becoming a difficulty.

The detection capability of the monitoring system was investigated by purposely introducing fault conditions into the test setup. The four fault types chosen were shaft rub, imbalance, mechanical looseness, and misalignments. Each anomaly type could be introduced in varying degrees of severity. Some faults introduced no discernible perturbation to the vibration signals; however, detection was always possible as the severity level was increased. After the anomalous conditions associated with fault testing were removed, the return to normal operation was verified by the monitoring system. Examples of the type of diagnostic

*Bently Nevada Corp., Minden, Nevada, Model RK-3.

data available from the system are presented as the individual tests are described.

Imbalance test: The balance of the rotor was altered by the addition of a 1.52-g mass 3.32 cm from the shaft centerline (translating to an imbalance force of 0.238 Nt m at 60 rps). The change in the vibration was readily detected by both horizontal and vertical displacement probes, as illustrated by the detection summary shown in Table 1. Any signature for which some descriptor was out of normal bounds is considered suspect. This was the case for all 1000 comparison signatures of each type comprising this summary. An interesting detail in this test is that the weight added actually improved the balance of the rotor. This can be seen in both Fig. 2, which shows the time-averaged orbit for both baseline and imbalance conditions, and in the detection summary, which shows a reduction (negative deviation) in the signal descriptors associated with the amplitude of the vibration. A change in vibrational amplitude at the first order is well established as the primary indication of changes in balance. However, as noted in Table 1, this descriptor was affected less dramatically than others. This results from the asymmetric domain (always positive) of power descriptors which reduces their statistical sensitivity to reductions in their magnitude. This can be corrected by using the log of their magnitudes. The phase of the first order does show significant variations throughout the entire speed range, as demonstrated in Fig. 3. The peak displacement was also significantly altered by the imbalance; Fig. 4 contrasts normal and anomalous variations for the peak displacement descriptor as a function of speed.

Misalignment test: The alignment of the rotor can be altered by placing shims under the bearing pedestals. The data shown resulted from raising one side of the inboard bearing pedestal by 1.32 mm, thus offsetting the centerlines of the motor and rotor shafts. This misalignment was readily detected, as indicated by most of the descriptors shown in Table 2. Unexpectedly, all descriptors except nonharmonic power showed a decrease in their magnitudes. Figure 5 shows this effect in detail for the power at the second order and is in contrast to Fig. 6 which shows the increase in the nonharmonic power.

The decrease in overall and harmonic vibration levels was not, however, an indication that the damage potential had been reduced, since the coupling to the motor destructively failed within 12 hours. The prominent peak in the plot of nonharmonic power, Fig. 6, resulted from data taken just prior to the destruction of the coupling. A reduction in vibration levels was not common to all misalignment tests; nonetheless, this case should serve to caution system designers that would ignore the importance of such effects.

Mechanical looseness test: This test was accomplished by loosening the screws that fasten the inboard bearing pedestal to the base plate. In this case, the accelerometers had a greater sensitivity to the abnormality than did the proximity probes. The rather pronounced effect on the accelerometer signatures, tabulated in the detection summary given in Table 3, most likely resulted from altering the mechanical impedance at the bearing pedestal (23). All descriptors influenced by the harmonic content of the signal were strongly affected. A plot of the extreme values experienced under both normal and loose conditions for the power at the second order as a function of speed is shown in Fig. 7.

Partial shaft rub test: In our tests, the presence of shaft rubs was indicated most strongly by the accelerometer signals. The data shown in Table 4 are from a partial shaft rub, where the rub screw (see Fig. 1) was allowed to lightly bounce against the shaft. This anomaly emphasizes again the importance of choosing descriptors which measure nonharmonic signal power (11). As seen from the detection summary (Table 4), the nonharmonic power is the only parameter which dependably indicates the presence of the rub. Detailed power spectra for the accelerometer under normal and rub conditions are shown in Figs. 8 and 9, respectively. The noise floor of the rub spectrum is raised over a rather broad order interval; this trait has been characteristic of rub anomalies we tested.

Summary and recommendations

The monitoring system automatically established limiting criteria during an initial learning period of a few days; subsequently, while monitoring the test rotor during several months of normal operation, the system experienced a false alarm rate of ∿0.5%. At the same time, the monitoring system successfully detected all fault types introduced into the test setup. Tests on "real-world" equipment are needed to provide final verification of the monitoring techniques. The incremental expense required to implement hardware for this purpose would be small in an industrial plant where sensors, electronics, and cabling already exist for vibration monitoring. Furthermore, the data required to make this monitoring approach effective would not hinder normal industrial operations.

There are areas that could benefit from additional investigation in the laboratory environment. A comparison of the relative values of alternative descriptors under given fault conditions would be worthwhile. This should be pursued in conjunction with extending the set of fault types available, e.g., bearing problems. Other tests should examine the effects of using fewer (more coarse) intervals to define the lumped operational states. Finally, techniques to diagnose the most probable fault should be developed by drawing upon the extensive data automatically logged by the monitoring system.

Appendix

In Table A-1 is a list of the descriptors which we chose to include in our vibration signatures. Many of these descriptors are commonly used and require no additional explanation. However, the following discussion and equations should serve to clarify the descriptors we used.

The waveform from a vibration sensor attached to a rotating machine has a repetitive component. Regardless of magnitude of this component, its presence can be enhanced by time-averaging the waveform. This process requires that the raw signal be sampled at some integer multiple of the frequency of rotation, f_o. These sampled values, $X(i\Delta t)$, are then averaged using the following formula

$$\bar{X}_i = \frac{1}{NREV} \sum_{n=1}^{NREV} X(i\Delta t + nT) \quad (i = 0, 1, 2, \ldots NPTS-1) \qquad (1)$$

where T is the period of rotation

$$T = NPTS \cdot \Delta t = \frac{1}{f_o} \qquad (2)$$

This time-averaging technique is equivalent to applying a comb filter to the original signal which passes only the fundamental frequency and its harmonics. The time averaged waveforms from two sensors at 90° to each other can be used to obtain average orbital plots which describe the motion of the shaft centerline at the monitored position. The "NPTS" values (usually 30) that describe the averaged waveform, $\bar{X}_i$, are correlated with the averaged waveform obtained initially as a baseline, $\overline{XB}_i$, to derive three additional quantities. The shape factor is the maximum value obtained for the normalized correlation function, H(J), which is defined by

$$H(J) = \frac{\sum_{i=1}^{NPTS} \bar{X}_{i+J} \cdot \overline{XB}_i}{\left[\sum_{i=1}^{NPTS} \overline{XB}^2_{e_i} \sum_{i=1}^{NPTS} \bar{X}^2_i\right]^{1/2}} \quad (J = 0, 1, 2, \ldots, NPTS-1) \qquad (3)$$

Values for $\bar{X}_{i+j}$ beyond $\bar{X}_{NPTS}$ are obtained by repeating the original waveform. The point J = L where H(J) is a maximum also defines the lag value, LAG, and the size factor, SZF, according to the following expressions:

$$LAG = L * \left(\frac{360}{NPTS}\right) ; \tag{4}$$

$$SZF = \frac{\sum_{i=1}^{NPTS} \bar{\bar{X}}_{i+L} \cdot \overline{XB}_i}{\sum_{i=1}^{NPTS} \overline{XB}_i^2} . \tag{5}$$

When analyzing the vibrational signals from rotating machinery, order-domain analysis (instead of the more familiar frequency-domain) simplifies interpretation of results, especially when variable speed operation exists. The basic relationship that allows conversion between the two domains is

$$Q = \frac{f}{f_o} , \tag{6}$$

where f_o is the fundamental rotational frequency.

Integral orders (Q = 1, 2, 3, etc.) occur at harmonics of the running speed. If the vibrational signal is analyzed for NREV revolutions, the minimum order resolution achievable is

$$\Delta Q = \frac{1}{NREV} . \tag{7}$$

The power at any order, Q_i, will be denoted by $G(Q_i)$, where $Q_i = i\Delta Q$, i = 1, NOC (number of orders calculated).

Thus the total power in the vibrational signal up to some desired order, Q_D, is obtained by summing

$$TPOW = \sum_{i=1}^{K} G(Q_i) , \tag{8}$$

where

$$K = \frac{Q_D}{\Delta Q} \ . \tag{9}$$

The harmonic power in the signal can be obtained by summing the power spectrum estimates at integral orders:

$$HPOW = \sum_{m=1}^{N} G(m) \ , \tag{10}$$

where N is the largest integer for which $Q_N \leqslant Q_D$.

The nonharmonic power is the difference of these two quantities

$$NHPOW = TPOW - HPOW \tag{11}$$

When combining power estimates over an order interval, another parameter of interest is the power-weighted average order. This parameter provides an indication of the order at which the power in the interval is concentrated. This is given by

$$ATO = \left[\frac{\sum_{i=1}^{k} Q_i^2 \ G(Q_i)}{\sum_{i=1}^{k} G(Q_i)} \right]^{1/2} \ . \tag{12}$$

Similarly the average harmonic order is given by

$$AHO = \left[\frac{\sum_{m=1}^{N} m^2 \ G(m)}{\sum_{m=1}^{N} G(m)} \right]^{1/2} \ , \tag{13}$$

and the average nonharmonic order is given by

$$\text{ANHO} = \left[\frac{\sum_{i=1}^{k} Q_i^2 \; G(Q_i) - \sum_{m=1}^{N} m^2 \; G(m)}{\sum_{i=1}^{k} G(Q_i) - \sum_{m=1}^{N} G(m)} \right]^{1/2} . \qquad (14)$$

All of the parameters defined above can be calculated from the time domain signal directly without the need for order domain transformations. The total power can be obtained by integrating the squared time signal:

$$\text{TPOW} = \frac{1}{T} \int_{o}^{T} \chi^2(t) \; dt \; ; \qquad (15)$$

$$\text{TPOW} \approx \frac{1}{\text{NDAT}} \sum_{i=1}^{\text{NDAT}} \chi_i^2 \approx \sum_{i=1}^{k} G(Q_i) \; . \qquad (16)$$

The total harmonic power can be obtained by integrating the time averaged waveform

$$\text{HPOW} \approx \frac{1}{\text{NPTS}} \sum_{i=1}^{\text{NPTS}} \bar{\chi}_i^2 \approx \sum_{i=1}^{N} G(m) \; . \qquad (17)$$

The sums of the squared orders, weighted by their power in Eqs. (12)-(14), are equal to integrating the square of the derivative of the time signal and the time-averaged signals, respectively:

$$\sum Q_i^2 \; G(Q_i) = \frac{1}{T} \int [\chi'(t)]^2 \; dt \; ; \qquad (18)$$

$$\sum Q_i^2 \; G(Q_i) \approx \frac{1}{\text{NDAT}} \sum_{i=1}^{\text{NDAT}} \left(\frac{\chi_i - \chi_{i-1}}{\Delta t} \right)^2 (\Delta t) \; ; \qquad (19)$$

$$\sum m^2\ G(m) \approx \frac{1}{NPTS} \sum_{i=1}^{NPTS} \left(\frac{\chi_i - \chi_{i+1}}{\Delta t} \right)^2 (\Delta t)\ . \qquad (20)$$

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Table 1. Detection summary (1000 signatures tested) for imbalance test over the speed range of 60 to 85 rps.

Signature Descriptor	Displacement Signature		Acceleration Signature	
	X Sensor No. Out (Dev.[a])	Y Sensor No. Out (Dev.[a])	X Sensor No. Out (Dev.[a])	Y Sensor No. Out (Dev.[a])
Lag values	997	802	994	0
Shape factor	0	8	0	0
Size factor	416 (-12.2)	1 (-18.9)	0 (0.0)	0 (0.0)
Peak values	416 (-10.4)	1 (-26.3)	0 (0.0)	0 (0.0)
Total power	81 (-10.6)	1 (-18.6)	0 (0.0)	0 (0.0)
Harmonic power	81 (-10.6)	1 (-18.6)	0 (0.0)	0 (0.0)
Nonharmonic power	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Average order	350 (8.7)	18 (12.5)	95 (8.0)	0 (0.0)
Average harmonic order	38 (8.9)	12 (11.8)	1 (7.5)	0 (0.0)
Average nonharmonic order	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
PSD order 1	71 (-10.9)	1 (-18.6)	0 (0.0)	0 (0.0)
PSD order 2	0 (0.0)	1 (-8.5)	0 (0.0)	0 (0.0)
PSD order 3	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Phase order 1	1000	416	1000	0
Phase order 2	726	914	445	0
Phase order 3	11	10	409	0
	No. of suspect signatures = 1000		No. of suspect signatures = 1000	

[a]Deviations from baseline data in approximate standard deviation units.

Table 2. Detection summary (500 signatures tested) for misalignment test over the speed range of 55 to 100 rps.

Signature Descriptor	Displacement Signature: X Sensor No. Out (Dev.[a])	Displacement Signature: Y Sensor No. Out (Dev.[a])	Acceleration Signature: X Sensor No. Out (Dev.[a])	Acceleration Signature: Y Sensor No. Out (Dev.[a])
Lag values	426	336	487	0
Shape factor	0	13	0	0
Size factor	463 (-18.1)	51 (-18.4)	2 (-8.8)	0 (0.0)
Peak values	310 (-13.7)	47 (-11.0)	0 (0.0)	0 (0.0)
Total power	313 (-13.1)	47 (-16.4)	0 (0.0)	0 (0.0)
Harmonic power	315 (-13.7)	47 (-18.7)	0 (0.0)	0 (0.0)
Nonharmonic power	459 (333.9)	461 (514.3)	38 (10.0)	0 (0.0)
Average order	23 (3.5)	6 (-10.7)	179 (10.4)	0 (0.0)
Average harmonic order	11 (9.6)	7 (18.7)	101 (14.4)	0 (0.0)
Average nonharmonic order	0 (0.0)	0 (0.0)	408 (-14.2)	14 (-8.3)
PSD order 1	315 (-13.7)	47 (-18.7)	5 (20.5)	0 (0.0)
PSD order 2	101 (-9.1)	47 (-8.3)	0 (0.0)	0 (0.0)
PSD order 3	10 (27.0)	11 (18.0)	14 (35.0)	0 (0.0)
Phase order 1	493	327	496	3
Phase order 2	1	189	22	0
Phase order 3	28	305	336	1
	No. of suspect signatures = 500		No. of suspect signatures = 500	

[a] Deviations from baseline data in approximate standard deviation units.

Table 3. Detection summary (1000 signatures tested) for mechanical looseness test over the speed range of 75 to 95 rps.

Signature Descriptor	Displacement Signature X Sensor No. Out (Dev.[a])	Displacement Signature Y Sensor No. Out (Dev.[a])	Acceleration Signature X Sensor No. Out (Dev.[a])	Acceleration Signature Y Sensor No. Out (Dev.[a])
Lag values	0	5	194	0
Shape factor	0	0	0	0
Size factor	7 (-8.6)	0 (0.0)	0 (0.0)	26 (9.9)
Peak values	8 (-9.0)	0 (0.0)	151 (9.8)	309 (17.1)
Total power	7 (-8.4)	0 (0.0)	137 (9.7)	210 (17.3)
Harmonic power	7 (-8.5)	0 (0.0)	114 (10.1)	313 (17.0)
Nonharmonic power	47 (24.9)	6 (9.9)	121 (15.8)	96 (16.1)
Average order	0 (0.0)	0 (0.0)	13 (9.1)	0 (0.0)
Average harmonic order	0 (0.0)	0 (0.0)	7 (9.1)	0 (0.0)
Average nonharmonic order	0 (0.0)	0 (0.0)	341 (-11.3)	15 (7.9)
PSD order 1	7 (-8.5)	0 (0.0)	0 (0.0)	112 (13.2)
PSD order 2	0 (0.0)	0 (0.0)	957 (154.0)	216 (21.5)
PSD order 3	0 (0.0)	0 (0.0)	901 (126.8)	131 (16.3)
Phase order 1	0	29	353	0
Phase order 2	0	32	419	0
Phase order 3	0	0	266	0
	No. of suspect signatures = 87		No. of suspect signatures = 1000	

[a] Deviations from baseline data in approximate standard deviation units.

Table 4. Detection summary (20 signatures tested) for partial shaft rub test over the speed range of 60 to 65 rps.

Signature Descriptor	Displacement Signature		Acceleration Signature	
	X Sensor No. Out (Dev.[a])	Y Sensor No. Out (Dev.[a])	X Sensor No. Out (Dev.[a])	Y Sensor No. Out (Dev.[a])
Lag values	0	0	0	0
Shape factor	0	0	0	0
Size factor	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Peak values	0 (0.0)	0 (0.0)	0 (0.0)	20 (27.1)
Total power	0 (0.0)	0 (0.0)	0 (0.0)	15 (17.9)
Harmonic power	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Nonharmonic power	4 (26.4)	17 (85.7)	19 (19.4)	20 (30.8)
Average order	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Average harmonic order	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Average nonharmonic order	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
PSD order 1	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
PSD order 2	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
PSD order 3	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Phase order 1	0	0	0	0
Phase order 2	0	0	0	0
Phase order 3	0	1	0	0
	No. of suspect signatures = 17		No. of suspect signatures = 20	

[a] Deviations from baseline data in approximate standard deviation units.

Table A-1. Descriptors in vibration signature

1. Time-averaged waveform ("NPTS" values)
2. Lag value of time-average waveform
3. Shape factor for time-average waveform
4. Size factor for time-average waveform
5. Peak signal value
6. Total signal power
7. Harmonic power in signal
8. Nonharmonic power in signal
9. Average order of signal
10. Average harmonic order of signal
11. Average nonharmonic order of signal
12. Power at first order of signal
13. Power at second order of signal
14. Power at third order of signal
15. Phase of first order of signal
16. Phase of second order of signal
17. Phase of third order of signal

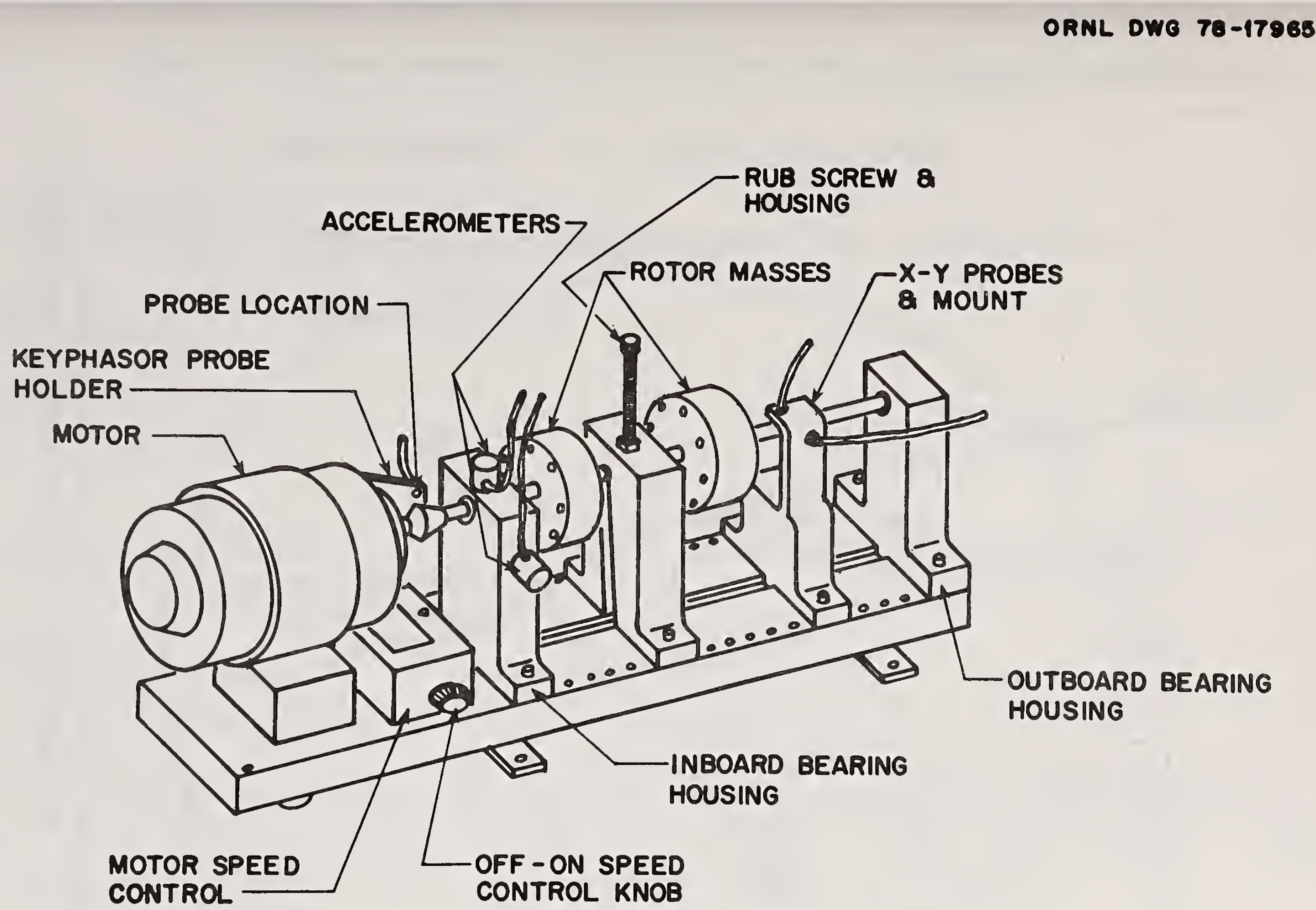

Fig. 1. The rotor assembly used in testing the monitoring system.

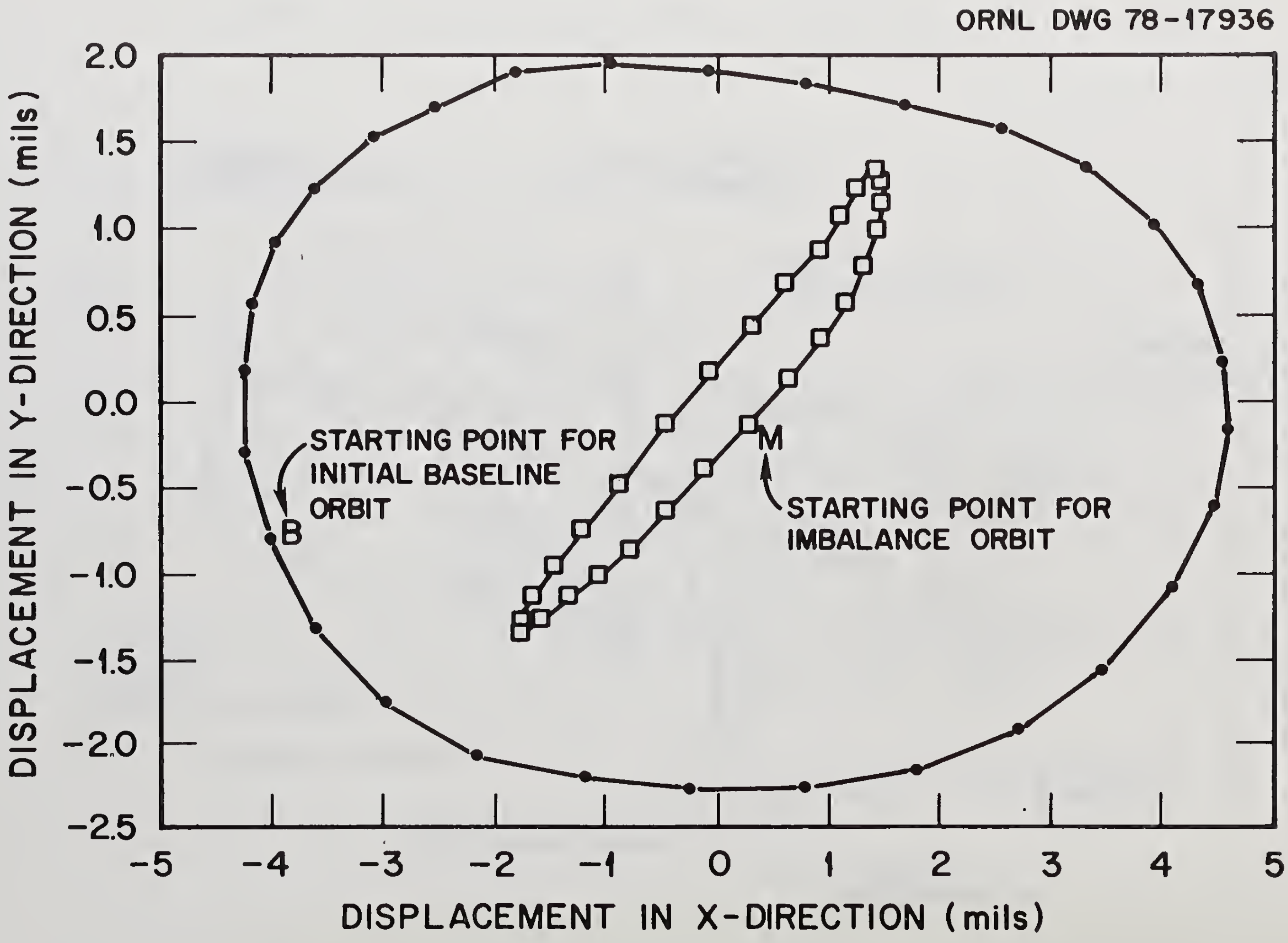

Fig. 2. The time-averaged orbits for normal and imbalance conditions.

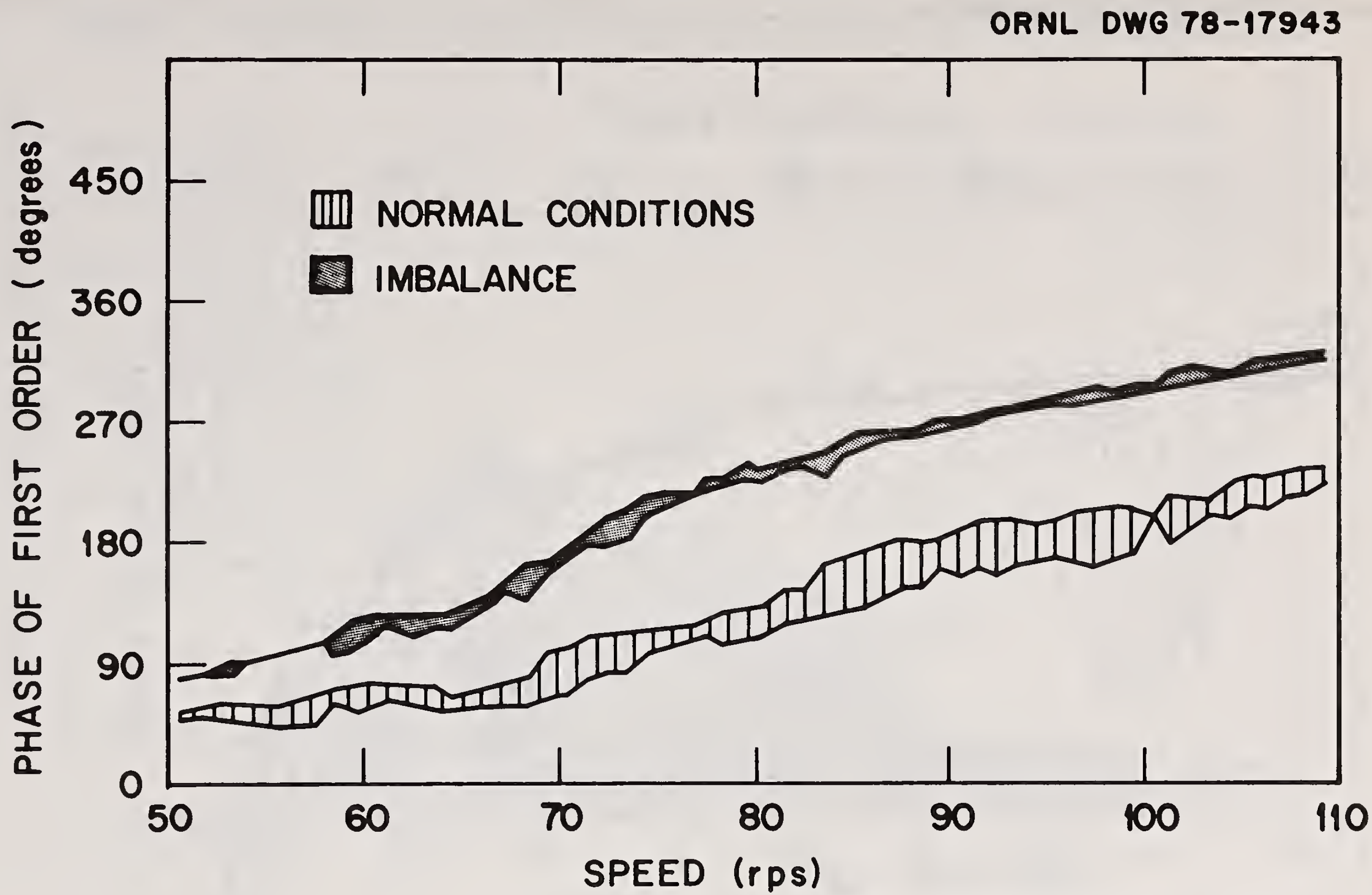

Fig. 3. The range of phase values (displacement probe) at the first order for normal and imbalance conditions vs speed.

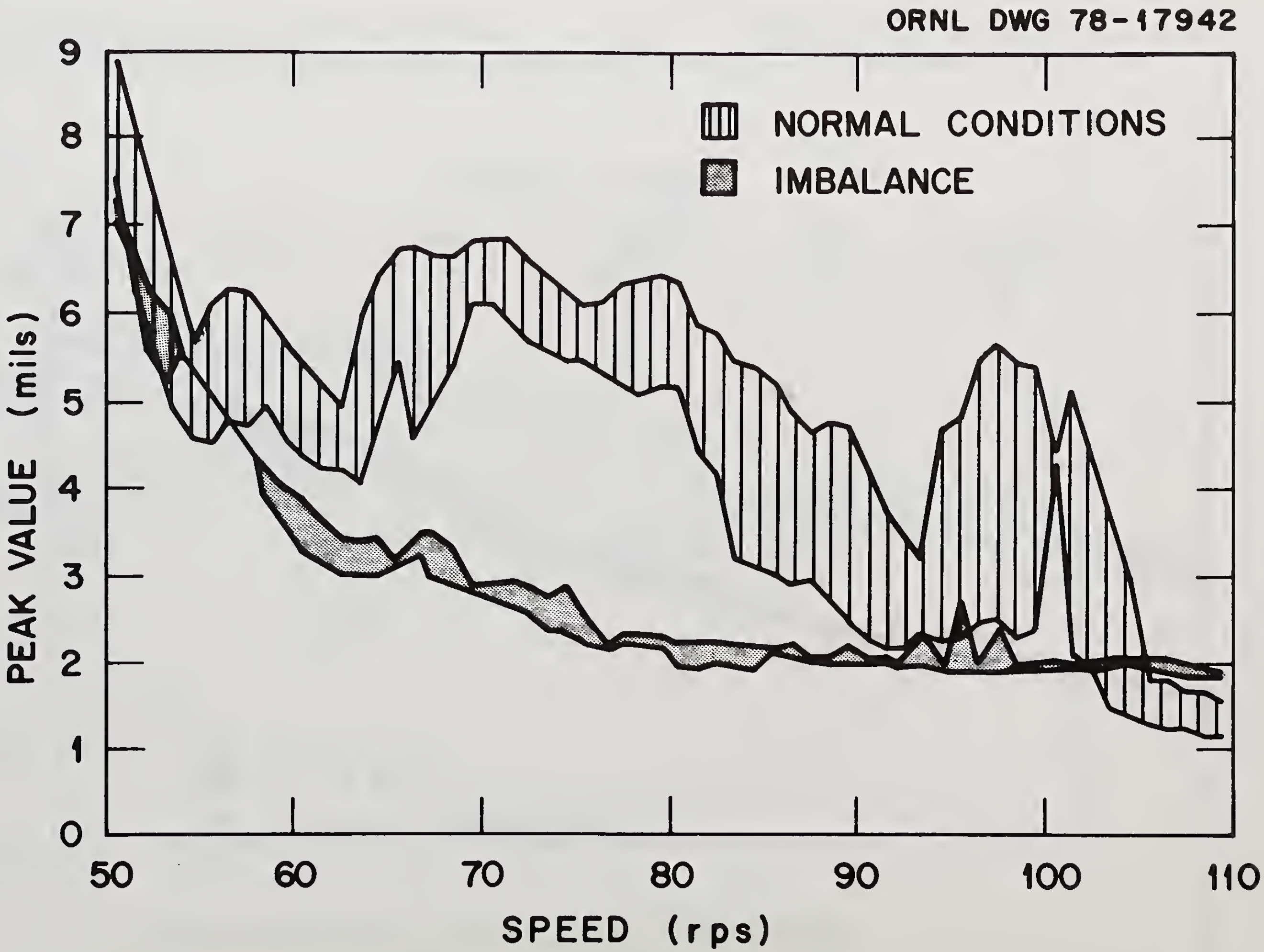

Fig. 4. The range of peak displacements for normal and imbalance conditions vs speed.

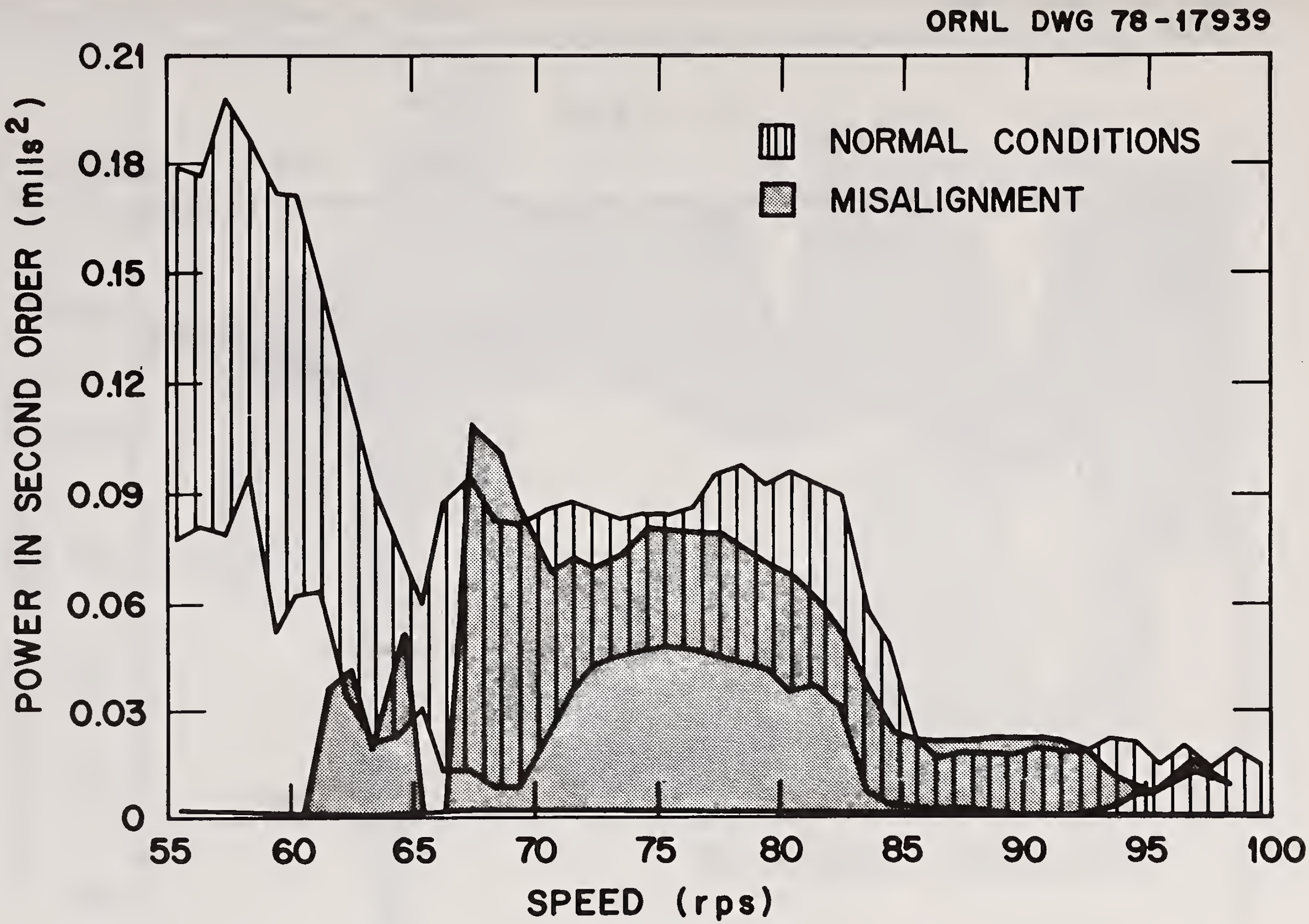

Fig. 5. The range of power estimates (displacement probe) at the second order for normal and misaligned conditions vs speed.

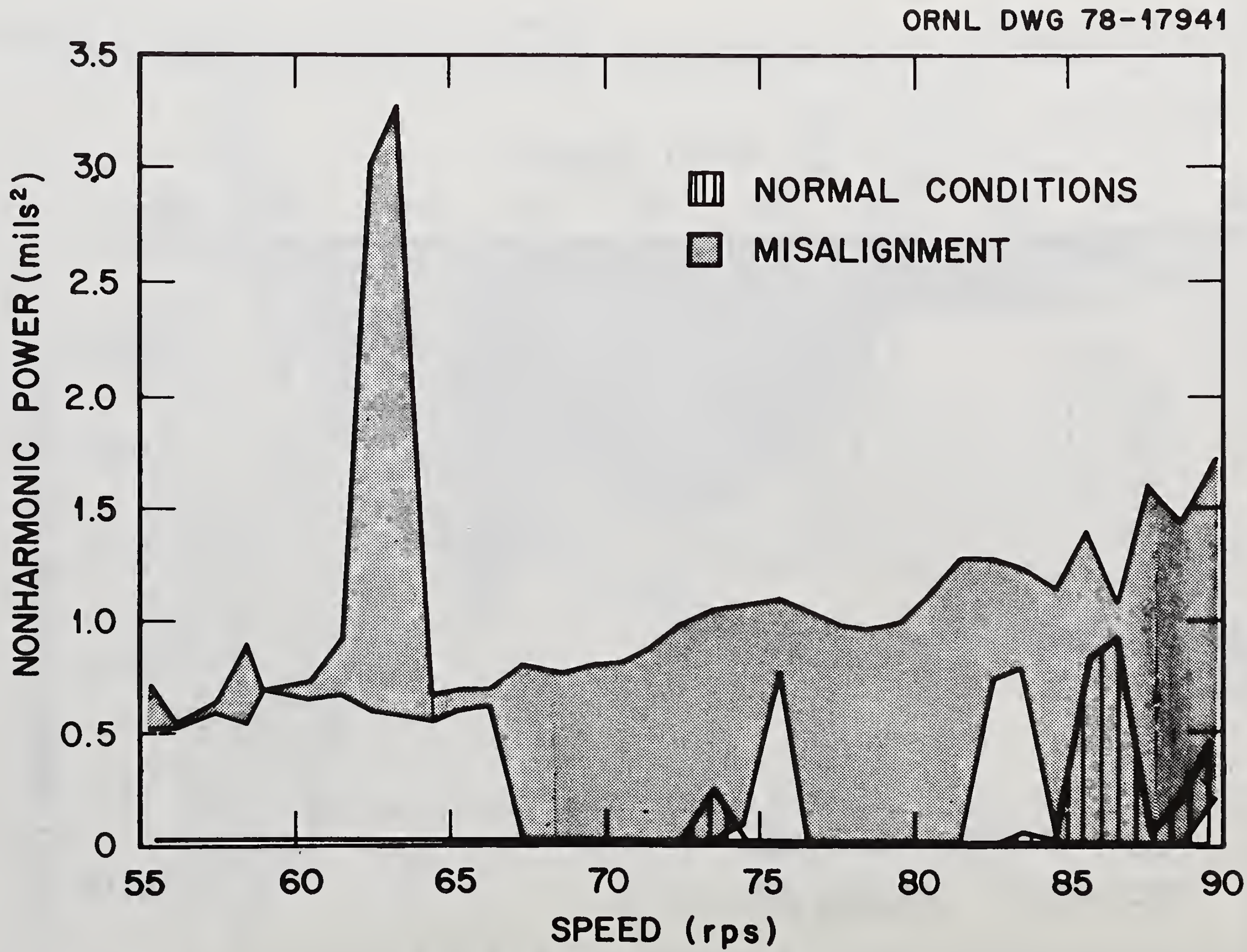

Fig. 6. The range of nonharmonic power estimates (displacement probe) for normal and misaligned conditions vs speed.

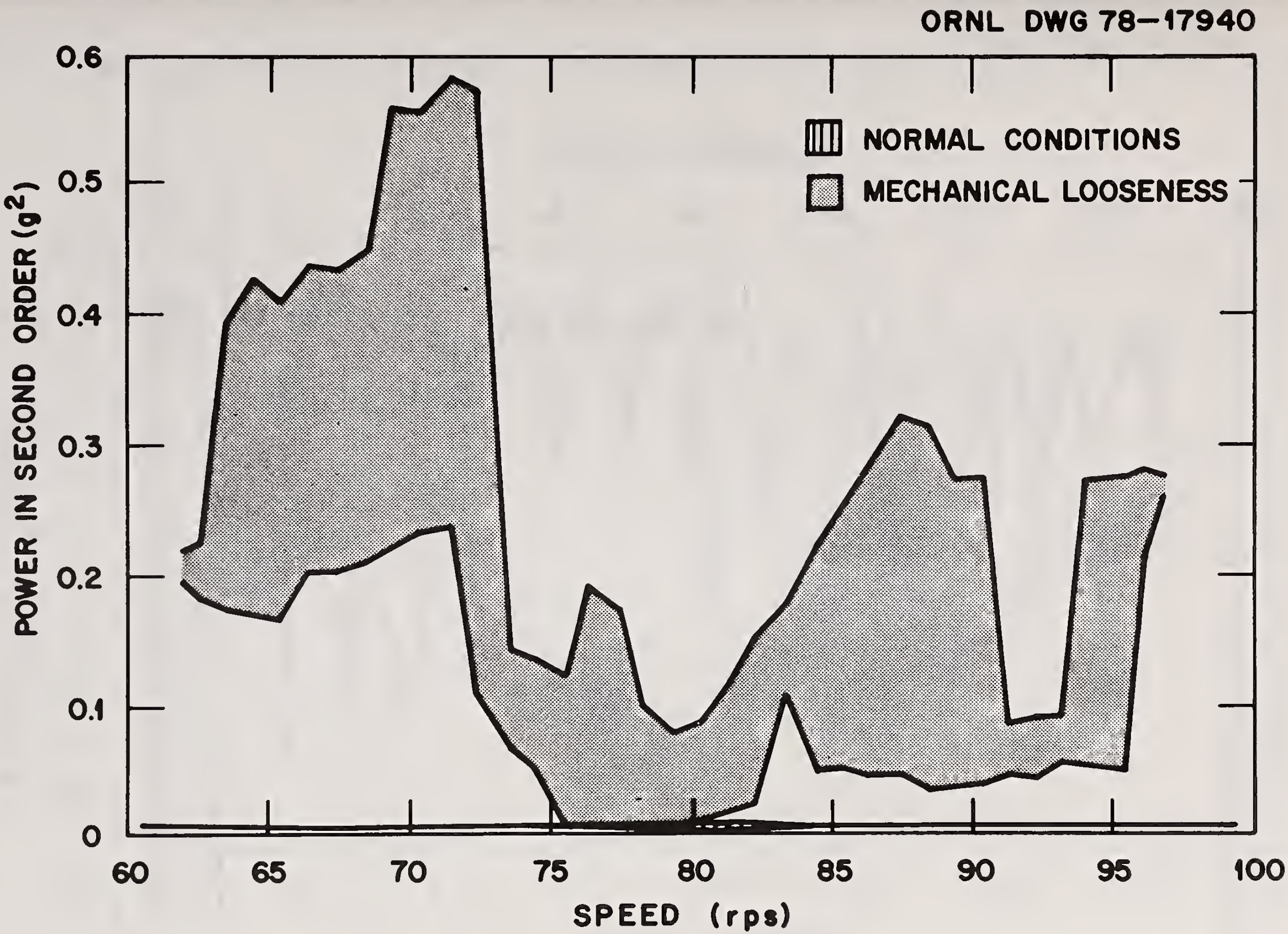

Fig. 7. The range of power estimates (accelerometer) at the second order for normal and mechanically loose conditions vs speed.

