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Report No. 32
Ultrasonic Instrumentation to Measure Hoop Stress in Cast-Steel Railroad Wheel Rims

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EXECUTIVE SUMMARY

Objective:

- Measure residual stress in the rims of railroad wheels.

Method:

- Acoustoelasticity, or the change in sound velocity with stress.

Problems:

- Very small (~0.01%) stress-induced change in velocity.
- Change in velocity from metallurgical texture.
- Errors from surface condition and acoustic coupling

Solutions:

- EMATs (electromagnetic-acoustic transducers) to eliminate timing errors due to couplant variations. Precise timing of a single cycle in the acoustic signal. Compare circumferential and radial polarizations to calculate the stress differential.
- Measure texture effect in multiple stress-relieved rim blocks. Subtract average value from wheel measurements.

Instrumentation (Current Configuration):

- Small personal computer with two plug-in cards (commercial).
- External box (pre-amplifier and polarization switch) with EMAT probe.

Verification History:

- Multiple measurements on test wheels at manufacturer's test facility, some compared against destructive tests done by saw-cutting.

Estimated Quality of measurements:

- Accuracy ≈ ±51 MPa (±8 ksi) - mostly due to texture variations.
- Precision ≈ ±28 MPa (±4 ksi) - mostly due to timing accuracy.
- Total stress error ≈ ±60 MPa (±9 ksi) - this is probably conservative

Status:

- System hardware and software assembled.
- Ready for field testing.

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This is Report Number 32 in a series covering research done by the National Institute of Standards and Technology for the Federal Railroad Administration. We report on a project by the Materials Reliability Division to develop and test an ultrasonic instrument package for measuring residual stress in the rims of railroad wheels. Stress, residual or applied, has an acoustoelastic effect. Measuring acoustic birefringence (the small change in velocity with direction of polarization) is a method for nondestructive evaluation (NDE) of stress. We have previously shown the viability of this approach for inspecting the rims of cast-steel railroad wheels. While the effect of metallurgical texture will preclude measurements of high accuracy, this ultrasonic method should be useful as a screening tool to find those wheels that have potentially dangerous tensile stresses. The current effort has been to develop instrumentation for use in the field. The factors considered were size and compactness, ease of use, and automation. In the present unit, most of the electronics are commercial, off-the-shelf items. There are two computer plug-in boards (pulser/receiver and ADC) in a "lunchbox" computer. The probe is an electromagnetic acoustic transducer (EMAT) in a case designed to fit the front rim face (frf) with the necessary precision. A software program collects digital signal information and analyzes it without operator intervention. In its present form, this package should be able to collect enough statistically significant information for determining stress in less than 30 seconds.

Key words: EMAT; instrumentation; nondestructive testing; railroad wheel; residual stress; ultrasonic

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1. INTRODUCTION

New wheel designs and extensive quality control by manufacturers have lessened the effects of thermal abuse in railroad wheels. Yet, there remains considerable concern about this problem in the U.S. and abroad. A former FRA rule required condemning a wheel if a discoloration band of 100 mm (4 inches) or more appeared in the wheel plate [1]. Destructive measurements questioned the reliability of this simple test [2]. However, lacking any other method of examining wheels for possible tensile stresses that could lead to wheel failure, this "4 inch rule" continues in practice. The consequences of wheel failure, though rare, are considerable in terms of personal, environmental, and economic consequences. Good economy requires replacing wheels when necessary, but only then.

To date, the only method to yield quantitative information in a manner useful in a shop environment is the careful measurement of the velocity of ultrasonic signals. Several research/commercial concerns (see Appendix I for a list) have worked on development and practical implementation of this technique. In each case, the basic physics is the same; the technique and equipment vary. The approach in this work was that the system should be

1. Automatic, for maximum utility in a working shop;
2. Simple, not requiring any particular training in ultrasonics or manipulation of probes;
3. Quantitative, able to differentiate compressive, near neutral, and tensile stresses;
4. Reliable, minimizing false positives or negatives;
5. Fast, measurement times <1 min; and
6. Immediate, measuring wheels mounted in trucks and on rail cars.

2. CONTRACT HISTORY

Our work to develop ultrasonic nondestructive evaluation methods for railroad wheels began in 1985. While the original emphasis was on roll-by detection of tread cracks, this changed to the development of a tool for the measurement of residual hoop stress in the rims. Under the current contract the goal was to develop instrumentation useful in a wheel shop environment. This work was done under an eighteen-month research contract with the Federal Railroad

Administration (FRA), Reimbursable Agreement No. DTFR53-96-X-00021 with an effective date of May 1, 1996 to November 1, 1997.

Several reports in this series from the National Institute of Standards and Technology have dealt with wheel inspection:

1. R.E. Schramm and A.V. Clark, Jr., "Report No. 18 - Ultrasonic Railroad Wheel Inspection Using EMATs," NISTIR 88-3906, December 1988.

2. R.E. Schramm, A.V. Clark, Jr., D. V. Mitraković, Y. Cohen, P.J. Shull, and S.R. Schaps, "Report No. 22 - Tread Crack Detection in Railroad Wheels: An Ultrasonic System Using EMATs," NISTIR 3967, May 1991.

3. R.E. Schramm, A.V. Clark, Jr., D.V. Mitraković, S.R. Schaps, and T.J. McGuire, "Report No. 23 - Residual Stress Detection in Railroad Wheels: An Ultrasonic System Using EMATs," NISTIR 3968, May 1991.

4. R.E. Schramm, J. Szelążek, and A.V. Clark, Jr., "Report No. 28 - Residual Stress in Induction-Heated Railroad Wheels: Ultrasonic and Saw Cut Measurements," NISTIR 5038, May 1995.