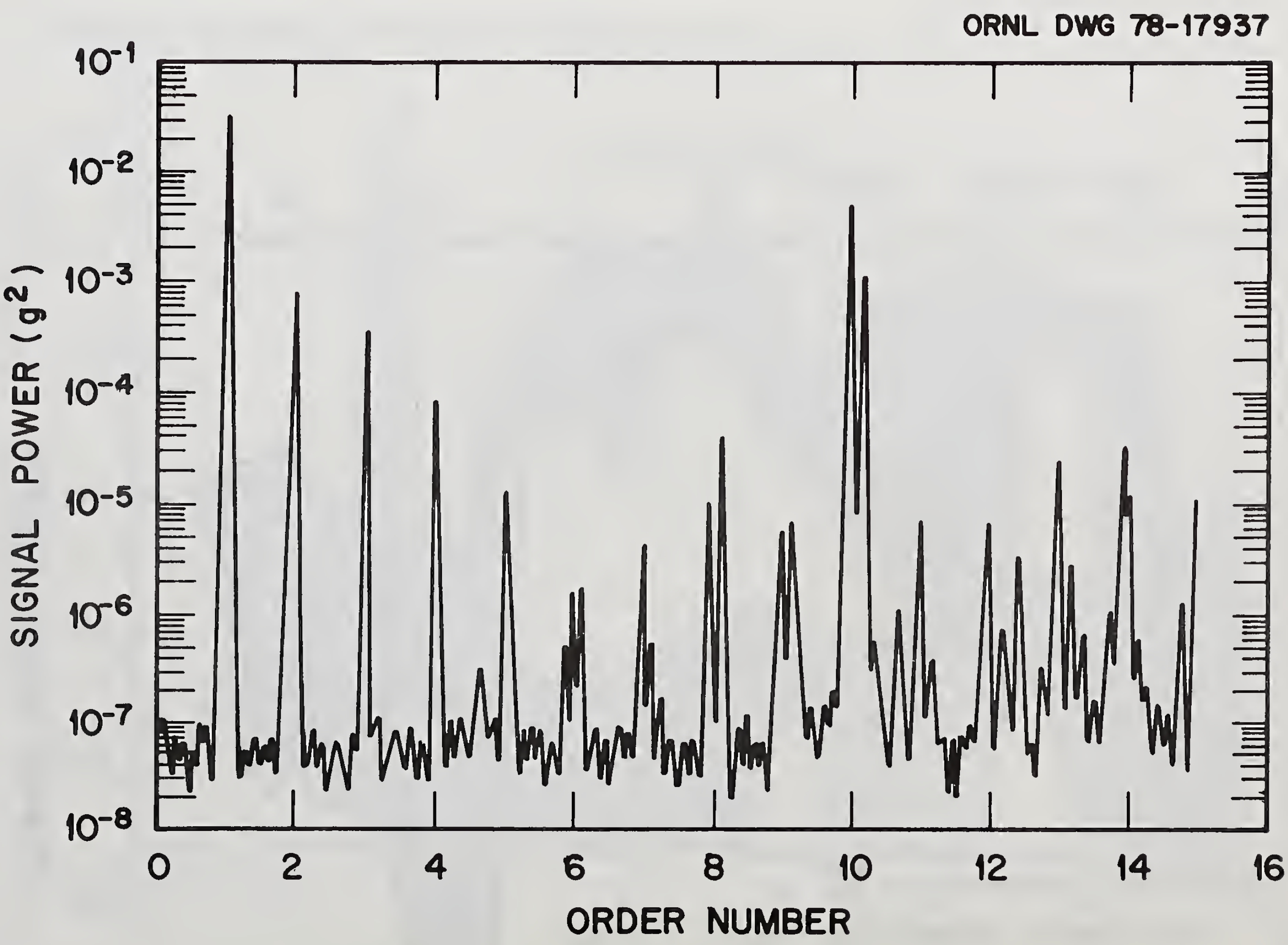

Fig. 8. Power spectrum of horizontal accelerometer during normal rotor operation at 59 rps.

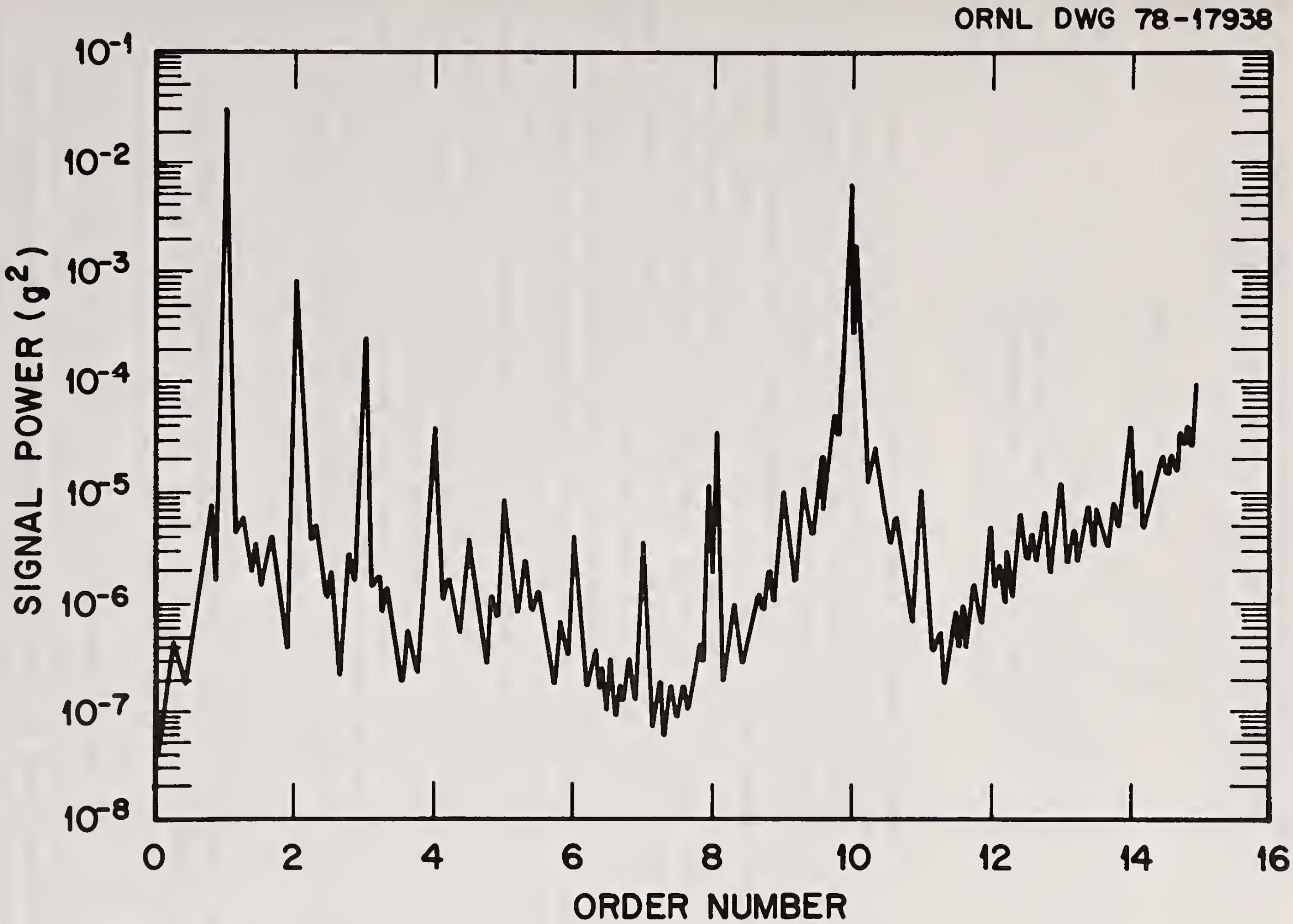

Fig. 9. Power spectrum of horizontal accelerometer during partial shaft rub test at 59 rps.

VIBRATION ANALYSIS METHOD FOR DETECTION OF ABNORMAL MOVEMENT OF MATERIAL IN A ROTARY DISSOLVER

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Abstract: Vibration signals generated by the movement of simulated nuclear fuel material through a three-stage, continuous, rotary dissolver were frequency analyzed to determine whether these signals contained characteristic signal patterns that would identify each of five phases of operation in the dissolver and, thus, would indicate the proper movement of material through the dissolver. This characterization of the signals is the first step in the development of a system for monitoring the flow of material through a dissolver to be developed for reprocessing spent nuclear fuel. Vibration signals from accelerometers mounted on the dissolver roller supports were analyzed in a bandwidth from 0 to 10 kHz. The analysis established that (1) all five phases of dissolver operation can be characterized by vibration signatures; (2) four of the five phases of operation can be readily and directly identified by a characteristic vibration signature during continuous, prototypic operation; (3) the transfer of material from the inlet to the dissolution stage can be indirectly monitored by one of the other four vibration signatures (the mixing signature) during prototypic operation; (4) a simulated blockage between the dissolution and exit stages can be detected by changes in one or more characteristic vibration signatures; and (5) a simulated blockage of the exit chute can not be detected.

Key words: Monitor system; rotary dissolver; signature analysis; vibration analysis.

Introduction: Vibration signals generated by the movement of simulated nuclear fuel material through a three-stage, continuous, rotary dissolver were analyzed to determine whether these signals contained characteristic signal patterns that would identify each of five phases of operation in the dissolver and, thus, would indicate the proper movement of material through the dissolver. This characterization of the signals is the first step in the development of a system for monitoring the flow of material through a dissolver to be developed for reprocessing spent nuclear fuel. Five phases of dissolver operation are present during the movement of material through the three-stage dissolver: (1) introduction of material into the inlet stage, (2) transfer of material from the inlet stage to the dissolution stage, (3) mixing of material in the dissolution stage, (4) transfer of material from the dissolution stage to the exit stage, and (5) discharge of material from the exit stage.

Dissolver description: The dissolver is a three-stage, continuous, rotary drum, 4 ft long and 4 ft in diameter. It rotates around a horizontal axis on two roller rings, one of which is V-shaped to provide lateral stability. Each roller ring is supported on two rollers. The dissolver is chain driven at the exit end. Figure 1 shows the internal components of the dissolver.

The dissolver rotates cyclically at a speed of approximately 3 rpm, as follows: rotate in a "forward" (clockwise) direction for a predetermined time period (∿20 min), stop, make one revolution in the "reverse" (counterclockwise) direction, and stop before repeating the cycle. Discrete batches of material (∿2 kg) are periodically (every 30 s) introduced into the dissolver. During forward revolutions, baffles in the inlet stage move the material into a wedge shaped chute (Fig. 1) which transfers the material into the dissolution stage. The material is mixed in the dissolution stage by a mixing-transfer baffle and remains in this stage until the dissolver stops and makes a reverse rotation. During this reverse movement, the mixing-transfer baffle in the dissolution stage moves the material into a conical transfer chute (Fig. 1) which transfers the material into the exit stage. Once the material is in the exit stage, the dissolver again rotates forward and repeats the cycle, and transfer baffles in the exit stage transfer the material into the exit chute which discharges the material from the dissolver.

The dissolver is a counterflow device; the fuel and the acid solution move in opposite directions. When nuclear fuel is reprocessed, it (cladding and oxide) will be chopped into pieces about 1 in. long. The chopped fuel will be introduced into the inlet stage and moved to the dissolution stage where an acid solution will leach the oxide from the cladding. The empty cladding will be moved to the exit stage and discharged from the dissolver. The acid solution will be introduced in the exit stage; it will flow to the dissolution stage where it will leach the oxide from the cladding, and finally to the entrance stage where it will be discharged for further processing.

In these experiments, simulated chopped fuel hulls consisting of stainless steel tubing packed with a mineral oxide were used instead of cladded nuclear material, and water was present instead of acid. These differences are insignificant to the results and conclusions of this study because the important physical properties of the simulated fuel and actual fuel are similar and the chemical reaction has a negligible effect on vibration.

Instrumentation: The vibration instrumentation consisted of four, Endevco, model 2233E accelerometers and a drum position and direction indicator. The accelerometers, having a flat-frequency response of ±3 dB, between 4 and 6000 Hz, were located as shown in Fig. 2. (Four accelerometers were installed to allow spatial analysis of the signals if this were shown to be informative, but this has not been attempted.) The signals from these sensors and indicator were conditioned and recorded on a Bell and Howell, model 4010, 14-channel FM tape recorder for off-line analysis.

The accelerometers were mounted with electrically isolated mounting studs, using oil coupling to bolts which are part of the support roller assemblies. Miniature coaxial cables, environmentally sealed at the accelerometer connection, transmitted the vibration signals to voltage preamplifiers. The single-ended signals were ac coupled with a 0.02-Hz high-pass filter, amplified to a ±1 V level, and band-pass filtered (3 Hz to 300 kHz) before being recorded.

The position of the dissolver was indicated by a 0- to 0.8-V signal from electronic circuitry with proximity probes to detect the teeth on the drive sprocket of the dissolver drum. The direction of dissolver rotation was indicated by a 1.25-V-forward, 1.5-V-reverse, logic signal from this same circuitry. The position and direction signals were suitable for recording without further conditioning.

Experimental procedure: These studies were devised to accomplish three goals, as follows: (1) to determine whether each of the five phases of dissolver operation could be characterized by the vibration signal associated with that phase of operation, (2) to determine whether the characterization of each phase could be identified during continuous operation when two or more phases might occur simultaneously, and (3) to determine if improper movement of material through the dissolver would result in significant changes in the characterization of the phases of operation.

To achieve the first goal, several single, 20-kg batches of simulated fuel material were processed individually through the dissolver. With only one batch of material in the dissolver at a time, the signals associated with each of the five phases of dissolver operation were separated and individually recorded and examined.

To achieve the second goal, several tests were conducted where 2-kg batches of material were added at 30-s intervals (simulating continuous operation) until 60-kg of material had been added. The dissolver was operated on approximately a 5-min cycle; thus, ∿20-kg loads of material were collected in the dissolution stage before transfer.

Two series of tests were conducted to achieve the third goal: in one, an artificial blockage was installed in the transfer chute between the dissolution and exit stages, and, in the second, an artificial blockage was installed in the exit chute ∿2 ft from the entrance. For both series, tests were conducted with both single, 20-kg loads and individual 2-kg loads introduced at 30-s intervals.

Data analysis: The recorded vibration signals from the accelerometers were frequency analyzed over a bandwidth from 0 to 10 kHz, using a fast Fourier transform (FFT) algorithm. The position indicator was used to arbitrarily divide each dissolver revolution into sixteen equal angular segments, or orientations. To correlate the analysis with the dissolver position, a separate FFT analysis was performed on the vibration signals received during each orientation. Since the drum period was 20 s per revolution, each orientation spanned ∿1.25 s. A frequency analysis was performed during each orientation, with a maximum frequency of 10 kHz (sampling rate of 20 kHz) and a resolution of ∿40 Hz. Data from only ∿0.8 s of each orientation were analyzed because of nonreal time processing which resulted because the computer was unable to finish processing one set of data before the next was ready to be processed.

For each orientation, the FFT analysis yielded a power spectral density (PSD), which is the amount of power in the signal at each frequency. Preliminary analysis showed that there were no prominent, discrete frequency spectra features, but that each phase of dissolver operation could be characterized by relatively broad-band (1-2 kHz) changes in the spectra. Therefore, a method was determined for condensing and extracting useful information from the numerous individual PSD spectra. The individual spectra were subdivided into ten, 1-kHz bandwidths over a range from 0 to 10 kHz, and the PSD values within each bandwidth were used to form a single, root-mean-square (RMS) quantity for each bandwidth for each orientation of each revolution. This allowed the orientation-dependent fluctuations in the bandwidth-limited RMS parameter to be studied. To simplify the analysis, a computer program was written which computed the bandwidth-limited RMS value without requiring an FFT analysis and plotted it versus dissolver orientation.

Results for single 20-kg charge: The results show that, although vibrations were produced over all analyzed frequency ranges, there is a frequency range for each phase of operation in which the vibration signals have a characteristic signature (or pattern) of RMS values when these values are plotted versus dissolver revolutions (16 orientations per revolution). Furthermore, one needs to observe only two frequency ranges, 2 to 3 kHz and 5 to 6 kHz, to determine the characteristic signature for each phase of operation.

Figure 3, a plot of the 2- to 3- and 5- to 6-kHz RMS values versus dissolver revolution, illustrates the characteristic signature for each phase. The test was started with the dissolver empty. The material was introduced into the inlet stage during revolution 5, transferred to the dissolution stage during revolutions 6 to 8, and mixed during revolutions 9 to 29. The dissolver was stopped at the end of revolution 29, and revolution 30 was a reverse revolution during which the material was transferred to the exit stage. Forward rotation of the dissolver was resumed to discharge the material during revolutions 31 to 38.

During revolution 5, the charging (entrance) of material produced vibrations and corresponding RMS spikes in both the 2- to 3- and 5- to 6-kHz frequency ranges. This single, large spike is the characteristic signature for material charging. This signature is identified in the 5- to 6-kHz range because of possible confusion with other spikes in the 2- to 3-kHz range and the better signal-to-noise ratio in the 5- to 6-kHz range.

The transfer of material from the inlet to the dissolution stage also produced spikes in both frequency ranges. The characteristic vibration signature for this phase of operation consists of spikes during orientation 13 for several revolutions after the material is charged (Fig. 3, revolutions 6, 7, and 8). This signature can be identified in either frequency range since no other phase of operation produces a spike in orientation 13, and there is no significant difference in the signal-to-noise ratio for the two frequency ranges.

Mixing in the dissolution stage produced spikes of significant amplitude only in the 2- to 3-kHz range, as seen in Fig. 3, revolutions 9 to 29. The signature for mixing is a relatively large spike during the last orientation of each revolution (orientation 16). These mixing spikes are periodic, are generated during forward revolutions, and are similar in amplitude.

The transfer of material from the dissolution stage to the exit stage also produced spikes of significant amplitude only in the 2- to 3-kHz range (Fig. 3, revolution 30). This signature is a relatively large spike during orientation 3 of the reverse revolution. This spike is similar to a mixing spike, but there are two important differences: it is generated during a reverse revolution, instead of during a forward revolution; and it is generated in orientation 3, rather than in orientation 16 (orientation numbers decrease with time during a reverse cycle).

Figure 3 shows that for revolutions 31 to 38 the discharge of material from the exit stage of the dissolver produced spikes in both frequency ranges, but these spikes have a better signal-to-noise ratio in the 5- to 6-kHz range. The signature for the discharge phase is four equally spaced spikes per revolution. These spikes are generated during forward revolutions following a reverse, and their amplitude tends to decrease as more material is discharged, leaving less material in the exit stage. The signature for the discharge of material was chosen in the 5- to 6-kHz range because the spikes in the 2- to 3-kHz range were similar to those for mixing. Since, in normal operation, mixing and discharge would occur simultaneously, separation of these two signatures in the 2- to 3-kHz range would be more difficult.

The vibration signatures in Fig. 3 were determined from the analysis of only one of the four accelerometers, accelerometer A. The data from all accelerometers were analyzed, and the results were similar. However, in general, the amplitudes of vibrations were larger from accelerometers located near the source than from those located farther away; i.e., for charging, accelerometers A and B on the inlet side had larger signals than accelerometers C and D on the exit side. Also, vibrations not caused by material movements (i.e., vibrations from individual rollers) could influence an adjacent accelerometer, but being attenuated by distance, they had little effect on the other accelerometers.

Results for 2-kg charges at 30-s intervals: The results in Fig. 4 (2 to 3 kHz) and Fig. 5 (5 to 6 kHz) show that a characteristic signature can be identified for each phase of dissolver operation except one during normal, continuous feed operation. In Fig. 5, the single, large-amplitude charging spikes (i.e., the charging signature) are identifiable because their amplitudes exceed 3×10^{-3} V,* and their occurrence is time dependent rather than revolution dependent, i.e., they do not occur at particular orientations of certain revolutions (see Fig. 5, revolutions 2, 3, 5, 6, and 8). Once these spikes have been identified in the 5- to 6-kHz range, their effect in the 2- to 3-kHz range can be inferred (i.e., a spike during revolution 2 of Fig. 5 means that charging also caused the spike during revolution 2 of Fig. 4, and a spike during revolution 6 of Fig. 5 means that charging contributed to the spike during revolution 6 of Fig. 4).

It is difficult to identify a characteristic signature for transfer of material from the inlet stage to the dissolution stage with a 20-kg charging load, and such identification is unreliable with 2-kg charging loads because the amount of material being transferred is less and the associated signal is smaller. However, this transfer may be indirectly monitored through the signature for mixing in the dissolution stage. If the transfer from the inlet stage to the dissolution stage did not occur, eventually (after the next reverse) there would be no material in the dissolution stage, and the mixing spikes would be absent.

In the analysis with 20-kg loads (Fig. 3), the signature for mixing in the dissolution stage is identified as a once-per-revolution spike during orientation 16 in the 2- to 3-kHz range. In Fig. 4, this same signature is found, although additional spikes are present. The effects of charging and discharging also produced spikes in the 2- to

*The two charges immediately following a reverse have a smaller amplitude because of analytical techniques.

3-kHz range, and these additional spikes must be considered (Fig. 4, revolutions 17, 20, 23, and 26). As previously stated, the spikes generated during the charging phase can be identified in the 5- to 6-kHz range, and similar effects can be found in the 2- to 3-kHz range. Later, it will be shown that the spike generated during the discharging phase can be handled in the same manner.

Thus, by using this method, one can determine the effects of charging and discharging in the 2- to 3-kHz range; then, since mixing spikes are generated during orientation 16, the mixing signature can be determined (Fig. 4, revolutions 17 to 26). However, possibly there is a problem: if charging or discharging occurs simultaneously with mixing, this analytical method is currently unable to separate the effects of each. To determine the mixing signature, enough spikes caused only by mixing must remain after the spikes caused by a simultaneous occurrence of phases (mixing and charging or mixing and discharging) are discounted. If a charging period is the same as a period of revolution, and if mixing and charging occur simultaneously, there will be no spikes caused only by mixing. Therefore, the analytical method is unable to determine the mixing signature in this instance.

The simultaneous occurrence of mixing and discharging is different because mixing and discharge can occur simultaneously only over a limited time period. Discharging occurs immediately following a reverse and lasts only several revolutions, with its effects diminishing in latter revolutions. Furthermore, during this same time period, the mixing stage is being refilled, and mixing is producing only small effects. Therefore, the simultaneous occurrence of mixing and discharging poses no significant problem in determining the mixing signature since the two phases cannot occur simultaneously over long periods of time.

The signature for transfer of material from the dissolution stage to the exit stage can also be identified in the 2- to 3-kHz range of Fig. 4 (revolutions marked "REV"). This signature is relatively easy to identify since it occurs only during a reverse and in orientation 3. It is possible that charging may occur simultaneously, but this will be indicated by a charging spike in the 5- to 6-kHz range. If this happens, the effects are not separable by the analytical method, and the transfer of material cannot be identified for this reverse revolution. However, there is an indirect indication of this transfer because if it did not occur, there would be no material transferred to the exit stage to be discharged during subsequent forward revolutions. Thus, the signature for discharging would be absent.

The signature for discharging of material from the exit stage, which is four equally spaced spikes per revolution, can be identified in the 5- to 6-kHz range of Fig. 5 (revolutions 13-17, 27-32, and 40-44). Generally, the amplitude of these spikes is less than 3×10^{-3} V, and it progressively decreases during the revolutions following a reverse.

It is possible for material to be charged simultaneously with the observation of these discharging spikes, and when it is, the amplitude of the resultant spike is greater than 3×10^{-3} V (Fig. 5, revolutions 14 and 16). The simultaneous presence of a charging spike with a discharging spike has no significant effect on the identification of the signature for discharging since there are four discharging spikes per revolution. In Fig. 4, it can be seen that the discharging spikes also produce effects in the 2- to 3-kHz range. By reasoning similar to that previously used with charging spikes, the discharging spikes can be identified in the 5- to 6-kHz range and the effects in the 2- to 3-kHz range can be found.

Results for artificially induced blockages: The results show that changes in the characteristic signatures for the phases of operation can indicate some, but not all, types of blockages. A blockage in the transfer chute between the dissolution and exit stages causes definite changes in some of the characteristic signatures. These changes can be seen in Figs. 6 and 7 which show the fluctuations in the RMS value for the 2- to 3-kHz and 5- to 6-kHz frequency ranges, respectively, for this blockage test.

Blockage of this transfer chute prevents material from passing to the exit stage where it is discharged from the dissolver. With no material being discharged, there can be no discharge signature in the 5- to 6-kHz range (four spikes per revolution), as indicated in Fig. 7, revolutions 13-17, 27-32, and 41-46. Furthermore, since all of the material collects and remains in the dissolution stage, mixing spikes of large amplitude are present in the 2- to 3-kHz range in forward revolutions immediately following a reverse (Fig. 6, revolutions 14-16, 28-30, and 42-43). Under normal operation, the dissolution stage should be refilling at this time, and the mixing spikes should be small, if present at all.

The characteristic signatures show no significant changes for a blockage installed $\sim$2 ft from the entrance of the exit chute in the exit stage. Figures 8 and 9 show the fluctuations in the 2- to 3-kHz and 5- to 6-kHz ranges, respectively, for this blockage test. Except for the presence of a blockage, this test was similar to the test of Figs. 4 and 5. The lack of significant differences in the data is best seen by comparing Fig. 4 with Fig. 8, and Fig. 5 with Fig. 9. The discharge of material is the only phase of operation which should have been affected by the blockage. However, the discharge signature is not significantly different between the two tests (Figs. 5 and 9). Also, the effects of discharging in the 2- to 3-kHz range (Figs. 4 and 8) show no major differences, and there are no unusual aspects of the data in Figs. 8 or 9 that would indicate abnormal operation of the dissolver. The reason for the lack of significant differences in the discharge signatures during this blockage test, we believe, is that the blockage is located at some distance from the exit chute entrance. This allows the discharged material to provide a normal discharge signature because the material moves into and down the chute in a normal manner before encountering the blockage. Because of restrictions at the test facility, the blockage could not be moved to the exit chute entrance for further testing.

Conclusions: A vibration monitoring system can be developed to detect abnormal material movement in a rotary dissolver. It has been established that (1) all five phases of dissolver operation can be characterized by vibration signatures; (2) four of the five phases of operation can be readily and directly identified by a characteristic vibration signature during continuous, prototypic operation; (3) the transfer of material from the inlet to dissolution stage can be indirectly monitored by one of the other four vibration signatures (the mixing signature) during prototypic operation; (4) a simulated blockage between dissolution and exit stages can be detected by changes in one or more characteristic vibration signatures; and (5) a simulated blockage of the exit chute can not be detected.

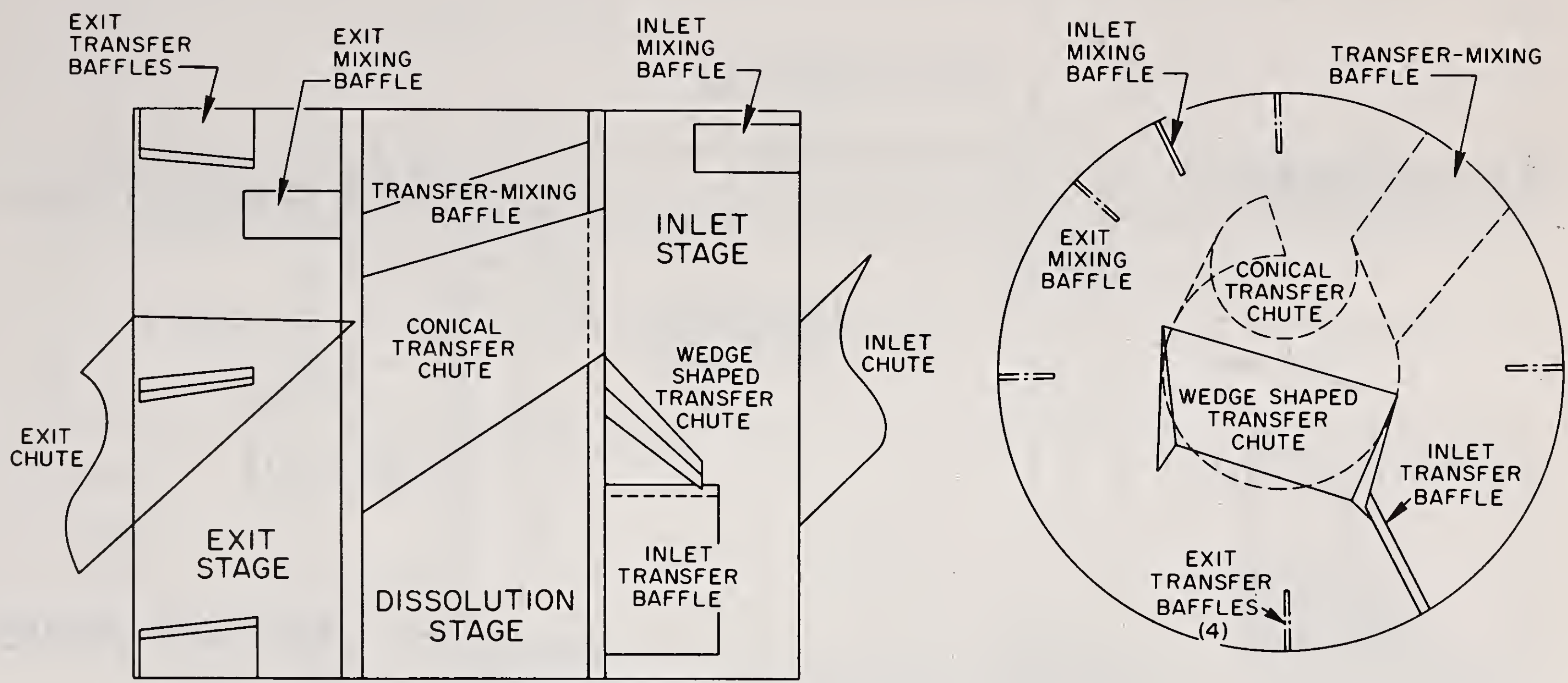

Fig. 1. Internal components of the three-stage rotary dissolver.

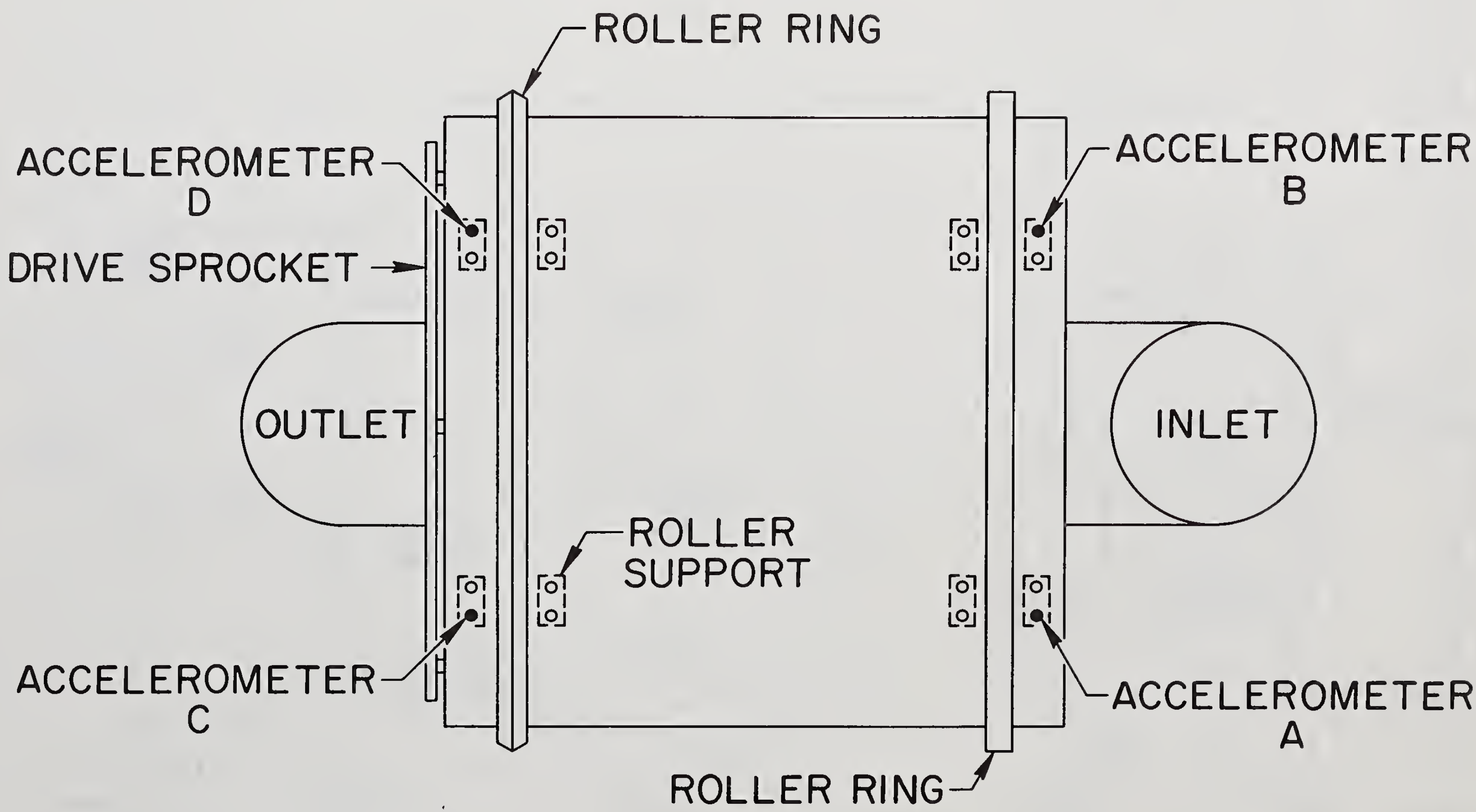

Fig. 2. Locations of the four accelerometers on the three-stage dissolver.

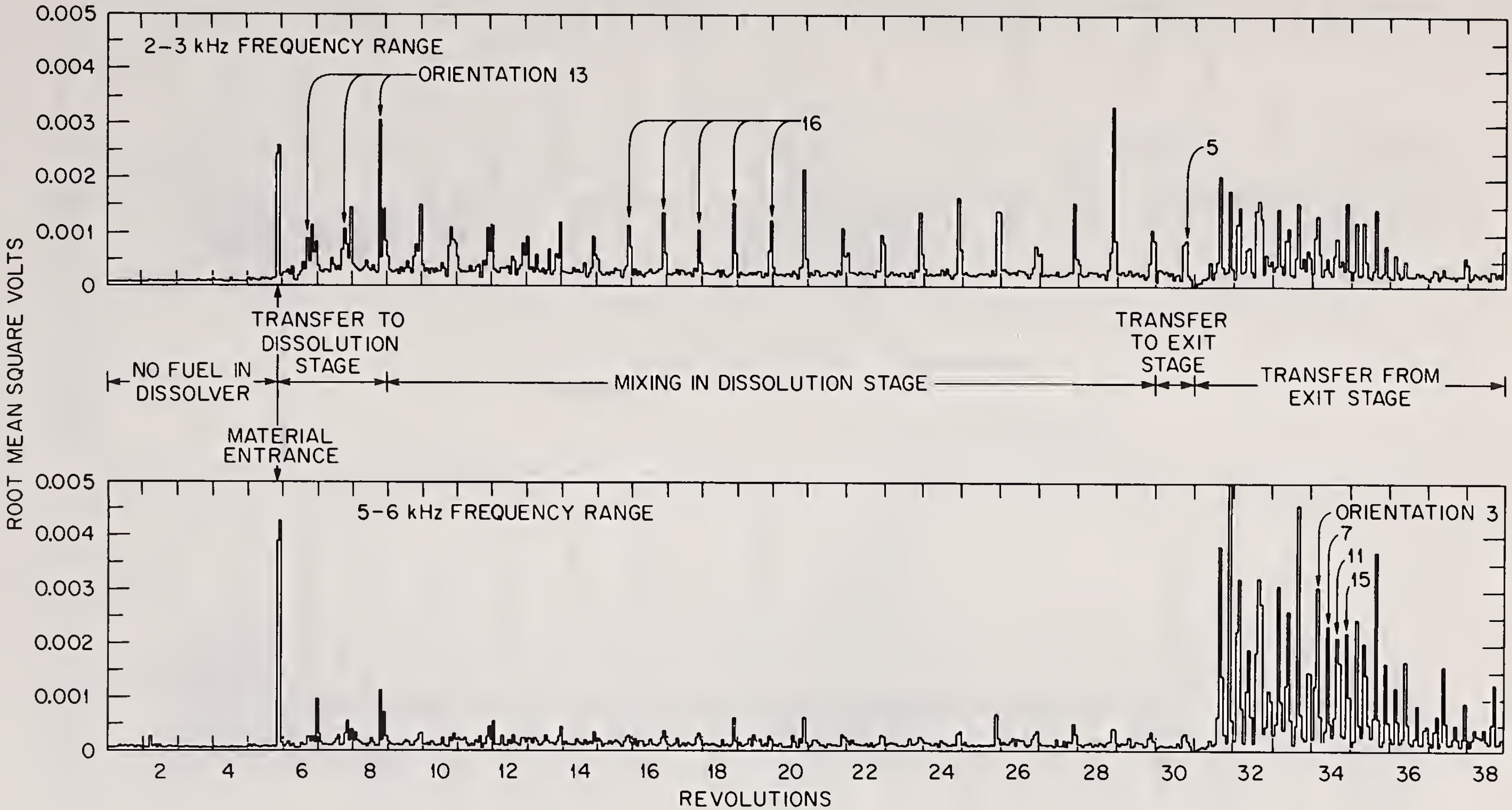

Fig. 3. Vibration signature at accelerometer A location during processing of a single 20-kg load of simulated fuel.

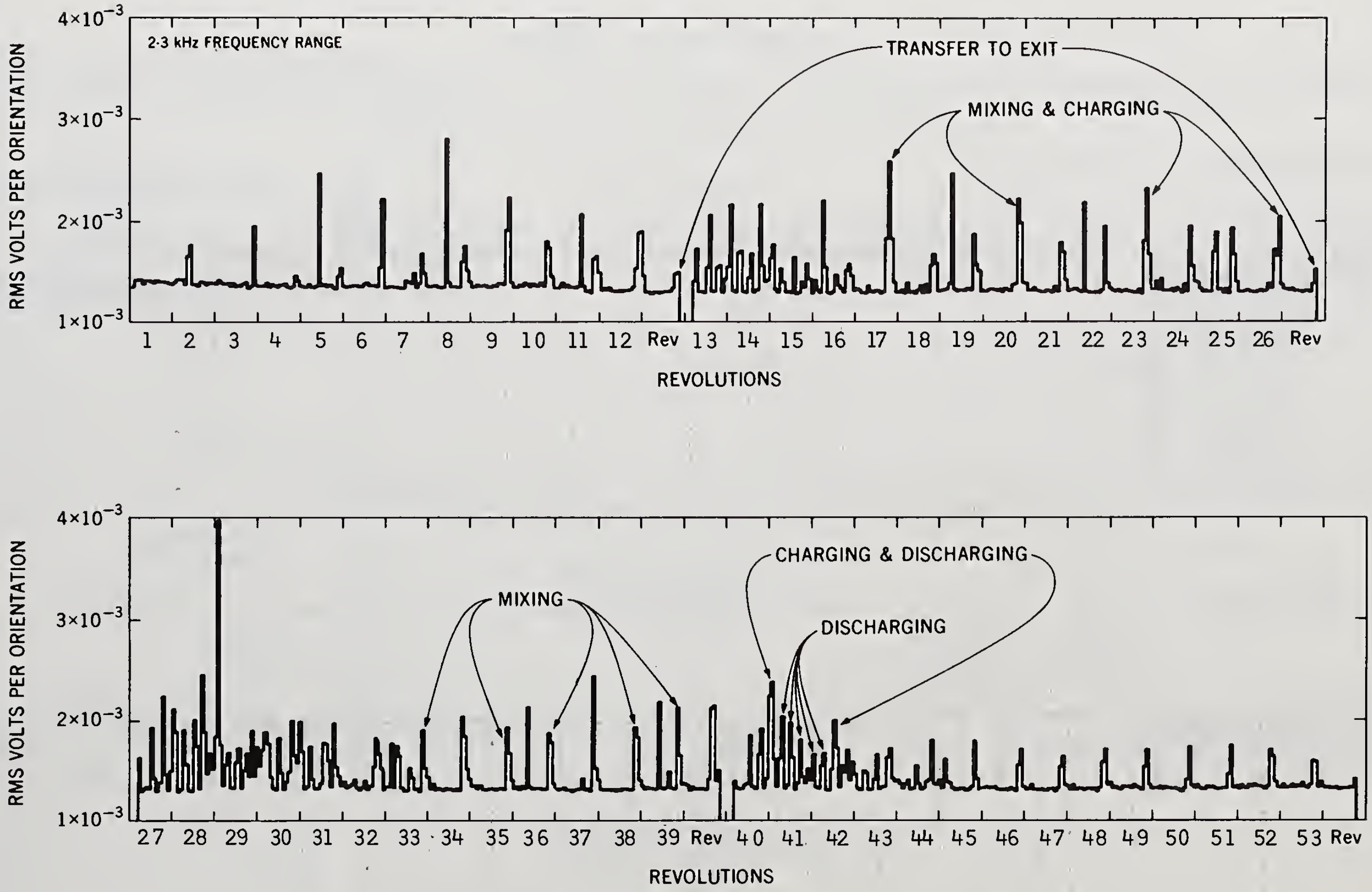

Fig. 4. 2-3 kHz RMS vibration signal at accelerometer A location during processing of 2-kg loads introduced at 30-s intervals.

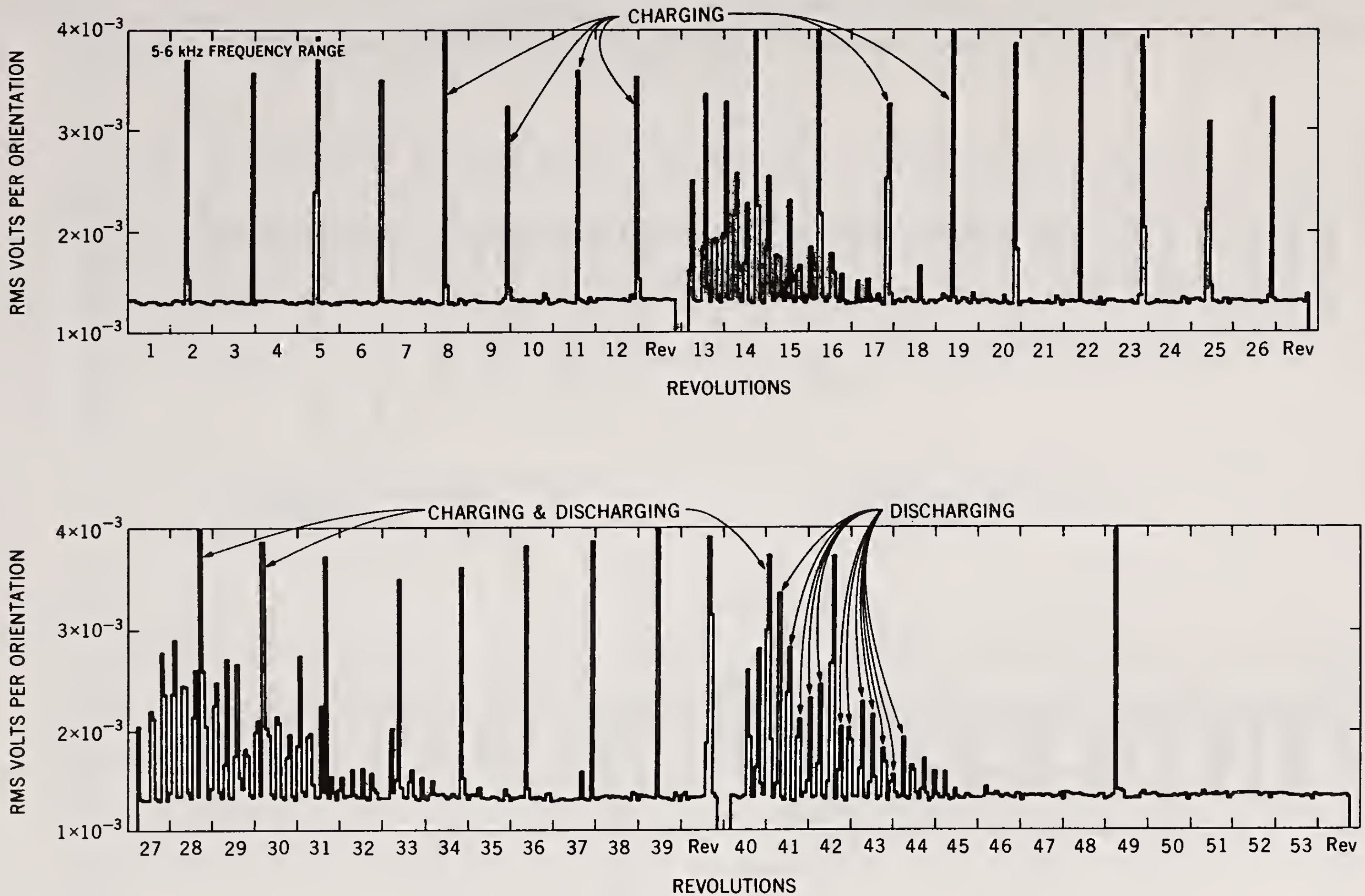

Fig. 5. 5-6 kHz RMS vibration signal at accelerometer A location during processing of 2-kg loads introduced at 30-s intervals.

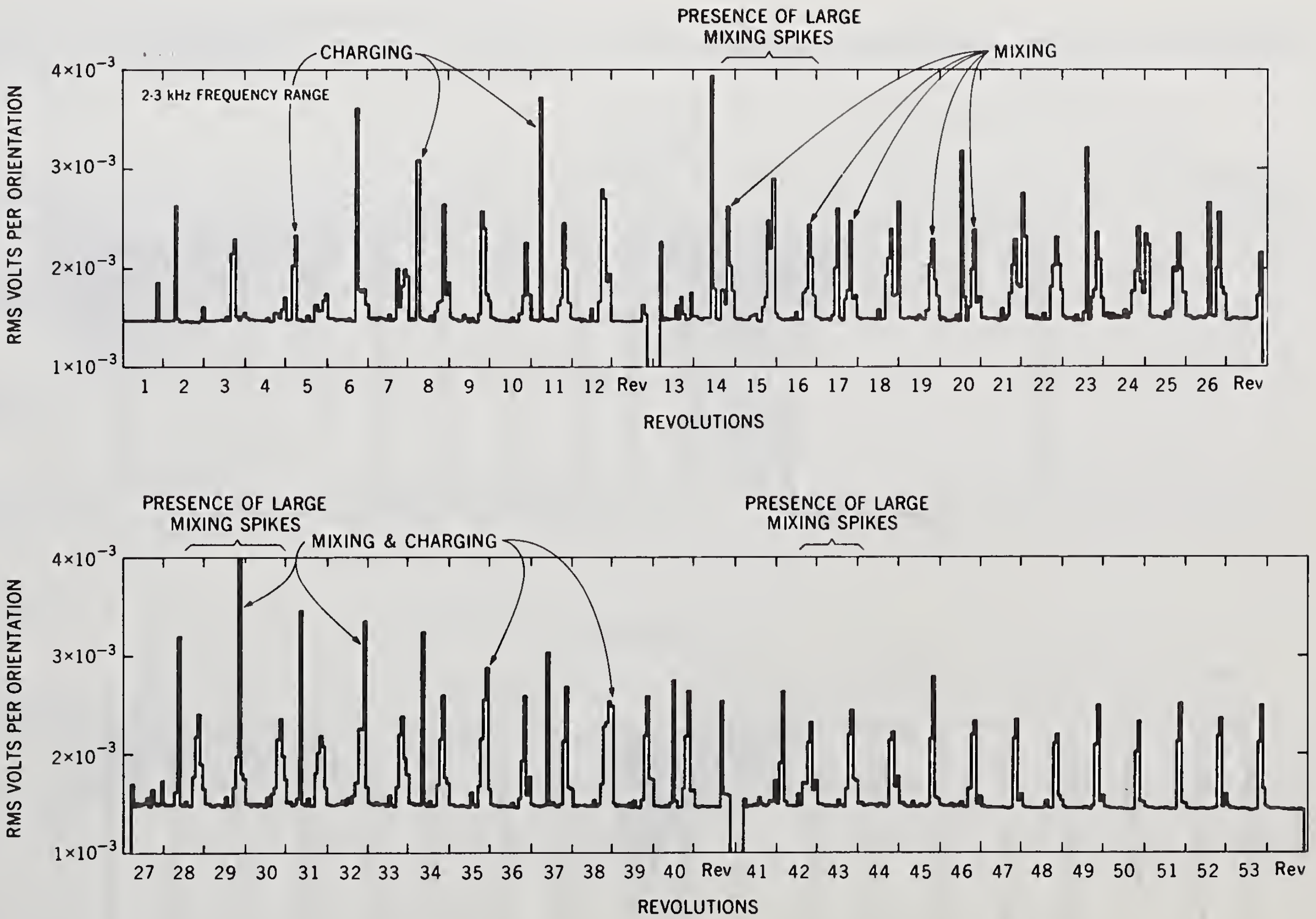

Fig. 6. 2-3 kHz RMS vibration signal at accelerometer A location during processing of 2-kg loads introduced at 30-s intervals with a blockage in the dissolution stage transfer chute.