5. R.E. Schramm, J. Szelążek, and A.V. Clark, Jr., "Report No. 30 - Dynamometer-Induced Residual Stress in Railroad Wheels: Ultrasonic and Saw Cut Measurements," NISTIR 5043, March 1996.

Several reports based on the rim-stress part of this work have also appeared in outside publications:

1. A.V. Clark, Jr., H. Fukuoka, D.V. Mitraković, and J.C. Moulder, "Characterization of Residual Stress and Texture in Cast Steel Railroad Wheels," *Ultrasonics*, Vol. 24, September 1986, pp. 281-288.

2. R.E. Schramm, A.V. Clark, Jr., and T.J. McGuire, "Ultrasonic Measurement of Residual Stress in Railroad Wheel Rims," in *Tenth International Wheelset Congress*, Institution of Engineers, Australia, 11 National Circuit, Barton, ACT, pp. 151-155 (1992).

3. R.E. Schramm, A.V. Clark, and J. Szelążek, "Ultrasonic Measurement of Residual Stress in Cast Steel Railroad Wheels," in *Determining Material Characterization:*

Residual Stress and Integrity with NDE, PVP-Vol. 276, NDE-Vol. 12, The American Society of Mechanical Engineers, NY, pp. 157-162 (1994).

4. R.E. Schramm, A.V. Clark, and J. Szelążek, "Safety Assessment of Railroad Wheels by Residual Stress Measurements," in *Nondestructive Evaluation of Aging Railroads*, Donald E. Gray, Daniel Stone, eds., Proc. SPIE 2458, pp. 97-108 (1995).

5. R.E. Schramm, J. Szelążek, and A.V. Clark, Jr., "Ultrasonic Measurement of Residual Stress in the Rims of Inductively Heated Railroad Wheels." *Materials Evaluation*, Vol. 54, August 1996, pp. 929-934. (The American Society for Nondestructive Testing awarded this their "Outstanding Paper Award for 1996.")

In the several years of this stress-measurement project, there were various phases in the work.

1. Development of a transducer and electronics for use on the rim of a cast-steel railroad wheel.

2. Collection of initial specimens and test of feasibility.

3. Electronic and mechanical modifications necessary for system development.

4. Extensive testing on special rimblocks and specimen wheels.

5. Development of instrumentation (subject of this report).

With the present compact, ruggedized, and automated system, the next step is the collection of extensive field data to define usage parameters (accuracy, reliability, texture variations, etc.).

Many people over the years have influenced and contributed to this program in significant ways. A partial list includes:

Monique Stewart, Don Gray, Clair Orth, Cliff Gannett; FRA, Washington, D.C.

Van Clark (who started this program), Steve Schaps, Todd McGuire; NIST, Boulder, Colorado.

Greg Garcia, Joe Kristan, Bob Florom, Dan Stone, Britto Rajkumar; TTC/AAR, Pueblo, Colorado.

Rich Pilon, John Oliver, Mike Gallagher; Griffin Wheel Co., Chicago, IL.

Jacek Szelążek, Julian Deputat; Institute of Fundamental Technological Research of the Polish Academy of Sciences (IPPT-PAN), Warsaw, Poland.

Dragan Mitraković; Faculty of Technology and Metallurgy, University of Belgrade, Belgrade, Yugoslavia.

Oscar Orringer; Volpe National Transportation Systems Center, Cambridge, Massachusetts.

Ansgar Wilbrand, Eckhardt Schneider; Institut für zerstörungsfreie Prüfverfahren (IzfP), Saarbrücken, Germany.

Of course, many others should be added to this list.

3. EXPERIMENTAL PROCEDURES

The measurement parameter is acoustic birefringence, or the relative change in sound velocity measured in two orthogonal polarizations. For wheel rim measurements, the two directions are the radial (r) and hoop (θ) directions [3-6]. The 2 MHz signals are shear horizontal (SH) waves traveling through the rim thickness (Figure 1).

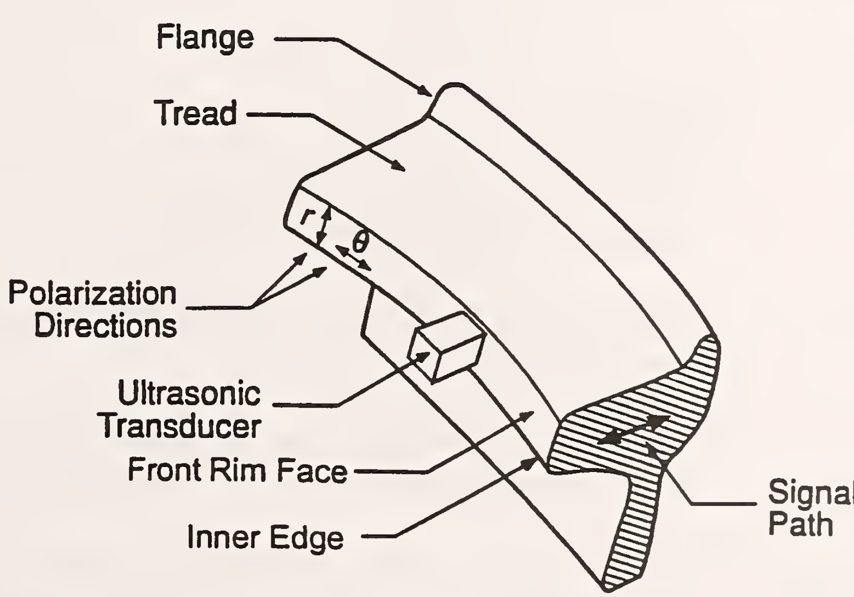

Figure 1. The ultrasonic transducer on the front rim face generates shear-horizontal waves polarized along the radial and hoop directions [3-6]. The arrival time of an echo from the back rim face is a measure of the velocity.