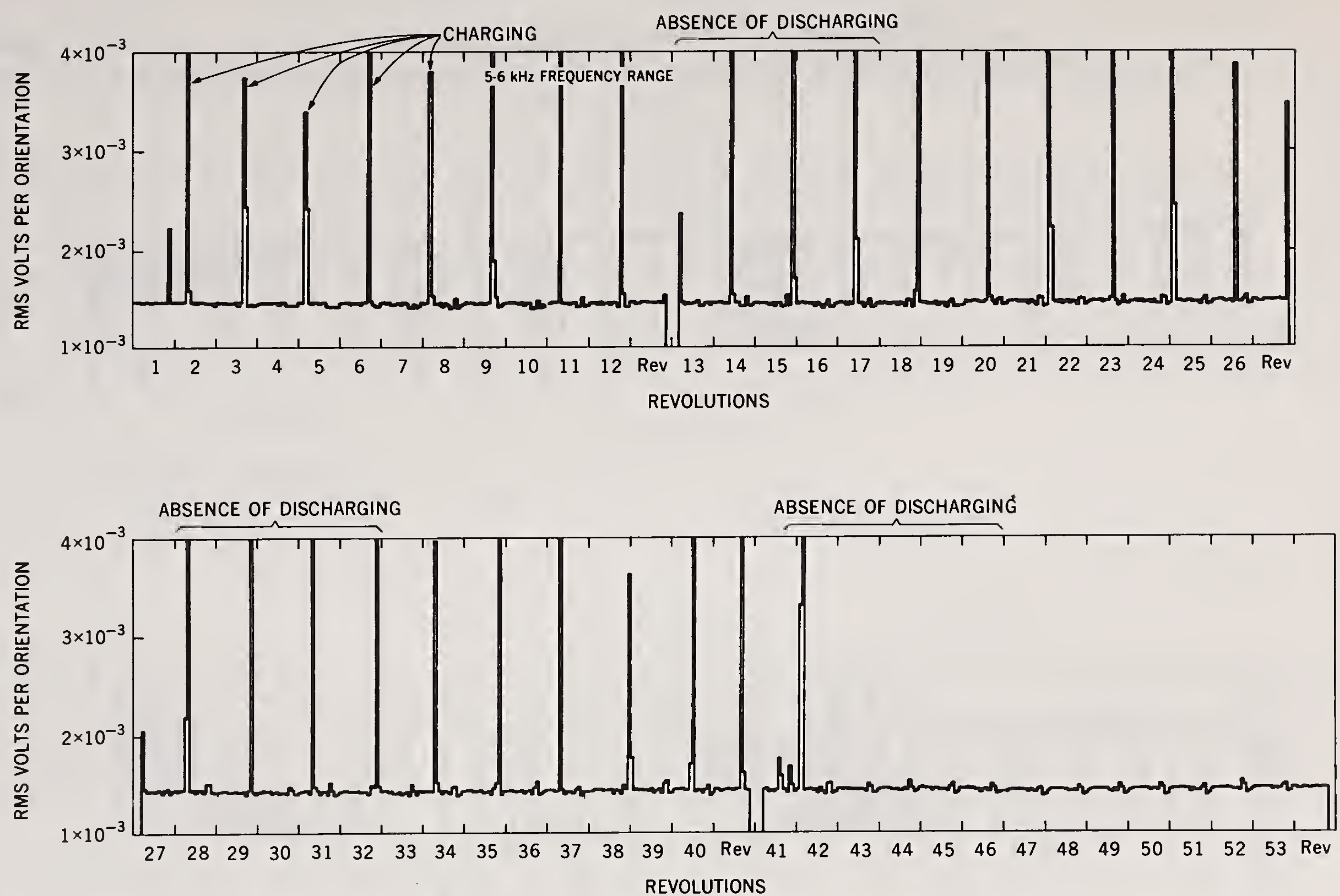

Fig. 7. 5-6 kHz RMS vibration signal at accelerometer A location during processing of 2-kg loads introduced at 30-s intervals with a blockage in the dissolution stage transfer chute.

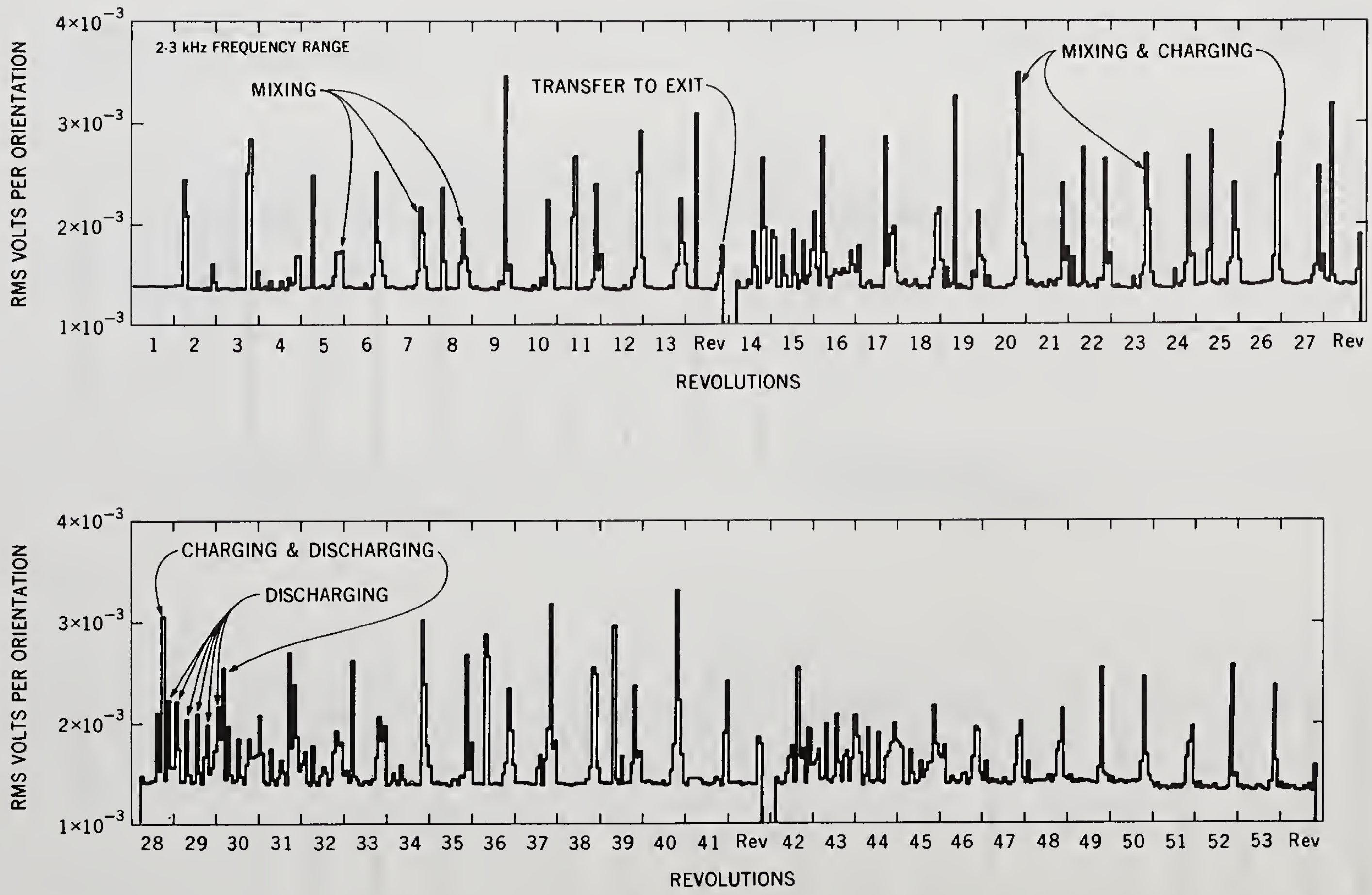

Fig. 8. 2-3 kHz RMS vibration signal at accelerometer A location during processing of 2-kg loads introduced at 30-s intervals with a blockage in the exit chute.

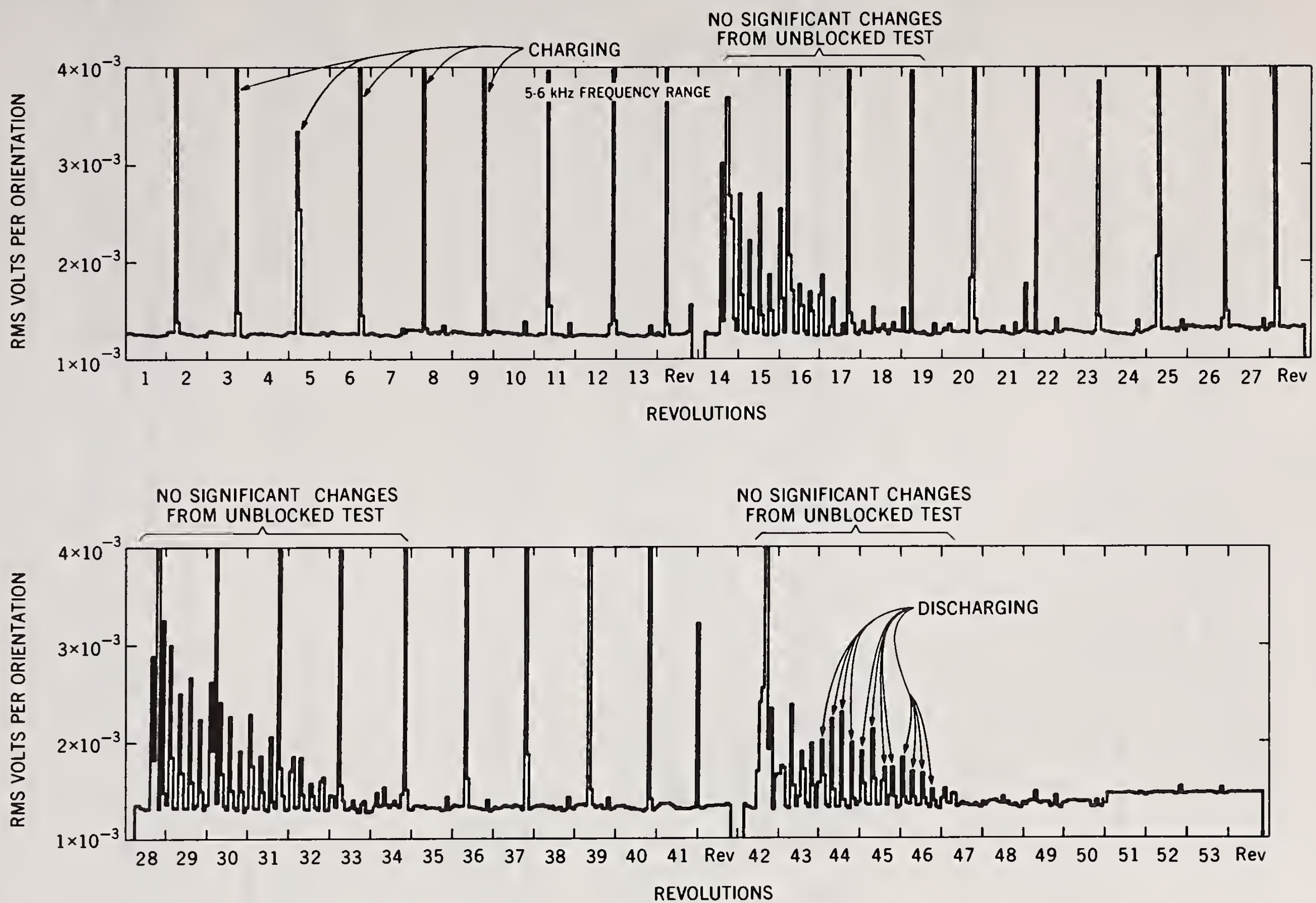

Fig. 9. 5-6 kHz RMS vibration signal at accelerometer A location during processing of 2-kg loads introduced at 30-s intervals with a blockage in the exit chute.

MONITORING INLET STEAM VALVES OF PWR 900 MW TURBOGENERATORS

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Abstract :

A study of the reliability of overspeed protection systems for turbines associated with nuclear reactors, confirms the essential role of steam valves in the general reliability of these systems, and consequently in the operational safety of the units.

Over and above the obvious reasons concerning operational safety, an improvement in investigation and diagnostic methods clearly provides beneficial spin-off in terms of equipment availability.

Assessment of turbine operational safety, and more particularly evaluation of the risks generated by non-closure of steam-valves, has led to a concentration of interest about three functional characteristics :

- stem movement quality,
- seal-tightness,
- "general condition".

Each of these characteristics can be subject to specific mechanical failures for which detection procedures exist, and which are described in this paper.

In application of these principles, examples of the technological solutions (including automatic surveillance system) adopted for monitoring the steam-valves of the units of the 900 MW standard are described, together with the first operating results for these methods and this equipment.

1 - NEW SURVEILLANCE AND DIAGNOSIS METHODS [1]

1.1 - Principles

A study of the reliability of overspeed protection systems for turbines associated with pressurized water reactors confirms the essential role of inlet steam valves (figure 1) in the general reliability of these systems and consequently in the operational safety of the units.

Conventional operating tests (on-off type) are performed weekly [2] on all the inlet steam valves of every E.D.F. turbine. These tests are now completed by using endoscopes for inspections during stops (figures 2.3).

New surveillance and diagnosis methods were developed in order to improve the quality of these classical tests. They are based upon two types of complementary actions :

a/ Permanent auscultation of simple parameters.

b/ Specific checking tests, deeper and finer but more complicated and for that reason performed only periodically (or in case of abnormality lity detection by the permanent auscultation system).

These methods obviously contribute to improve the reliability of the valves by providing advanced warning in some cases of deterioration ; but they also improve their availability by providing information on their behaviour during operation and this information can be used to optimize preventive maintenance and may even lead, in the future, to predictive maintenance.

According to the evaluation of the risk generated by non-closure of valves and to the statistical study of the most probable failures, we concentrated most of our interest on three fundamental functional characteristics :

- Stems' motion quality,
- Seal tightness,
- "General condition".

1.2 - Stems' motion quality

A statistical study of the fossil fuel thermal plants' incidents showed that the main risks the stems' motion may be subjected to are incipient seizures or stickings between the stem and its guides.

This type of degradation is one of the most important both for the safety of the plant because of the possible consequences of a valve non-closure and for the equipment availability for it is responsible for 1/3 of the inlet steam valves' incidents.

Consequently, it is particularly interesting to detect such defects and for this purpose we chose to record, as a permanent auscultation parameter, the closing time of every cutout valve (HP and LP) at every closure.

On the other hand, the conventional weekly performed checking test of "closure or non-closure" was improved by systematically plotting the stroke/hydraulic pressure curve during the motion.

At last, in case of abnormality detected through one of the two above mentioned methods, more complete closure tests may be performed by measuring :

- The instantaneous stem speed with a laser velocimeter.
- The stem vibrations during the motion.

The measurement of the instantaneous stem speed with a laser velocimeter, by providing very rich information about the dynamics of the valves' motion during the closure (figure 4) has already led us to a better knowledge of this motion and allowed us to build up a computation model (figure 5) to explain the main characteristics of this movement. Unfortunately, this test needs a heavy equipment to be performed and it will be used only in case of important abnormality.

The stem's vibrations measurement during its motion is, on the contrary, very simple. The sensor is the accelerometer mounted on the stem for the permanent monitoring (see below). The signal processing device is a mere oscilloscope (or a sonorisation). In case of normal sliding motion of the stem between its guides, the vibration level is low except for the shocks produced by the normal movement (figure 4). In case of dry friction or sticking, high levels of stresses are generated along the friction area in a very broad frequency band. Many resonances are excited in the metal (particularly at high frequencies) and the corresponding vibrations can be easily detected by the piezoelectric accelerometer which is especially sensitive to high frequency vibrations. Simulation laboratory tests showed (figure 6) an increase of the vibration level of more than + 46 dB in case of sticking for an area of only 0.8 cm^2.

1.3 - Seal tightness

Another common possible defect is a seal tightness defect following the valve plug or seat erosion by the steam. This defect causes, when the valve is supposed to be completely closed, a leak of steam into the inlet pipes of the turbine with two important effects :

a/ It brings some residual mechanical energy into the turbine.

b/ It emits a very broad band noise produced both by the jet itself and by the collision of the jet inside the piping.

The first effect induces a motor torque on the turbine shaft and consequently modifies the rotor deceleration curve. It has been shown that the K-coefficient (coefficient of the tangent hyperbola) of this curve is the most appropriate representation to detect such modifications. In this case too, a computational model was built up with several coefficients adjusted on the experimental values. In this way, a leak constant motor torque has been simulated (figure 7).

Consequently, we decided to record the rotor speed during every deceleration and to compute and plot automatically the K-coefficient curve. Any modification of this curve may signify a global tightness defect of the turbine.

Then, in order to localize and perhaps quantify the defect, we can perform the specific ckecking test based upon the second effect : the measurement of the leak noise.

Many studies and tests have been previously performed to characterize this noise and its transmission through the casing to the outside wall of the valve. In fact the acoustic emission frequency range is very broad : from a few hertz up to 1 MHz ; for the industrial mechanical noise is mostly concentrated under about 100 kHz, the best signal/noise ratio is obtained in the high frequency range and can be measured by a piezoelectric accelerometer working on its whole frequency range including its resonance. Even better results can be obtained using an ultrasonic piezoelectric sensor (acoustic-emission type) with a higher resonance frequency (figure 8).

1.4 - "General condition"

Several other defects are liable to affect the steam valves as excessive clearances or disunions between parts (seal and casing for instance), cracks (of the stem for instance) and so on.

Very generally, such defects induce modifications of the vibrational characteristics and in most cases increase the energy dissipated by vibrations.

Consequently, we consider that measurement of the global (RMS) vibration level is an accurate permanent auscultation parameter for the general mechanical condition of the valve (see below the description of the measurement).

In case of previously detected abnormality a deeper vibration signal analysis may be performed by using directly the signal from the accelerometer.

Some laboratory tests showed that in case of excessive (abnormal) clearances between parts, the vibratory excitation by the turbulent steam flow induces incipient shocks inside the valve which may be easily detected by the stem accelerometer using only the time representation of the signal (display or sonorisation) (figure 9).

An experimental study of the evolution of the first bending mode frequency of a cracked stem with the crack depth shows (figure 10) that only major cracks can be detected by this way.

2 - PERMANENT AUSCULTATION SYSTEM

Permanent auscultation is obviously the first stage of all the above described surveillance methods. A specific automatic device was achieved for this purpose (figure 11).

2.1 - Measurements

As said above three types of permanent auscultation parameters are considered :

- closing times of cutout valves (12/turbine),
- rotor speed (1/turbine),
- overall vibration level of all the valves (24/turbine).

Closing times are elaborated from the position information of the cutout valves. The vibration levels are elaborated by electronic signal conditioners (amplifiers, low pass filter, RMS detector) from the output signal of the accelerometer mounted on the stem of every valve.

At the same time, some other parameters have to be recorded both to provide automatically statistical information on the valve operating conditions and to help us to understand the auscultation parameters' variations.

These "statistical parameters" are :

- the logical states (open or closed) of the cutout valves (12 binary data/turbine),
- the positions of the HP control valves (6/turbine),
- the electrical power output of the turbogenerator (1/turbine).

2.2 - Data recording

All the above mentioned measurements sensors are connected with the central data acquisition device (figure 12) and get in through appropriate electronic interfaces :

- Closing time printed boards compute the closing times from the information about the position at every closure and record them in a buffer memory.

- The rotor speed printed board computes the speed value (numerical data) from the analog signal.

- The logical states of the valves board record in a buffer memory the new state in case of any change.

All the other analog measurements (overall vibration levels, position of the control valves, power output) are digitally converted through two multiplexer levels.

The microprocessor monitors all these interfaces and scans all the measurement inputs with a very short period cycle (a few seconds).

Some of them are systematically recorded i.e. everytime there is a value : the closing times and the logical states of the valves.

The others have continous variations (vibration levels, position of the control valves, power output, rotor speed) and are recorded only when the difference between the scanned value and the last recorded one is larger than a certain previously defined threshold (relative or absolute).

Every record contains the measured value and the instant of measurement. This method allows to record very few values in case of small variations and, on the contrary, a large number of values in case of important variations (when it is interesting) (figure 13).

The record is performed on a magnetic tape cassette which is periodically (every week) sent to a computer system to be processed.

2.3 - Data processing :

During a first stage, simple computer programs were developed in order to read back the cassette and plot the time-evolution of every parameter.

Then, from the study of the first results we began to define the principles of the "automatic surveillance" programs. The idea is simple : first, we calculate, for every surveillance parameter, the "reference state" from a statistical study (mean and standard deviation) of the first results. Sometimes these characteristics are assumed to be dependent on another parameter and have to be represented as a function of it, by a polynomial regression.

For the HP control valves' vibrations, the influent parameter is obviously their own position.

As to the vibrations of the other valves and the closing times, it is supposed to be a matter of the power output of the plant.

As for the K-coefficient during rotor deceleration the most accurate representation to detect the leak influences is to plot it as a function of the inverse of the speed.

In each case, a confidence interval is plotted on each side of the mean curve. It is defined from a compilation of the experimental data assuming that the statistical distribution of these data is, roughly, a Laplace-Gauss distribution.

Then, at the end of this first period, the automatic surveillance programs compare the newly recorded values with the previously calculated "reference states" and any value outside its confidence interval is supposed to be an "abnormal value" and consequently triggers an alarm message.

Thus, normally, only a little information (alarm messages) has to be considered each week during operation. This information is recorded with some simple statistical characteristics of each parameter in order to detect any time-modification in the statistical characteristics.

3 - FIRST RESULTS

The automatic surveillance system was first set up on the first six PWR units.Now, more than one year of continuous monitoring has been performed on the first two units.

3.1 - Closing times :

The closing times of the cutout valves appeared to be as good as an example of a surveillance parameter can be. Indeed, the first results show (figure 14) :

- they depend very little on the power output,
- their standard deviation is very small.

Consequently, we may consider that any important modification of a closing time would be significant of a stem's motion quality defect and in this case immediately perform the specific checking tests.

Defining the confidence interval at 95 % probability level, until now, we have had no significant alarm message.

3.2 - Rotor deceleration curves :

A compilation of the first experimental results shows that the K-coefficient curve is mainly dependant on the vacuum value inside the turbine and, when this vacuum value is the normal one, roughly constant (figure 15, figure 16).

Thus boundary curves have been defined with their fitting theoretical coefficients in the model. In case of normal vacuum, the experimental curve must be between these boundaries.

A leak motor torque has been simulated and the model shows the fairly good sensitivity of the method (figures 17, 18). Nevertheless the relation between this theoretical leak torque and some real tightness defect still has to be established by experimentation on an actual-size turbine.

If an experimental curve exceeds the boundary values, we have first to look for a vacuum value modification before thinking of a leak defect.

3.3 - Vibration levels :

Here, the above statistical processing method was a little more difficult to perform because the number of recorded values is very much larger (permanent scanning) and their, a priori, standard deviation is very important.

Under these conditions, the direct computation of the "reference states" from all the experimental data gave very large confidence intervals and thus the detection of an "abnormal value" was in most case impossible.

A closer study of these vibration levels showed that they are roughly constant during the constant power operation and they are subject to very large variations during the power variations.

These variations (figures 19, 20) stay for a certain interval of time (say 1 hour) after the power plant variations probably because of the stabilisation (relaxation time) of some operating parameters.

Consequently we decide to consider as non significant and to eliminate all the measurements recorded during the power plant variations. Furthermore in order to avoid electrically or mechanically caused erratic values, we also eliminate all the values, the duration of which is shorter than a certain interval of time.

Finally, we obtained acceptable reference curves (figure 21) and we defined their confidence interval at 99 % probability level.

In order to avoid too frequent "statistical" alarms it is necessary to eliminate the same kind of measurements during the automatic surveillance phase. Nevertheless and to minimize the consequent information loss we consider that these measurements are, in any case, significant of a defect (and trigger an alarm message) when their values are up to a certain critical level.

4 - CONCLUSIONS

The theoretical and experimental studies as well as the first operating results confirm the interest of the permanent auscultation and the expected possibilities of the complementary specific checking tests.:

After one year operation, the methods and the important "reference states" have been defined. We have now to :

- confirm the detections capacity of the method on real defects (if any !),
- optimize the numerical criteria from a long period operation experiment (best probability law, appropriate alarm threshold).

In the future, we plan to complete the permanent auscultation system including new operations parameters to improve the permanent auscultation parameters' analysis and otherwise the surveillance of the rotor shaft vibrations (at nominal speed and during decelerations).

Anyway it is a new method applied on new equipment. We have finished defining the first operating regulations and now, the method capabilities will be improved, following the better knowledge of the reliability of the equipment, of the main defects and their consequences for the detection method provided by industrial operation.

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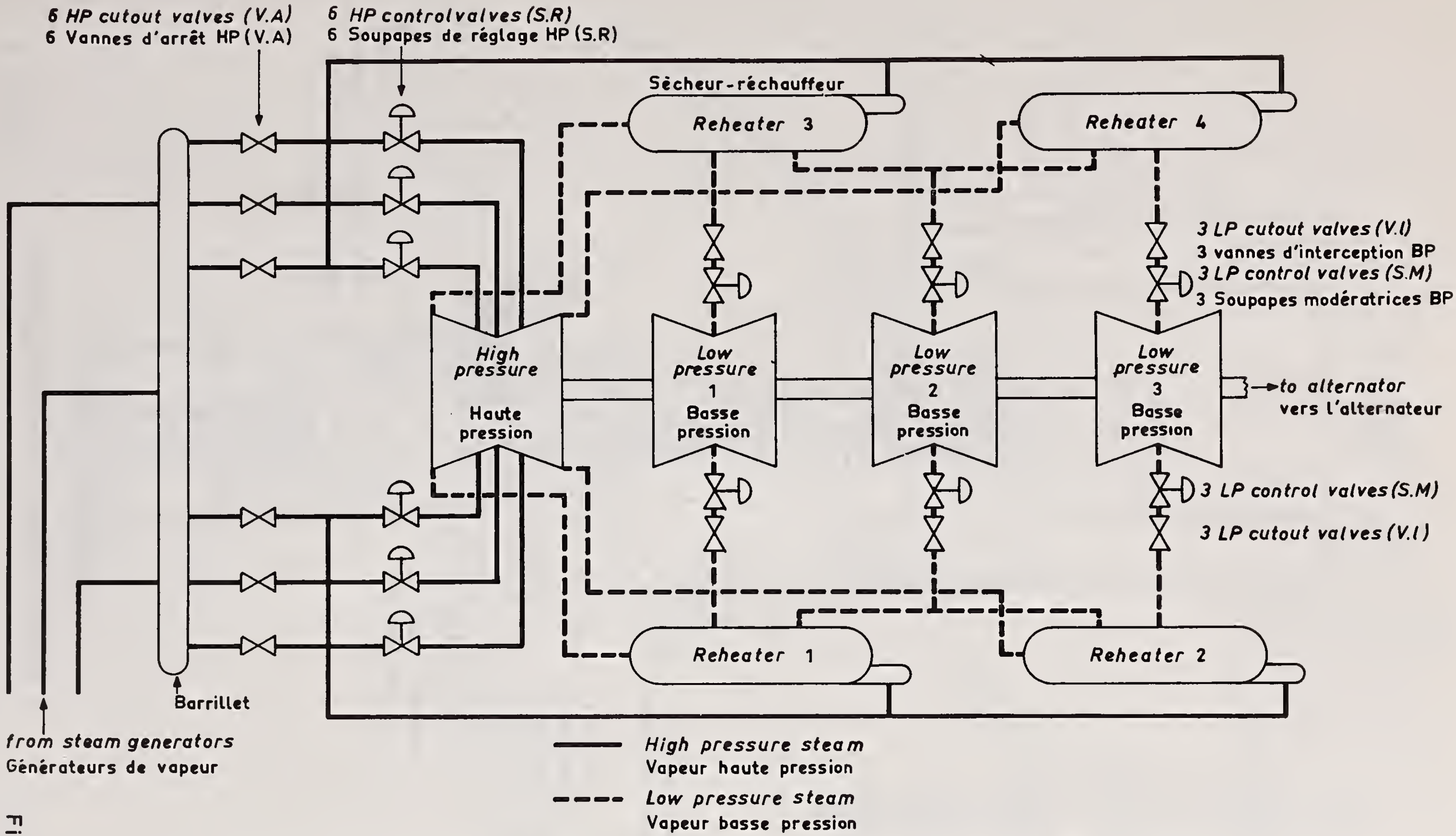
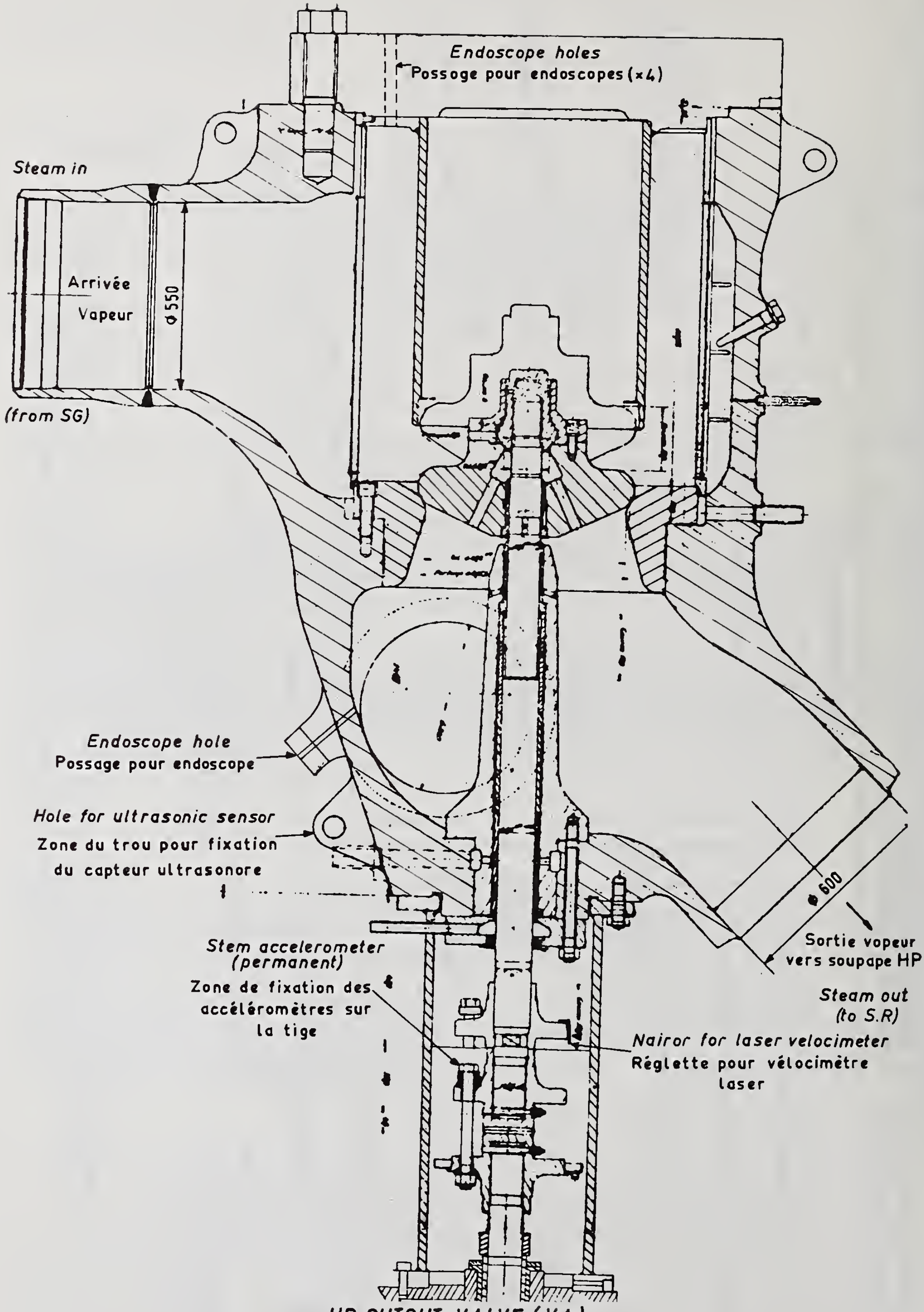


Figure 1

POSITION OF THE 24 STEAM VALVES ON THE INLET STEAM CIRCUIT OF THE TURBINE

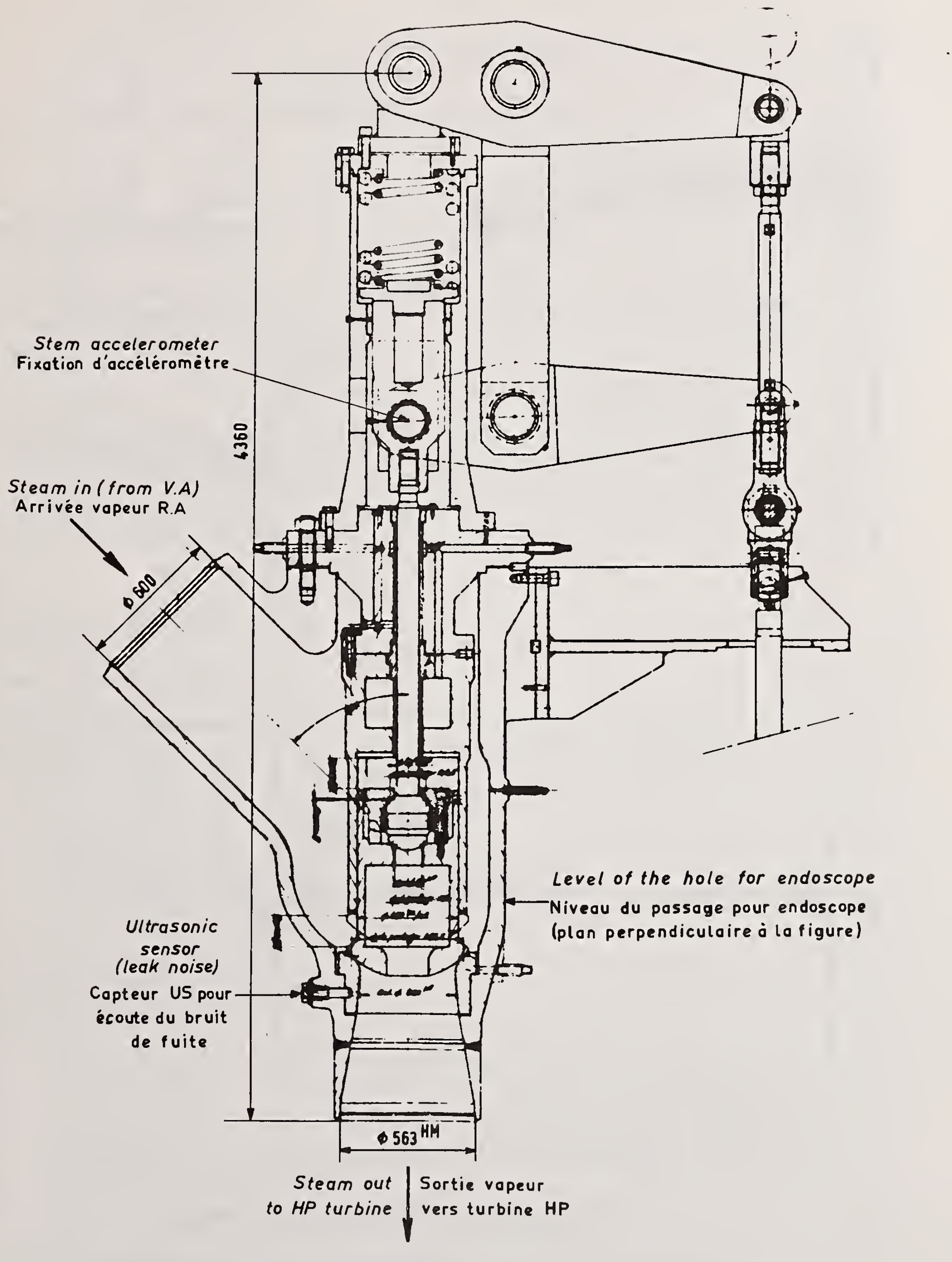
SCHEMA DU CIRCUIT D'ADMISSION VAPEUR D'UNE TURBINE 900MW



HP CUTOUT VALVE (VA)

ROBINET D'ADMISSION HP PRINCIPAL

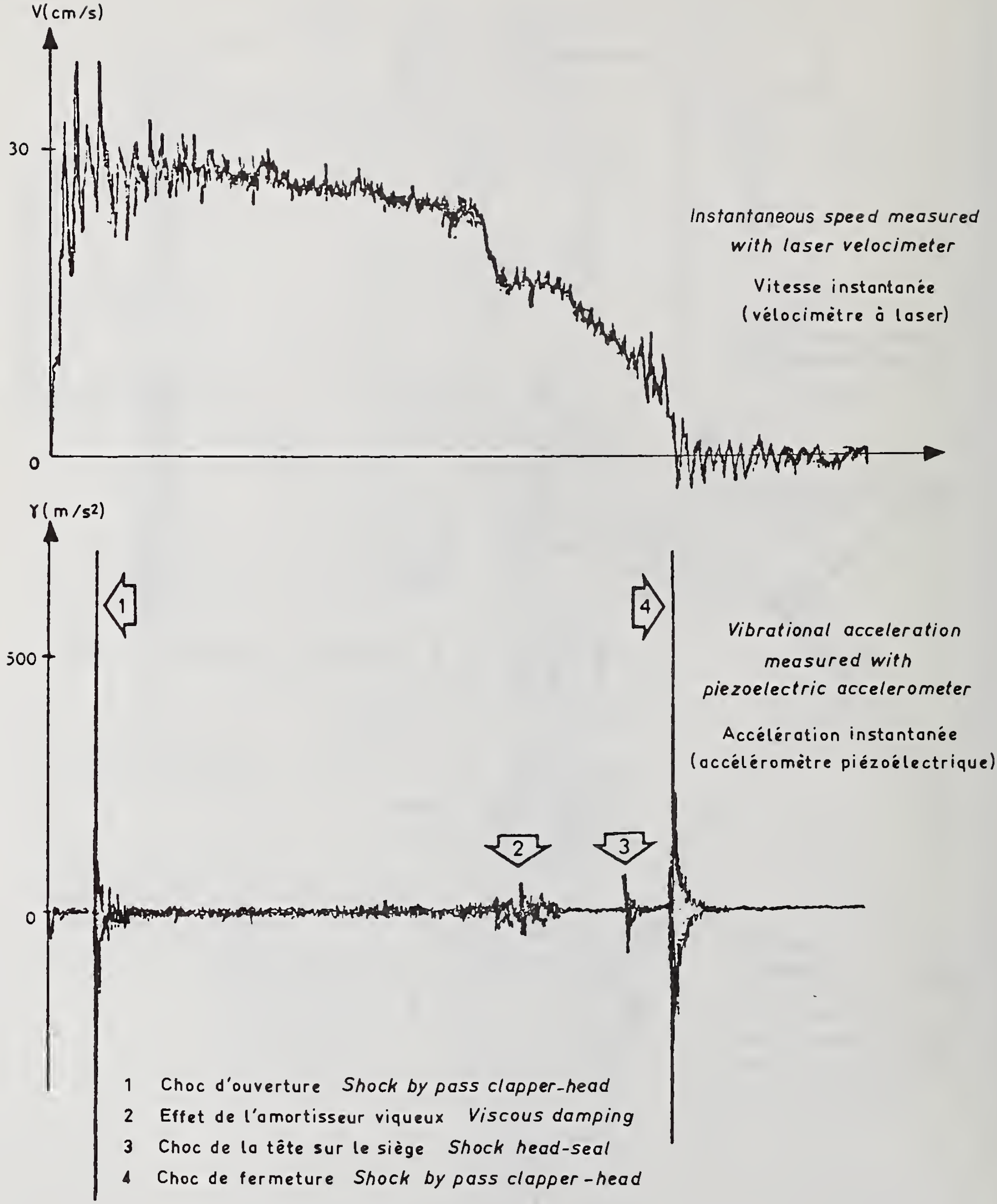
Figure 2



HP CONTROL VALVE (SR)

SOUPAPE DE REGLAGE HP PRINCIPALE

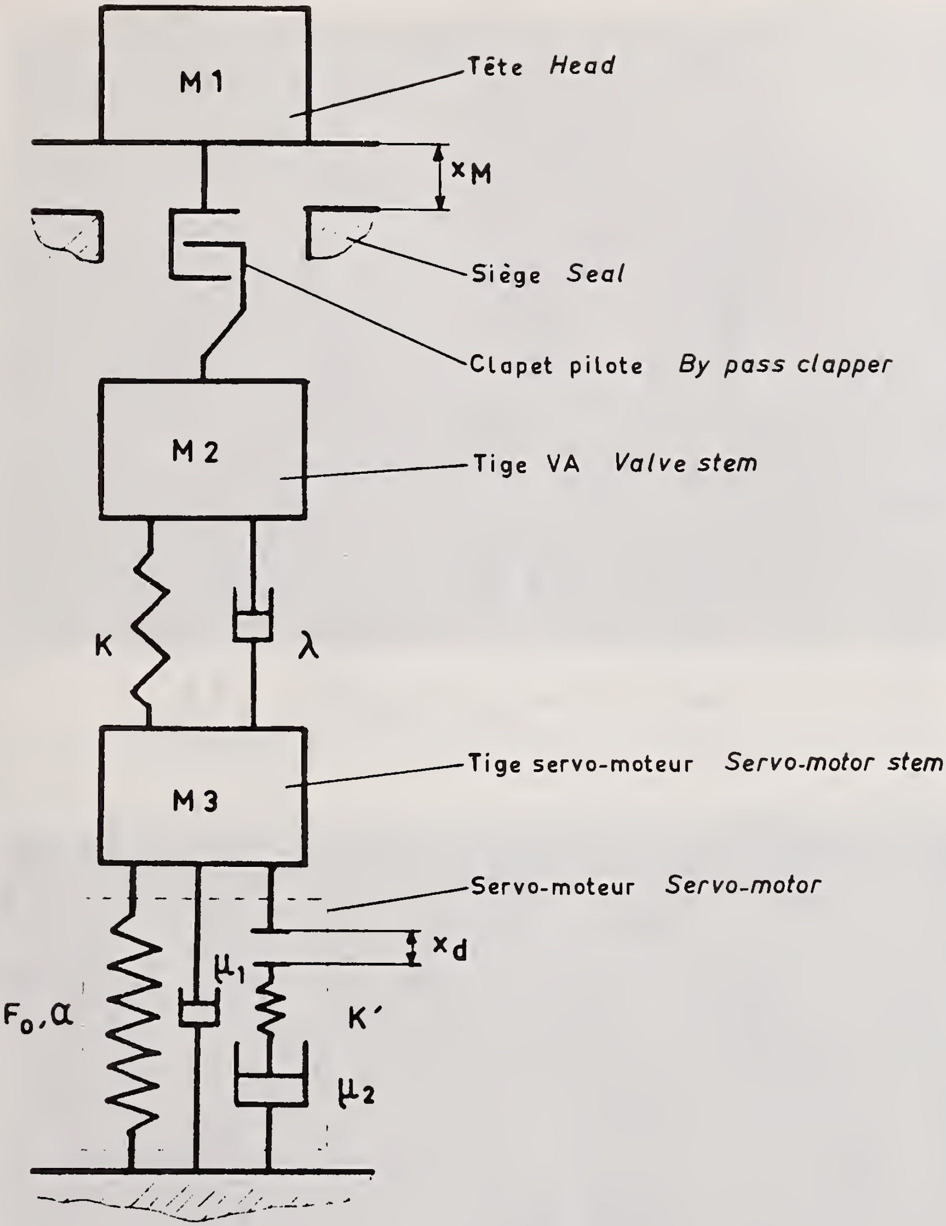
Figure 3



CLOSING OF A CUTOUT HP VALVE (VA)