Two measurements are necessary to calculate the birefringence,

$$B=\frac{V_\theta - V_r}{\overline{V}},$$

where

B =	birefringence,
V_θ =	velocity with hoop polarization,
V_r =	velocity with radial polarization, and
$\overline{V}$ =	average of V_θ and V_r.

Since the travel distance for the echo from the back rim face is the same for both polarizations, we can calculate B from the arrival times, t_θ, t_r, and their average, $\overline{t}$.

$$B=\frac{t_r - t_\theta}{\overline{t}}.$$

The stress calculation from birefringence is

$$B=B_0 - C_A(\sigma_\theta - \sigma_r),$$

where

B =	birefringence measured in the sample,
B_0 =	average birefringence due to metallurgical texture—measured on several stress-relieved rim blocks,
C_A =	stress-acoustic constant—a material parameter reasonably consistent for ferritic steels (literature value = -7.8×10^{-6}/MPa) [5], and
$\sigma_\theta - \sigma_r$ =	stress difference in the two polarization directions—generally, σ_r is small and negligible.

Since the signal has traveled through the thickness of the rim, the measured stress is the average over this distance.

Metallurgical texture means that the crystallographic orientation of grains is not uniform and random. In cast steel wheels, there are long dendritic grains that grew from the surface as well as smaller, more irregular grains near the center (Figure 2).

The texture effect on the birefringence, B_0, can be of the same order of magnitude as the stress effect. Therefore, it is necessary to have a reasonable idea of its value. There is also the question of how constant that value is from wheel to wheel, batch to batch, year to year, etc. Over a limited range of heat-treated rimblocks representing several years of one manufacturer's production, the measured B_0 was sufficiently constant for reasonable estimates of rim stress [7]. This parameter remains the largest source of uncertainty.

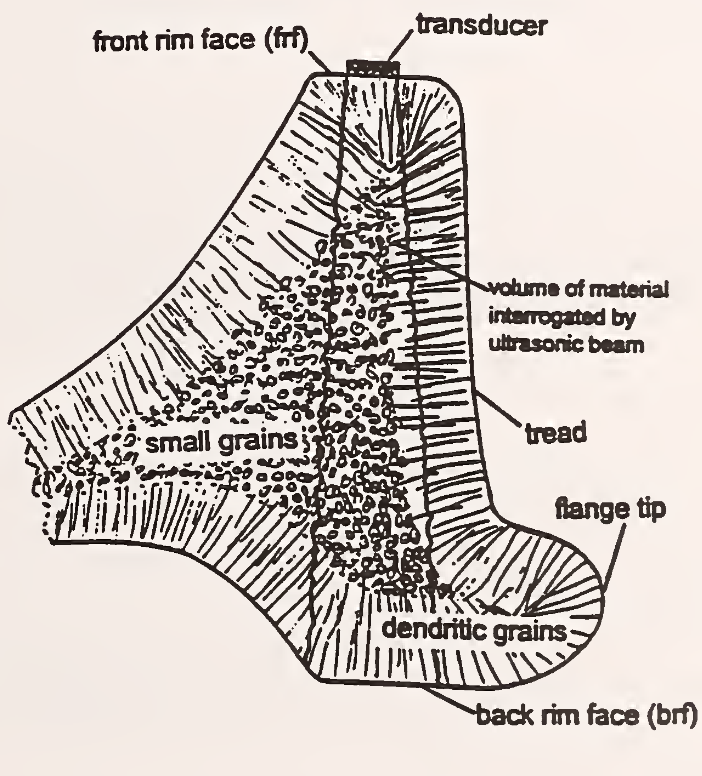

Figure 2. Schematic of the cross section of a cast-steel wheel rim [7]. The outer grains are dendritic and normal to the surface. In the interior, the grains are mostly small with random orientation.

The ultrasonic transducer used here is an EMAT. A high-current pulse through a coil induces an eddy current in nearby rim face. This interacts with an external magnetic field to generate an ultrasonic signal at 2 MHz. Two coils stacked at right angles to each other make it possible to generate two polarizations without rotating the EMAT (see section 5.1).

Compare with standard piezoelectric transducers:

EMAT	No fluid couplant Weak signal
Piezoelectric	Needs fluid or rubber couplant Strong signal

4. SUMMARY OF PRIOR WORK

All measurements thus far have been on cast steel wheels, 36 in (0.91 m), class C; these are in common use in the U.S.

The transducer aperture is about 10 mm square. Because of the rim's complex geometry and the distribution of the grain structure (texture), there is a large gradient in the birefringence with radial position on the front rim face. The inside edge of this face is a useful index point since it is sharper than the outside edge and sees no wear. We chose to locate the center of the EMAT at 14 mm from this edge since the gradient was relatively flat in this vicinity [5].

Tests included three series of measurements:

1. To measure the size and variability of the texture effect, we tested 10 stress-relieved rim blocks cut from wheels removed from service. They covered several years of manufacture and several production plants. We estimate [5] the average $B_0 = -2.1 \times 10^{-4}$, with a spread $\Delta B_0 \approx \pm 4 \times 10^{-4}$.

2. The first series of whole-wheel measurements used new wheels that had received varying amounts of damage from induction heating. The ultrasonic measurements clearly showed the effects [5, 6, 8, 9].

3. The final measurements were on a series of new wheels thermally damaged on a unique dynamometer at the manufacturer's test facility. The data show an ability to sort wheels with no, moderate, or severe damage (Figure 3) [7].