VITESSE ET ACCELERATION INSTANTANEES RELEVEES LORS DE LA FERMETURE D'UN ORGANE EN BON ETAT

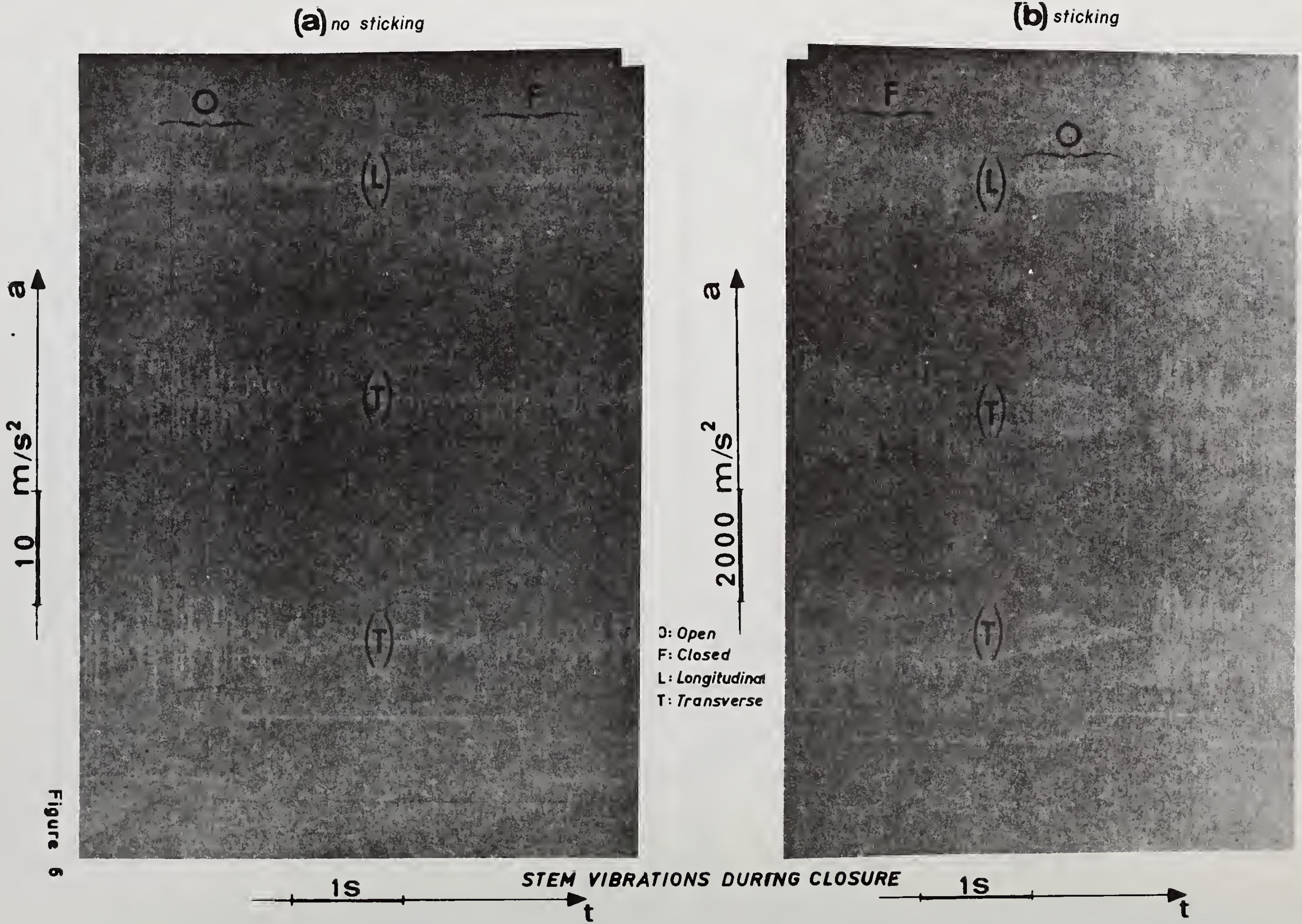
Figure 4



COMPUTER MECHANICAL MODEL OF A VALVE

MODELE MECANIQUE D'UNE VA

Figure 5



STEM VIBRATIONS DURING CLOSURE

Figure 6

(1) Couple de fuite nul *No leak*

(2) Couple de fuite constant (*) égal à 0,7 % du couple de perte total à vitesse nominale
Constant assumed leak motor torque 0,7 % of the total loss torque at nominal speed

(3) " " " 2 % " " "

(4) " " " 7 % " " "

(*) hypothèse simplificatrice

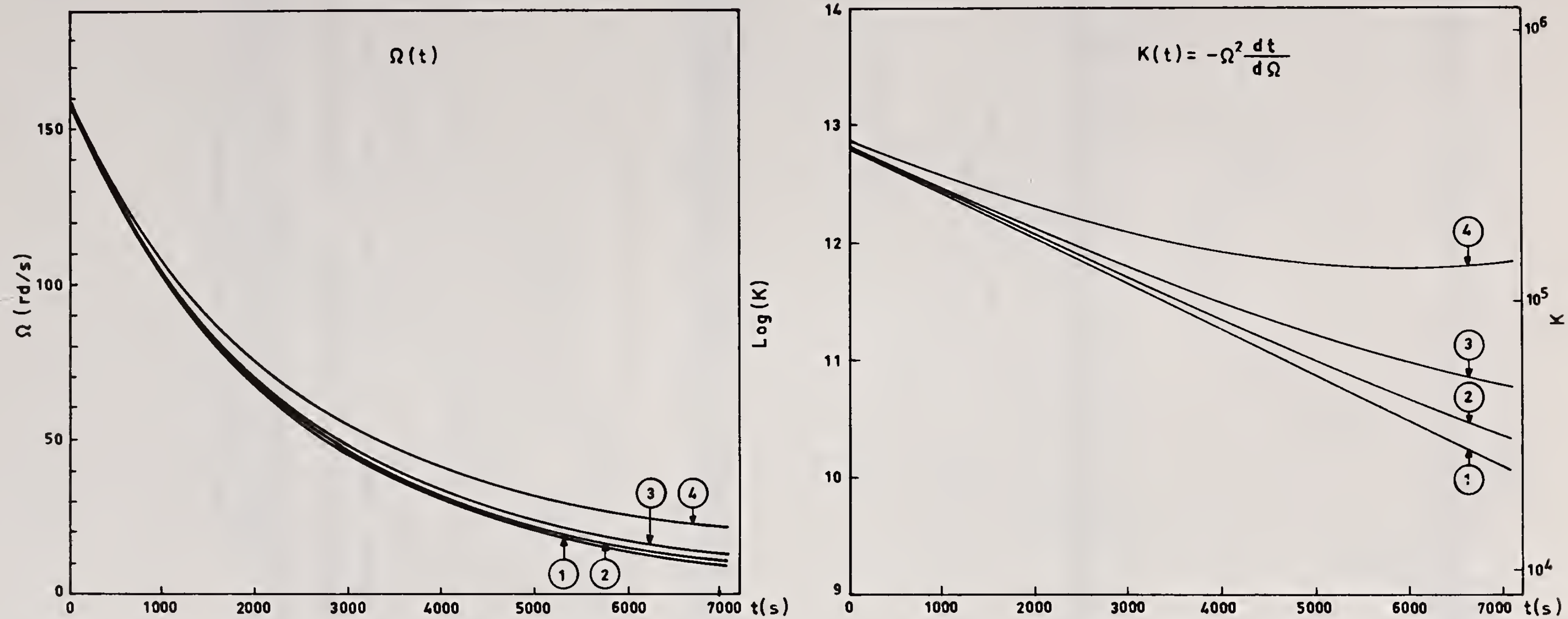
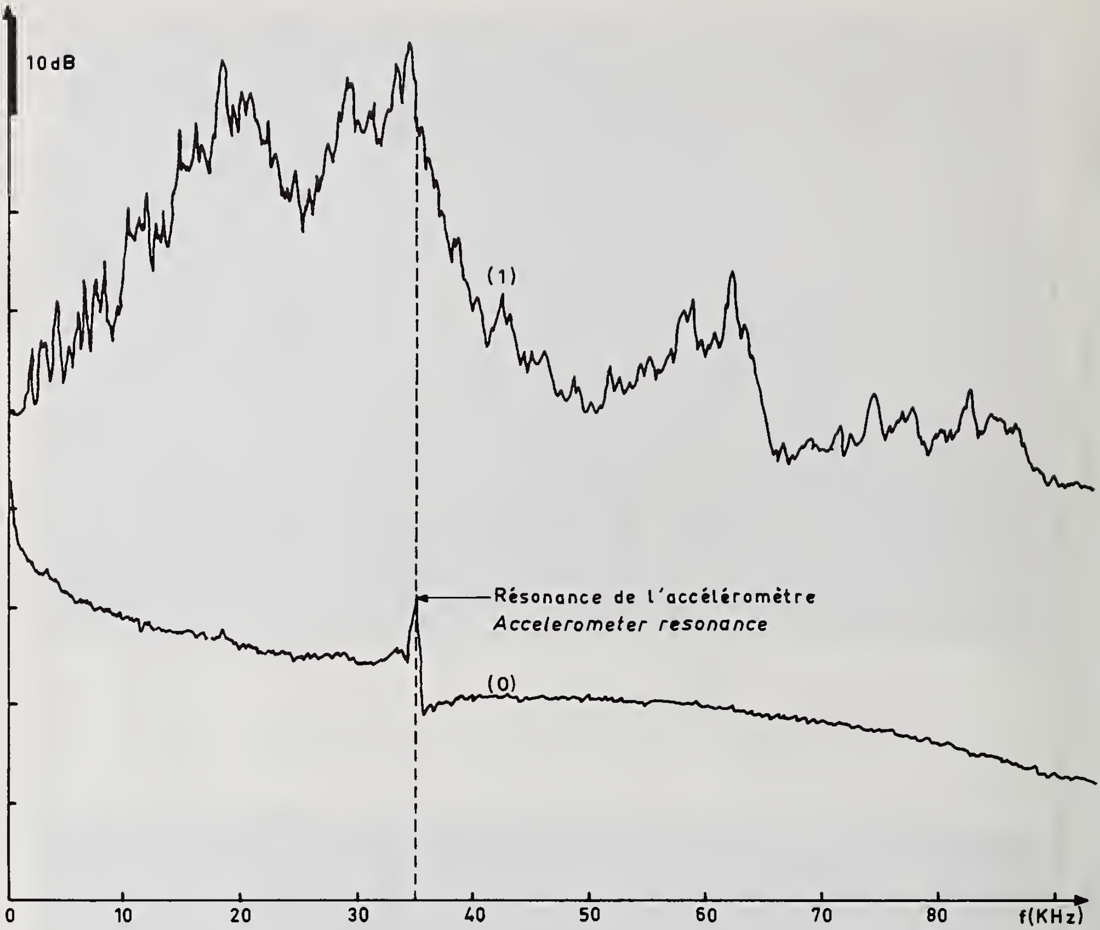


Figure 7

ROTOR SPEED (Ω) AND DECELERATION COEFFICIENT (K) CURVES AS A FUNCTION OF TIME DURING A DECELERATION WITH SEVERAL SIMULATED LEAKS

COURBES Ω(t) ET K(t) POUR QUELQUES VALEURS DU COUPLE MOTEUR DU A UNE FUITE A L'ADMISSION



(0) Bruit de fond électronique *Electronic noise (no leak)*

(1) Bruit de fuite *Leak noise*

Pression amont : 6 bars *Upstream pressure*

Pression aval : 1 bar *Downstream pressure*

Section de fuite : 0,46 mm² *Leak equivalent section*

RMS values ratio $\frac{\text{leak noise}}{\text{electronic noise}} = 43\ dB$

POWER SPECTRUM DENSITY OF A LEAK NOISE MEASURED WITH A PIEZOELECTRIC ACCELEROMETER

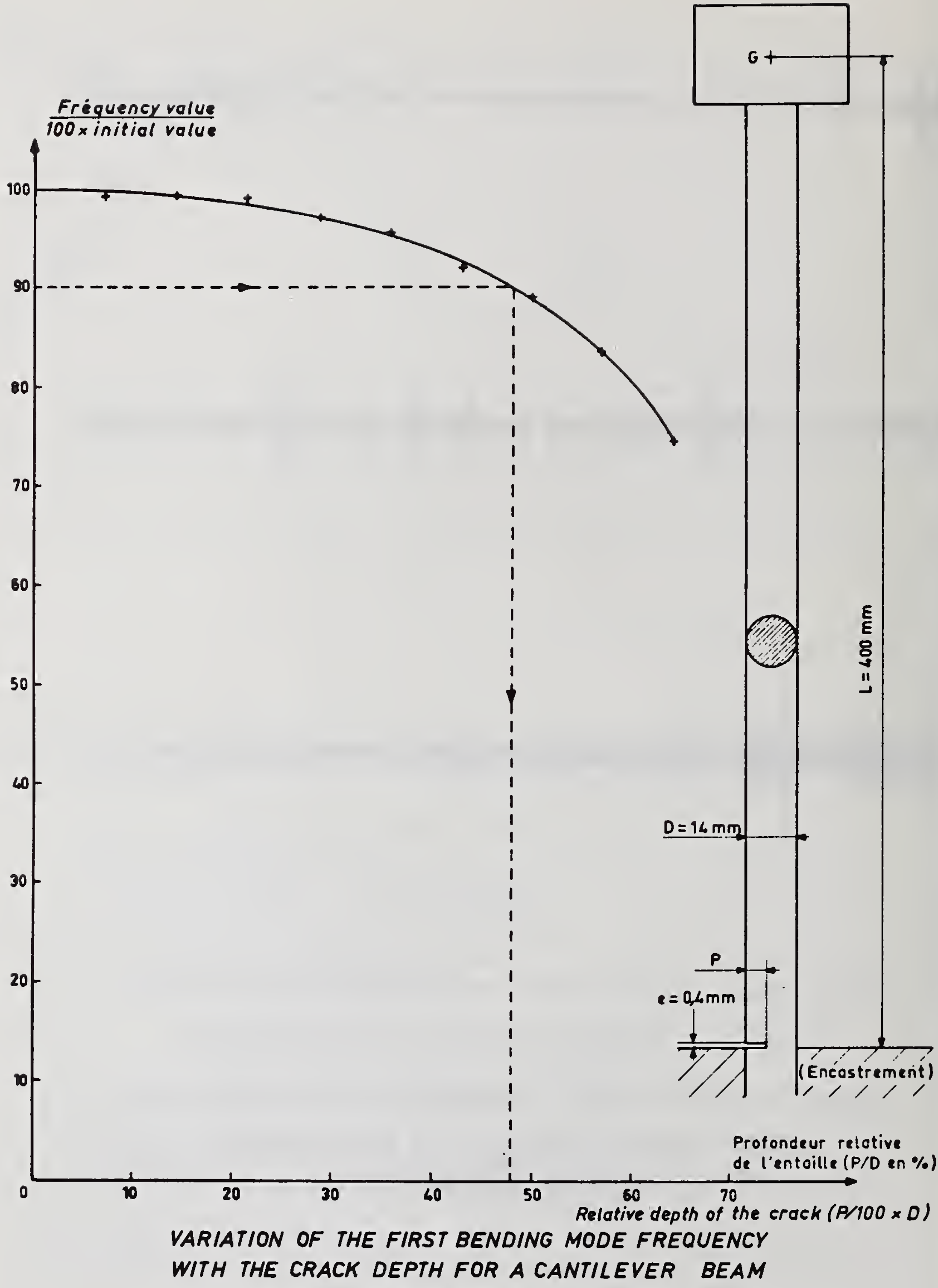
DENSITE SPECTRALE DU BRUIT DE FUITE TRANSMIS PAR VOIE SOLIDE, MESURE A L'AIDE D'UN ACCELEROMETRE PIEZO-ELECTRIQUE SUR UN ROBINET D'AIR COMPRIME

Figure 8

TYPICAL SIGNAL SHAPE FROM A PIEZOELECTRIC ACCELEROMETER IN CASE OF MECHANICAL SHOCKS ON THE STRUCTURE

ALLURE TYPIQUE DU SIGNAL DELIVRE PAR UN ACCELEROMETRE FIXE SUR UNE STRUCTURE QUI EST LE SIEGE DE CHOCS MECANIQUES REPETES

Figure 9



VARIATION OF THE FIRST BENDING MODE FREQUENCY WITH THE CRACK DEPTH FOR A CANTILEVER BEAM

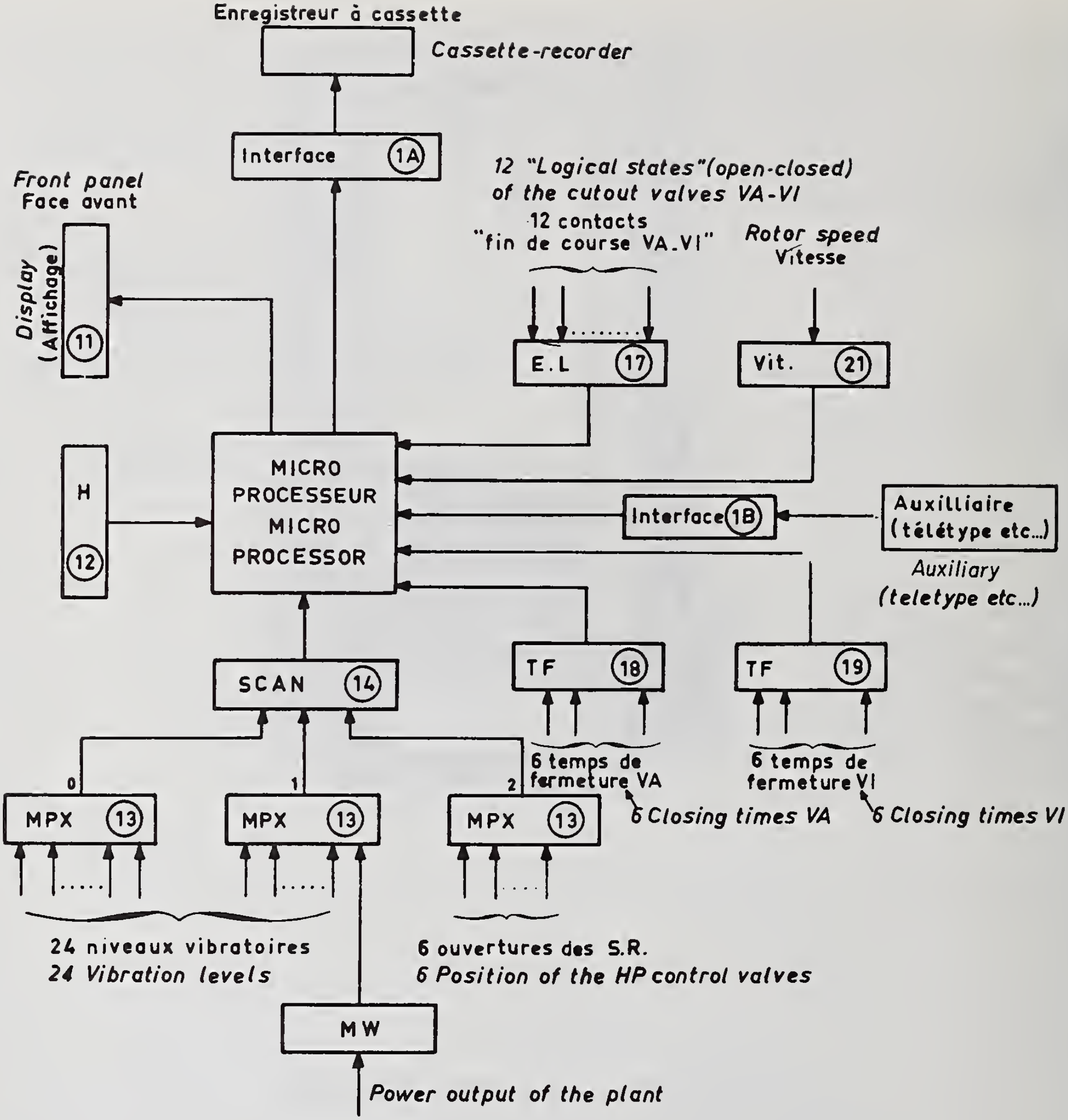
VARIATION DE LA PREMIERE FREQUENCE PROPRE EN FLEXION D'UNE TIGE ENCASTREE LIBRE EN FONCTION DE LA PROFONDEUR D'UNE ENTAILLE A L'ENCASTREMENT

Figure 10

THE PERMANENT DATA ACQUISITION SYSTEM

PHOTO DE LA BAIE D'AUSCULTATION (FACE AVANT)

Figure 11

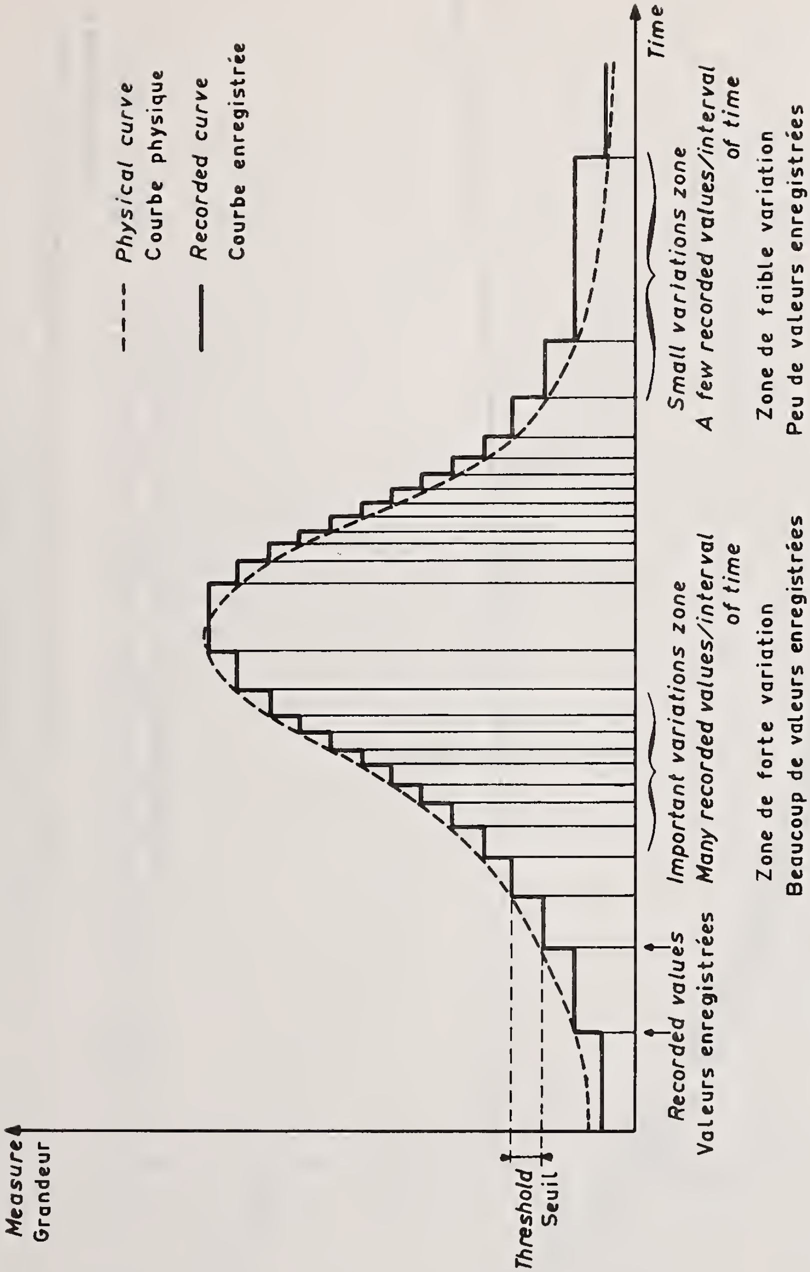


H : Carte horloge *Electronic clock board*
SCAN: Multiplexeur 2ème niveau + convertisseur analogique digital.
Multiplexer + analog-digital converter board
MPX : Multiplexeur 1er niveau *Multiplexer board*
MW : Carte puissance (amplificatcur d'isolement) *Power output board*
TF : Carte temps de fermeture *Closing time board*
E.L : Carte états logiques *"Logical states" board*
Vit : Carte vitesse *Rotor speed board*

PRINCIPLE OF THE DATA ACQUISITION SYSTEM

SCHEMA GENERAL DE PRINCIPE DU SYSTEME D'ACQUISITION

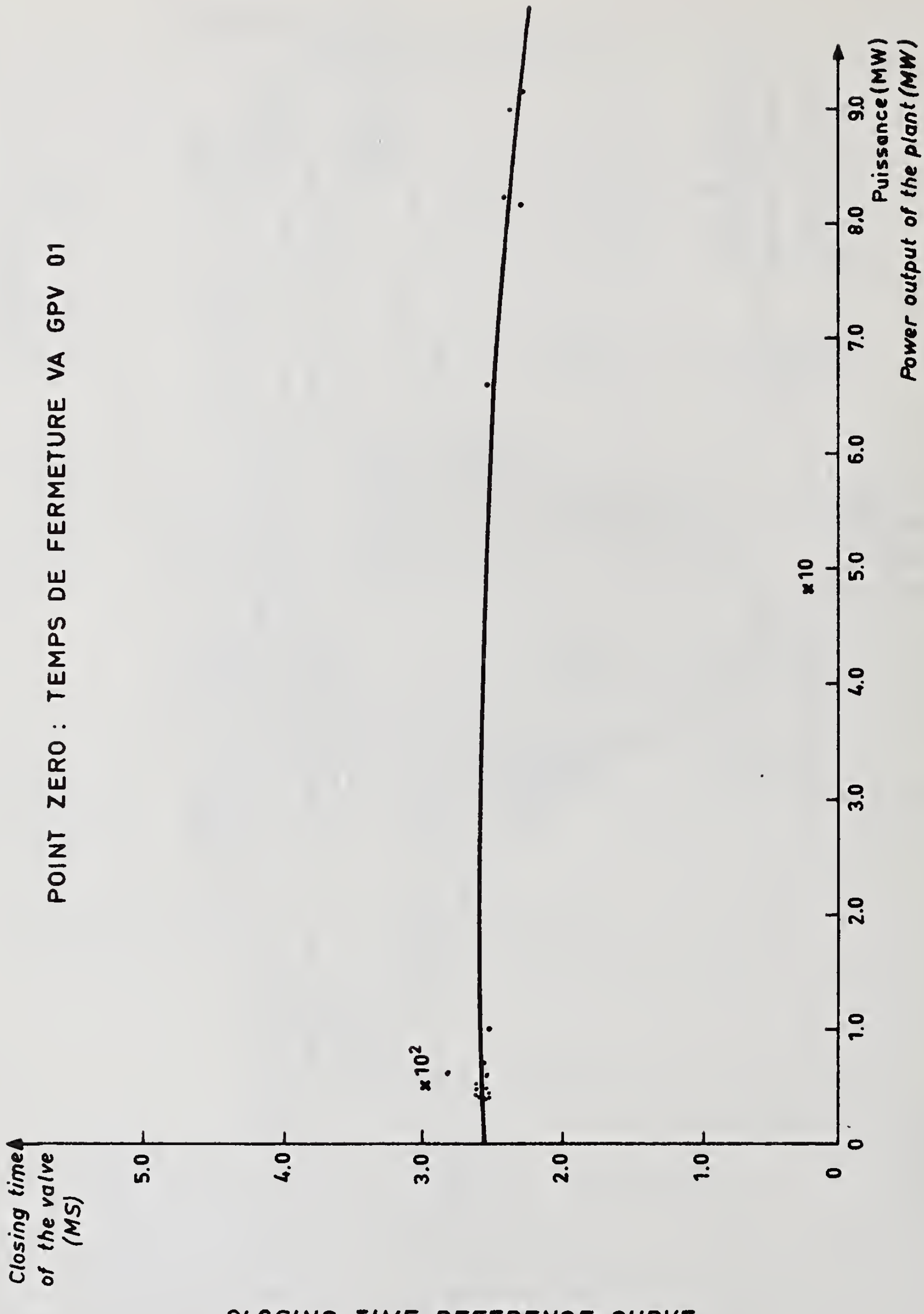
Figure 12



DATA ACQUISITION PRINCIPLE

PRINCIPE DE L'ACQUISITION DES DONNEES

Figure 13



CLOSING TIME REFERENCE CURVE

COURBE "POINT ZERO" D'UN TEMPS DE FERMETURE

Figure 14

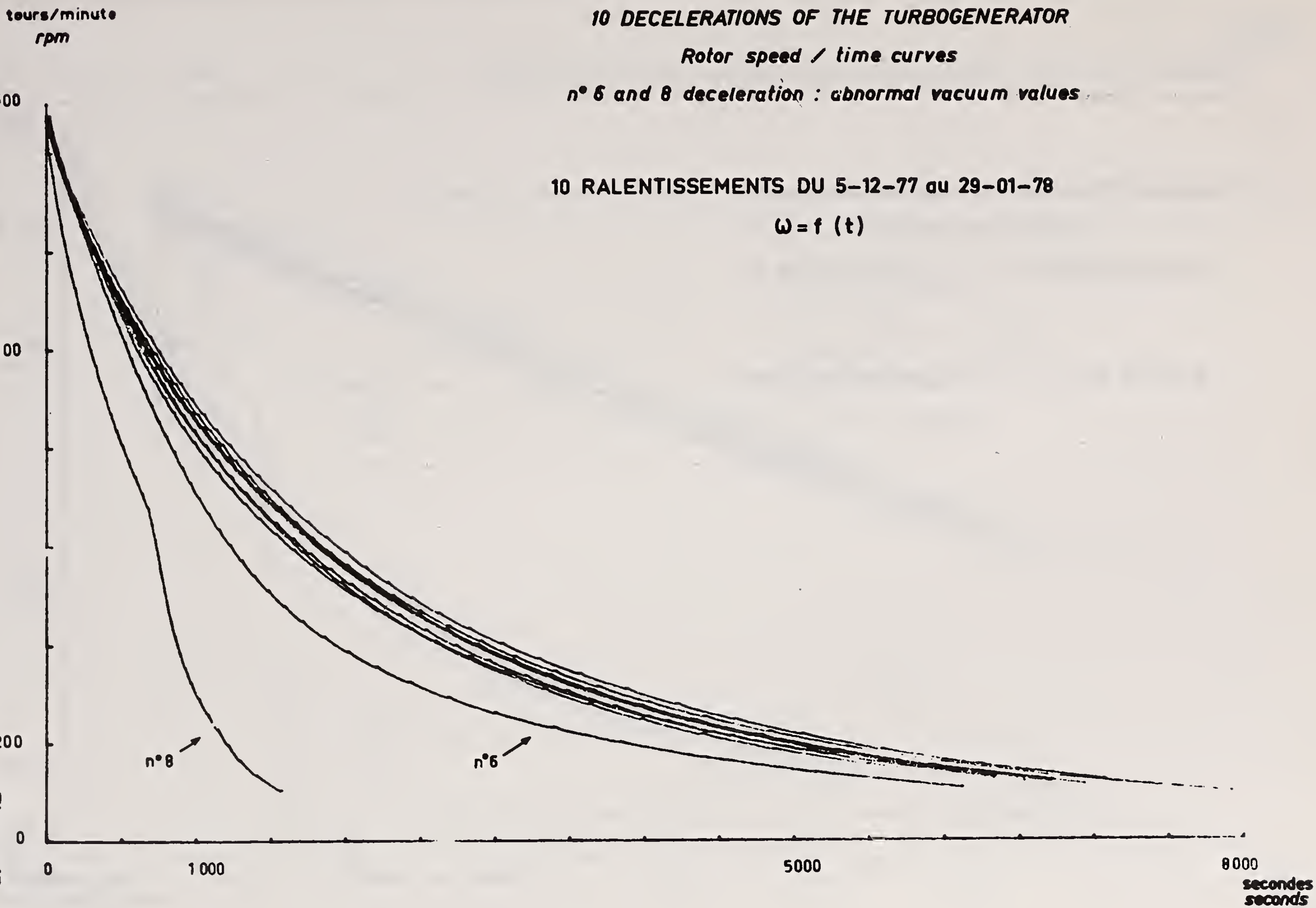
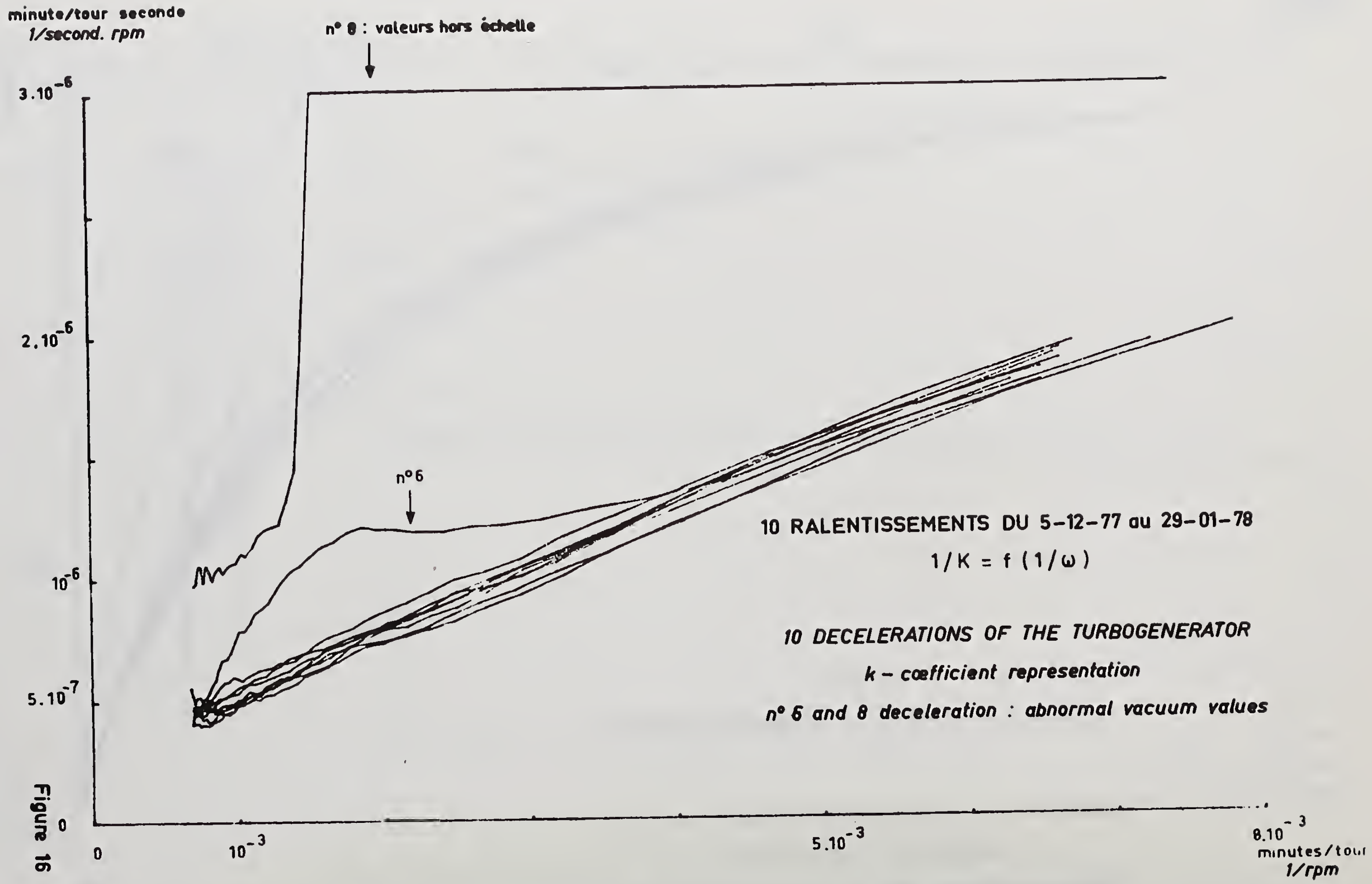

10 DECELERATIONS OF THE TURBOGENERATOR
Rotor speed / time curves
n° 6 and 8 deceleration : abnormal vacuum values
10 RALENTISSEMENTS DU 5-12-77 au 29-01-78
ω = f (t)
tours/minute
rpm
1500
1000
200
0
0
1000
5000
8000
secondes
seconds
n°8
n°6

Figure 15


minute/tour seconde
1/second. rpm
n° 8 : valeurs hors échelle
3.10^-6
2.10^-6
10^-6
5.10^-7
0
n° 6
10 RALENTISSEMENTS DU 5-12-77 au 29-01-78
1/K = f (1/ω)
10 DECELERATIONS OF THE TURBOGENERATOR
k - cœfficient representation
n° 6 and 8 deceleration : abnormal vacuum values
0
10^-3
5.10^-3
8.10^-3
minutes/tour
1/rpm
Figure 16

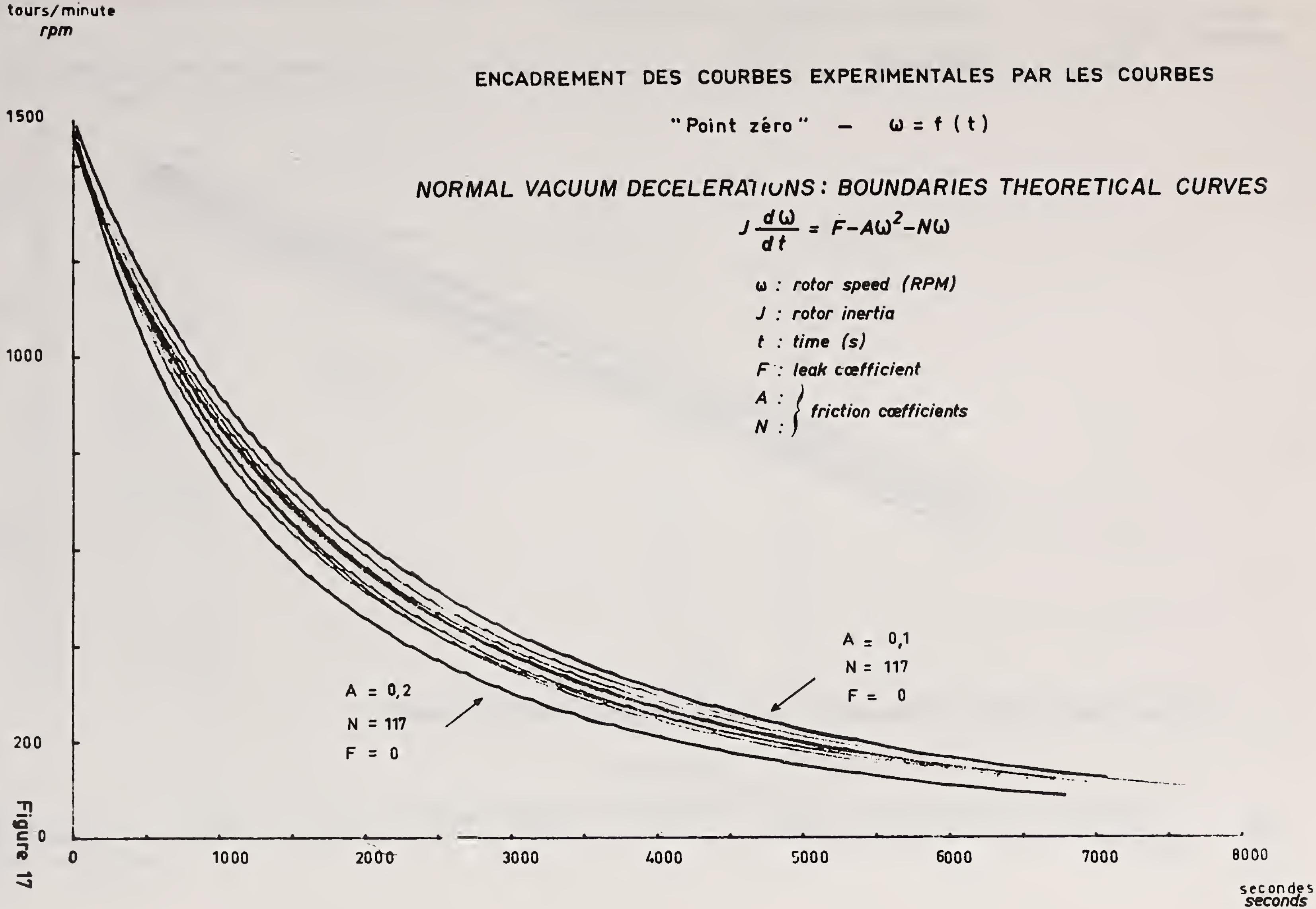

ENCADREMENT DES COURBES EXPERIMENTALES PAR LES COURBES
"Point zéro" — ω = f (t)
NORMAL VACUUM DECELERATIONS : BOUNDARIES THEORETICAL CURVES
J dω/dt = F-Aω²-Nω
ω : rotor speed (RPM)
J : rotor inertia
t : time (s)
F : leak cœfficient
A : } friction cœfficients
N : }
A = 0,1
N = 117
F = 0
A = 0,2
N = 117
F = 0
tours/minute
rpm
1500
1000
200
0
0
1000
2000
3000
4000
5000
6000
7000
8000
secondes
seconds

Figure 17

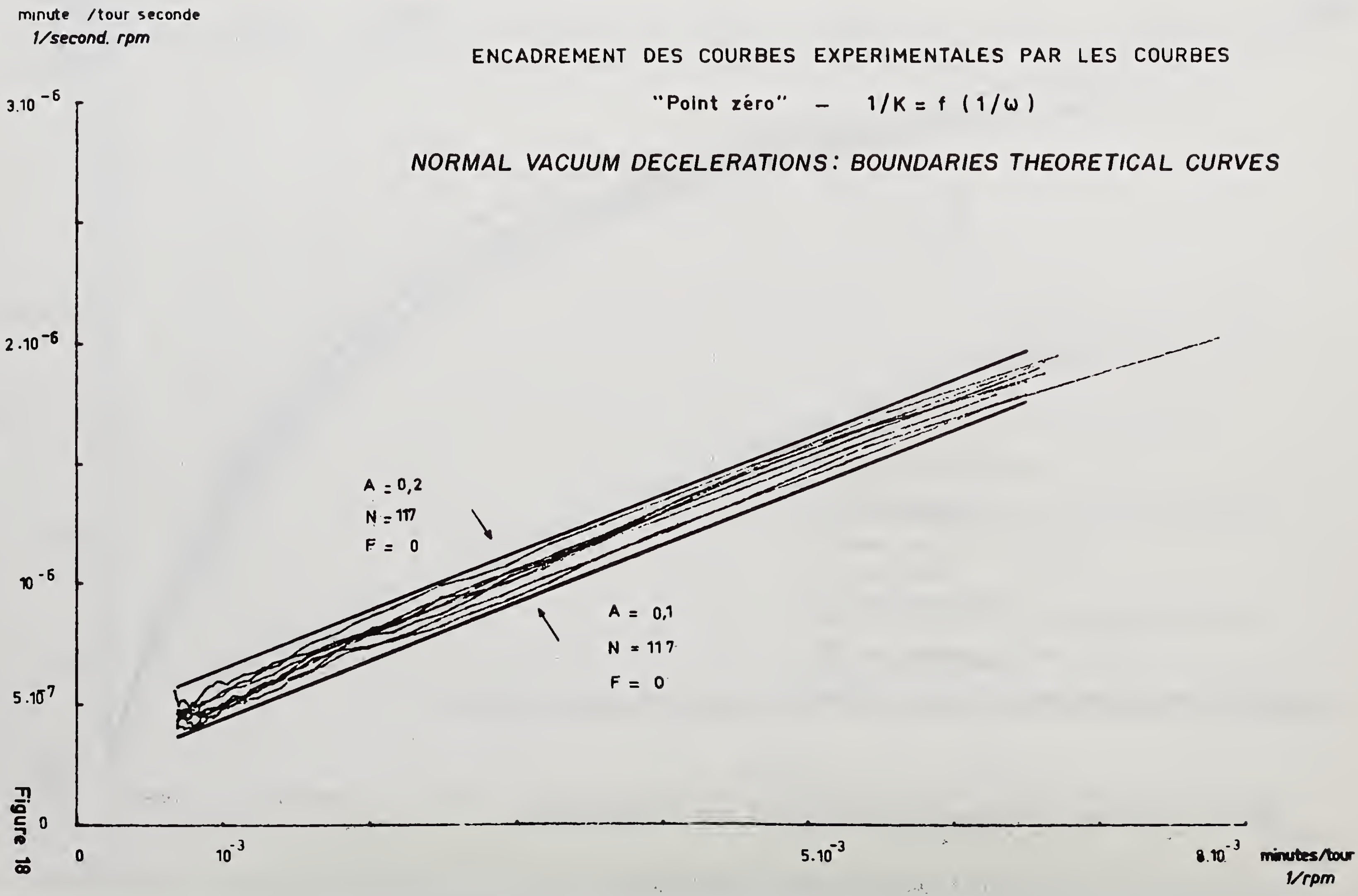

ENCADREMENT DES COURBES EXPERIMENTALES PAR LES COURBES
"Point zéro" – 1/K = f (1/ω)
NORMAL VACUUM DECELERATIONS: BOUNDARIES THEORETICAL CURVES
minute /tour seconde
1/second. rpm
3.10^-6
2.10^-6
10^-6
5.10^-7
0
A = 0,2
N = 117
F = 0
A = 0,1
N = 117
F = 0
0
10^-3
5.10^-3
8.10^-3
minutes/tour
1/rpm

Figure 18

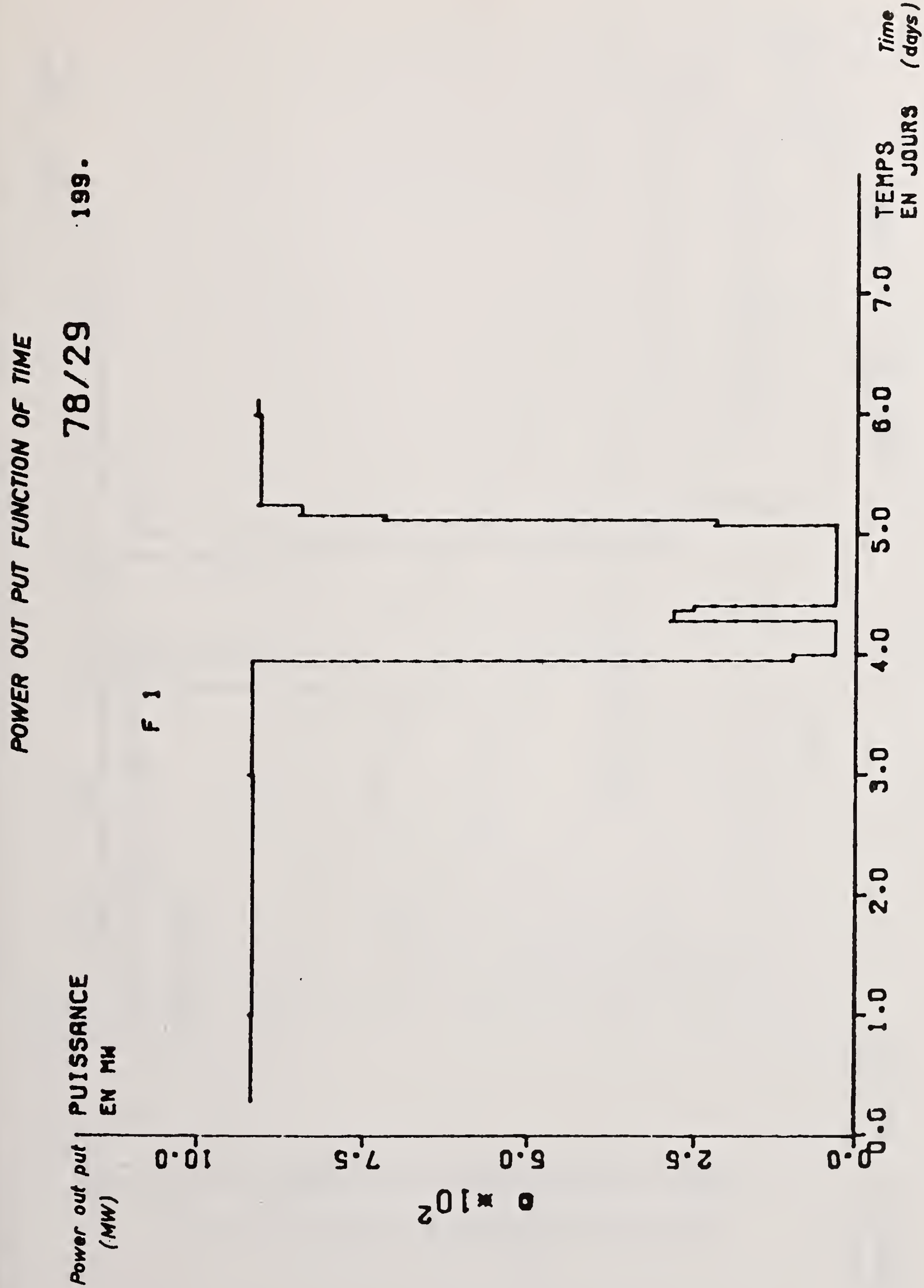

POWER OUT PUT FUNCTION OF TIME
78/29
199.
F 1
PUISSANCE
EN MW
Power out put
(MW)
0 *10^2
0.0
2.5
5.0
7.5
10.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
TEMPS
EN JOURS
Time
(days)

Figure 19

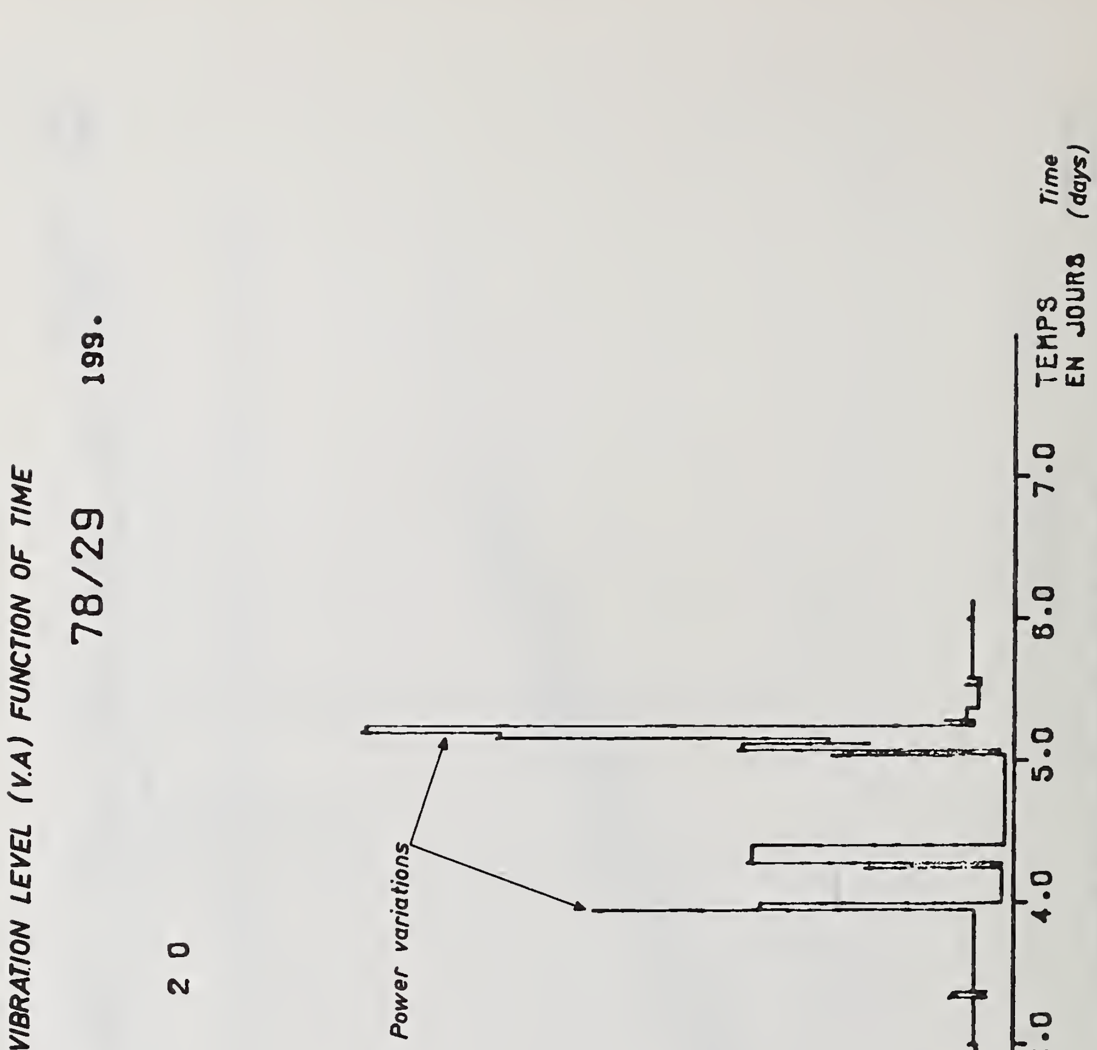
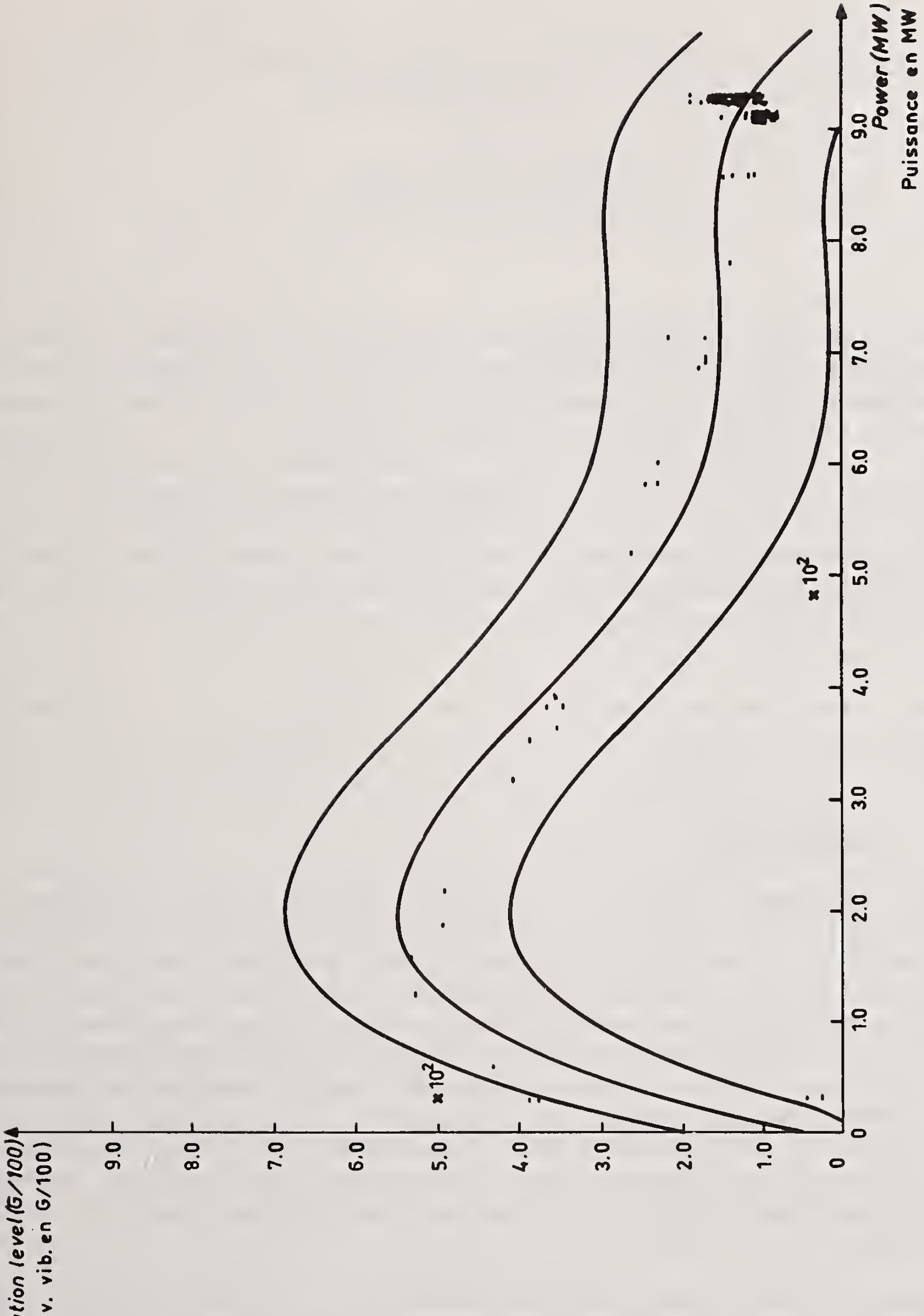

VIBRATION LEVEL (V.A) FUNCTION OF TIME
78/29
199.
2 0
NIV.VIB.
EN G/100
Vibration level
(G/100)
G *10²
15.0
10.0
5.0
0.0
Power variations
stabilised power
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
TEMPS
EN JOURS
Time
(days)

Figure 20



VIBRATION LEVELS FUNCTION OF POWER OUTPUT

POINT ZERO NIVEAUX VIBRATOIRES PUISSANCE

Figure 21

AN APPROACH TO MONITORING EXISTING UTILITY TURBOGENERATORS

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Abstract: A three stage program of minicomputer based, continuous monitoring development and application is currently in progress on several large turbogenerators. The first stage is a period of planning the primary development effort in terms of review of existing vibration sensors, selection of additional sensors, and identification of operating parameters which influence vibration. The second stage involves gathering data in many different operating states in order to develop a vibration comparison algorithm which removes the effects of the operating state. In the final stage, the machine is monitored quasi-continuously with the intent of detecting progression of failure modes as changes in the vibration response of the machine.

Key words: Vibration monitoring; vibration signal processing; rotating equipment

INTRODUCTION

The sudden, unplanned outage of a utility turbogenerator resulting from mechanical failure is, in the least severe case, a major hardship for those served by the utility. In worse cases, castrophic failures can result in millions of dollars damage and even loss of life. Many equipment failure modes are progressive in nature, and thus lend themselves to detection in a machinery monitoring program. With early detection, only minor repair may be required while the load is shifted elsewhere at no inconvenience to the customer. The central goal of a machinery monitoring program is to anticipate failures before they actually occur, and thus, to allow for a planned, orderly shutdown of the machine. Comparison of the costs and benefits makes proper monitoring mandatory at the present time.

A turbogenerator monitoring program begins with assumptions about the information available regarding the state of the machine. It is usually assumed that a machine with no progressive failures occurring has minimal vibration during operation. Increasing vibration is presumed to be associated with the progression of one or more failure modes. This suggests that the measurement, analysis and comparison of present vibration with previous vibration will allow the prediction of approaching failures. Many vibration phenomena occur at the fundamental rotational speed of the machine, which is 60 hz for a 3600 rpm machine. For some failure modes, high frequency spectral components are generated which become apparent earlier than the fundamental components. Detection of these high frequency components will give a greater lead time for corrective action. Other phenomena associated with turbine blading also occur at relatively high frequencies. Comprehensive monitoring thus requires a broad spectrum approach. The Fast Fourier Transform algorithm, along with signal processing techniques from the sonar, radar, and communications fields are the tools for extracting useful information from the observed vibration data.

Radian Corporation has undertaken to monitor several large, existing utility turbogenerators using both vibration and acoustic emission information. The vibration monitoring aspects are described below. This work is presently in different stages at several sites.

MONITORING SYSTEM HARDWARE

Monitoring a large turbogenerator entails the rapid acquisition of large amounts of data, the need for on-site reduction for data acceptance or rejection, and a need for versatility as the monitoring program develops. This all points to a minicomputer based monitoring system such as will be described.

Vibration data is taken from the machine via vibration sensors installed as part of the monitoring program and, in some cases, other pre-existing vibration sensors as well. These sensors are accelerometers, velocimeters, and various types of displacement sensors as indicated for the measurement situation. The resulting analog signals are the primary vibration data for the monitoring program. A multiplexer sequentially samples the various sensors, either singly or in pairs, under computer software control. These analog signals are digitized in a high speed analog to digital converter. Computer selectable low pass filters are provided between the multiplexer and the computer input to remove the high frequency components before the signal is digitized and thus avoid aliasing. Switchable filters are required for compatibility with the various sampling rates of the analog to digital converter. The computer system consists of a minicomputer with 64 K memory and also a disc unit. A magnetic tape unit is provided to transfer information from the minicomputer monitoring system to a large, central site computer. A graphics terminal is included for spectra, orbits, and other displays of interest to an analyst at the monitoring site.

All primary vibration data is obtained through the multiplexer and high speed analog to digital converter acting directly under computer control. At the same time, a low speed, programmable data acquistion system gathers operating parameter values. This information is held in the low speed system until requested by the computer. The application of this equipment will be in three steps: an initial study period called Phase I, a development period called Phase II, and an on-going program of continuous monitoring, Phase III.

MONITORING PROCEDURE

Initial Study - Phase I

The initial study, or Phase I, is a period of learning how to monitor a particular machine. While there are similarities among machines of a given class, the details of each machine must be considered for a successful monitoring program. Most utility turbogenerators of recent vintage are equipped with some monitoring equipment. In most cases, the signal processing portion of the existing monitoring system is inadequate for the present monitoring program, however, the existing vibration sensors may be useful. Remembering that the existing vibration sensors were, in most cases, designed for low frequency response and only simple signal processing, the initial study begins with an evaluation of the existing vibration sensors in the light of the signal processing to be performed here. This should be an evaluation of the actual transducers as they exist, not simply an evaluation of their specifications. Anticipating the need for additional vibration sensors, a survey is also made for supplemental sensor sites. The principal concerns of this survey are access, environment at the sensor site, and value of data from each site. On existing machines, access to the rotor is generally limited to areas adjacent to the bearings or at the couplings. High temperatures and oil mist are typical adverse sensor environments encountered. A mathematical rotor dynamic analysis may be used to predict vibration frequencies, amplitudes, and the location of nodal points. This analysis can be of limited value since the required detail design information is generally considered proprietary. Much of the same information may be obtained from the pre-existing vibration sensors, within the range of sensor credibility.

One of the major efforts of Phase II is the correlation of vibration spectral components with the operating state of the machine. In order to do this, it is necessary in Phase I to identify those operating parameters which may be expected to influence the vibration response. These include the electrical load, various steam temperatures, stator and casing temperatures, and the exciter current. The experience of the operating personnel is valuable in identifying these operating parameters which must be monitored in Phase II.

The full hardware complement described in section 2.0 is not required for Phase I. The operating state parameters to be monitored are selected during Phase I, and only in later stages is the low speed data acquisition system required to record them. If the low pass vibration signal input filters are not available, some aliasing will occur but will not have a large effect on the results of Phase I. Since all necessary analysis can be performed in the minicomputer, the tape system is not needed to return data to a central site for processing. The required components are the minicomputer with disc unit and the high speed analog to digital converter with multiplexer.

Development - Phase II

The emphasis of Phase II is development of the means to extract useful information from the raw vibration data. The full hardware complement described in section 2.0 is required for this effort. The low speed data acquisition system regularly samples and holds the list of operating parameters that affect vibration. These are the operating state parameters associated with then current vibration spectra. Broadband vibration data is obtained from the vibration sensors that were supplemented on the basis of Phase I results.

The intent of vibration monitoring is to detect failure modes in progress by observing changes occurring in the vibration spectra. Yet, the operating parameter list developed in Phase I clearly recognizes the dependence of the spectra on the operating state of the machine. The direct comparison of spectra from two different times will reflect both the different operating states (probably different electrical loads and associated steam flows) and possible failure mode progression, in an inseparable fashion. In order to compare spectra obtained at different times and correspondingly different operating conditions, it is useful to define a "Standard Operating State". The standard operating state is a machine condition defined by specified values for each of the monitored operating parameters. Associated with the standard operating state are the vibration spectra that would be observed if the machine were actually operated at the standard operating state. These spectra vary only with the status of the failure modes. An algorithm is required to translate the spectra associated with an actual operating state to equivalent spectra for the same machine condition at the standard operating state. There is some statistical uncertainty associated with the equivalent spectra. When spectra from different times have been reduced to equivalent spectra in the standard operating state, any differences exceeding the uncertainty can properly be ascribed to physical changes in the machine, i.e., the progression of a failure mode. The development of the necessary algorithms begins with the correlation of spectral components and the operating state parameters. The first approximation to the algorithm is a linear relation between spectral amplitudes and operating state parameters. This is extended as a power series expansion about the standard operating state with as many terms as required. For this reason, it is best for the standard operating state to be chosen as a central, interior point of the operating variable domain, rather than a boundary point of that domain. The algorithm development requires acquisition of large quantities of vibration data representing widely varied operating states followed by a regression analysis. The necessary observed spectra are recorded on tape and returned to a central site for the correlation and algorithm development work.

Early in Phase II, vibration measurements are made and processed into the baseline spectra. It is not necessary to know if a progressive failure mode is present at the time the baseline data are taken. It is intended to use this data only for comparison, and not in an absolute sense. When a satisfactory standard operating state reduction algorithm is defined, the baseline spectra are transformed to the standard operating state and stored in the minicomputer to serve as a basis for comparison in Phase III.

When a particular spectral component or group of components has attracted attention, the question remains, "What does it mean?" One of the most formidable tasks in any monitoring program is the identification of spectral lines with physical phenomena existing within the machine. Experience is certainly a major tool in this effort. Much is also learned from the manipulation of mathematical models to predict expected spectral components, in so far as the necessary physical data is available. Determination of these physical parameters from machine drawings is a lengthy, expensive process even if the drawings are available. An attractive alternative is the determination of these parameters directly from the physical part during an open case inspection modal analysis and identification procedures.

The final step in the monitoring program development is the establishment of warning criteria and threshold values. Here again, experience and mathematical models each play a roll in the definition of these parameters. The experience of power plant operating personnel may be considered to define upper limits on many of these variables, but in many respects, this judgement is too coarse to be employed with the spectral information available. Comprehensive, well-verified mathematical models provide a means to assess quantitatively the impact of proposed failure mechanisms as they affect the vibration spectra. The threshold levels representing significant deviations from the baseline spectra are set as fractions of the warning criteria which have been established.

Continuous Monitoring - Phase III

The final stage in the monitoring program is establishment of quasi-continuous monitoring under computer control to continue indefinitely in the future. In Phase III, each of the vibration sensors is regularly sampled at frequent intervals by the computer via the high speed analog to digital converter. The low speed data acquisition system continues to supply the operating variable values. The observed spectra are processed almost in real time, transformed to the standard operating state, and compared to baseline spectra. Only spectra that deviate from the baseline by more than a prescribed threshold are saved. These exceptional spectra and associated operating states are recorded on tape. If the deviation exceeds the warning level, this information is relayed to the operating personnel.

The tape with its record of exceptional spectra and their associated operating parameter values is periodically returned to the central site for off-line analysis and interpretation. This includes possible recommendations for maintenance work, shut-down of the machine, or other operating changes. The tape also provides the basis for further refinements to the standard operating state reduction algorithm and improvements to the threshold and warning criteria. The payoff for the entire monitoring program is expected to occur during this Phase III activity, the on-going analysis and interpretation of the data generated leading to the early detection of problems.

ENHANCING MACHINERY PROTECTION THROUGH AUTOMATED DIAGNOSTICS

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Abstract: Shaker Research Corporation under contract to Electric Power Research Institute, has installed an automated vibration monitor system in Northeast Utilities Millstone II Nuclear Power Plant. The objective of the program is to demonstrate that the system can provide insight into the condition of critical pumps and thus guide the planned maintenance during scheduled shutdowns. To provide this insight, the system must be capable of processing a large amount of vibration data and based on the results, draw conclusions about the condition of the unit. Both aspects of the system will be discussed.

Key Words: Automatic diagnostics; digitizes data; spectrum analyzers; steady state mode; tolerance vibration levels.

It is becoming quite common for large rotating machinery to be equipped with some type of vibration transducer along with their associated monitors and alarm systems. These systems may have been installed initially as alarm devices to warn of out of tolerance vibration levels or even to automatically shutdown the machine if a given vibration level is exceeded. It has become readily apparent to the maintenance engineer that these transducer signals when analyzed periodically by modern data processing equipment such as real time spectrum analyzers have provided additional information on mechanical condition. Signal characteristics associated with certain defects may be recognized long before an alarm level. Trend information on the amplitude of vibration components also provide an insight into the rate of machinery deterioration. All of these data allow better machinery protection and improved maintenance efficiency during scheduled (or unscheduled) plant down time.

Two problems are quickly encountered by one starting down this path to improved maintenance. How does one attain the skill necessary to recognize significant signal characteristics and even if it can be attained, how does one inspect, compare with the last inspection and trend the data from a large number of rotating machines. Under the sponsorship of the Electric Power Research Institute (EPRI), Shaker Research Corp. has installed an Automatic Vibration Monitor System at Northeast Utilities Millstone II Nuclear Power Plant. The objective of this program is to demonstrate solutions to both these problems. This paper describes some of the aspects of the program and the monitor system.

System Requirements. Drawing on many years of experience in machinery troubleshooting, it was concluded that a system could be built that could automatically recognize some of the more common signal characteristics that are related to machinery defects. In effect the system would become an automatic diagnostic system. Additionally, for those signals and defects not automatically diagnosed, data must be saved and recalled in a format that allows a diagnosis to be made. Finally, it should be easy to "teach" the system new symptoms so that the extent of automatic diagnostics will continue to expand.

Clearly, if the automated diagnostics is going to be based on years of human troubleshooting experience, then the system must be capable of analyzing data during machinery operating conditons that have been found to be productive in the past. These have included:

1. Normal analysis of vibration spectra for machinery steady state operation.
2. Analysis of transients such as start-stops, amplitude vs. speed and waterfall data processing is included.
3. Demodulation of high frequency resonances to determine the source of excitation, i.e., rubs, ball bearing defects, etc.
4. Separation of mechanical and electrical runout from true vibration data for displacement probes.

This automated monitor system also includes the provision for continuous on line monitoring of overall signals from each sensor. If the signal level from any sensor exceeds the warning or alarm level, the computer is automatically alerted and the system switches into the transient mode to gather and analyze data from the distressed machine at this time.

System Description. The three modes of operation are shown in Fig. 1. In start stop mode, the system digitizes data from all sensors on the machine. After the start or stop the data is processed. Data presentation equivalent to tracking filter plots are calculated using a Discrete Fourier Transformer for the first three harmonics and are compared with the last start or stop. Another presentation known as a waterfall plot is also produced and stored for future reference. A typical waterfall plot is shown in Fig. 2.

In the alarm mode, the computer is interrupted when either a warning or alarm level is exceeded on the continuous monitor panel. The system digitizes data from the machine sensors, and checks to see if the signal level is still increasing. When the signal level no longer increases, the trend of the overall amplitude of each sensor is plotted.

The system operates in the steady state mode the overwhelming majority of the time. In this mode, the system cycles through all sensors and produces spectra from each sensor. These include low frequency spectra as shown in Fig. 3 and also high frequency spectra as shown in Fig. 4. Comparisons are made with the last spectrum and with original data. As new signals appear or signals always present vary in amplitude these facts are printed out along with the source of the signal and its seriousness. Fig. 5 is a typical diagnostic printout. The signal amplitude is also stored in a trend area. These data may be retrieved and plotted as shown in Fig. 6.

The operator may take control of the system at any time and has several options at his disposal to either change system constants, to extract information or to run system diagnostics. A menu is presented to the operator showing his choices and this is shown in Fig. 7. Using this option, the operator may increase the diagnostic capability of the system as new symptoms appear and are related to known mechanical degradation.

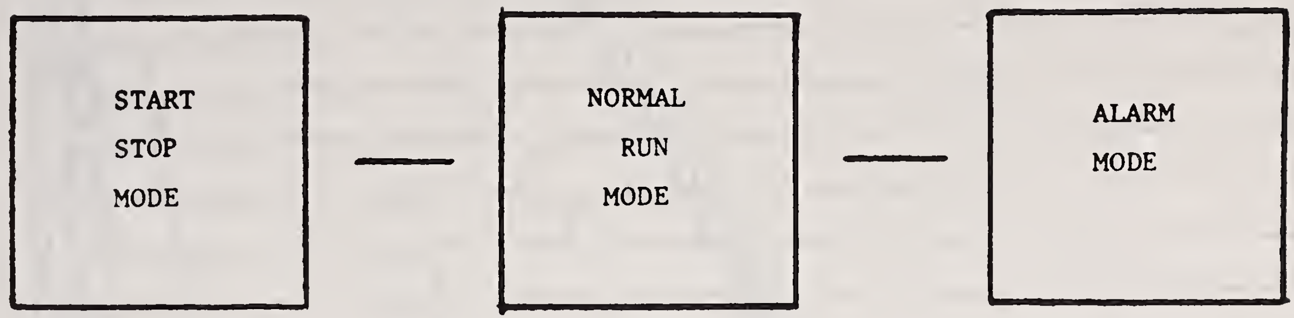

Figure 1

Automated Operating Modes

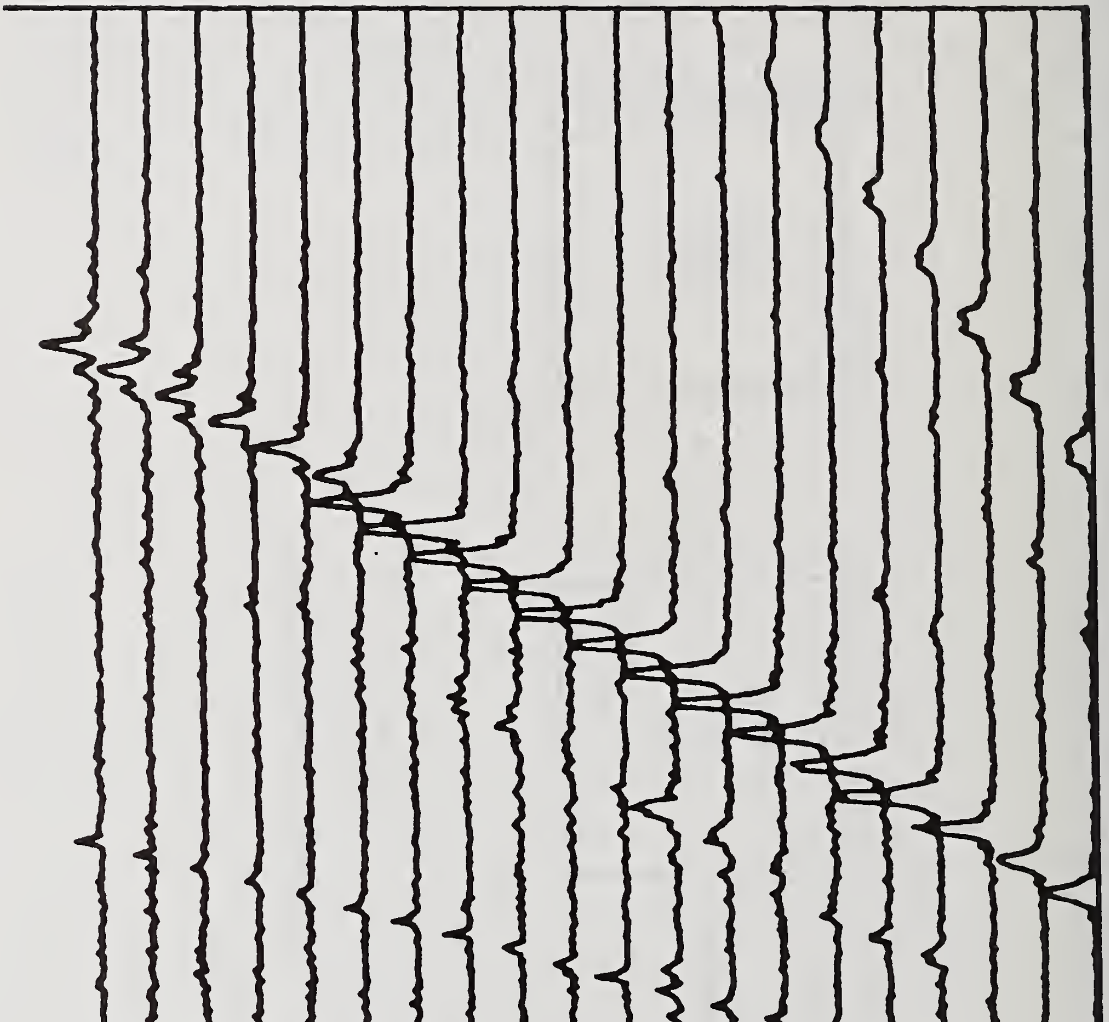

Figure 2. Waterfall

RCP-A MOTOR RAD

YEAR	DAY	HOUR	MIN
1979	4	13	9

MAXIMUM PEAK:	1419G'S
RPM:	875 ØØ R.P.M.
POWER:	1ØØ.ØØ %

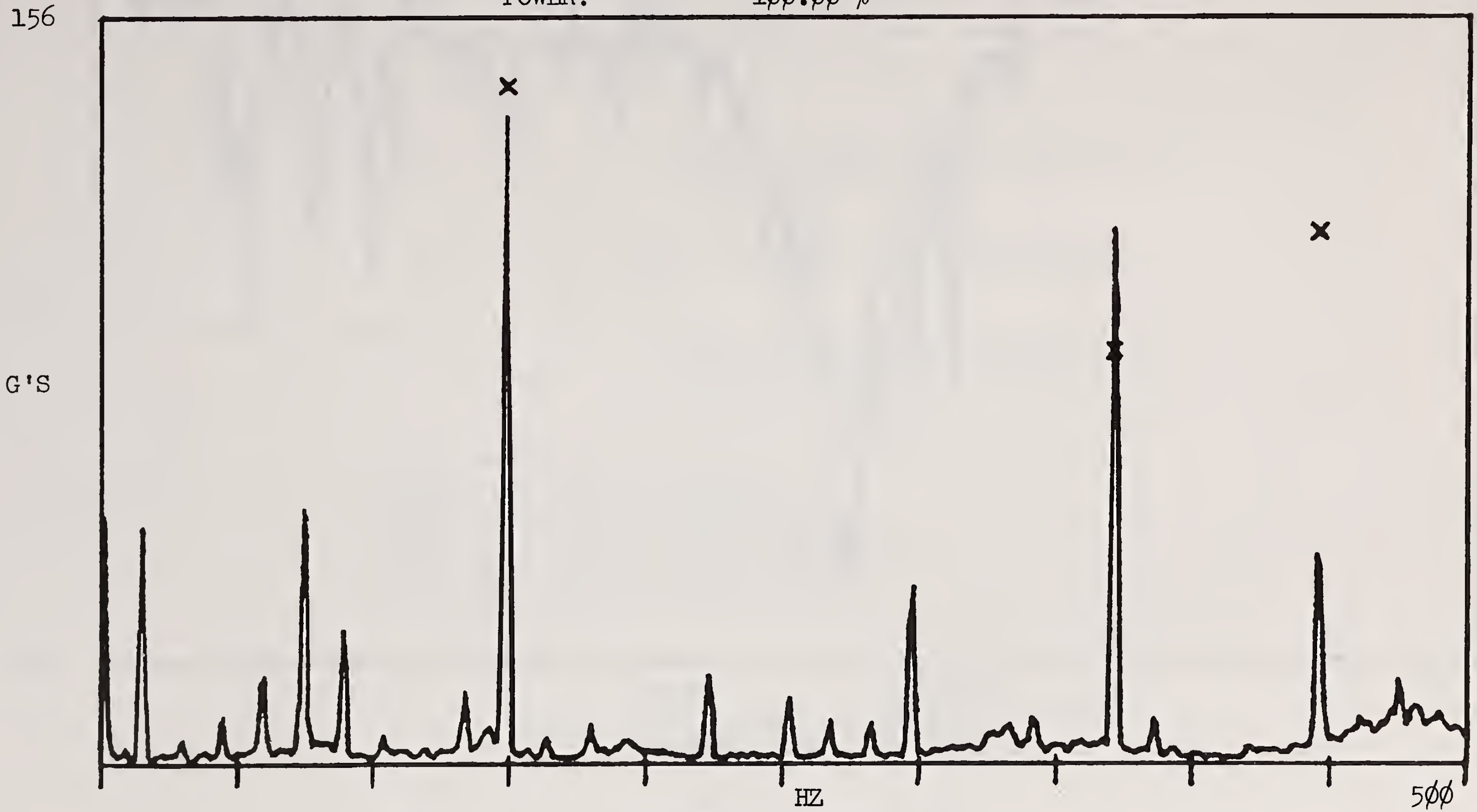

Figure 3. Low Frequency Spectra

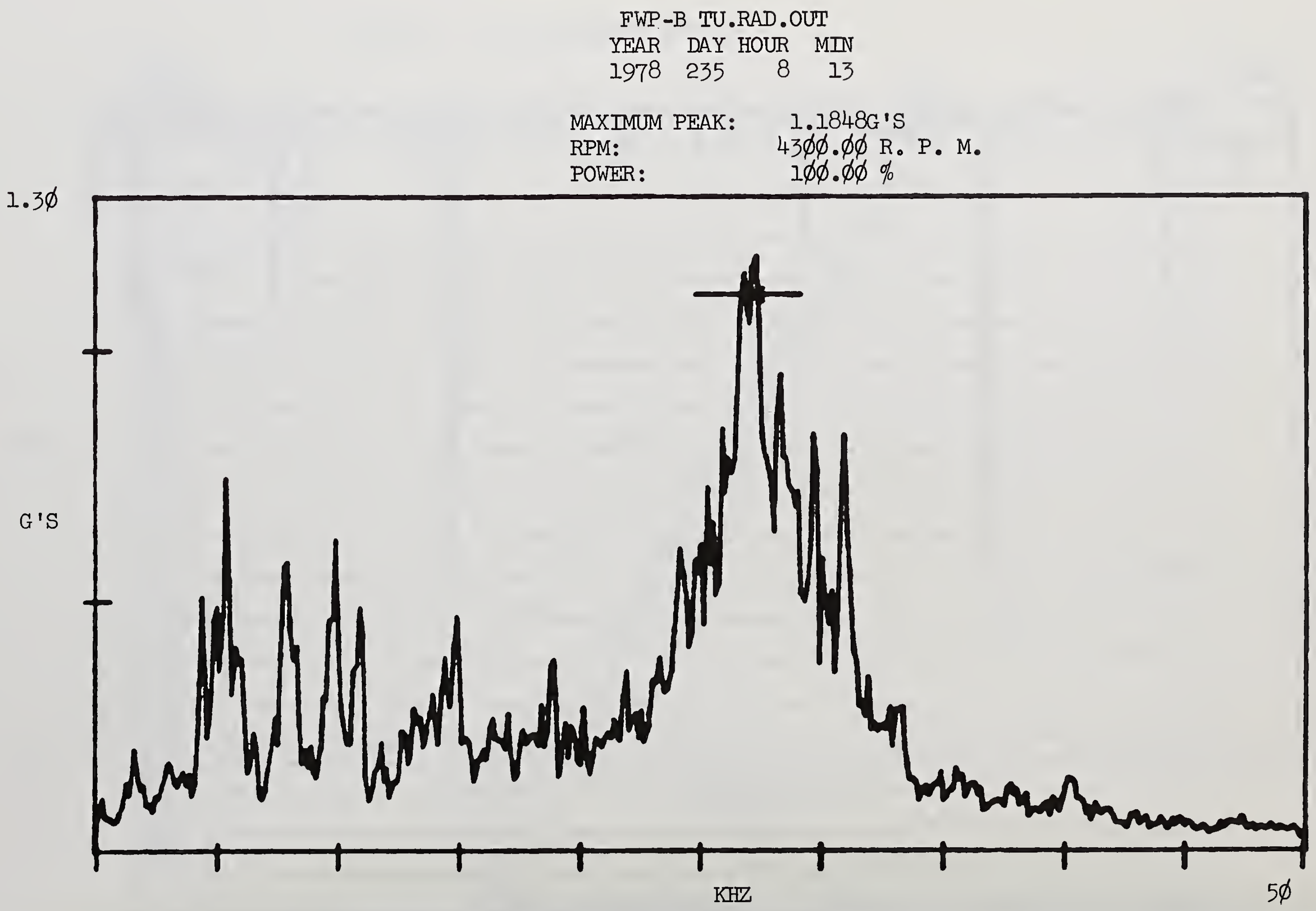

Figure 4. High Frequency Spectra

```
DATE     7-24-1978      TIME   Ø94Ø

SENSOR     FREQ  CHANGE        LEVEL        MESSAGE
            HZ     CODE  PRES  WAR  ALA
   1        15     2Ø3    15   23   35   UNBALANCE
   3        15     2Ø3    12   23   35


                         SLOW DECREASE OVER REFERENCE SET
                         CONTINUE OPERATION


   4        13     2Ø3   16Ø  3ØØ  6ØØ   SUB HARMONIC


                         SLOW DECREASE OVER REFERENCE SET
                         CONTINUE OPERATION


SENSOR  # 1 IS RCP-C PUMP AX.
SENSOR  # 2 IS RCP-C PUMP RAD
SENSOR  # 3 IS RCP-C MOTOR RAD
SENSOR  # 4 IS RCP-C PUMP DISP
SENSOR  # 5 IS RCP-C MOTOR DISP
```