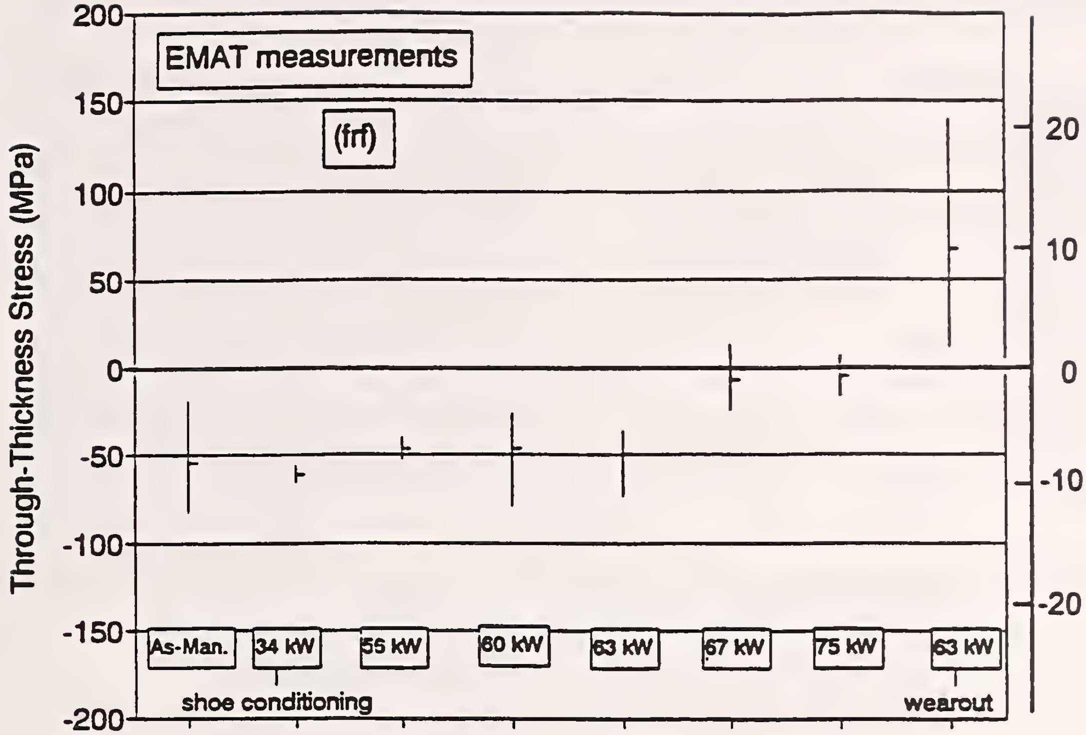

Figure 3. Ultrasonic measurements (average and spread around the circumference) of rim stress in wheels damaged on a dynamometer [7]. There was no significant damage below 62 kW, moderate damage at 67 kW to 75 kW, and considerable damage in a final wheel at 63 kW (different test scenario). This last wheel exploded during sawcutting.

The manufacturer did destructive measurements by sawcutting of selected wheels for quantitative verification of the NDE tests.

We were very fortunate during a large part of these tests to have the cooperation of the Institute of Fundamental Technological Research of the Polish Academy of Sciences in Warsaw, Poland. Dr. Jacek Szelążek of that laboratory duplicated many of these measurements using their piezoelectric-based instrument.

Timing capability (>5 ns precision) and mechanical positioning would allow determining stress to ±28 MPa (±4 ksi). The texture, however, contributes an uncertainty of about ±51 MPa (±8 ksi). Statistically combining these, we estimate our total stress error as ±60 MPa (±9 ksi). This leads to high confidence in finding compression or tension in a wheel rim.

5. INSTRUMENTATION DEVELOPMENT

The goal of this program was to develop a package that was compact, highly automated, and rugged enough for use in a shop environment. For greatest utility, most of the electronics are commercial, off-the-shelf (COTS). The photographs in Figure 4 and the block diagram of Fig 5. give an overview.

5.1 EMAT and Case

The photographs in Figure 6 show the transducer assembly. Figure 7 illustrates the essential elements of the EMAT. The magnet is a block (52 mm × 26 mm × 31 mm) of Nd-Fe-B with a nominal energy product of 0.28 MJ/m^3 (35 MG·Oe). A pole piece of mild steel concentrates the field to the 10 mm square active area [3-6].

The ability to generate ultrasonic signals with orthogonal polarizations is the result of stacking two identical pairs of coils at right angles. Each pair has two counterwound "racetrack" coils (inductance L). The straight portion of each coil is about 10mm to 12 mm long. Winding 35 turns of 36 AWG enameled wire gives a coil half-width of 5mm to 6 mm; when the two coils are aligned and connected properly, there is an aperture about 10 mm square under the pole tip where the rf current is flowing in the same direction.The DC resistance of the pair is about 4.1 Ω.

For maximum current flow, each pair of EMAT coils has a series capacitor (C). With the proper capacitor (in this case, 330 pF, mica), the LC circuit resonated at the 2 MHz operating frequency (Figure 8). For mechanical protection for the coils, they are encased in ¼-mm thick sheets of fiberglass-epoxy. To allow ready replacement of the coil package in the event of damage, there are three plug-in pins (common ground between the two coil pairs) to match sockets in the aluminum case. It is possible to switch coil packages in seconds.

The cable to the EMAT contains individually shielded twisted pairs. The rugged connectors have threaded shells that keep the connections clean.

The aluminum case (Figure 9) serves several functions: rf shielding, mechanical support, and the electrical connections, housing for the tuning capacitors and connections to the coils, and gripping/holding for the user. The most critical function, however, is the mechanical positioning of the EMAT. Two "ears" on the case locate the index point (inside edge of the front rim face) and center the active aperture at 14 mm from the inner edge of the front rim face. The EMAT magnet provides strong attraction to the wheel, but four additional disc magnets in the case assure that the whole package is self supporting even when the test wheel is vertical.