Figure 5. Diagnostic Printout

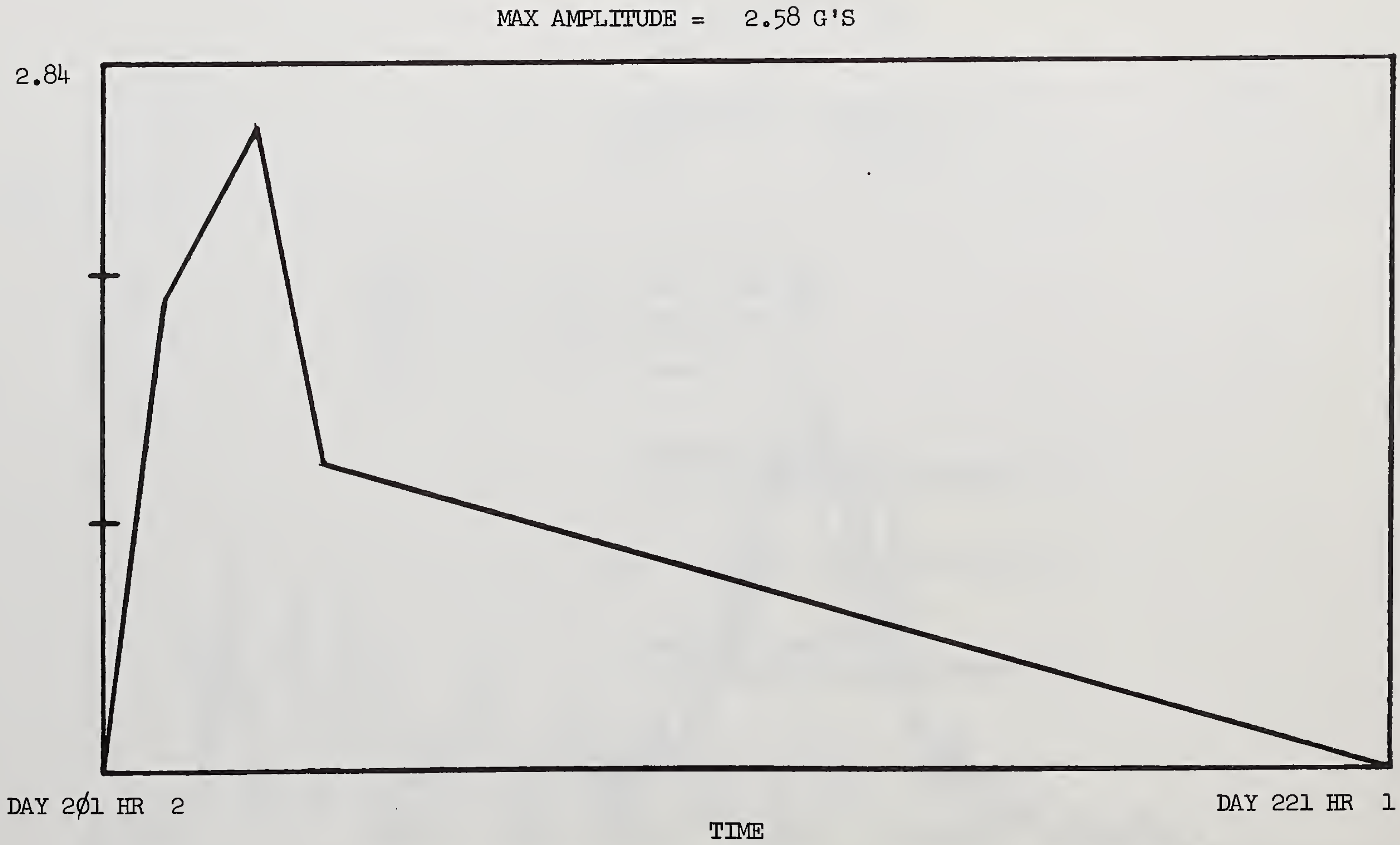

Figure 6. Trend

```
***********MENU**************

 1 CHANGE PROBE TYPE
 2 CHANGE NOISE & PEAK DIFFERENCE LEVELS
 3 EDIT DIAGNOSTIC IDENT TABLE
 4 EDIT CONDITION & RECOMMENDATION FILE
 5 EDIT SENSOR NAME FILE
 6 CHANGE % LEVEL FOR FLAGS
 7 CHANGE STORED PEAKS
    INCLUDES OPTION TO GET NEW SPECTRA
 8 PLOT DATA
 9 EDIT MESSAGE FILE
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SESSION V

NEW TECHNOLOGY

Chairman: William R. McWhirter, Jr.
Naval Ship Research and Development Center
Co-Chairman: Henry R. Hegner
Mantech of New Jersey Corporation

REPORT ON INDUSTRY/JOINT SERVICES PROJECT TASK GROUP 1-d

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Abstract: Recognition by the armed services of a need for definition in Automatic Test Arena led to the establishment of first a Navy/Industry project and later to the establishment of a Tri Service/Industry project. The Tri Service project, started in the last quarter of 1976, included numerous committee meetings, a general meeting in January of 1977 and a major working symposium in April of 1977. The symposium attendance was 860 with an approximate 60/40 ratio of industry/DOD attendance. The project included a specific task group to deal with the application of Automatic Test Techniques and Equipments to the testing of non-electronic equipments.

The non-electronic testing group, chaired by Donald A. Prue of Hamilton Standard, presented a series of findings regarding the application of automatic testing to non-electronic equipments. These findings include the recommendation for:

- Equipment failure mode analysis
- Equipment designed for testability
- Standardization of test interfaces

The implications of these recommendations in terms of acquisition costs were recognized by the group and the need for an effective means of demonstrating cost effectivity was established.

Key words: Military systems; non-electronic equipment; testing.

In October of 1975, the Navy and Industry established an Ad Hoc Automatic Test Equipment project under the joint sponsorship of AIA, EIA, NSIA, SC/A, and WEMA. The efforts of the participants in this project were directed towards establishing communication between the Navy and the various members of industry who are concerned with the utilization and production of the automatic test equipments. The success of this project led to a tri-service/industry briefing in June of 1977 and the formation of the Industry/Joint Service ATE project in the fall of 1977. This project had expanded horizons in that the problems of all three services were considered with a corresponding expansion of the industrial representation. It is apparent that this project, like its predecessor, has been highly productive and will lead to some major realignment in the field of ATE.

The organizers of the Navy project, recognizing the need for some degree of automatic testing or monitoring of non-electronic equipments, established a specific task group to collect and present data concerning this field. This task group, designated A-4 Propulsion, Electrical, and Auxiliary Systems Monitoring, concerned itself in main with these elements as installed in ships. One of the major findings of this group, which will come as no surprise to the MFPG members, is that the need for improved test techniques for non-electronic equipments is more pressing than in the area of electronic equipment testing.

As a consequence of this finding, Task Group 1d was formed in the joint service project to carry on the work started by the A-4 group. The 1d group was chaired by Don Prue of Hamilton Standard and ably supported by W. (Bill) McWhirter, Jim Johnson, Barney Poppet and Hans Kohler from the Navy and J. (Jeep) Hnatczak and R. (Bob) Watts of the Army.

In the formative stages of Group 1d, it was decided to limit the scope of the task to a small class of complex machines, rather than the more encompassing field covered by the previous study. It was hoped that by limiting the scope of the effort, a more in-depth analysis of the requirements could be achieved. As you well know, the family of complex machines which have been subject to the most intensive study and for which the most extensive set of field test data exists, is the internal combustion engine, i.e. gas turbines, diesels, and spark ignition engines. Accordingly, the project was limited to a study of these devices and their associated auxiliaries. A further limit introduced in the course of the study reduced the scope to applications in which these devices were used as propulsion units for ships or land vehicles. This excludes, in the case of gas turbines, aircraft applications. This latter restriction was imposed due to a simultaneous study by SAE which provided more depth in the area than could have been achieved within the framework of this project.

The project effort included:

- Task group meetings.
- Individual data collection and analysis by members.
- A joint workshop in San Diego of all task groups.
- Preparation of the final report including recommendations.

In addition to these activities which were directed to the technical effort, there were numerous meetings between the chairmen of the various task groups and an executive steering committee. These meetings provide a forum at which the general policy of the project and specific direction of the activities of the task groups could be discussed and developed.

The study showed that within the restricted field considered:

- There are numerous commercial applications in which cost effectivity has been adequately demonstrated.

- The methods used for proving cost effectivity in the commercial world include setting values on availability. A method of carrying this through to the military is required.

- There are numerous military applications which have been carried far enough to warrant implementation.

- As a minimum, one major military program must be fully implemented - full production implementation. The need for field data feedback from such a program is required for the development of future programs.

In the more general area concerned with other types of non-electronic equipments, the picture is not so well defined. The major difference is related to the relative attention which has been given to various types of machines. It is apparent from available data that the following elements require consideration:

- There is the same need for a method to assign a dollar value to availability.

- There is a need for system by system failure mode analysis.

- There is a need for standarization of instrumentation and test interfaces.

- There is an opportunity for the military to begin a design for testability program on new equipment.

Task Group 1d will meet in New Orleans in December of 1978 to review and approve the final report which will be one section of the final report for the Industry/Joint Services Project Report in 1979. The opportunity to exchange ideas regarding an emerging technology has been a rewarding experience for the participants and it is hoped that the data provided to the joint services will aid in solving some of the problems associated with the maintenance of non-electronic equipment.

A POLYMER SENSOR FOR MONITORING BALL-BEARING CONDITION

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Abstract: Noise spectra have been used frequently in the past to detect faulty bearings and to provide some indication of how the faults worsened with time. Usually accelerometers or microphones were used to detect the noise spectrum. This paper describes how the use of piezoelectric polymer sensors coupled with spectrum analyzers now available make this technique more useful. Improvement in accuracy and reproducibility, lower cost, greater convenience, and speed are potential benefits.

Key words: Bearing noise; failure prevention; machinery noise; noise signature; non-destructive evaluation; piezoelectric polymer; spectrum analysis; strain gage.

Introduction

Non-destructive evaluation of ball and roller bearings by detection and analysis of their noise spectrum is a well-established procedure. It has been shown that periodic monitoring of the noise spectrum of a bearing is a useful diagnostic tool.[1,2] Changes in the relative spectral power distribution, and especially an increasing proportion of high-frequency components, can give warning of deterioration long before failure occurs. The provision of early failure warning has important economic implications, as it permits an operator to replace damaged bearings at a convenient time (e.g., during a scheduled maintenance period) and may prevent consequent damage to expensive components such as machine spindles or even to entire machines. All too common are examples of machine design in which sudden failure of a bearing (for example, a bearing supporting a massive rotating assembly or part of a pump for lubricating fluid) results in extensive damage.

The sensors used in most bearing studies have been either accelerometers or microphones. There are, however, several deficiencies associated with the use of these instruments for analyzing bearing condition. For microphones, the presence of numerous sound sources in addition to the specimen bearing itself makes analysis difficult, and requires inconvenient and expensive noise shielding which may not be fully effective. Accelerometers having adequate high-frequency response are usually expensive; more important concerns are that they conventionally require a machined mounting flat, occupy a not negligible volume, and may have sufficient mass to bring about significant changes in mechanical loading in some applications. Also, it is usually impossible to mount an accelerometer close enough to the specimen bearing to avoid interfaces in the path between bearing and accelerometer; such interfaces will generally constitute discontinuities in acoustic impedance.

A few years ago, Jesse Stern of the NASA Goddard Space Flight Center suggested that the use of piezoelectric polymer gages (responding to quantities such as strain, force, acceleration) would avoid many of the difficulties associated with conventional sensors. Staff of the Polymer Science and Standards Division, NBS, have designed and constructed a number of polymer sensors, both piezo- and pyroelectric for a variety of applications, and developed means for evaluating their performance. This report describes an experiment aimed at investigating the usefulness of piezoelectric polymer gages as indicators of bearing condition. The thesis offered is that polymer gages provide a practical alternative to accelerometers with advantages of importance in some applications.

Construction of a Polymer Gage

The sensing element of a polymer gage is made from the poled portions of a thin sheet of polymer material. "Poled" refers to the process by which the material is made piezoelectrically active--in this case, by the application of an electric field to metal electrodes in contact with each side of the film while the material is at an elevated temperature (above room ambient). A simplified picture of the poling process is that some of the electric dipoles present in the polymer structure tend to become oriented with respect to the applied electric field (which is of the order of 10^8V/m) when the material is heated, and remain oriented when the polymer is cooled and the field removed. The result is that instead of a random distribution of dipoles pointing in all directions, there is a preferred orientation in one direction, and the material responds to strain with a change in its internal electric field and hence with charge appearing at its surface.

Each gage was constructed with the following steps (some of these steps are shown in figure 1):

(1) An aluminum electrode pattern is evaporated onto one surface of the starting material, which in this case is polyvinylidene fluoride (PVDF) in sheets 25 µm thick. The pattern for single gage element (each gage uses two elements) consists of a dot 2 mm in diameter with a 100 X 0.4 mm "tail", which will serve as connection to the dot for poling and in the completed device.

(2) The reverse surface of the sheet immediately opposite the 2 mm diameter dot is covered by a second metalization to form the ground electrode. Care is taken to insure that the ground electrode is opposite as little of the tail electrode as possible so that there is

minimal contribution from the tail to the signal from the completed device (only polymer directly between energized electrodes becomes poled).

(3) Electrical connections are made to the tail and shield electrodes, the poling field applied, and the material heated to approximately 100°C. After 30 minutes, the material is cooled to room temperature and the field then removed.

(4) Each gage is assembled as a sandwich of two elements bonded together with flexible, insulating epoxy resin, with the dot-and-tail electrodes in contact as the "filling" and the shield electrodes as the outer surfaces. A short length of copper wire is inserted lengthwise between the ends of the lead electrodes and bonded in place with conductive epoxy resin.

(5) A single large aluminum electrode is evaporated onto each exterior surface of the bonded gage. This electrode will serve as part of the electrical shielding of the completed gage. The wire connecting to the interior electrodes is masked (together with the end portion of the bonded sandwich) so that no aluminum is evaporated onto it, which would result in a short between the interior electrode and the shield.

(6) A miniature coaxial connector is made an integral part of the gage, with its center conductor soldered to the wire and the body of the connector and the ends of the PVDF strips potted together with insulating epoxy resin.

(7) Electrical connection between the shield of the connector and the shield electrodes is made with conductive paint, which is applied to the lead structure for half its length or more. When the paint has cured, the gage is complete.

The finished gage is approximately 60 μm thick at the sensor. Gages as thin as 15 μm have been constructed from 6 μm PVDF sheet. Aluminum is generally used as the electrode material because it is the easiest to apply. However, for applications requiring submersion in water or for biomedical applications gold electrodes are preferable. Other electrode materials that are compatible with the fabrication process and with PVDF are nickel and indium. Note that the gage construction places the relatively heavy connector far enough away from the active element to minimize mass loading.

Evaluation of Polymer Gage as Bearing Monitor

Figure 2 shows the apparatus used in this work: a motor-driven test shaft supported by two specimen bearings mounted in pedestals. A polymer gage is cemented in place directly on the stationary race of each bearing, and an accelerometer is mounted above each bearing on an aluminum cross piece that connects the bearing pedestals. Both the method of mounting and the accelerometer locations are intended to simulate field installation. The apparatus, with aluminum top and bottom plates and a solid steel shaft between the bearings, constitutes a closely coupled mechanical system. In order to reduce the effects of variations in motor speed and torque and the transmission of mechanical noise to the bearings, the driving electric motor is mounted on vibration isolators and coupled to the test shaft by a rubber belt. For the experiments, both specimen bearings were degreased; one was relubricated to serve as the "quiet" bearing, while the other was run dry as the "noisy" bearing.

Preliminary measurements indicated that for the purposes of this study, the members of each pair of gages--accelerometers or polymer gages--could be considered identical.

A consideration in comparing the signals from a crystal accelerometer to those from a polymer gage, is that both frequency response and directional response differ for the two types of instruments. The accelerometers used have, according to the manufacturer's characterization, a peak response at approximately 90 kHz, whereas the resonance corresponding to the thickness of the polymer sensor is considerably above 2 MHz, and any resonances at lower frequencies are well damped. For the kind of measurements used in this study, the accelerometers respond only to motion along the designed sensitive axis, for these experiments in the plane of the speciman bearing; the polymer gage provides an approximately equal output in response to strain in any direction in the plane of the sensor, which in these experiments includes the sensitive axis of the appropriate accelerometer.

Figure 3 shows the output of one accelerometer and one polymer gage as a function of frequency when, with the shaft stationary, the pedestal supporting one bearing is excited by a PZT (lead zirconate titanate) piezoelectric ceramic driver cemented to the vertical surface near the bearing. The amplifier gain for the accelerometer signal had to be reduced to the point that the signal below 30 kHz is in noise in order to avoid overloading the instrumentation at the 75 kHz resonance frequency of the structure. (An indication of the true instrumentation noise level can be obtained from the accelerometer trace as being less than -52 dB referred to 0.1 V). In contrast the output from the polymer gage shows a significantly lower and broader peak to the 70 kHz region and meaningful signal in the low-frequency range, with an average of -35 dB over 10 to 40 kHz. It is conjectured that the peak at 70 kHz is the result of a resonance from the PZT exciter and does not derive from the polymer gage. (Other experiments have indicated that similar gages produce nearly constant output over the range 100 kHz to 1 MHz in response to a hydrostatic pressure pulse; this performance can be interpreted as demonstrating no resonance behavior to the upper resonance.) This experiment demonstrates that the polymer gage does respond to high-frequency signals while the accelerometer response falls off rapidly above its resonance.

The next several figures show output as a function of frequency from both quiet and noisy running bearings. Figure 4 shows recorded polymer gage signals from the quiet and noisy bearings over a frequency range from 0 to 100 kHz. Examination of the two traces shows that there is a definite difference between them, with the level at a given frequency in the trace from the noisy bearing greater than that from the quiet bearing if the difference between the two traces is significant at that frequency. It is obvious that the signal falls off rapidly with increasing frequency. Note also the rather noticeable difference in the 40-60 kHz region. Figure 5 shows a similar set of traces of the accelerometer signals from the quiet and noisy bearings. Examination of the two traces shows less marked differences between them, and at some frequencies the higher level signal is associated with the quiet bearing; there is no roll-off with frequency probably because the high frequency components are amplified by the mechanical resonance of the accelerometer. The behavior of the mechanical system which leads to these four traces can be explained by considering the effect of the interfaces between the steel stationary race of the bearing and the aluminum pedestal. Unavoidable machining errors, differences in surface finish, and difference in specific acoustic impedance cause most of the sound generated in the bearing to be reflected at the interface and build up a reverberant sound field in the races of the bearing. Little sound is transmitted across the interface to the pedestal and the crosspiece joining the pedestals. Very much less sound is transmitted across both interfaces to the other bearing. Thus most of the sound generated in each bearing stays in that bearing. Most of the small amount of sound that gets into the aluminum structure stays there and builds up another reverberant sound field which, above about 15 kHz, takes the form of a standing wave pattern. The signal from either accelerometer at a particular frequency depends on its location relative to the standing wave pattern and has little relation to the nearer noise source. In contrast, the polymer gage, in direct contact with its intended noise source, sees negligible contribution from the second source, and internal reflections of the intended source from the local interface serve to augment the desired signal.

Discussion and Conclusions

Fundamental work predicting the frequencies to be observed, which result from specific types of defects in specific locations for ball bearings with given dimensions and numbers of balls, has been reported by a number of workers.[3,4] The purpose of our work has not been to carry out any detailed analysis of frequency or mechanical bearing parameters. It has rather been to investigate whether changes in the character of the signals from an undamaged and from a damaged bearing can be detected using polymer gages and if polymer gages show advantages compared to crystal accelerometers in this application. We believe that the results justify a positive conclusion.

It may be of interest to contrast some of the properties of polymer gages with those of crystal accelerometers to see why polymer gages should be particularly useful as indicators of bearing performance. The gages are low in mass with flexible sensing elements that conform readily to any curved surface; these properties, together with their materials of construction, permit them to be bonded in place in close contact with the bearing noise source so that sound energy from other sources is attenuated relative to the desired signal. The fabrication process lends itself to constructing gages of virtually any desired shape and in a wide range of sensing areas. The gages tend to be free from resonances below several hundred kilohertz (the range of interest) and are in principle inexpensive to construct so that it becomes practical to mount them in place permanently on every critical bearing in a given piece of major equipment.

(A possible disadvantage of polymer gages relates to the temperature response, both with respect to a pyroelectric contribution and to change in gage sensitivity as a function of temperature. Future work may determine if this is a problem in practice, as well as provide a more detailed analysis of gage performance.)

Conventional crystal accelerometers, on the other hand, have much greater mass than polymer gages, even for relatively small high-frequency types. The accelerometer housing is usually designed to screw into or be bolted to a flat machined surface, with a requirement for good contact over the intended mounting surface. Accelerometer mass and the relative rigidity of signal connections may preclude adhesive bonding. Accelerometers may have sensing crystals of different sizes, but it is not usually feasible to tailor size to application, except approximately. As has been noted, crystal accelerometers will have resonances in their response substantially below 100 kHz.

Accelerometers vary widely in cost, but apart from calibration costs (which, although by no means a small part of instrument cost, may be assumed to be the same for polymer gages), the high-frequency types most suited for the bearing and other similar applications are relatively expensive.

Our overall conclusion is thus that polymer gages have a good potential for monitoring bearing and other machinery noise, particularly with respect to nondestructive evaluation of performance, and that for some applications the polymer gage has demonstrated distinct advantages over the use of more conventional sensing instruments.

This work was supported by the Office of Nondestructive Evaluation.

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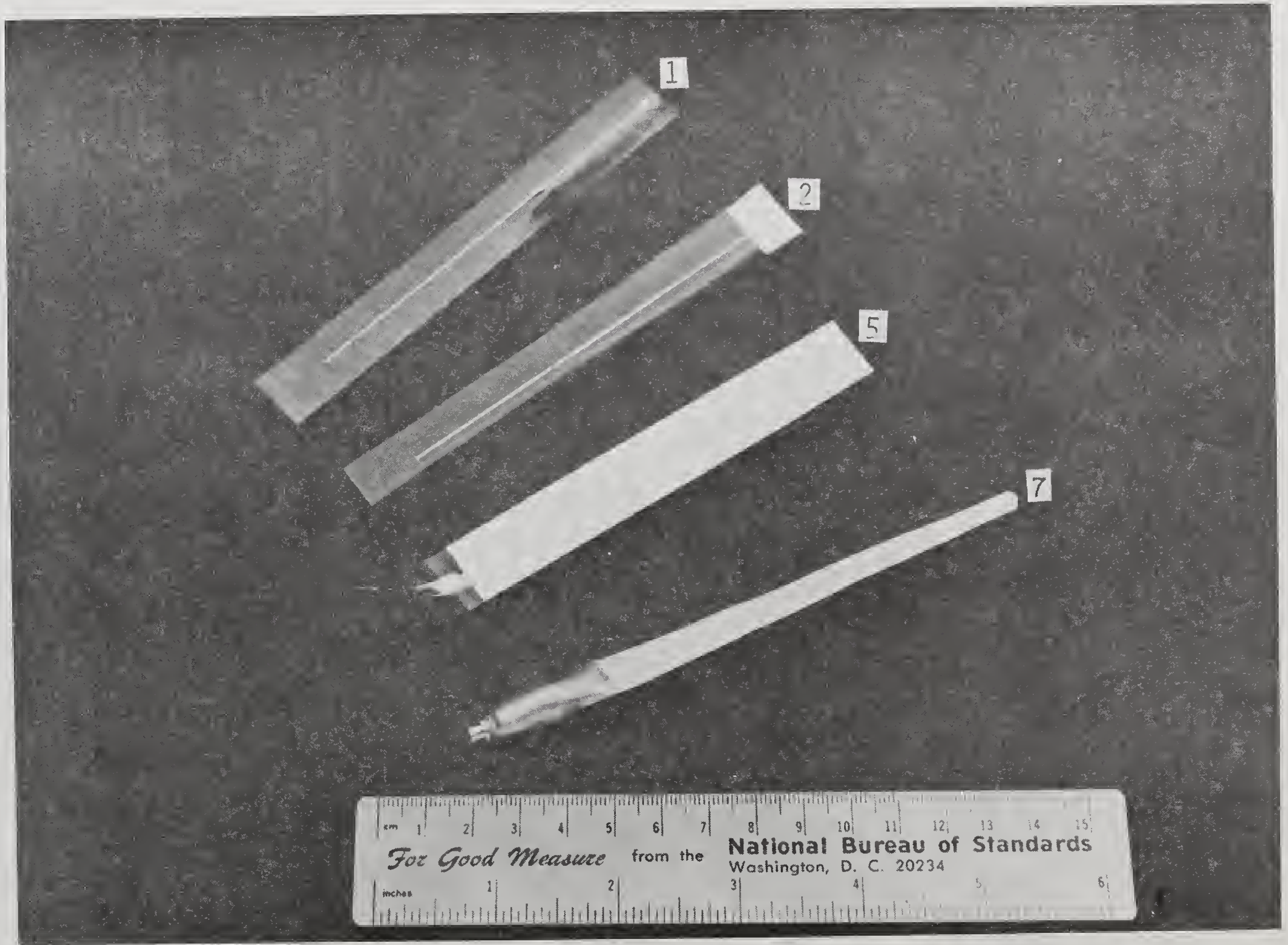


FIGURE 1. SELECTED STEPS IN THE FABRICATION OF A POLYMER GAGE. THE NUMBERS CORRESPOND TO STEPS IDENTIFIED IN THE TEXT (SECTION 2).

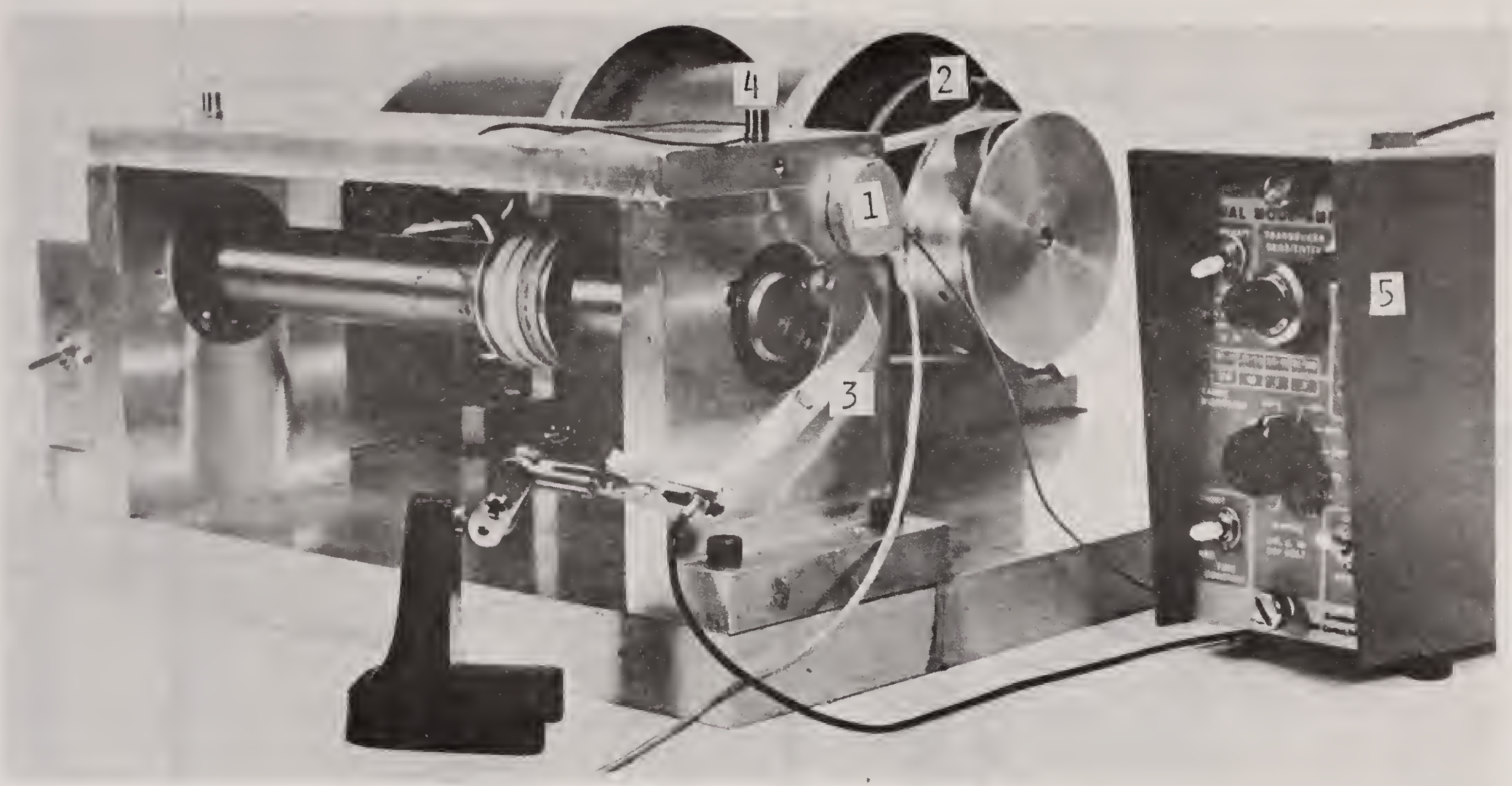


FIGURE 2. TEST APPARATUS FOR STUDYING GAGES AS BEARING MONITORS. IDENTIFIED ARE 1) PZT DRIVER, 2) DRIVE MOTOR, 3) POLYMER GAGE, 4) ACCELEROMETER, AND 5) CHARGE AMPLIFIER.

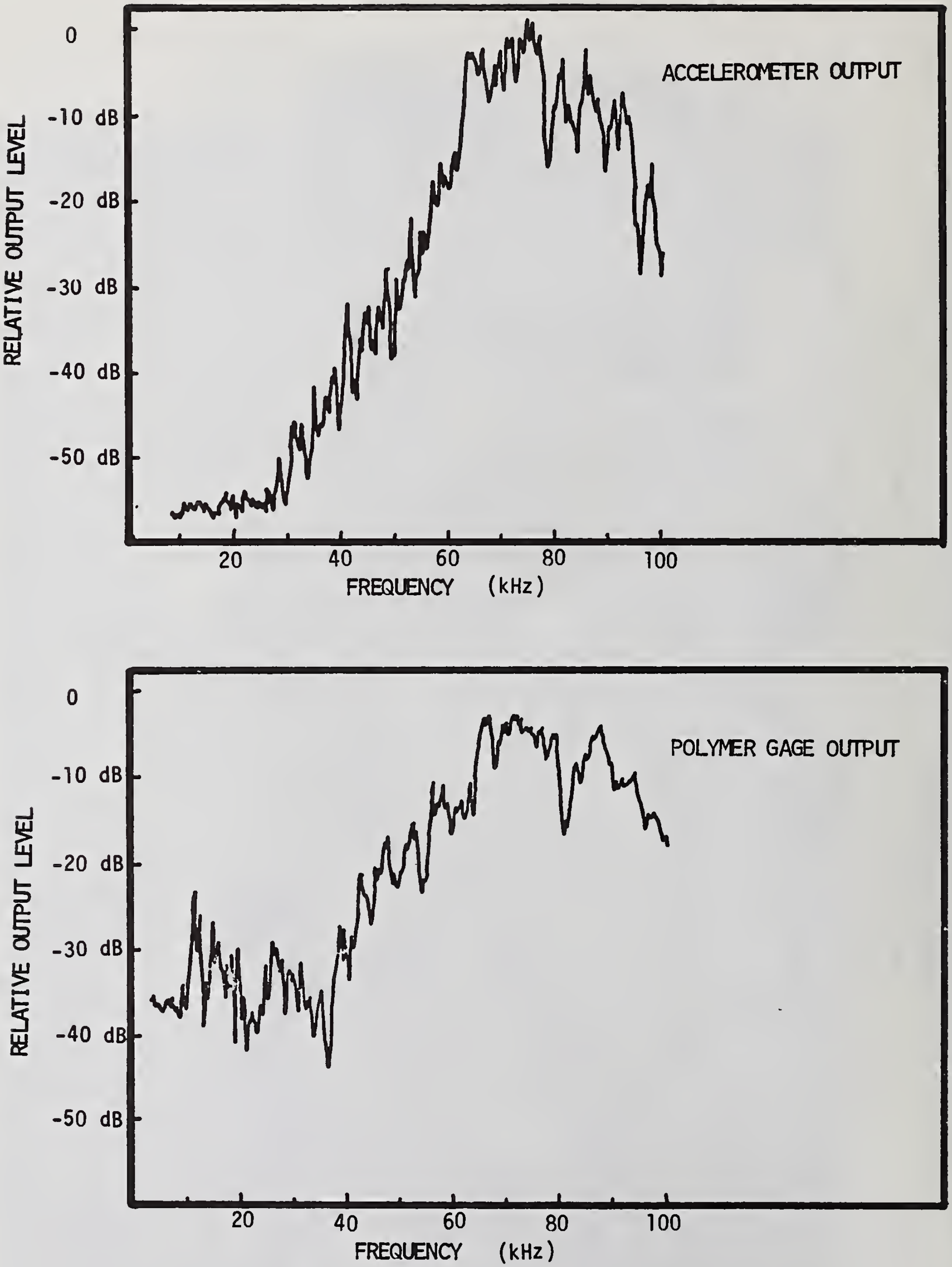


FIGURE 3. OUTPUTS OF ACCELEROMETER AND POLYMER GAGE IN RESPONSE TO EXCITATION BY PZT DRIVER, AS A FUNCTION OF FREQENCY.

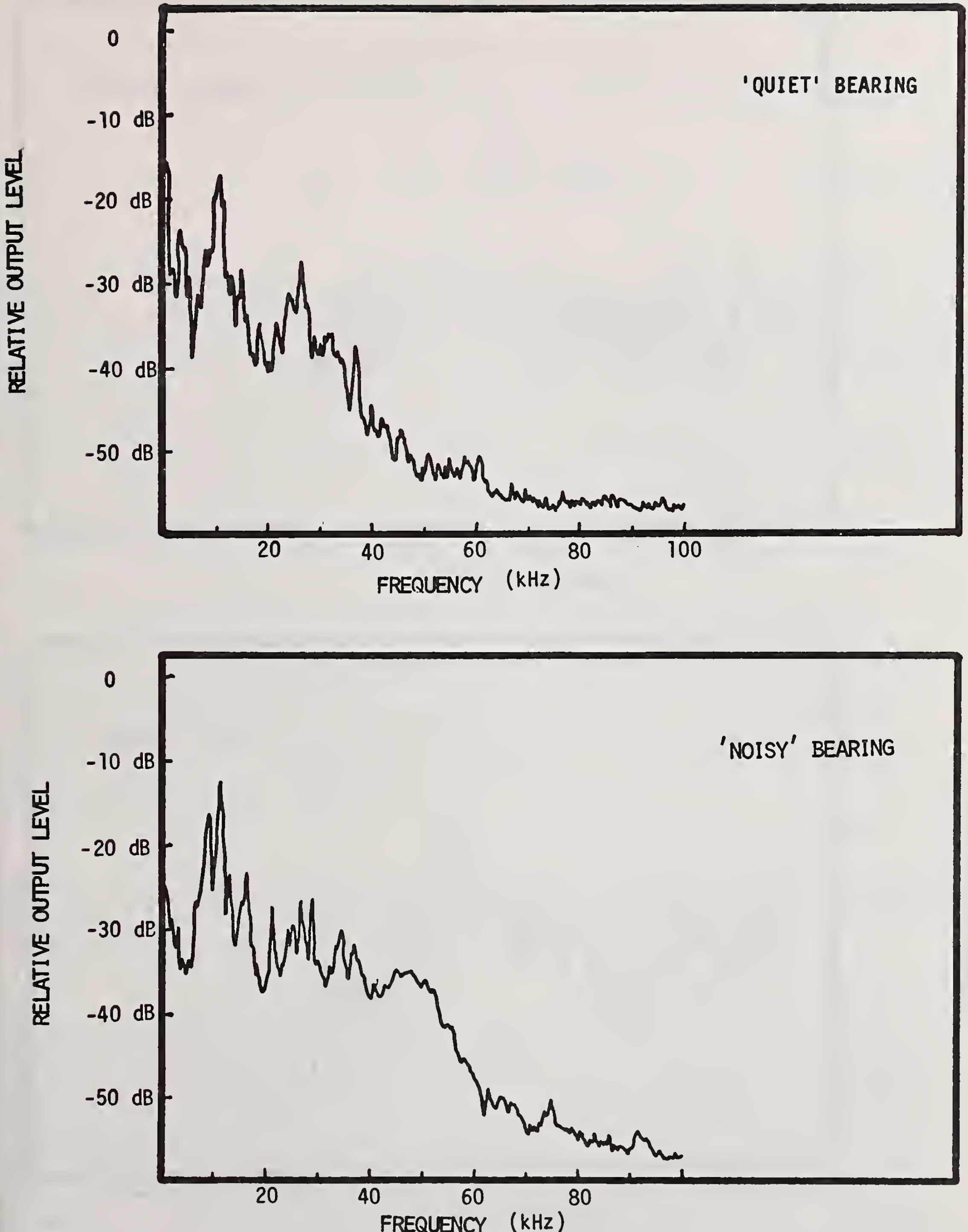
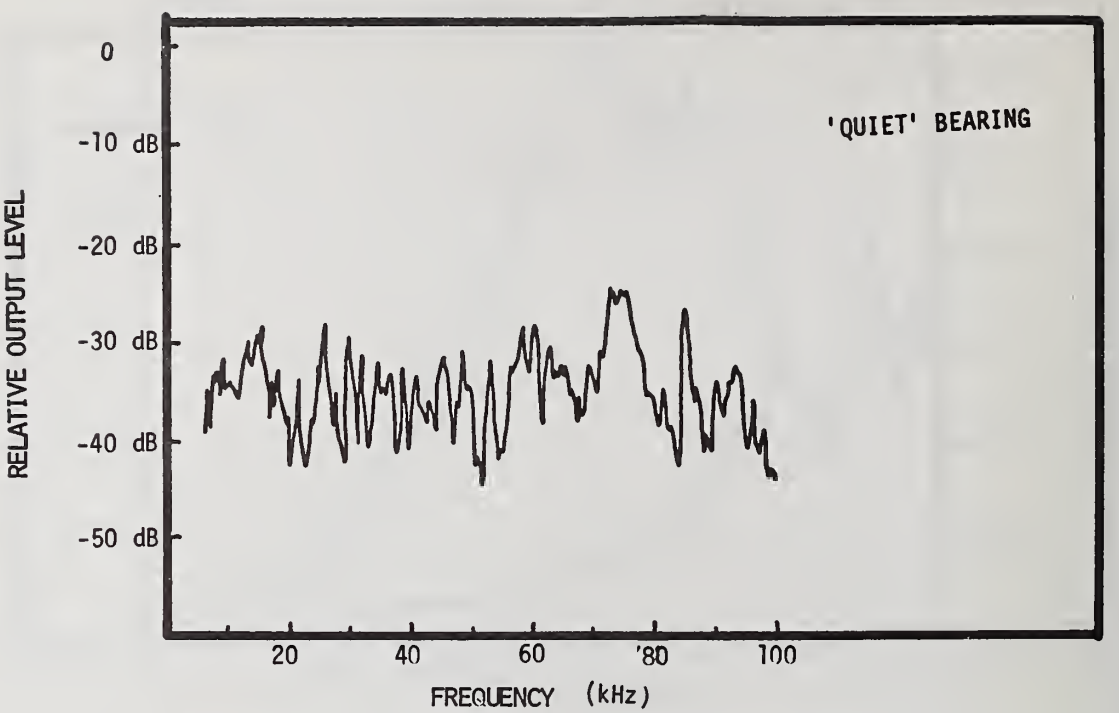


FIGURE 4. POLYMER GAGE OUTPUTS IN RESPONSE TO SIGNALS FROM BEARINGS AS A FUNCTION OF FREQUENCY.



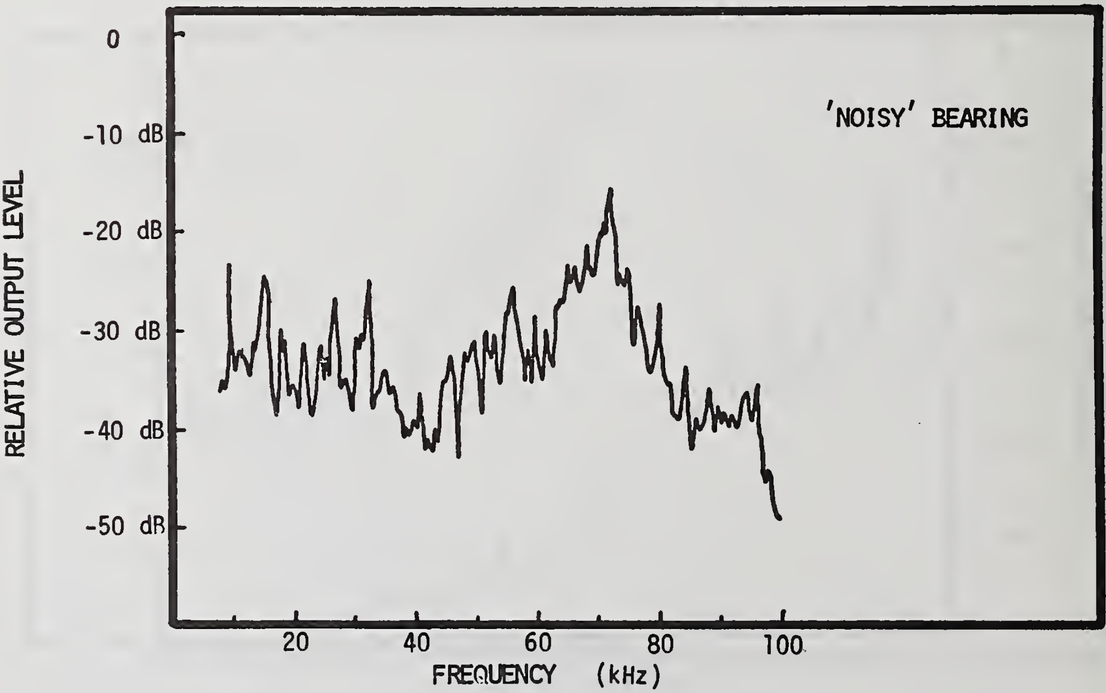


FIGURE 5. ACCELEROMETER OUTPUTS IN RESPONSE TO SIGNALS FROM BEARINGS AS A FUNCTION OF FREQUENCY.

AN INSTRUMENTATION TECHNIQUE TO EVALUATE SPECTRA FOR ENGINE DIAGNOSTICS

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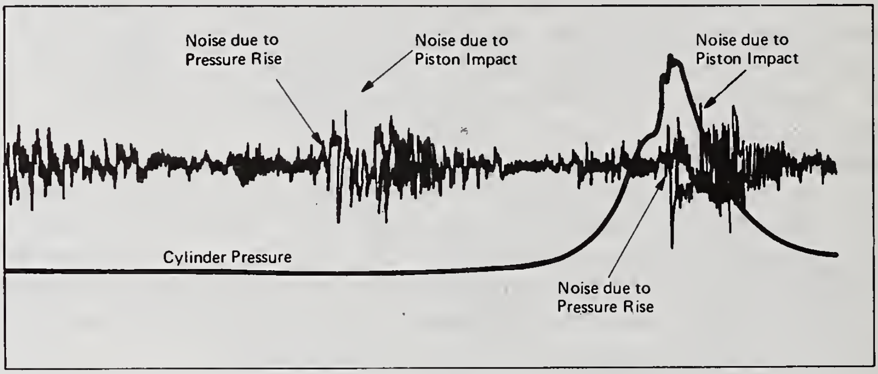
Abstract: This paper describes a method of using a digital frequency analyzer as a "sliding time gate" when analyzing complex time signatures (e. g. as those produced by reciprocating machines). To isolate individual events such as valves opening and closing, firing and exhaust pulses, rather than take a composite frequency analysis of the complete engine signature produced during one rotation, implies a triggered, movable, variable width window which can be used to view each occurrence. Timing can be with reference to any arbitrary occurrence during a cycle, but a known reference such as Top Dead Center (TDC) is normally used. An integral part of any flexible Digital Narrow Band Analyzer should be the settable After Trigger Recording facility allowing the memory contents to be locked at any time relative to an incoming trigger pulse. If the incremental settings available on the After Trigger Recording are sufficiently small, this will enable the memory length to be used as a window to look at any part of the incoming time signal. A triggerable Gating System with variable delay and window length will also be described. The results gathered from using the technique on a marine diesel engine will be presented.

Key words: Gated frequency analysis; Gaussian window; Impulsive, complex signals; Linear averaging; Reciprocating; Records after trigger; Tape loop; Time signal; Time window.

Complex, impact-like time signatures are common occurrences in nature. The pumping action of the human heart, the punch press in a busy machine shop and, of course, the structural vibration and cylinder pressure and temperature variations during the operating cycle of reciprocating machines are typical examples. The time signal for any one revolution is very complex in the last instance because of the different exciting forces experienced. These are basically the primary force (the cylinder gas force due to combustion or compression), the secondary forces (the crank mechanism, and piston, ring, bearing and timing gear impacts), and the forces generated in ancillary machinery (generator, water pump, valve gear, etc.).

The impulsive signals produced by the combustion process are very low in repetition rate compared to the natural frequencies of the stiff engine structure. A four-stroke engine will have a firing rate on one cylinder somewhere between 5 and 25 times per second for a speed range of 600 to 3000 RPM. Engine block and structural resonant frequency components will be in the 800 to 2000 Hz region. Signal pickup can be by a variety of transducers, but most commonly the acoustic signatures (using a good measuring microphone), cylinder head vibration signatures (using a high quality accelerometer), or cylinder pressure signatures are taken. Each of these is normally related to a "once-per-rev." tachometer signal located at some convenient part of the mechanical cycle (e. g. TDC), since each occurrence is uniquely time related to the instantaneous flywheel position. Certain occurrences such as cooling fan noise, coolant cavitation, turbocharger noise are either non-integrally related to the rotational speed or entirely dependent on other phenomena (e. g. exhaust gas velocity).



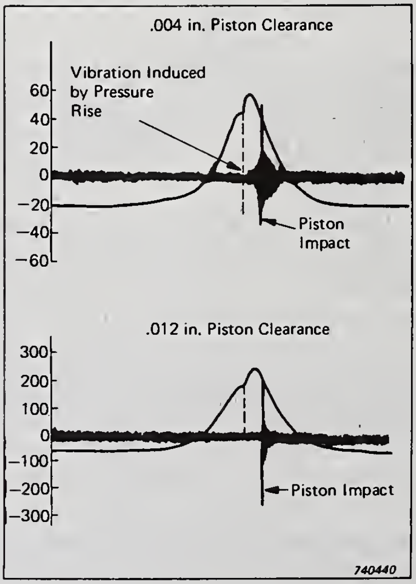
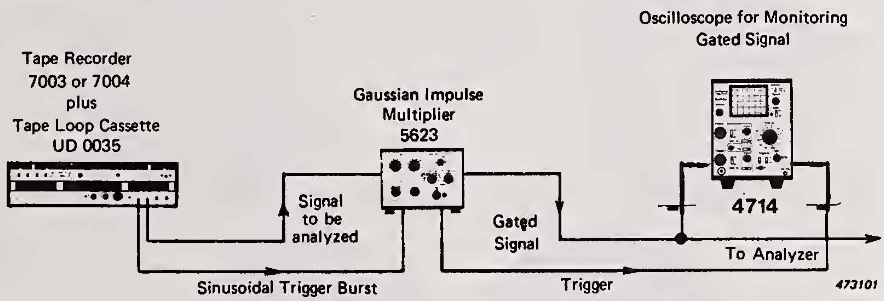


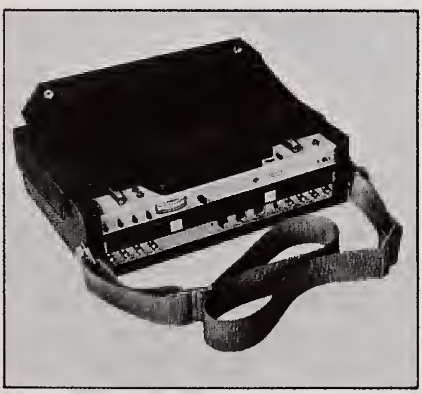
Fig. 1

To date, most diagnostic techniques are associated with relating occurrences on the complex time history to engine timing marks (Fig. 1). Much experience has been gained in this way, but techniques do now exist to further extend this valuable technique.

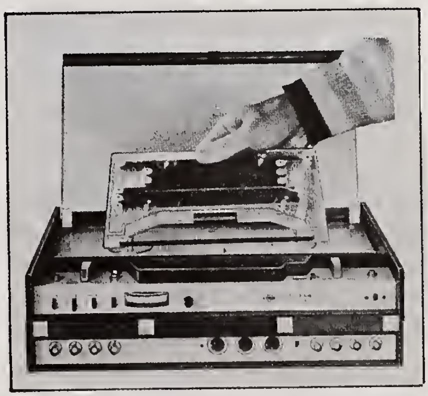
An example of the usefulness of the time-signal analysis technique is shown, relating tight and loose piston clearances. The impact noise signal produced by the piston slap is easily identifiable. However, this type of analysis precludes the use of the frequency domain. A doctor listening to a heartbeat with a stethoscope does not only hear a distinct level but does a running series of Fourier analyses of the signal in his mind. He listens for the low steady "thump-thump" but also for, say, higher frequency flutter noises associated with "leaky" valves; each noise telling him a different story. This series of frequency responses has up to now only been possible with the use of complex electronics.



Use of the Gauss Impulse Multiplier Type 5623 for gating signals recorded with the 7003 or 7004 Tape Recorders



One of the recorders fitted with carrying case and shoulder strap



Tape Loop Casette Type UD 0035 being fitted to one of the tape recorders

Fig. 2

A system developed by B & K Instruments some years ago uses a Gaussian shaped "time window" to slide along a repeated time signal. Each repetition was gated at a slightly different point with respect to the previous point, and a frequency analysis was made of the output of the gate.

The instrumentation required is shown in Fig. 2, and some typical outputs from the Gaussian Impulse Multiplier are shown in Fig. 3.

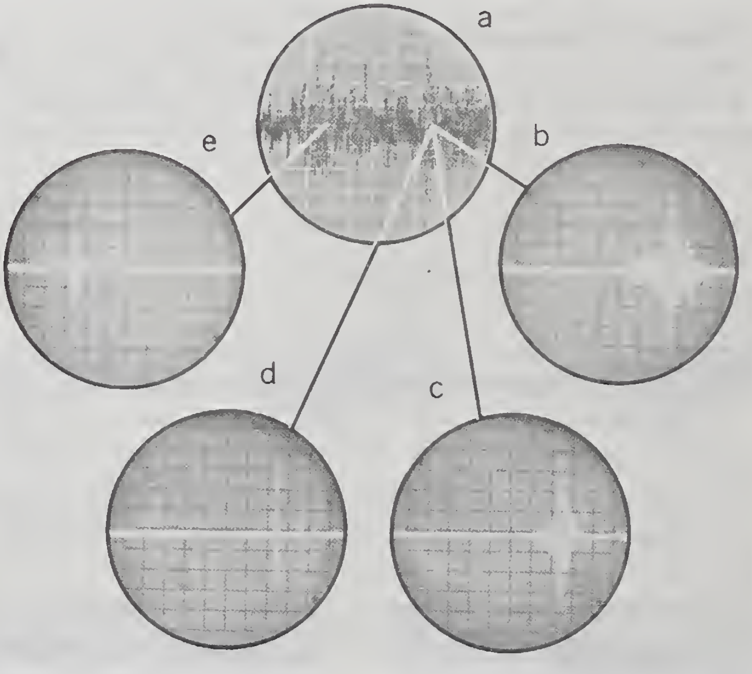


Fig. 3

The Gaussian Impulse Multiplier pulls out individual portions of the signal and allows each to be frequency analyzed separately. Without this facility the spectrum obtained would be a smeared amalgamation of all of the separate events occurring in the signal.

The important factors to note are that 1.) the signal to be analyzed must be repeated through the analyzer a number of times (this can be by natural repetition if the signal is fully repeatable or by use of a Cassette Tape Loop addition to an Instrumentation Tape Recorder, as shown in Fig. 2); 2.) the window can be placed anywhere in the time history under review and 3.) the width of the gate is variable allowing greater or less resolution of separately occurring events.

Updates of the technique first included replacing the Tape Recorder by a Digital Transient Recorder, but the most recent advance has been to use the Digital Narrow Band Spectrum Analyzer Type 2031. This consists of a 1024 point digital memory to store the sampled input analog signal and an FFT processor to transform from the time to the frequency domain. The time history length contained in the memory depends on the sampling rate, which in turn defines the upper frequency of the analysis. The memory length can be selected from 40 s to 20 ms, covering a 0-10 Hz frequency range to a 0-20 kHz frequency range, in a 1-2-5 sequence. External sampling facility is also available for other memory lengths. The change in memory length is equivalent to varying gate widths.

Positioning of the "gate"relative to a known point on a flywheel is done using the Records After Trigger facility. If the initiation of a frequency transformation is delayed with respect to the trigger signal, the 2031 Spectrum Analyzer will continue to input data during the delay. The Records After Trigger (R.A.T.) can be varied in 0.1 increments from 0.1 to 9.9 times memory length.

The window shape used is not Gaussian in this case but is a Hanning window. The slight degradation of overall filter selectivity is acceptable because of the simplification of the hardware used.

The 2031 Spectrum Analyzer has a very significant advantage over previously used techniques in that it has a Linear Averaging mode allowing the Tape Loop to contain a number of firing pulses and "once-per-rev." trigger signals. Each firing pulse is slightly different, but since they are analyzed at the same instant relative to the trigger pulse, an averaging technique can be applied to enhance the repetitive and remove the randomness.

A practical measurement was made of a marine diesel engine rotating at 60 RPM. Each cycle is approximately 1025 ms long and using the 200 ms memory length with the Hanning weighting gives an effective window width of 100 ms. The signal duration was approximately 5.1 memory lengths and incremental steps of 0.3 memory lengths were chosen for the analysis. A Linear Average of 16 spectra was made at each R.A.T. position. The results are shown in Figures 4-a and 4-b. The signal can be seen to be characterized by an initial high frequency component and later by a low frequency spike.

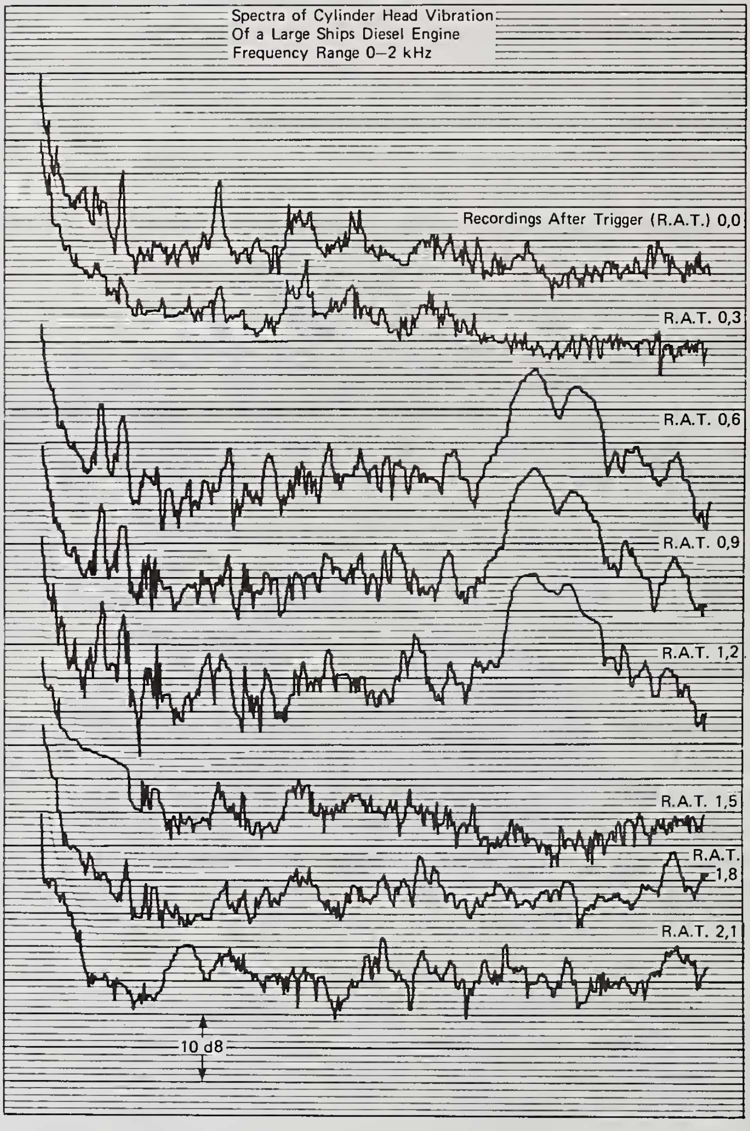


Fig. 4-a Spectra of cylinder head vibration of a large ship's diesel engine

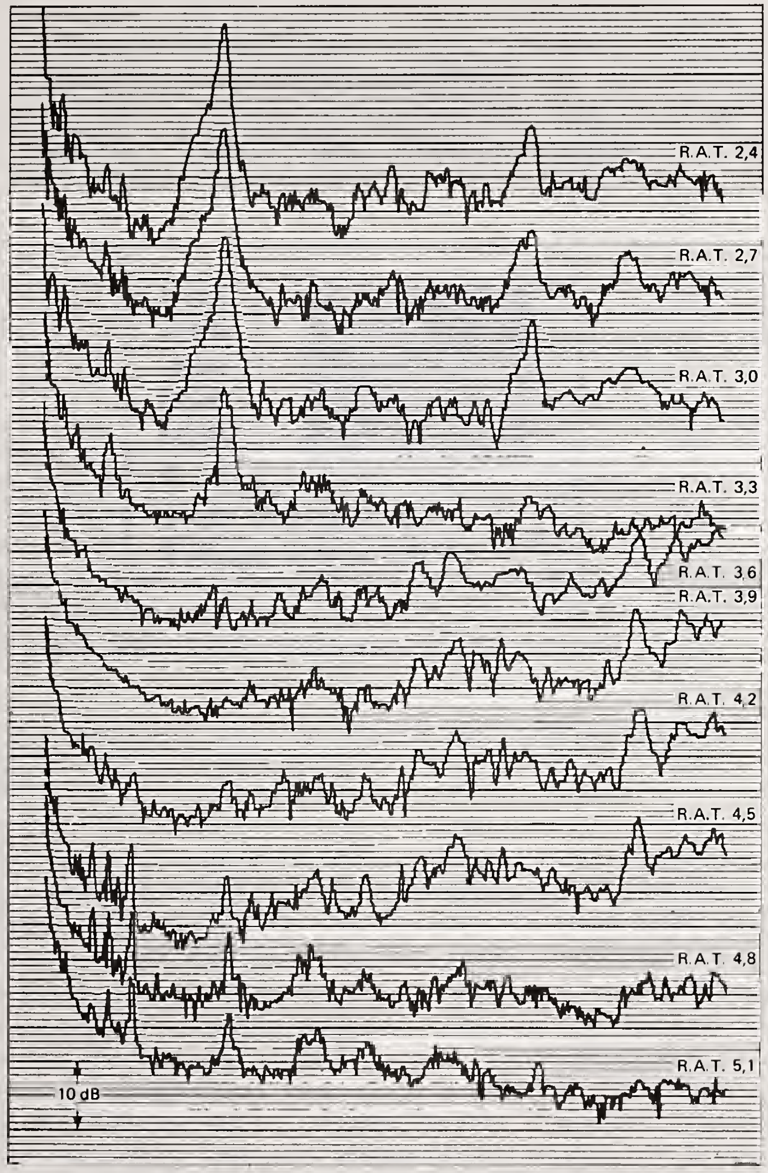


Fig. 4-b Spectra of cylinder head vibration of a large ship's diesel engine (cont'd)

Conclusions.

Use of modern Spectrum Analyzers with flexible Records After Trigger control allows a new dimension in reciprocating machine analysis. Sophisticated and flexible analysis set-ups can be made using the IEEE bus interfacing capacity of an analyzer such as the 2031 Digital Spectrum Analyzer together with a desk top calculator to control the analysis procedure.

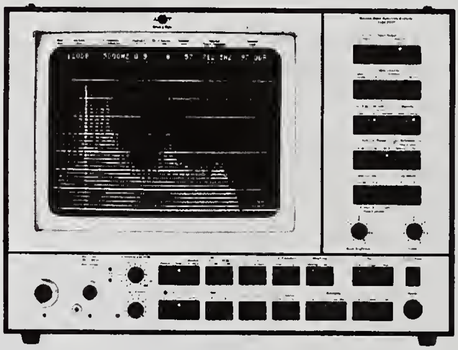


Fig. 5 Narrow Band Spectrum Analyzer Type 2031

THE DIRECT READING FERROGRAPH

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Abstract: The principle of operation, design, calibration, and a field application are discussed for the direct reading ferrograph, a system for rapid on-site monitoring of wear in oil-lubricated machinery. The principle of operation is the magnetic precipitation of wear particles from an oil sample within a glass tube. Light attenuation measurements at two cross sections of the glass tube provide a measure of large and small wear particles present in the oil sample. Oil samples resulting in high severity of wear indices may be further scrutinized by analytical ferrography. Calibration of the direct reading ferrograph was performed with known weight concentration samples of ferrous wear particles generated in a gear box. Comparison of direct reading ferrograph data to spectrometric data for the same oil samples is made. A typical field application and results are discussed.

Key words: Ferrography; machine condition monitoring; oil analysis; oil sampling; wear; wear particles.

Introduction: Ferrography (1), a technique to separate particles from fluids for microscopic examination and subsequent analysis, was originally developed to magnetically precipitate ferrous wear particles from lubricating oils, thus the name ferrography. The first application was to condition monitor military aircraft engines, but now other applications have emerged, including modification of the method to precipitate non-magnetic particles from both oil and other fluids. This is of interest for hydraulic systems where particles of non-magnetic material, such as bits of seal material, found in the hydraulic fluid, may indicate impending failure. Recent research on particles found in the synovial fluid, or lubricating fluid of human joints, offers new understanding of joint diseases, such as degenerative arthritis, offers the ability to monitor joint implantments and may result in bioengineering improvements. However, established applications are for failure prevention in jet engines, diesel engines, transmissions, bearings, and similar oil-lubricated machinery.

The Ferrograph: Two instruments are available for ferrographic analysis. The direct-reading (DR) ferrograph (2) provides information on the concentration and size distribution of fluid borne wear particles. The

DR ferrograph is used for routine machine monitoring and for sample screening prior to preparation of a ferrogram. The analytical ferrograph is used to prepare a ferrogram which is subsequently examined using a bichromatic microscope.A ferrogram,Figure 1,is prepared by pumping fluid through teflon tubing by means of a peristaltic pump onto specially prepared microscope glass which has a non-wetting barrier painted on one surface to centrally channel the liquid. The ferrogram is slightly tilted, with the entry end elevated, so that the fluid flows downward within the oval ended barrier to a drain tube which delivers the oil to a waste bottle. The ferrogram is mounted above two permanent magnets which are separated by an aluminum sheet about 1/16" thick. The ferrogram is positioned such that the separating aluminum sheet is under the middle of the fluid channel of the Ferrogram. The magnets are separated with their magnetic poles counterposed; that is, where one magnet pole is considered north, the other magnet across the aluminum strip is south, such that a strong magnetic field gradient is created in the vertical direction above the aluminum strip. Magnetic particles in the fluid experience a strong downward force. These particles migrate through the fluid down to the glass surface where they are deposited in strings perpendicular to the direction of fluid flow. The strings are formed because particles align themselves with north to south pole, etc. The strings are separated from each other by some distance because the particles will be mutually repulsed if an aligned particle is pulled down directly above another aligned particle. After all the fluid in a given sample has been run across the ferrogram, a fixer solution is run across the ferrogram to remove residual fluid. After the fixer dries, which takes a few minutes, the ferrogram is ready for observation using the microscope.

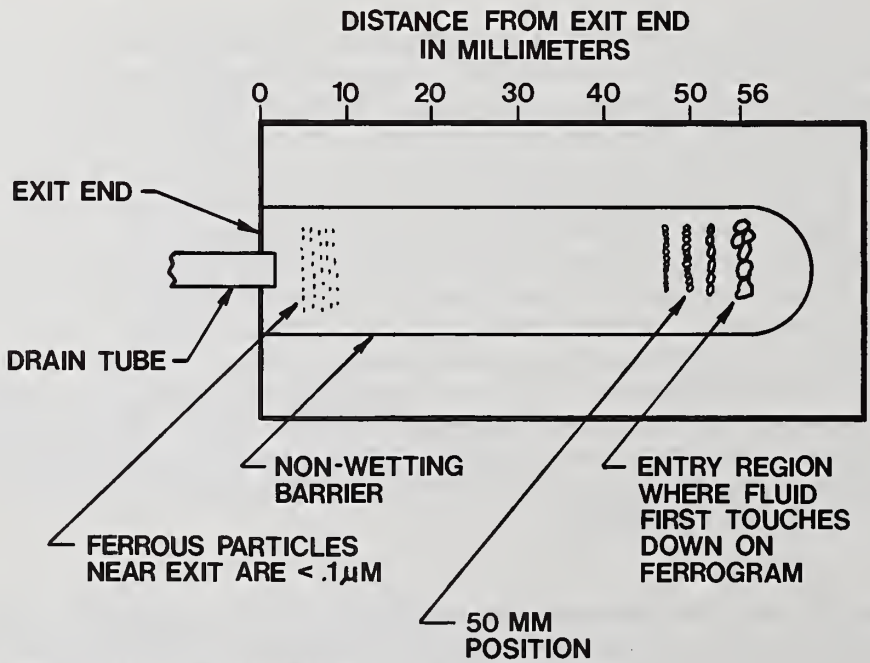

Figure 1. Particle Deposition on a Ferrogram

The Microscope: A special microscope is used to examine ferrograms equipped with both reflected and transmitted light sources which may be used simultaneously. This combines features of a biological microscope with those of a metallurgical microscope. A recommended method for sorting out metal particles from compounds, organic material, etc., is to use red reflected and green transmitted light. This lighting scheme, called bichromatic illumination, will show metal as red and non-metal as green. Polarized light may be used for either light train as well. Metallurgical (dry) objectives are used. The microscope is also equipped with camera attachments and a ferrogram reader, which provides a mechanically determined light extinction measurement which corresponds to particle concentration at various locations on the ferrogram.

Particle Deposition: Ferrous particles are deposited on a ferrogram according to size because the force acting on a particle is proportional to volume whereas the viscous resistance of the suspending fluid is proportional to surface area. Therefore, for spheres, force increases with the cube of the diameter but resistance increases only with the square of the diameter. The largest ferrous particles are therefore deposited at the entry region of the ferrogram where the fluid, such as lubricating oil, first touches down on the glass surface. Figure 1 indicates a typical deposition pattern, although individual particles cannot be seen with the naked eye. At a position further along the ferrogram, all ferrous particles larger than a characteristic size will have already been precipitated. Near the exit end of the ferrogram, ferrous particles greater than about .02μm (20 nanometers) will have been precipitated. For non-ferrous particles, such as aluminum, brass, white metal, etc., precipitation will occur because these materials are weakly magnetic. However, the deposition of these materials will be less size selective. Consequently, large particles of non-ferrous metals may be found anywhere along the length of the ferrogram.

The Particles of Wear: Examination of the ferrogram in the bichromatic microscope reveals details of size, shape, and quantity of particles from which the condition of oil-lubricated parts may be assessed (3). Machines operating normally usually generate small flat particles at a slow steady rate. If the number of particles increases, and particularly the ratio of large or small particles, it is an indication that a more severe mode of wear has begun. The generation of large severe wear particles signals the imminent failure of the wearing surface. Abrasive wear, which is analogous to a crude machining process, generates particles in the form of loops, spirals, and bent wires. Increase in the number and size of these particles shows that an abrasive wear mechanism is progressing rapidly.

Various mechanisms generate characteristic particles. Six regimes of wear have been identified with sliding wear (4). Miscellaneous shaped particles are associated with break-in wear. Small platelets are associated with normal rubbing wear. As operating parameters become more arduous, the metallic rubbing wear particles increase in size, become oxidized, and finally, just prior to failure, large metallic severe wear particles are produced.

Three types of particles are associated with rolling mechanisms. These are spheres, fatigue chunks and laminar particles. Spheres are generated as microcracks open up on rolling surfaces. Fatigue chunks represent material removed as rolling elements spall. Laminar particles, which are large, very thin platelets, result from material being passed through the rolling contact.

Combined rolling and sliding, as in gears, produces scuffing particles and fatigue chunks. Lubricant starvation will result in partially oxidized wear particles.

Elemental Identification of Particles: Determination of the composition of particles can establish their origin. The site of deposition, reflectivity, and color of particles aid their identification. If available, energy dispersive x-ray analysis in conjunction with a scanning electron microscope can establish elemental composition. Otherwise, a simple heating of the ferrogram will allow categorization into broad alloy classes by examination of oxide layer (temper) colors (5).

The Direct Reading Ferrograph: There is general agreement among researchers investigating wear that the particle concentration and size distribution are critical indicators of machine condition. As a machine runs, particle concentration in the oil increases until the loss rate equals the generation rate. For many machines, the time for this to occur is relatively short. If the probability for any one particle being lost or destroyed is independent of the presence of other particles, the loss rate is proportional to the concentration. It can be mathematically demonstrated that the particle concentration in the oil of any machine reaches an equilibrium concentration (6) if it is assumed that particle removal mechanisms such as sedimentation, filtration, and impaction are proportional to the number of particles present. For example, in certain jet engines, equilibrium takes about 20 minutes to establish. If wear increases, the particle concentration during dynamic equilibrium will be greater. The onset of severe wear is accompanied by an increase in the number of large particles, which causes the ratio of large to small particles to increase. The direct reading ferrograph provides the necessary information about particle concentration and size distribution to indicate a changing wear situation.

Design: Experience with analytical ferrography, where optical densitometer readings of particle deposits are taken in conjunction with the bichromatic microscope, indicated that the entry point of the oil sample onto the ferrogram, where the largest particles are deposited, and a position some 5 mm down from the entry, where 1 - 2 μM size particles are deposited, are the most sensitive locations for detecting a changing wear situation. Accordingly, the direct reading ferrograph was designed to quantify particles in these two size ranges. The same criteria also apply to the on-line ferrograph, a compact, microprocessor controlled instrument intended for airborne use, which is currently under development.

As shown in figure 2, oil from a sample is siphoned through a precipitator tube, where a magnet assembly located beneath the tube precipitates the wear particles according to size. Virtually all unwanted carbon dirt particles are not precipitated, but are carried away by the oil.

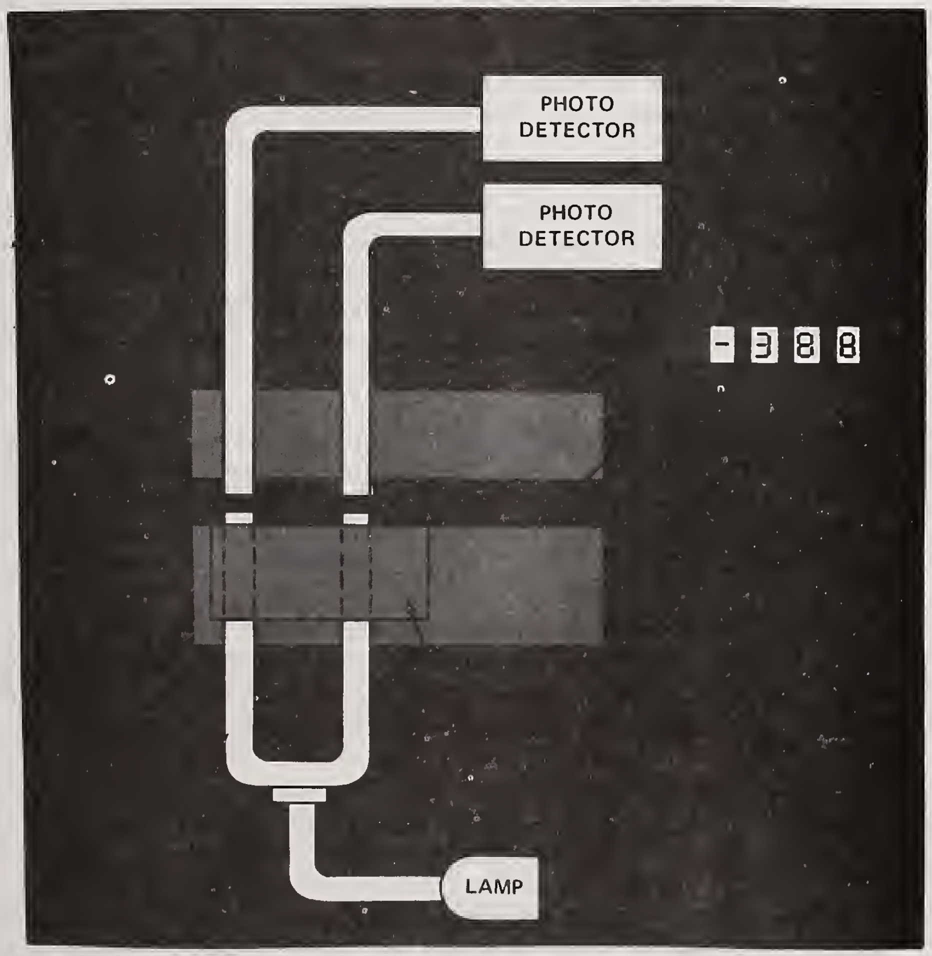

Figure 2. Schematic of a direct reading ferrograph optical system.

The large particles are deposited first and the smaller ones further down the tube. Two light beams pass through the precipitator tube. The first beam is located near the tube's entry where the larger (L) particles (>5 μM) are deposited, and the second beam crosses the tube where the smaller (S) particles (1 to 2 μM) are deposited. The reduction in light intensity indicates the amount of wear particles deposited at each location. The level of light is sensed, amplified and displayed in terms of units on a digital meter. The digital meter has a range of 0 to 190 units, where a reading of 100 units, which corresponds to approximately one-half of the area covered, is the recommended upper limit because, for readings greater than 100, the instrument response is nonlinear due to coincidence effects; that is, particles pile on top of one another so that less light is attenuated. A switch allows selection of either the L reading or the S reading.

So that variations in oil opacity will not affect the readings, the sample oil is stopped just after it enters the glass precipitator tube while two potentiometers are adjusted to bring the L and S readings to zero. Two neutral density filters are included with the instrument to allow periodic calibration checks. By inserting one of the filters in the light path, without the precipitator tube in place, a reading within a certain range will result if the instrument is functioning properly.

Interpretation of Results: Recommended sample volume is 1 cm^3. If too many particles are deposited, the sample must be diluted so that the ferrograph readings are within range. Occasionally, oil samples are encountered which result in low readings, in which case the operator may choose to run a greater sample volume than 1 cm^3 so that enough particles are precipitated.

The readings obtained from the instrument are assigned the terms D_L and D_S, for the large particles and small particles, respectively. The normal wear process generates particles with a maximum size of 15 μM, the majority of which are 2 μM or less. Any abnormal wear mode generates particles larger than 15 μM.

In view of this, for normal wear processes, D_L would be similar to D_S. In practice, D_L is slightly greater than D_S. However, for abnormal wear, D_L will be significantly larger than D_S. Consequently, the parameter $D_L - D_S$ may be used as an indicator of abnormality.

The onset of an abnormal wear mode results in a significant increase in the quantity of wear debris. To indicate an increase in particle concentration, the term $D_L + D_S$ may be used.

A single parameter, sensitive to the onset of severe wear, the product of $D_L - D_S$ (severity) and $D_L + D_S$ (quantity) may be used. This quantity, termed the severity of wear index, I_s, is $I_s = (D_L - D_S)(D_L + D_S) = D_L^2 + D_S^2$.

Since different machine lubrication systems exhibit extreme variations in both particle concentration and size distribution, it is impossible to use I_s as an absolute quantity. Instead, the user must establish what normal running values of I_s are for each machine he intends to monitor. When comparing I_s between samples, it is important that reference be made to the sample volume passed through the instrument. From a practical standpoint, if the readings are reported as nD_L and nD_S, where n is the dilution factor (it will be a fraction if more than 1 cm^3 of sample is used), then $I_s - (nD_L)^2 - (nD_S)^2 = n^2 (D_L^2 - D_S^2)$, and I_s will be comparable for samples run with different dilutions.

Instrument Calibration: Samples of known weight concentration of ferrous wear particles were prepared and subsequently analyzed by the direct reading ferrograph. These tests were run in order to obtain a calibration of the instrument in which the iron in the oil was weighed by a balance. The data generated during these tests is available elsewhere (2) and will be provided by the author upon request. These tests demonstrated that the direct reading ferrograph responded linearly to wear particle gravimetric concentration within the recommended operating range and produced results consistent with spectrometric oil analysis.

Applications: Certain applications of ferrography have been discussed in the literature such as gas turbines (7), (8), diesel engines (9), and gear boxes (2). Ferrographic analysis service is offered at several commercial oil analysis labs including the author's lab. Certain other applications such as oil additive optimization and military condition monitoring have not been publicly discussed for obvious and justifiable reasons.

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(2) D.P. Anderson and R.S. Silva, "The Direct Reading Ferrograph - Design, Calibration, and a Field Application" presented at the 33rd Annual Meeting of the American Society of Lubrication Engineers, April 17 - 20, 1978, Preprint No. 78-AM-1A-1.
(3) E.R. Bowen and V.C. Westcott, "Wear Particle Atlas", prepared for the Naval Air Engineering Center, Lakehurst, New Jersey, under Contract No. N00156-74-C01682, July, 1976.
(4) A.A. Reda, E.R. Bowen, and V.C. Westcott, "Characteristics of Particles Generated at the Interface between Sliding Steel Surfaces", Wear, 34, (1975) 261 - 273.
(5) F.T. Barwell, E.R. Bowen, J.P. Bowen, and V.C. Westcott, "The Use of Temper Colors in Ferrography", Wear, 44 (1977), 163 - 171.
(6) D.P. Anderson and R.D. Driver, "Equilibrium Particle Concentration in Engine Oil", submitted to Wear magazine for publication.
(7) D. Scott and V.C. Westcott, "Predictive Maintenance by Ferrography" Wear, 44 (1977), 173 - 182.
(8) D. Scott, P.J. McCullagh, and G.W. Campbell, "Condition Monitoring of Gas Turbines - An Exploratory Investigation of Ferrographic Trend Analysis", Wear, 49, (1978), 373 - 389.
(9) M.V. Hofman and J.H. Johnson, "The Development of Ferrography as a Laboratory Wear Measurement Method for the Study of Engine Operating Conditions on Diesel Engine Wear", Wear, 44 (1977), 183 - 199.

AN ADVANCED REAL-TIME OIL DEBRIS MONITOR

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Abstract: Diagnostic methods based on oil sampling tend to disregard the fact that particles larger than 200 microns are reliable indicators of incipient failure. This is confirmed by the success of diagnostic methods which utilize visual inspection of lube system filters and of magnetic chip collectors. Apart from the morphology of such particles, these methods rely on correlating the particle size and quantity with data obtained from previous experience.

TEDECO has developed an in-line centrifugal oil monitor which separates debris particles above 100 micron from the oil stream and deposits them on a magnetic sensor. Each particle is counted individually in accordance with its mass, magnetic susceptibility and shape. Digital circuitry registers and stores each event and permits calculation of debris production rates. The debris is retained and easily accessible for visual inspection.

A number of such systems are currently undergoing field evaluation on an Air Force TF-39 engine, on a Navy LM-2500 engine and on a Westland Lynx helicopter transmission.

A similar system tested during the Army AIDAPS program on a transmission implanted with defective parts confirmed the soundness of this diagnostic approach.

Key words: Aircraft component failure; condition monitoring; failure detection; diagnostic techniques; debris monitoring; lubrication system monitoring.

The propulsion system of a helicopter is highly decentralized. It usually consists of one or two engines, a main rotor transmission, an intermediate and a tailrotor gear box (Figure 1). Larger helicopters have even more complex and dispersed drive systems. Each component has its own, self-contained lubrication system. The engine and transmission lubrication systems are of the circulating type and have filters, coolers and pumps, while the intermediate and tailrotor gear boxes are usually sump lubricated. Despite these differences, an integrated helicopter lube debris monitoring system should detect failures in each component with equal reliability. In fact, a failure in the tail rotor drive system is often more critical than a failure in an engine or in the transmission, since it can cause loss of control over the aircraft. An advanced helicopter condition monitoring system should therefore consist of relatively inexpensive peripheral sensors and a central signal processing system.

By comparison, a gas turbine engine has a centralized lubrication system (Figure 2). The oil returning from the individual shaft bearings and from the accessory drive module combines on its way back to the reservoir. Since each of these mechanical components is equally critical, a modern gas turbine engine frequently has one full-flow debris monitor in the main scavenge line. For failure isolation on the ground, magnetic chip collectors are installed in the individual bearing and gear box sumps or in their scavenge return lines.

An additional challenge to the lube debris monitoring system is the variety of materials and failure modes of oil wetted drive system components. Each engine and transmission may behave differently with respect to its predominant failure modes. This is especially true for immature systems. They frequently have peculiar failure modes which are not of the surface-fatigue or corrosive wear type but involve cracking or abrasive wear. Since these failure modes tend to reduce mean component life substantially, efforts are generally made to eliminate them through design changes during the development of the aircraft.

Surface-fatigue type failures, scuffing and corrosive wear are the most frequent wear modes. Extensive experience with many jet engines in service with certain European airlines[1)] indicates that invariably such failures are characterized by particles of steadily increasing mean size and by increasing debris production rates. Even corrosive wear by itself may not produce large debris particles, the local loss of the oil film subsequently leads to other wear modes which do.

Figure 3 shows a model for development of the wear particle spectrum with time during a surface-fatigue type failure. Initially, while operating conditions are still normal, a steady "background" of small to medium-sized wear particles is produced.[2)] Some isolated large particles may also be generated from time to time, either as machining debris left in the engine or from burrs and other macroscopic component flaws.

As a failure develops, the debris production rate and the mean particle size increase. The European airline experience cited earlier relies completely on the appearance of ferrous debris particles 1000 micron in size and larger on magnetic chip collectors which are sampled at regular intervals. At British Airways, this has been a completely reliable, systematized and fully documented failure detection system for many years.[3)] Further clues for failure location and severity are obtained from particle morphology by microscopic analysis and, sometimes, electromicroscopic analysis. Similar data have been generated by the U.S. Army Research and Development Laboratory Ft. Eustis.[4)]