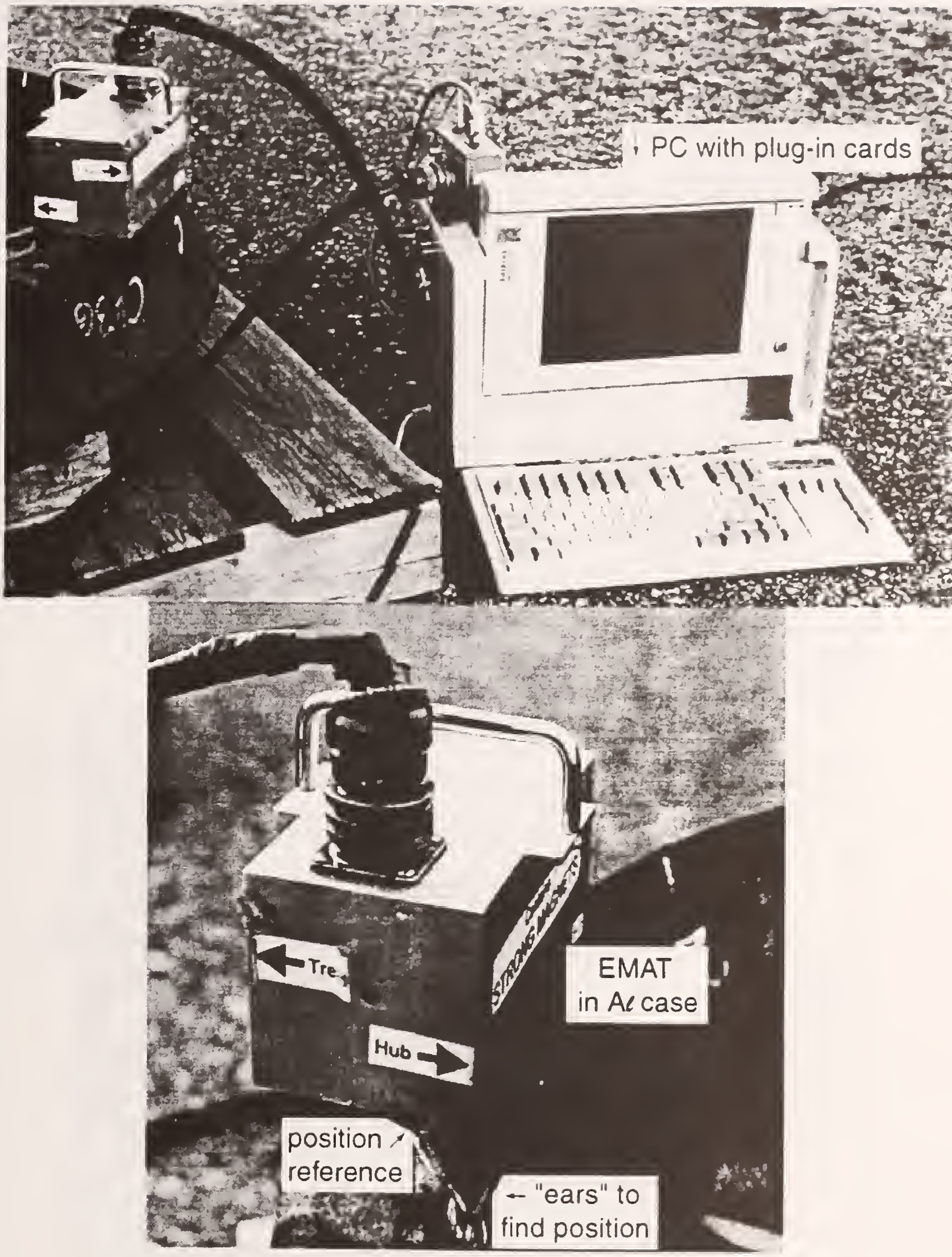

Figure 4. Rim stress measurement system:

a. "Lunchbox" computer with two plug-in cards. A small external box of electronics connects the 2 m long cable to the EMAT.

b. Transducer in position on the front rim face.