The experience with the General Electric T-700 engine has also demonstrated the soundness of this model. During the recently completed development program of this engine, every bearing failure was isolated in time (and not prematurely) through the appearance and detection of such large particles in the oil stream.

An illustration of the rapid increase in debris particle production rates during a failure is shown in Figure 4. These data were developed on a large commercial turbofan engine which, as sole debris monitoring device, has a magnetic chip collector in the main scavenge line. The normal debris deposit rate lies below .01 mg/hour, as evidenced by the decline of the curve after replacement of the failed intermediate gear box. During the development of the failure, the deposit rate increased by a factor of at least 10^3. Using this same technique, American Airlines never removes this type of engine from the aircraft unless SOAP data are confirmed by the appearance of large debris on the chip collector.[5)]

It must be emphasized that all condition monitoring techniques based on oil sampling, rather than debris sedimentation and collection, of necessity ignore these large particles. As is well known, sedimentation rates in reservoirs are such that in real operating environments particles larger than 100 microns rarely appear in the samples. More importantly, the production rate of large particles is, of course, many orders of magnitude lower than that of small ones and the probability of obtaining one of the large particles in a sample is negligible.[6)]

Recognizing the reliability of large debris particles as failure indicators, a quantitative debris sensing system was developed and has been evaluated in service. Figure 5 shows in cross section an oil debris monitor for a gas turbine engine or a helicopter main transmission. The unit has a cylindrical chamber, into which the oil enters through a tangential inlet. The resulting vortex flow separates the debris from the oil and deposits it on the surface of a magnetic sensor. A quick-disconnect mechanism and an automatic shut-off valve permit simple removal of the collected debris for visual or laboratory analysis. The separation efficiency of this cyclonic debris separator, at a flow rate of 16 GPM oil and 10 GPM air is indicated in Figure 6. Figure 7 shows a photograph of the unit.

The sensor is also usable as a sump-type debris detector. As magnetic debris particles are attracted, it generates a pulse whose amplitude is a function of the particle mass, magnetic susceptibility and its shape factor. With suitable electronic circuitry, as shown in Figure 8, this pulse is amplified, converted to a digital count and stored in an accumulation register. Real-time particle counts are therefore available for direct read-out or, more usefully, rate calculation by computer.

The system shown in Figure 8 was developed for participation in the Air Force Integrated Engine Condition Monitoring System (IECMS) Program. Two units are installed on a General Electric TF-39 engine on an Air Force C-5A aircraft. The preamplifier was required as a result of the 100 ft. distance between engine and signal conditioning equipment. The system is computer-interrogated and also must respond correctly to a computer-generated test command which is injected at the sensor level. System output is 0-5 VDC. In addition, a "large chip" signal is generated if a single particle larger than 500 microns in size is captured.

A second system is installed on a General Electric LM-2500 engine on the U.S. Navy's "Admiral Callaghan". The ship has concluded several voyages to Europe and, after calibration runs, the system is performing well.

Recently, a similar system has been supplied to Westland for evaluation. The sensor will be installed in the oil sump of a Lynx helicopter main transmission.

A somewhat less sophisticated system based on magnetic, quantitative debris sensing was evaluated during the U.S. Army AIDAPS program at Bell Helicopter Textron. Excessively worn gears and bearings were implanted into a UH-1 main transmission and were correctly identified through persistent, quantitative indications.

Currently, the resolution of the system is at the level of particles of 200 x 200 x 50 microns (.008 x .008 x .002 in.) This size corresponds to spall flakes typically generated by bearings several tens of hours before secondary failure. The resolution is expected to improve as the system is further developed. However, it must be taken into consideration that resolution of a range of particles from, say, 100 x 100 x 20 to 1000 x 1000 x 200 involves a scale factor of 1000 in mass. The limited dynamic range of electronic equipment (digital or analog) of reasonable size, cost, weight and complexity therefore requires a choice of a certain optimum spectral range in which all particles are to be reproduced in accordance with their actual magnetic imprint. Particles above this range are recorded as if they had the same size as those at its upper limit.

A simplified system with the capability to classify debris particles in real time into three ranges has recently been developed (Figure 9). Owing to its simple circuitry, small size and low cost, such a real-time particle counter promises an entirely new approach to aircraft lube debris monitoring.

Footnotes

1) R. C. Hunter, "Engine Failure Prediction Techniques", Aircraft Engineering, March 1975.
   A similar method is used with excellent results by CP Air, Vancouver.

2) This background of "normal wear fuzz" is responsible for most nuisance indications of conventional electric chip detectors which today are the most widely used lube debris detection devices in helicopters. The recent development of the Pulsed Chip Detector successfully deals with this problem. This device is now going into production for the Sikorsky S-76, UH-60A Blackhawk, Hughes YAH-64 and is under development for the Bell 222 and 214ST.

3) A visit to the British Airways Condition Monitoring Laboratory at Heathrow Airport, London, is highly instructive (Chief: Gordon Grant, British Airways, European Division).

4) D. Lubrano, USAMRDL; private communication.

5) P. Roberts, American Airlines, Tulsa, Oklahoma; private communication.

6) The average engine oil system has a capacity of 10 liters, while the average oil sample is 10 milliliters. Even without sedimentation problems, the probability of seeing a large particle in the sample is therefore a factor of 10^{-3} smaller than its production probability.

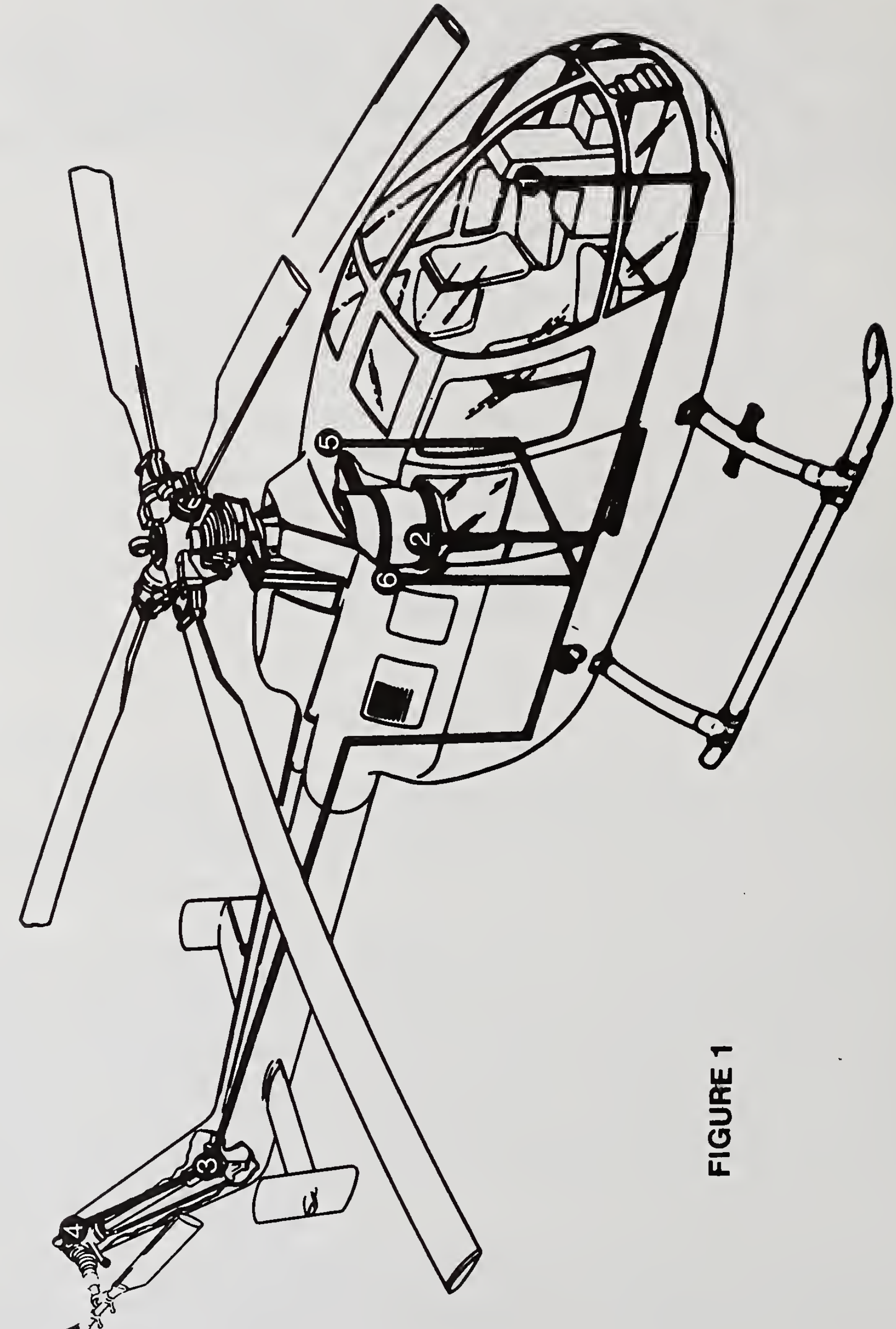


FIGURE 1

JET ENGINE LUBE DEBRIS MONITORING SYSTEM

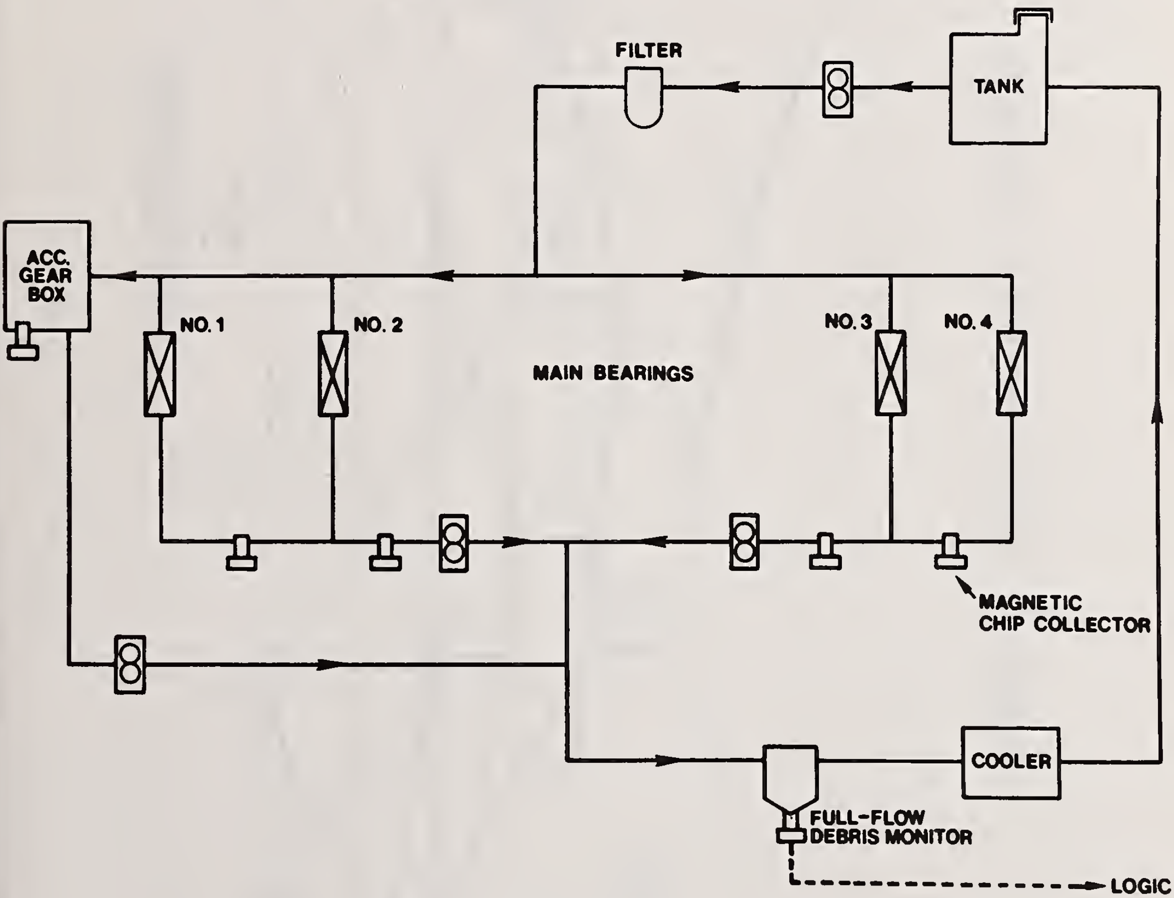
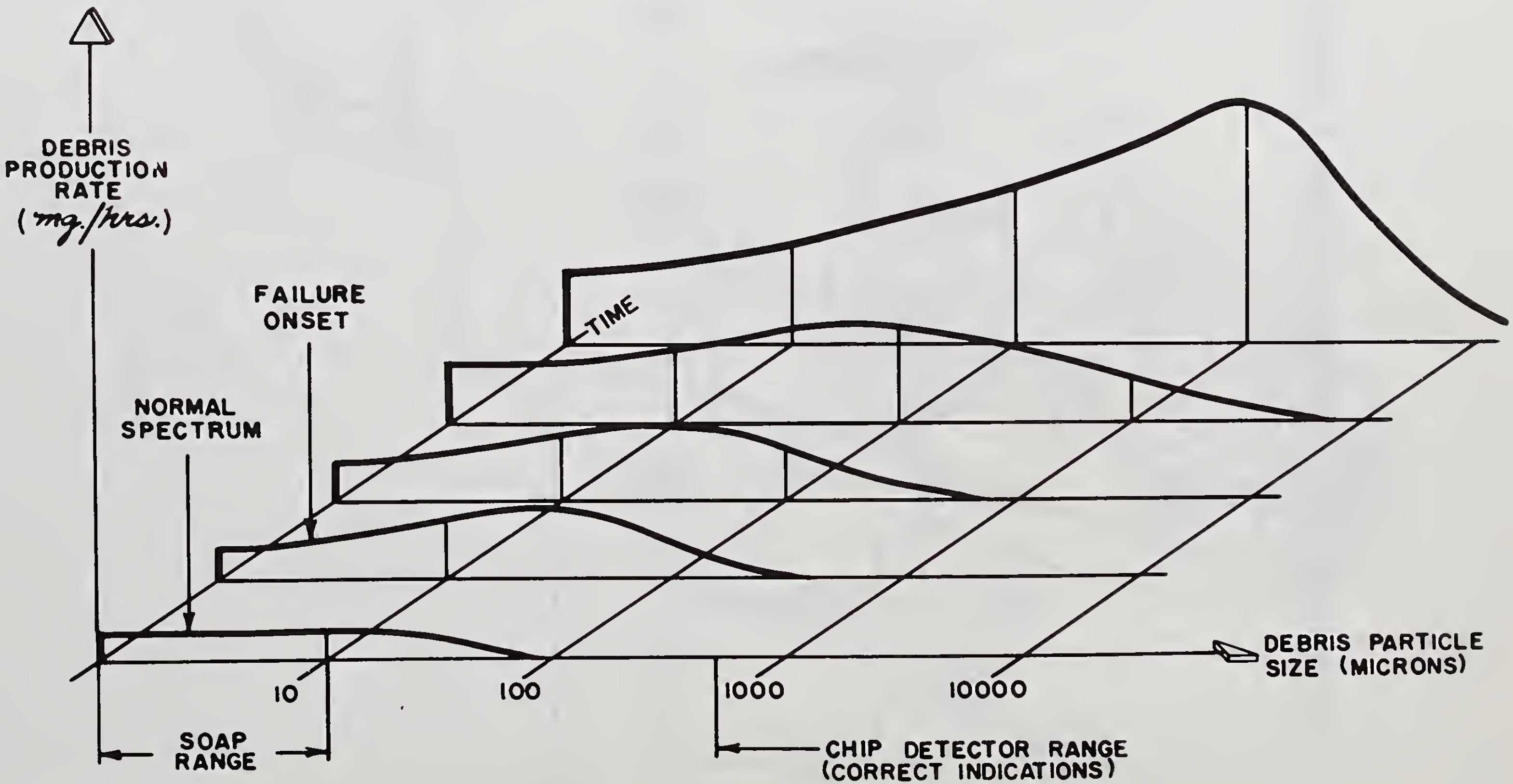


FIGURE 2

FIGURE 3 DEBRIS PARTICLE SPECTRUM



DEBRIS DEPOSIT RATE
MAGNETIC CHIP COLLECTOR

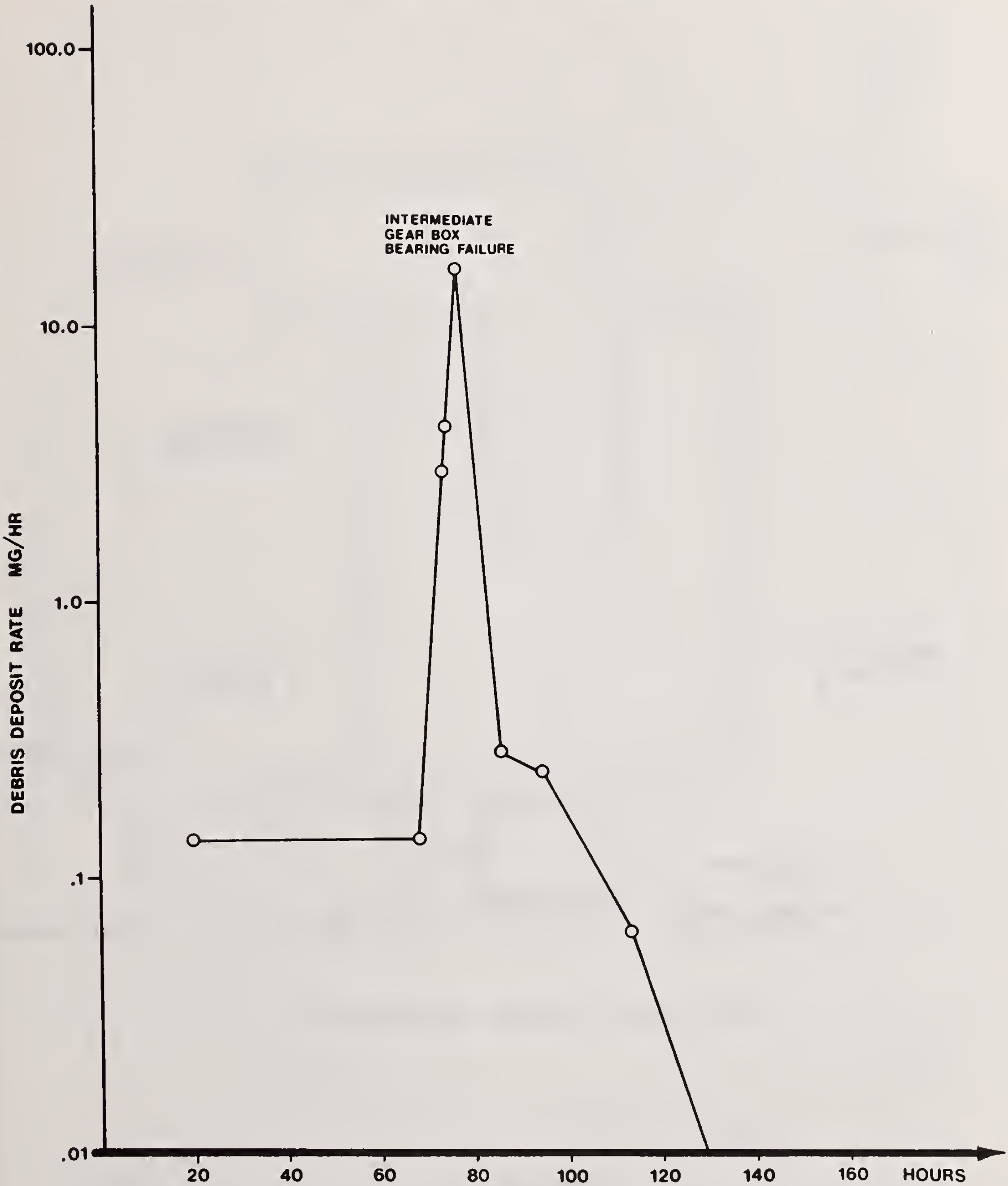
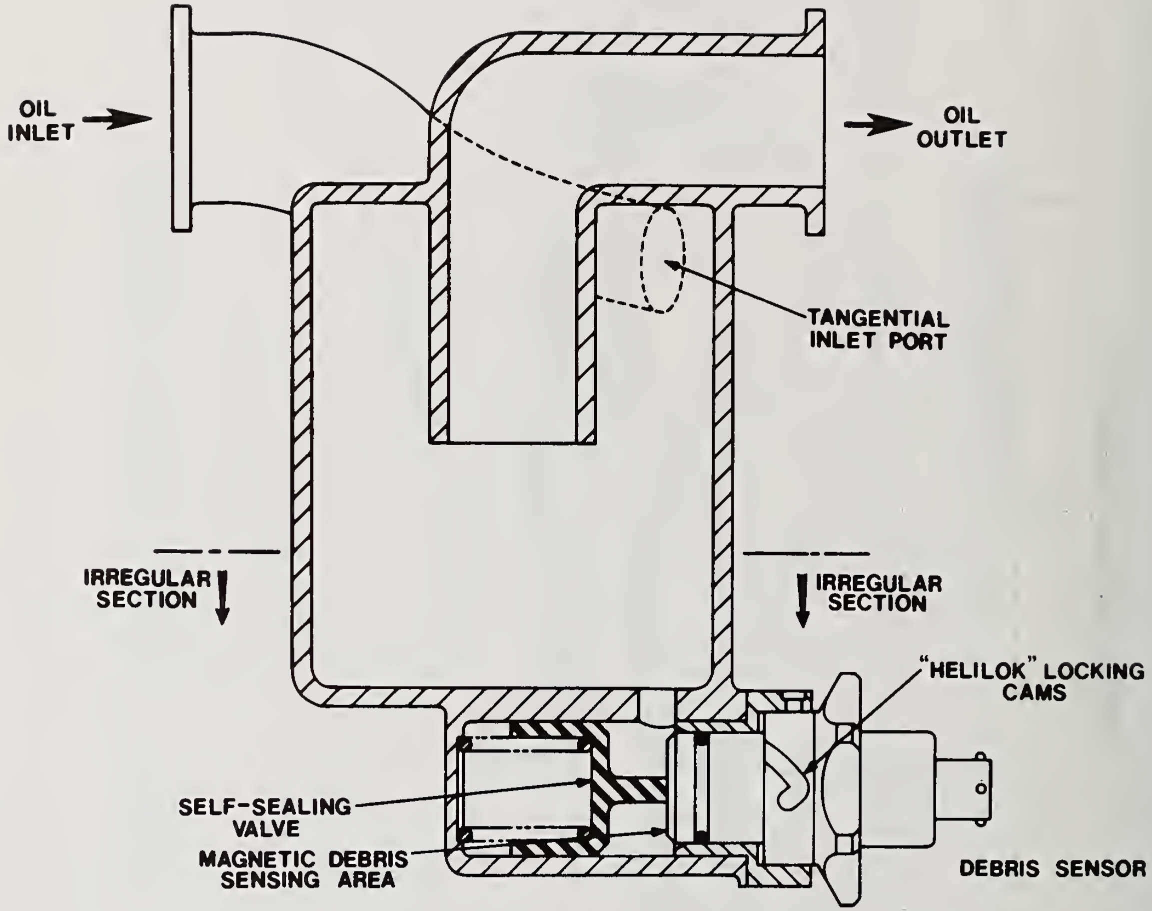


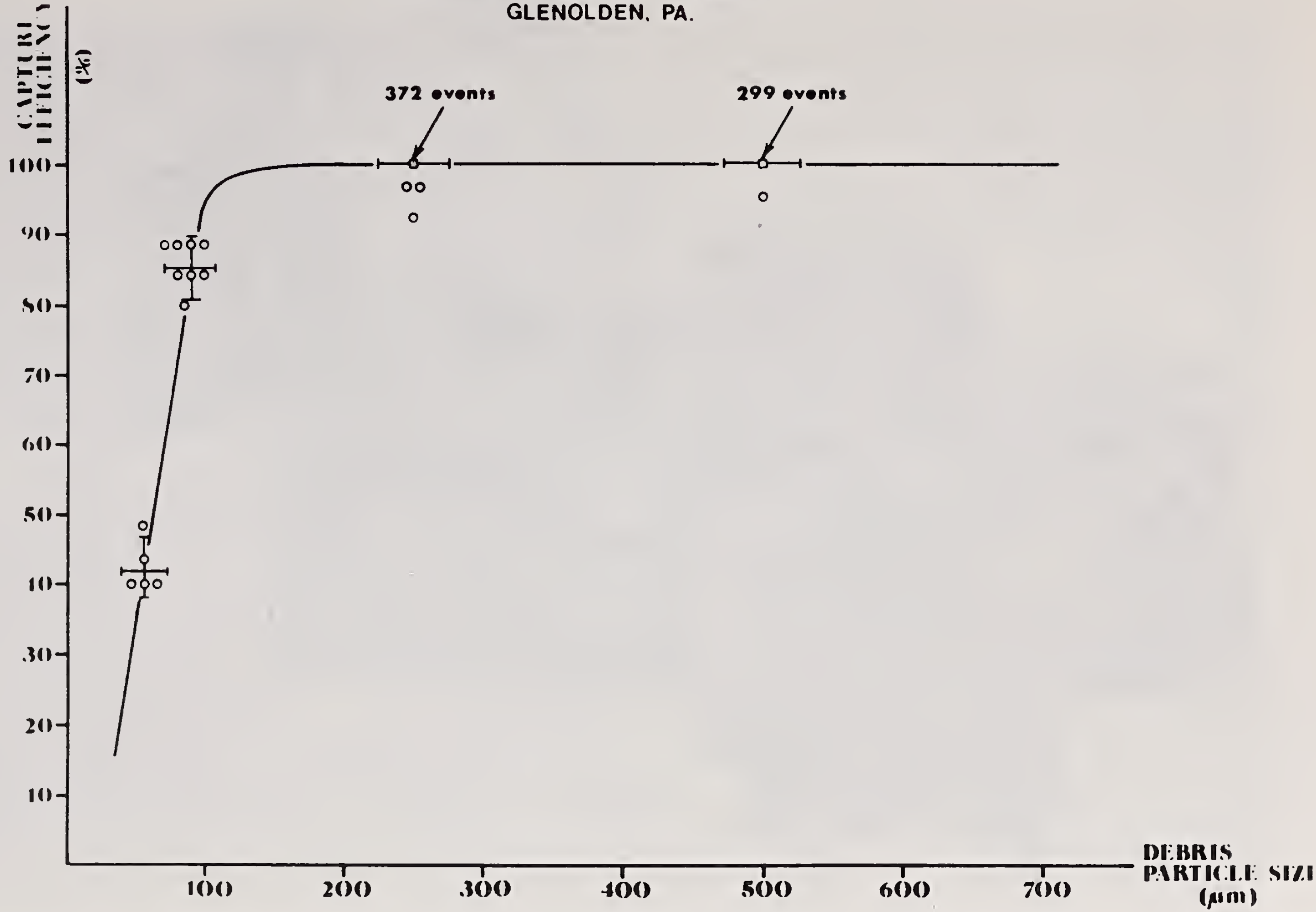
FIGURE 4



CYCLONIC DEBRIS SEPARATOR

FIGURE 5

TECHNICAL DEVELOPMENT CO.
GLENOLDEN, PA.



CAPTURE EFFICIENCY, CYCLONE DEBRIS SEPARATOR A8727

FIGURE 6

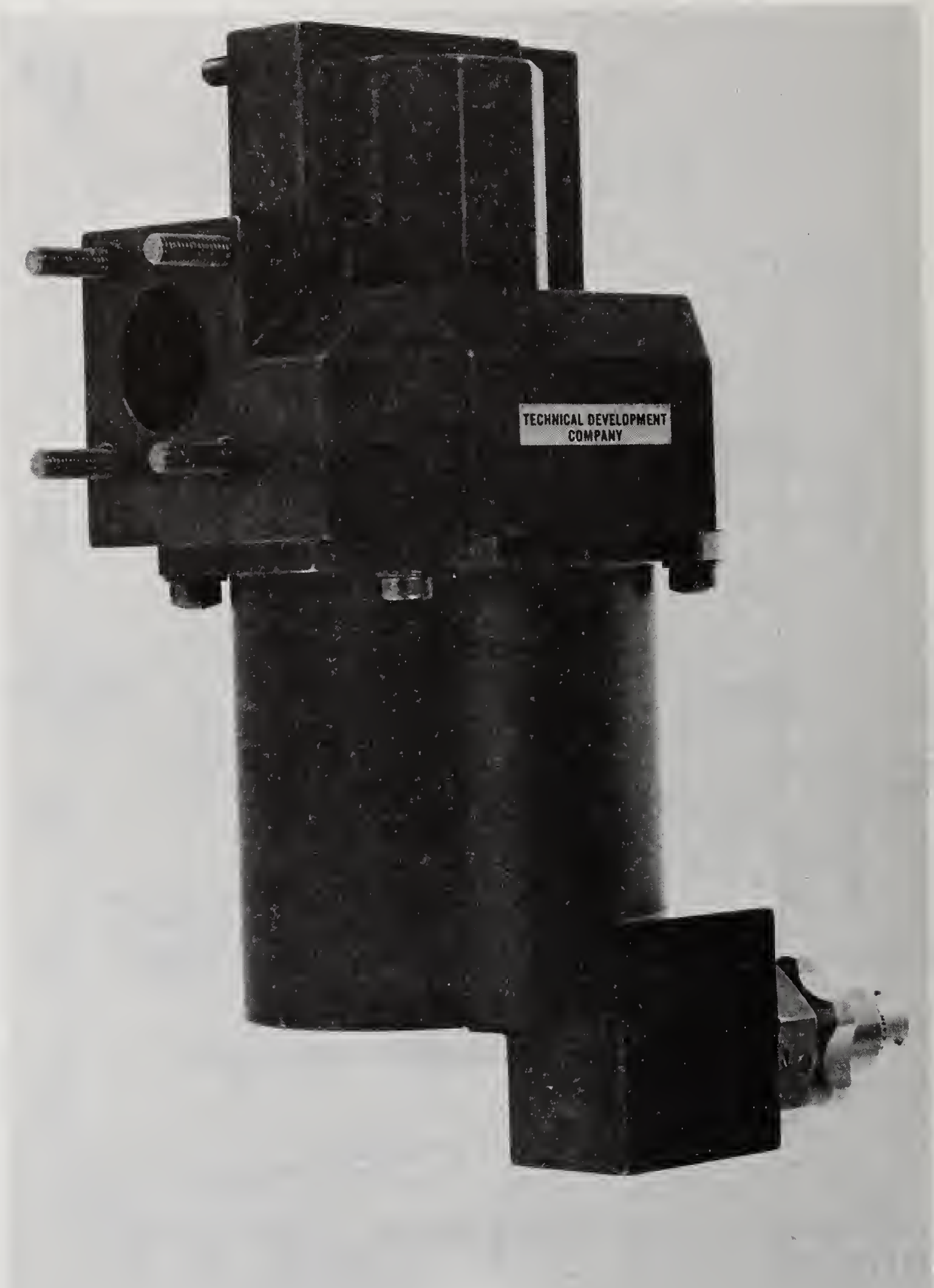


FIGURE 7

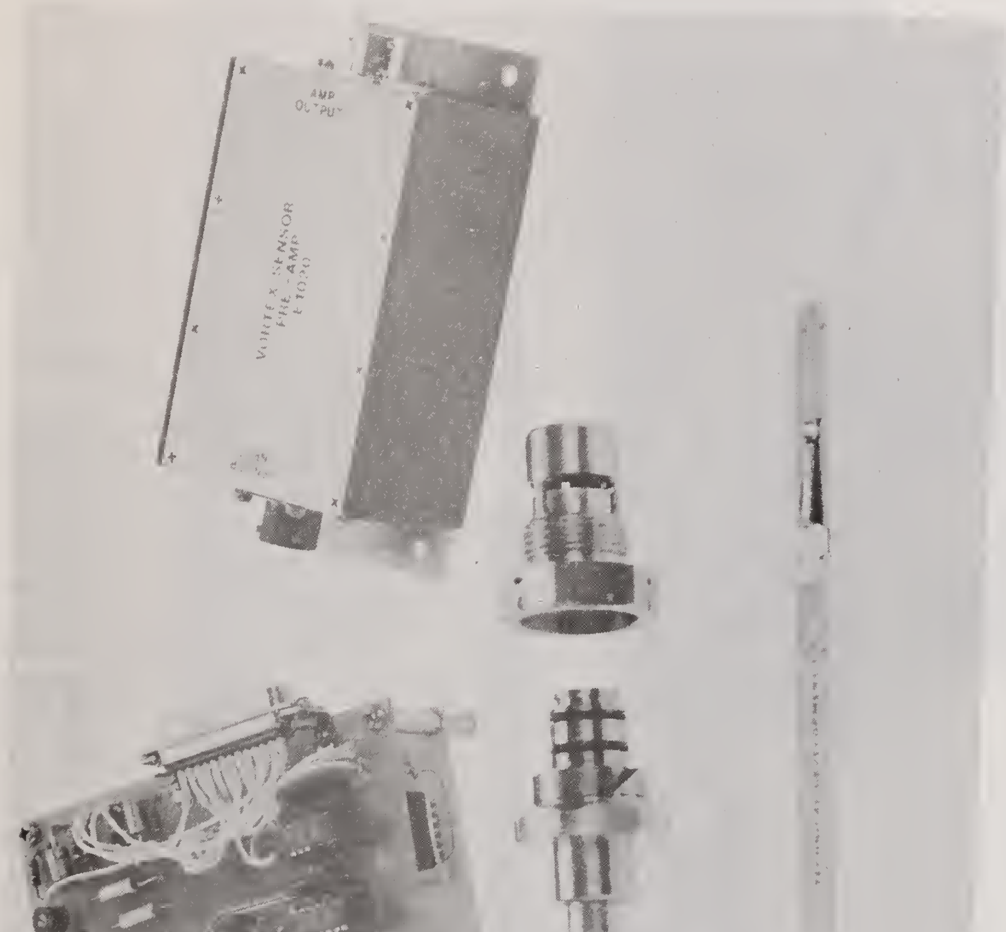


FIGURE 8


SMALL
MEDIUM
LARGE
TECHNICAL DEVELOPMENT COMPANY
GLENOLDEN, PA.

FIGURE 9

A PRACTICAL APPROACH TO AIRCRAFT SYSTEM COMPONENT MALFUNCTION DIAGNOSIS

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ABSTRACT

Aircraft fluid system component failures and the associated costs of unscheduled maintenance and loss of operational readiness can be reduced significantly with proper system monitoring. The author describes a multi-function monitoring system built into the aircraft that will provide a signal at one central location when the maximum allowable limit has been reached for the system and/or component function being monitored. The appropriate maintenance action can then be implemented or scheduled for a convenient time without interrupting the operational service of the aircraft. This concept would give a go-no-go signal and not require interpretation or special training. Another feature is that the monitoring is performed by ground personnel at pre-flight or post-flight checkout. The benefits of a system incorporating instant diagnosis and analysis of fluid system component malfunctions are increased system operating utility, reliability, and safety along with reduced logistic support and reduced maintenance and operating costs.

Key Words: Accumulator; analog; centralized; check-out system; desiccant; discrete; displacement; fiber optics; filters; flight critical; flow; fluid; go-no-go; ground readout; hydraulic; IMACS; instantaneous diagnosis and analysis; level; maintenance oriented; malfunction detection; monitoring; onboard; patented; pressure; pumps; reservoirs; sensors; tailorable; temperature.

INTRODUCTION:

Increasing costs associated with aircraft maintenance and unscheduled downtime require a cost effective method to deal with this problem. Current gas turbine powered aircraft employ a variety of fluid systems, components, and functions which are critical to the proper operation of these sophisticated systems. Thus, the demand to diagnose system and component critical operating functions has been growing out of necessity.

Maximum cost effectiveness can be applied by optimizing the maintenance inspection[1]. Early identification of component malfunction and incipient failure is the basis for a reduction of unscheduled repairs. This type of repair, in contrast to preventive repairs, is most costly because of the secondary damage caused by premature component failure. An example of this is abrasive particle fluid contamination generated by a failing system component which causes other system components to be damaged and subsequently fail. However, even without an actual failure of another system component, the overall system repair is more costly and usually involves preventive component repairs and extensive system decontamination.

Much of the aerospace industry effort to provide system function information has been applied to the engine fluid systems. For over a decade monitoring of the metal wear debris particles taken from fluid samples of lubricating oil systems has been used to predict oil wetted component failure. But, this methodology is limited as a future diagnostic tool. The reason for this is that there is now a better understanding of the mechanisms of wear and how they apply to system components[2]. These principles were recognized some time ago with the application of 3 micrometre absolute lube oil filters for the Avco Lycoming[3] T-53 Engine and the application of 3 micrometre absolute filters on G.E.'s T-700 Engine. However, the use of more efficient fluid system filters to combat the most damaging particles in film thicknesses of 0.1 micrometres (1000 Angstroms) to 1.0 micrometres (10,000 Angstroms) will effectively remove those sizes of particles presently monitored[4]. This problem is presently being worked on by various research institutes.

More elaborate aircraft engine monitoring systems are evolving[5]. Some transmit information to the cockpit, and some gather data in-flight and store it for extraction and analysis by engine diagnostic equipment on the ground[6]. These monitoring systems along with others in helicopter transmissions and other fluid systems are testimony to the increasing awareness and need for reduced costs, increased safety, improved maintainability, reduced logistic support and increased operational utility. The desired benefits can be achieved through the application of conditional monitoring of critical system component parameters which provide diagnosis of a flyable system and incipient failure analysis.

HYDRAULIC SYSTEMS:

Systems which can benefit greatly from a built-in monitoring system are the aircraft's hydraulic systems. They are composed of a large number of fluid components which are subject to degradation and failure. Let us review some of the background associated with hydraulic system problems:

It is well known that free and entrained air in hydraulic systems has resulted in serious system malfunctions sometimes terminating in crashes and loss of life.

Water in pneumatic bottles has frozen at discharge during emergency procedures also with disastrous results.

Low fluid level in reservoirs has caused loss of prime of pumps with the result of a loss of system pressure and flight control.

Improperly performed maintenance has resulted in reversed control linkages, disconnected linkages and pulleys, reversed installations of check vàlves, failure to reinstal filter elements and many others which caused results ranging from annoyance to catastrophic.

Servoactuators have suffered from loss of metering edge, seal deterioration, and jamming causing hardover signals.

Hydraulic pumps wear out and fail in a variety of failure modes.

Hydraulic fluid which can leak into emergency air bottles during resetting of system, depleting the charge of the bottles.

Accumulators are subject to blow by and internal leakage.

Filter elements are often left in the system too long resulting in malfunctions of components such as, high backpressure on pump cases reducing cooling flow.

Contaminates in the fluid have been responsible for a broad number of component malfunctions and failures such as, malfunctions of electromechanical servovalves.

The maintainability of the hydraulic systems contributes greatly to the operational utility, reliability, and safety of the aircraft. Pre-flight and post-flight checkout is an intrinsic part of maintaining these hydraulic systems, however, a large block of costly manhours and materials are consumed in the process. Therefore, let us examine an approach to providing a cost effective built-in monitoring system for aircraft hydraulic systems.

THE SYSTEM CONCEPT:

Provide at one central location an onboard, lightweight, self-contained monitoring system to automatically test the operability of the hydraulic system.

Provide in-system sensors that can measure component functional parameters to give early warning of malfunction and failure.

Provide an on-the-ground instantaneous go-no-go on-condition signal identifying what monitored component and/or system parameter has reached the predetermined functional limit. Let this signal be the basis for planned maintenance action.

Provide a monitoring system utilizing flight tested hardware which is not only applicable to new aircraft designs, but one that is retrofittable into present aircraft to extend vehicle service life economically.

Provide a real time monitoring system with continuous in-flight active sensors which will not affect the hydraulic system operation, even if a sensor fails.

Provide a programed microprocessor in a self-contained monitoring system to increase reliability vs integrating into existing aircraft computer system.

Provide a system which reduces skill level required for routine maintenance and that is universally implementable in present maintenance systems, minimizing the use of ground support equipment.

Provide a system to instantaneously diagnose and analyze fluid system component malfunction to decrease aircraft operating downtime, increase reliability and safety.

FLIGHT CRITICAL SYSTEM COMPONENTS:

Figure 1 lists the flight critical system components and necessary functional parameters for system monitoring and diagnosis by maintenance during ground checkout.

The different types of reservoirs used in aircraft hydraulic systems are shown along with the critical parameters of level and temperature.

Main system hydraulic filters in the pressure and return lines are monitored for differential pressure, and pump case drain lines are monitored for differential pressure and temperature.

Accumulators are used for a variety of purposes in hydraulic systems for stored energy devices and pump ripple attenuators such as for brakes, ram air turbine, canopy and main system. These are monitored for precharge pressure.

Likewise, pneumatic bottles used for emergency release of canopy, landing gear, doors, and tail hooks are monitored for pressure, and the presence of moisture.

Shock struts critical to takeoff and landings are monitored for precharge pressure and fluid level.

The heart of the hydraulic system is the pumps, and these are monitored for maximum allowable case drain leakage and discharge pressure. The system leakage is monitored for maximum quiescent flow.

For the flight controls; components such as the rudder, stabilizer and flaperon actuators are monitored for parameters of differential displacement and maximum allowable quiescent flow. These aircraft controls are monitored for differential displacement of the controls vs the controlled surface.

The utility system will, of course, contain some of the same redundant flight control actuators along with actuators for flaps, landing gear and other fluid power functions. These actuators should also be monitored.

The desiccant for reservoir pressurization, window defogging and other onboard uses is monitored for moisture saturation.

Hydraulic and spoiler type backup packages are monitored for over temperature.

An elapse time meter records system operating hours and flight duration.

Fluid system contamination monitoring provides for quantity of particles or fluid cleanliness level, water and chlorine.

System relief valves are monitored for leakage via fluid temperature.

IN-SYSTEM SENSORS:

Let us now look at Figure 2 which describes a typical monitoring system diagram used to determine acceptable system operability. The proper reservoir fluid level is checked automatically, along with external system leakage. In addition, air in a boot strap reservoir is also indicated.

Backup fluid power packages are checked for over temperature operating conditions.

The systems filter elements are checked to determine if they are plugged and should be changed. System fluid samples can also be obtained to determine contamination levels.

If the system relief valve is leaking fluid, temperature will give the required indication.

Accumulator precharge pressure is determined instantaneously without manual system discharge and is automatically compensated for temperature.

Onboard emergency pneumatic bottles are checked for acceptable charge pressure and the presence of moisture is conveyed to the panel optically by the use of fiber optics.

Hydraulic pump discharge pressure, pump maximum allowable case drain leakage, and maximum temperature are monitored to indicate malfunction of each pump. In addition, maximum allowable system discharge leakage is also monitored by a quiescent flow sensor.

Rudder control pedal differential displacement and rudder actuator differential displacement are checked to ensure mechanical connections are correct prior to flight. Other surfaces can be checked in a similar fashion.

Rudder actuator maximum permissible quiescent leakage is also indicated. The diagnosis of actuator maximum quiescent flow requires a leakage sensor at each actuator. Sub-systems can be checked for maintenance investigation in the same manner.

Pneumatic desiccant condition is checked for saturation by employing fiber optics, to visually transmit a color change at remote locations.

External struts, precharge pressure and fluid level are also provided for. These functions are particularly critical for naval aircraft prior to launch.

SYSTEM SIGNAL TRANSMISSION AND INTEGRATION:

The signals from the in-system sensors, as shown in Figure 3, are transmitted to a conveniently located ground accessible display panel. All of the signals are transmitted by a low power drain 5 Volt D.C. system including the generation of the fiber optic signals.

The discrete and fiber optic signals monitoring the components shown are received directly into the display panel.

The analog signals from sensors monitoring the components shown in Figure 3 are fed through analog digital converters to a preprogramed microprocessor all contained within the display panel.

Provision for tieing into the cockpit warning panel can also be accomplished from the display panel.

DISPLAY PANEL:

Shown in Figure 4 is the diagnostic, analysis and interrogation display panel installed at some convenient point onboard the aircraft for use by ground maintenance.

The display and interrogation black box measures approximately 12 x 6.5 x 4.5 inches and together with the electronics and batteries weighs approximately 8 lbs. Contained within the panel are:

- a microprocessor
- nickel cadmium batteries
- battery heating and charging circuit
- analog to digital converters
- memory logic
- counters
- lamp drivers
- display grain of wheat lamps
- fiber optic interface outlets
- power interface (115V, 400 Hertz AC)
- circuit and system test circuits
- shift registers
- elapse time meter

Grouped on the face of the panel are the flight critical components and functions being monitored for diagnosis of malfunction and out-of-limits performance. Each function is represented by a red color grain of wheat bulb which can be seen in direct sunlight as well as in the dark.

There is also provided on the panel a spring-loaded "center off" three position CIRCUIT TEST switch. In the first position it tests all of the grain of wheat bulbs, and in the second position it tests sequentially the wiring to the in-system sensors for each group of monitored components.

A spring-loaded "center off" three position SYSTEM TEST switch is also provided. In the first position before engine start, accumulator and pneumatic bottles precharges are checked along with reservoir fluid level before pressurization. Red lights would immediately indicate maintenance action for the indicated condition.

The engines are then started and the second position of the SYSTEM TEST switch is activated. Interrogation of the operating hydraulic system then provides instantaneous diagnosis and analysis of every function being monitored. A red light will instantaneously pinpoint a maintenance action.

The entire maintenance check procedure can literally be performed in a matter of seconds without the use of any ground support equipment.

The discrete in-system sensors generate a simultaneous local visual signal of component malfunction which must be cancelled manually. Therefore, the monitoring system provides a quality assurance check that the malfunction has been corrected, thus increasing reliability and safety of operation. Furthermore, the system requires no special training or support.

ADVANTAGES OF SYSTEM:

This patented instantaneous maintenance analysis check-out system can be tailored to any aircraft and maintenance schedule.

The advantages of the instantaneous maintenance analysis check-out system are:

- reduces pre-flight hydraulic system check-out time of flight critical components
- display panel identifies malfunctioned components throughout the vehicle
- reduces skill level required for routine maintenance
- allows for component removal on "as required" basis between major overhauls as scheduled, thus reducing logistic support and costs
- maintains in-flight check of all critical components
- identifies faulty components on post-flight check
- minimizes use of ground support equipment for check-out
- increases maintenance efficiency and operational utility
- proven and available hardware
- simple, reliable, practical and essentially maintenance free
- can be tailored to incorporate additional design and maintenance requirements

SYSTEM FLEXIBILITY:

Additional benefits can be derived from the monitoring system by providing a two bulb display for each monitored system function. The red bulb would indicate as before that the maximum allowable limit was reached requiring an immediate maintenance action. However, an amber warning bulb could also be provided to indicate that an abnormal condition is being approached and maintenance should plan to correct it at some convenient time in the near future. This would further increase operational readiness by not delaying the scheduled flight because of a required maintenance action. It would also reduce logistic support further.

SUMMARY:

In summary, the instantaneous maintenance analysis check-out system (IMACS) is a practical cost effective and time saving means of attaining fleet operational readiness and extending service life of aircraft through increased maintainability.

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TYPICAL FLIGHT CRITICAL SYSTEM COMPONENTS FOR MONITORING

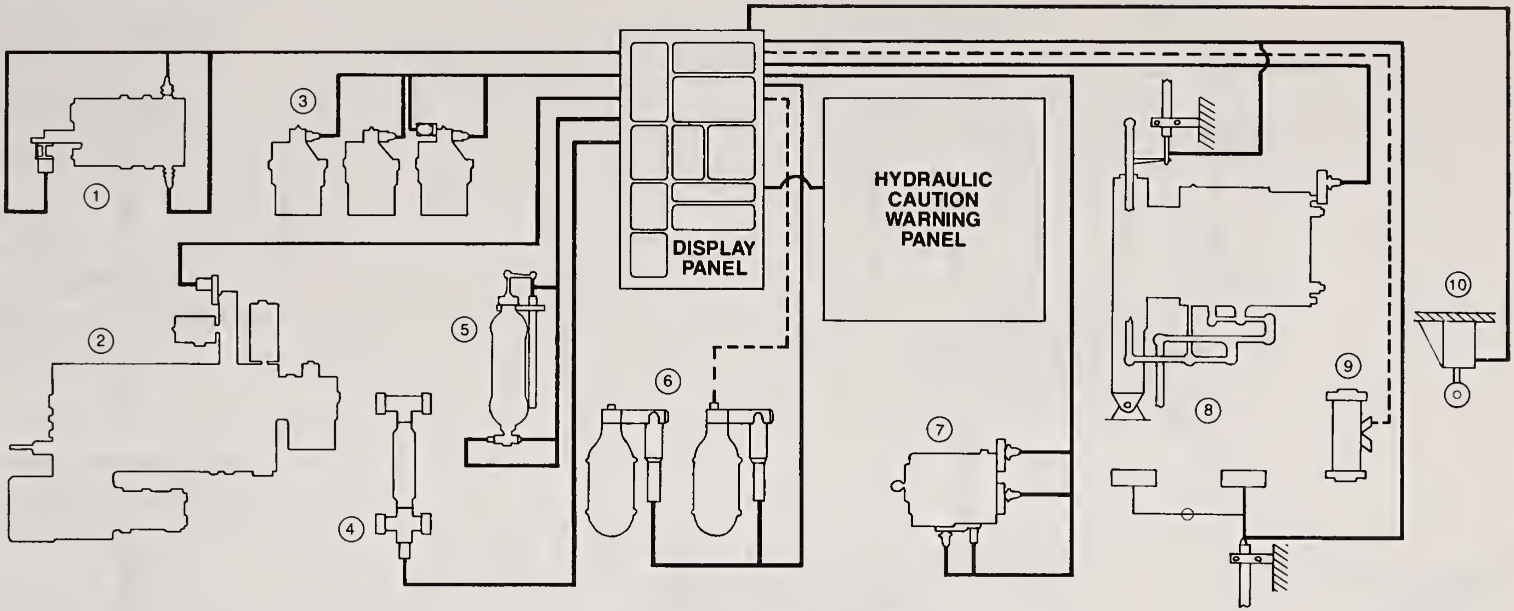
MONITORED PARAMETER	SYSTEM COMPONENT
	o HYDRAULIC RESERVOIRS
L&T	— Air oil
L&T	— Bootstrap
L	— Backup System
	o FILTERS
ΔP	— Pressure
ΔP	— Return
ΔP&T	— Pump case drain
	o ACCUMULATORS
PC	— Brake
PC	— Ram air turbine
PC	— Canopy
PC	— Main system
	o PNEUMATIC BOTTLES
P,M	— Canopy
P,M	— Landing gear
P,M	— Door
P,M	— Tail Hook (Dashpot)
	o SHOCK STRUTS
PC&L	— Nose Gear
PC&L	— Main Gear
	o HYDRAULIC PUMPS
F&T	— Case drain (flow)
QF	— Pressure, flow (quiescent)
P	— Pressure
	o FLIGHT CONTROLS
D.D.&QF	— Rudder Actuator
D.D.&QF	— Stabilizer Actuator
D.D.&QF	— Flaperon Actuator
D.D.	— Control Column
	o PNEUMATIC DESSICANT
S.	— Moisture (Saturation)
	o HYDRAULIC BACKUP PACKAGE
T	— Over Temperature
	o SPOILER SYSTEM & HIGHLIFT BACKUP PACKAGE
T	— Over Temperature
	o ELAPSED TIME METER
H.	— System operational hours
	— Flight duration
	o FLUID SAMPLING
FS	— Particulate matter (cleanliness level)
	— Water
	— Chlorine content
	o RELIEF VALVE
T	— Over temperature

LEGEND

L	Indicates level	D.D.	Indicates differential displacement
P	Indicates pressure	S	Indicates moisture saturation
ΔP	Indicates differential pressure	T	Indicates over temperature
PC	Indicates precharge pressure	H	Indicates hours & tenths
F	Indicates flow	M	Indicates mixture H_2O/oil in pneumatic bottles
QF	Indicates quiescent flow	FS	Indicates fluid sampling

Figure 1

TYPICAL MONITORING SYSTEM DIAGRAM



ITEM	SYSTEM COMPONENT	MONITORED PARAMETER	IN SYSTEM SENSOR	SIGNAL TYPE
1	RESERVOIR	LEVEL	MECH/ELECTRICAL	POTENTIOMETER
		AIR	MECH/ELECTRICAL	POTENTIOMETER
		TEMP	ANALOG SIGNAL GEN.	I.C.
		PRESS.	MECH/ELECTRICAL	TRANSDUCER
2	BACKUP PACKAGE	TEMP	MECH	SWITCH
3	FILTERS			
	PRESS.	ΔP	MECH	SWITCH
	RETURN	ΔP	MECH	SWITCH
	CASE	ΔP	MECH	SWITCH
4	RELIEF VALVE	TEMP	MECH	SWITCH
5	ACCUMULATOR	PRESS	MECH/ELEC.	POTENTIOMETER
		TEMP	ANALOG SIGNAL GEN.	I.C
		DISP	MECH/ELEC	TRANSDUCER
6.	PNEUMATIC BOTTLE	PRESS	MECH. PRESS	SWITCH
		LIQUID	OPTICAL PROBE	OPTICAL COUPLER
7.	PUMP			
	OUTLET	PRESS.	MECH	SWITCH
	CASE	LEAKAGE FLOW	MECH	SWITCH
		TEMP.	MECH	SWITCH
	SYSTEM	LEAKAGE FLOW	MECH	SWITCH
8.	RUDDER ACTUATOR	DIFF. DISPL.	MECH/ELEC.	POTENTIOMETER
		QUIESCENT FLOW	MECH	SWITCH
	PEDALS	DIFF. DISPL.	MECH/ELEC.	POTENTIOMETER
9.	DESSICANT DRIER (RESERVOIR)	MOISTURE	OPTICAL PROBE	OPTICAL COUPLER
10.	STRUTS	PRESS.	MECH/ELEC.	TRANSDUCER
		LIQUID LEVEL	OPTICAL PROBE	OPTICAL COUPLER

Figure 2

TYPICAL MONITORING SYSTEM BLOCK DIAGRAM

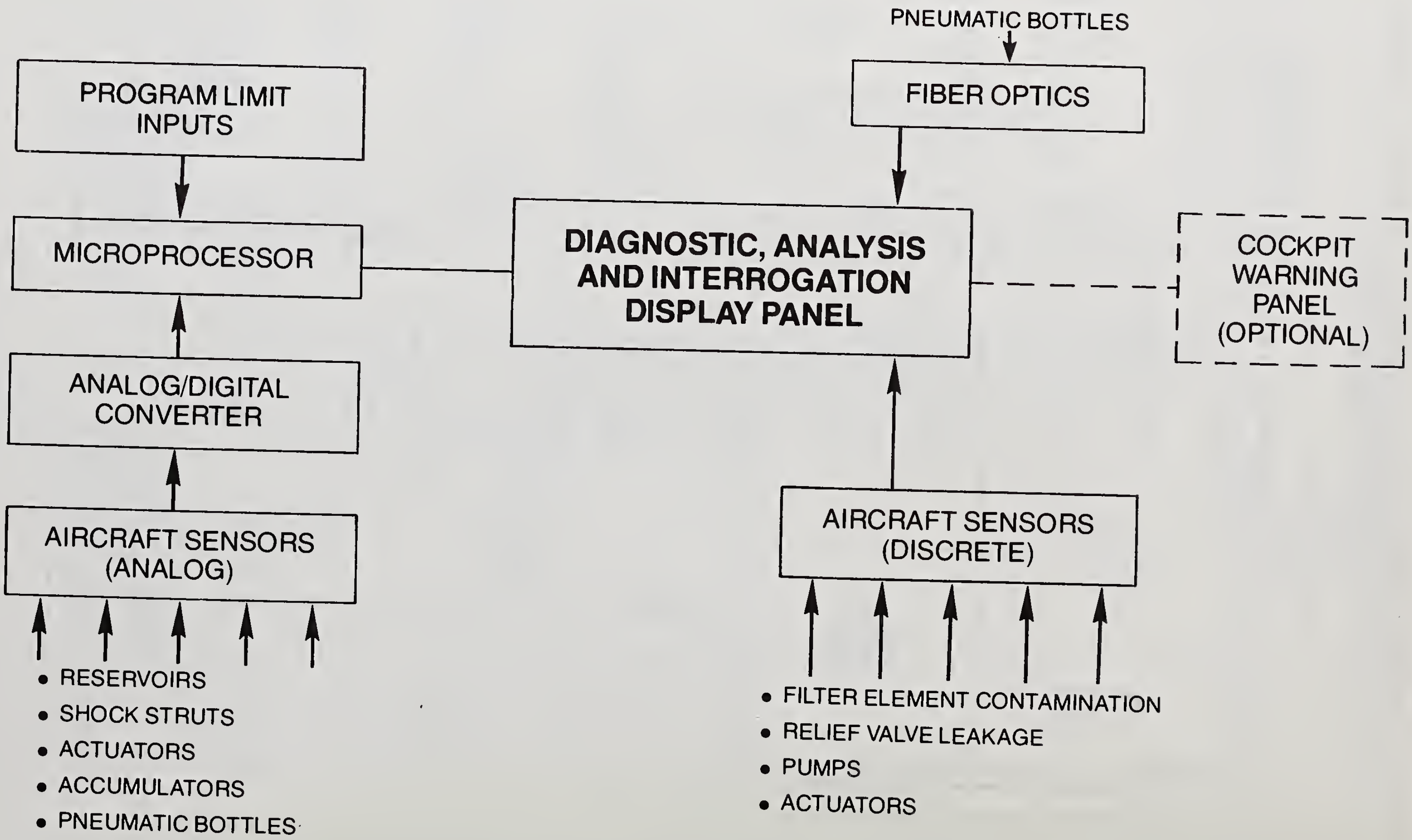


Figure 3

TYPICAL ON-BOARD DIAGNOSTIC, ANALYSIS AND INTERROGATION DISPLAY PANEL

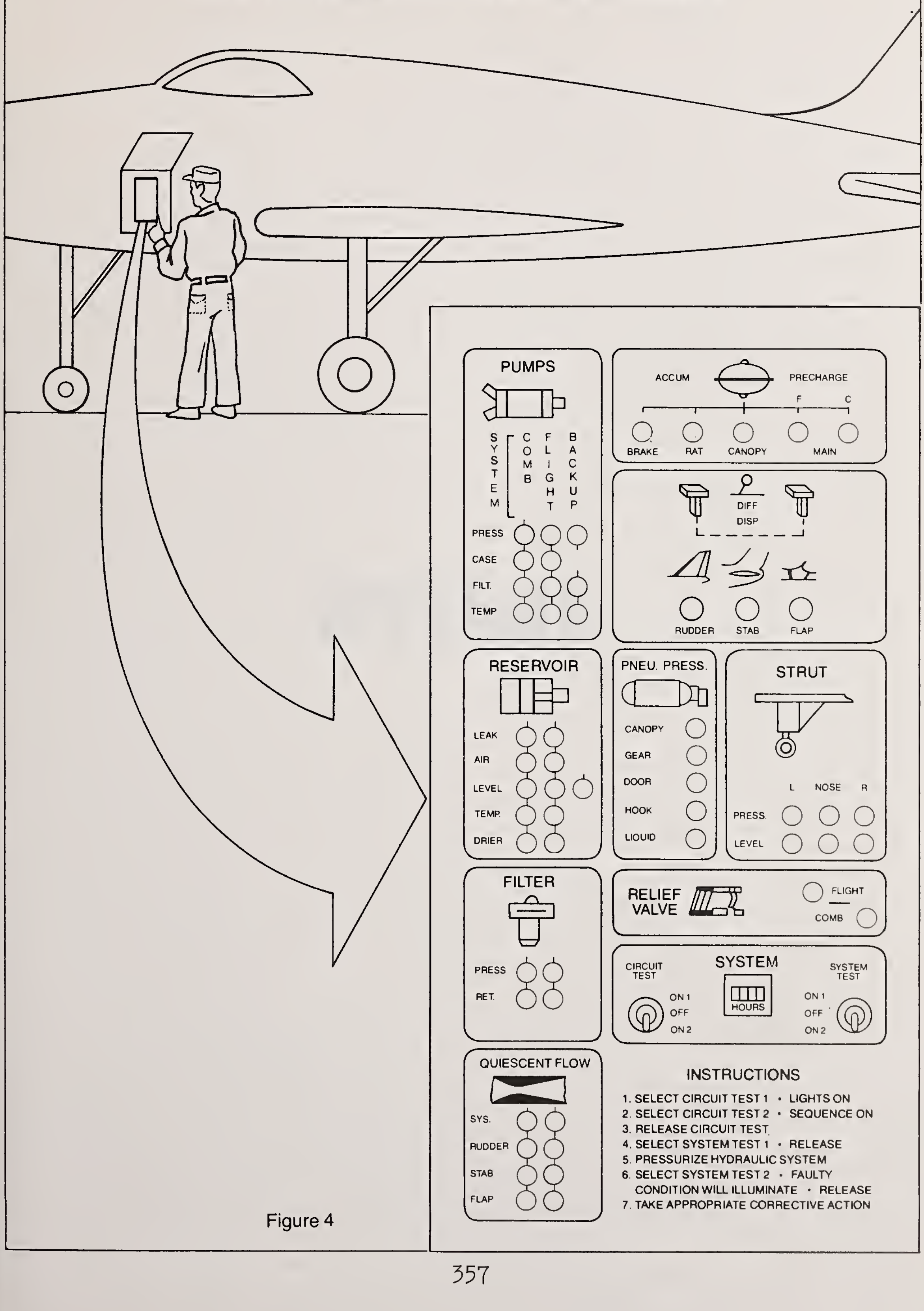


Figure 4

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15. SUPPLEMENTARY NOTES

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

These proceedings consist of a group of twenty five submitted papers from the 28th meeting of the Mechanical Failures Prevention Group which was held in San Antonio, Texas, November 28-30, 1978. The central theme of the proceedings deals with detection, diagnosis, and prognosis as related to mechanical failure prevention. Special emphasis is on aerospace applications, land based applications, marine applications and industrial application.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Bearing analysis; condition monitoring; engine diagnosis; failure detection; failure diagnosis; failure prevention; maintenance; performance monitoring

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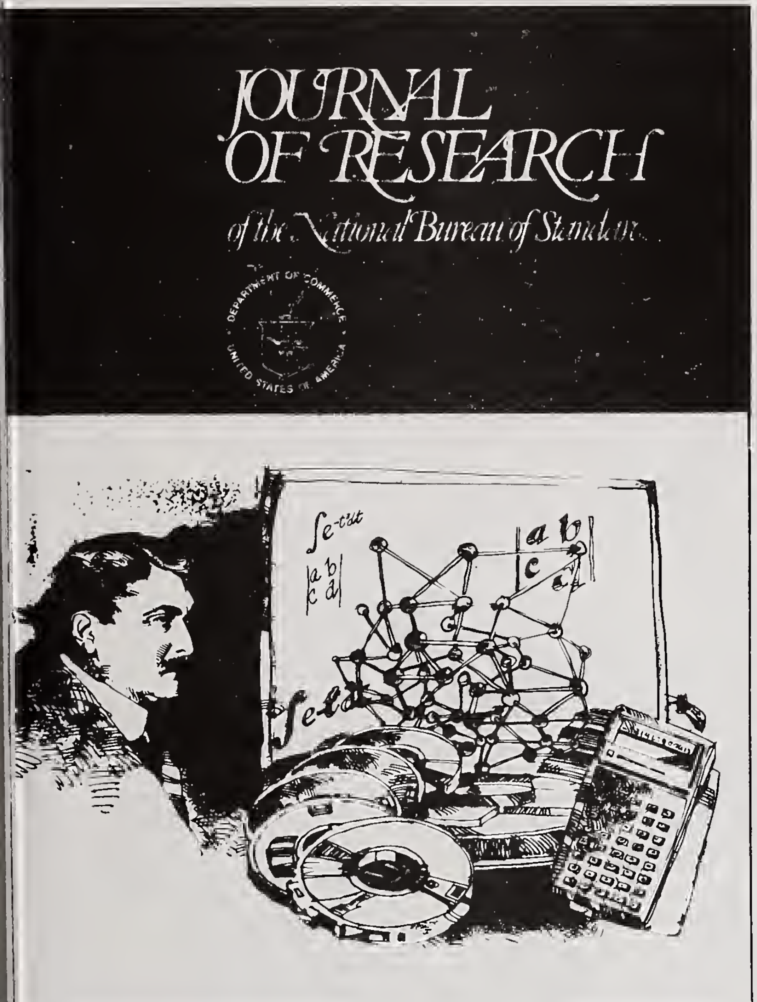
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