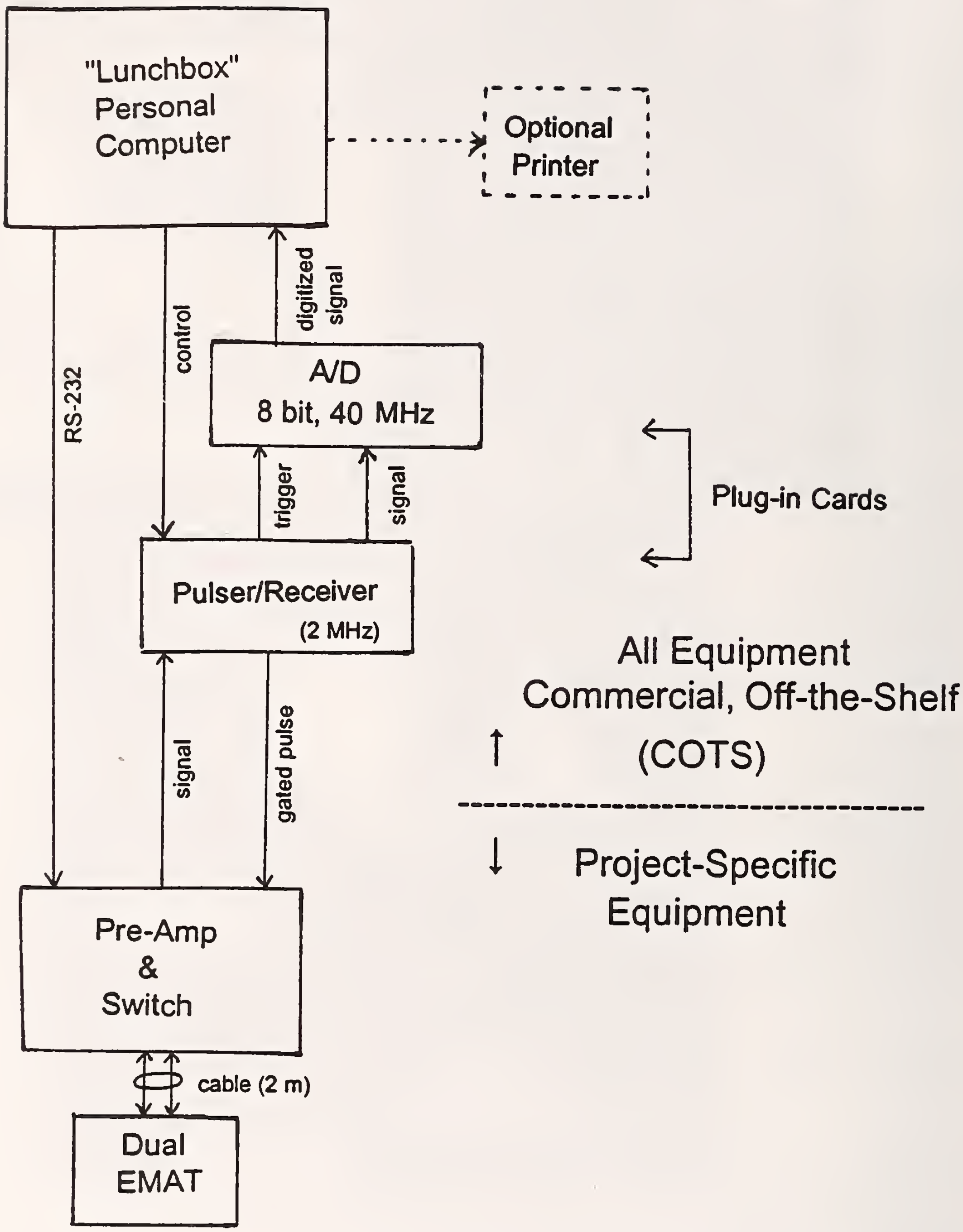

Figure 5. System elements, showing signal connections. The computer and plug-in cards are commercial items.

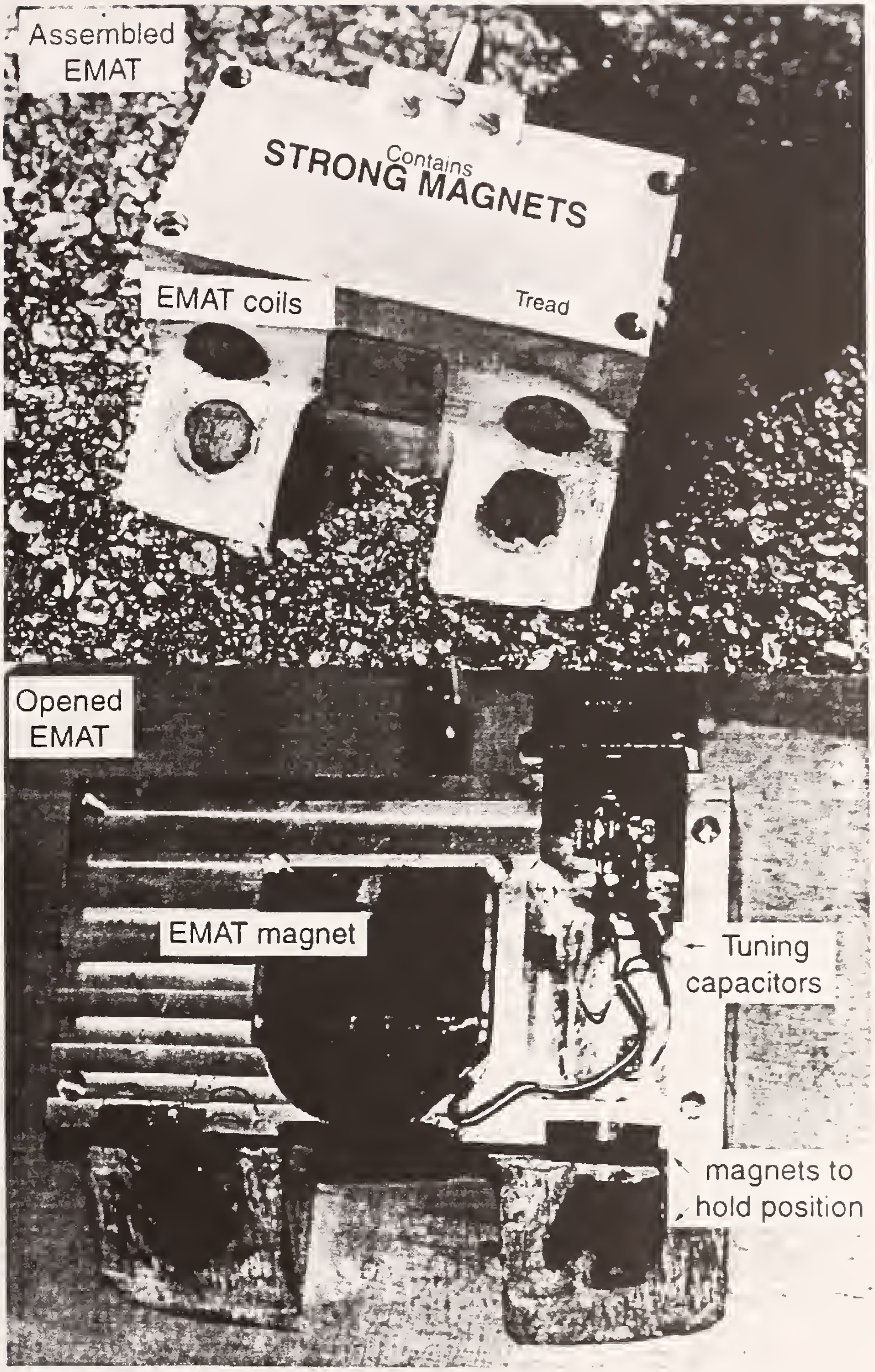

Figure 6. EMAT package:
a. Assembled. b. Opened.

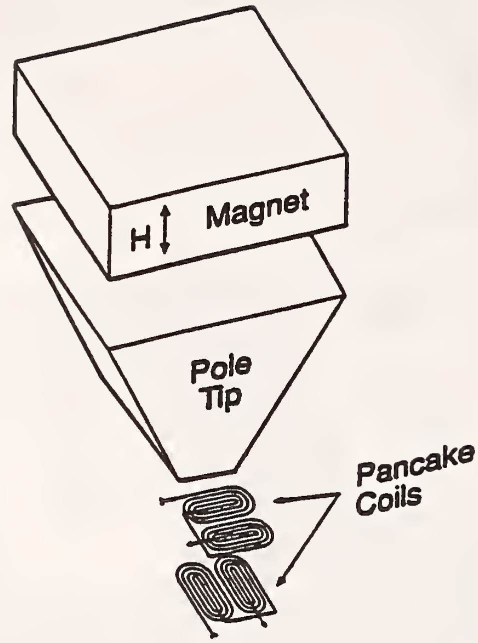

Figure 7. Schematic of the EMAT that generates orthogonally polarized shear horizontal (SH) waves on the front surface of the wheel rim [3-6].

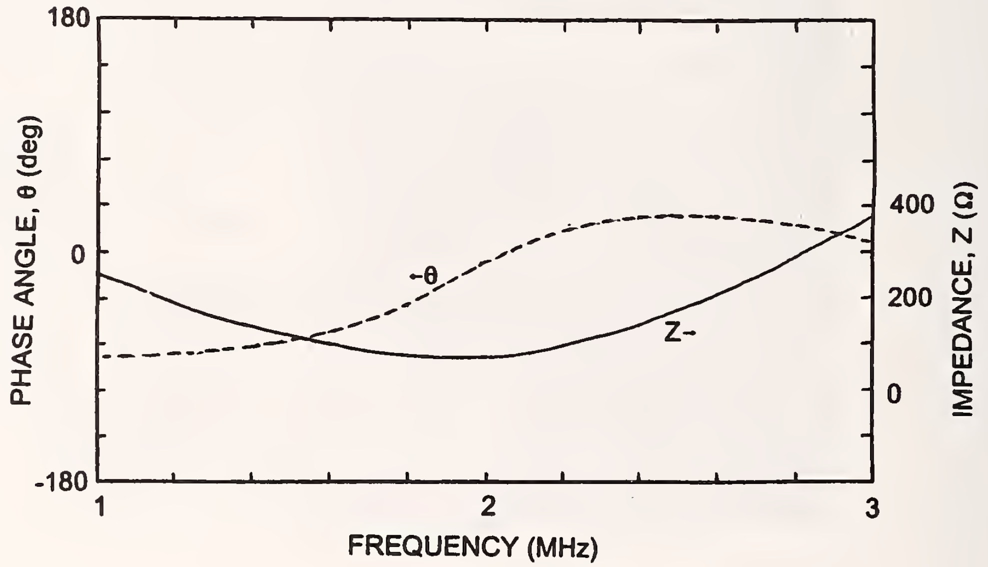

Figure 8. Sample of phase/impedance on an EMAT coil. Transducer in position on a rimblock; series capacitor = 330 pF; measured from the end of the transducer cable. At 2 MHz, Z ≈ 60 Ω to 70 Ω and θ < ±10°.

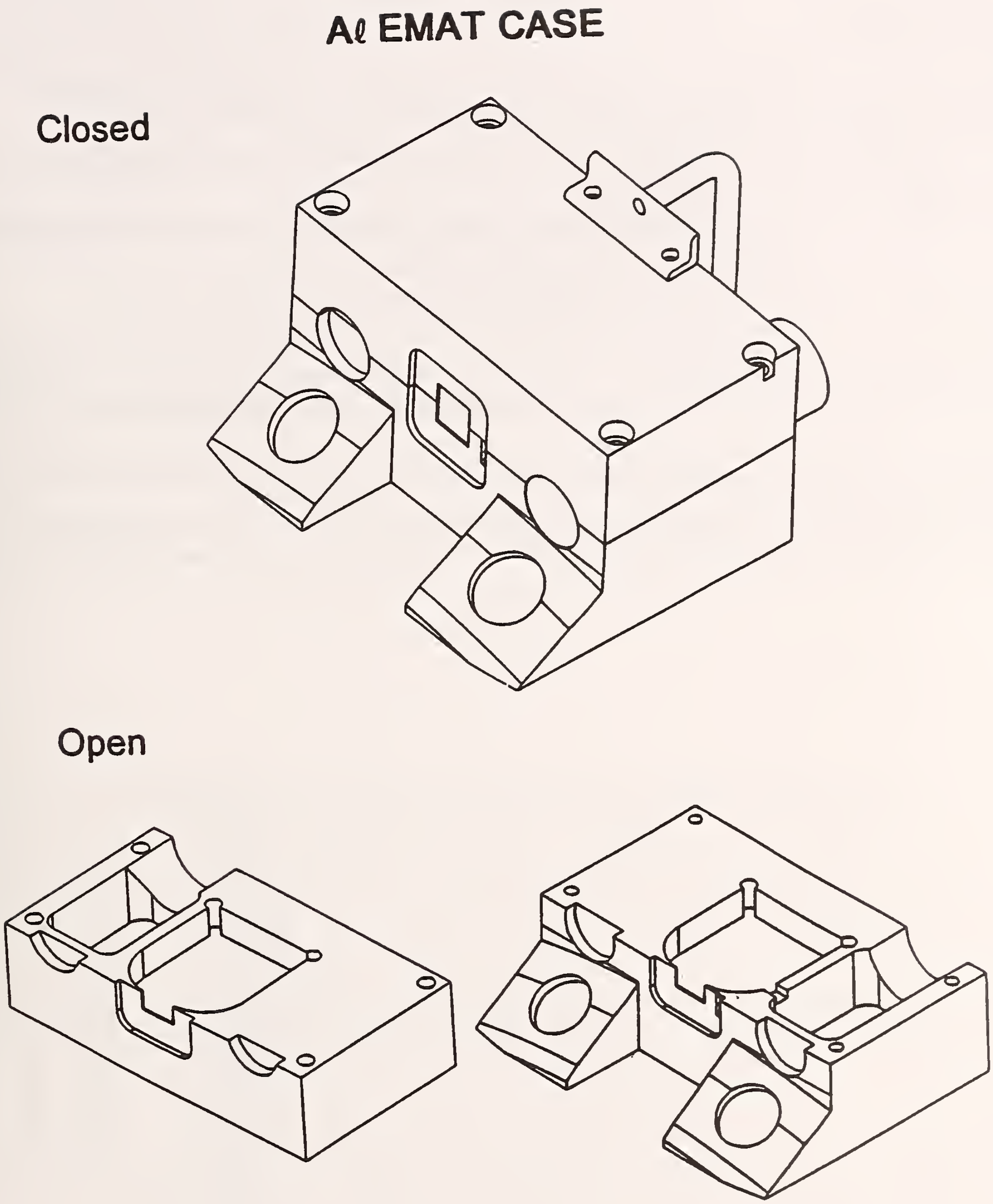

Figure 9. Schematic of aluminum case for the EMAT. There are two main sections with an attached handle. Internal recesses hold (1) magnet and pole piece, and (2) tuning capacitors and electrical connections. External recesses hold (1) coil package, (2) cable connector, and (3) four form-holding magnets.

5.2 Electronics

The platform for all the electronics is a "lunchbox" personal computer operating at 100 MHz. This is a compact system able to hold two full-length plug-in cards:

1. A pulser/receiver delivering a gated pulse of sufficient power to the EMAT, and an amplifier for the received signal.
2. An ADC (analog-to-digital converter) operating at sufficient speed to digitize the signal for timing calculations in a computer program.

A list of the commercial equipment used in the current form is in Appendix II.

The pulser/receiver used here seemed to be the only one commercially available configured as a standard plug-in card. While a custom modification that would approximately double the available power at 2 MHz is available, the standard card can still deliver a gated pulse of sufficient power into the present EMAT. Figure 10 shows a typical measurement of the voltage and current at the coil. These data give the peak-to-peak values of voltage and current (V_{pp} and I_{pp}), and the phase angle (θ). It is then possible to calculate the root-mean-square power:

$$P_{rms} = \frac{V_{pp} I_{pp}}{8} \cos\theta .$$

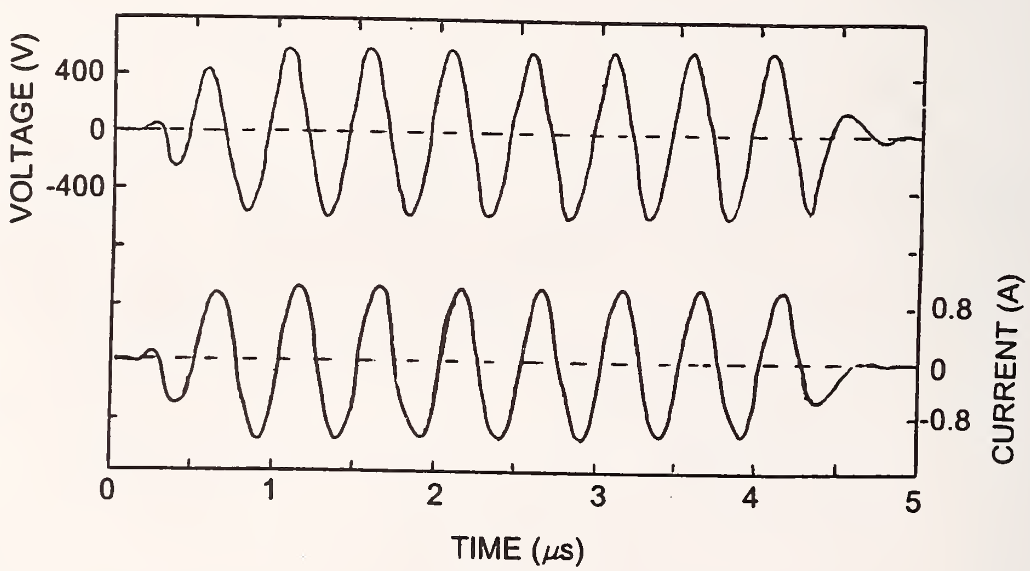

Figure 10. Typical voltage and current in an EMAT coil: eight cycles at 2 MHz. Tuning was done with a 330 pF series capacitor and the transducer was on a rim block. Operational phase angle came from these measurements.

Typical values measured on four coils (two stacked pairs) were:

V_{pp} = 1130 V to 1330 V,
I_{pp} = 1.4 A to 3.2 A,
θ = 18° to 38°, and
P_{rms} = 225 W to 375 W.

While the coils are nominally identical, there is a difference between top and bottom coils due to differences in coupling to the steel; some of the spread is also due to the hand construction of the coils and package. Figure 11 shows a typical acoustic signal.

For digitizing the acoustic signal, fast rates and many digits are desirable. For this application, we found it was sufficient (section 6) to use eight bits at a sampling rate of 40 MHz; such capability is readily available now at moderate prices.

A small case external to the computer contained a specially-built preamp (Appendix III) that we found necessary to condition the signal before the main amplifier on the pulser/receiver. The case also contained a relay controlled by the RS-232 bus to switch between the two orthogonal EMAT coils. A 2 m long cable connected this case to the EMAT.

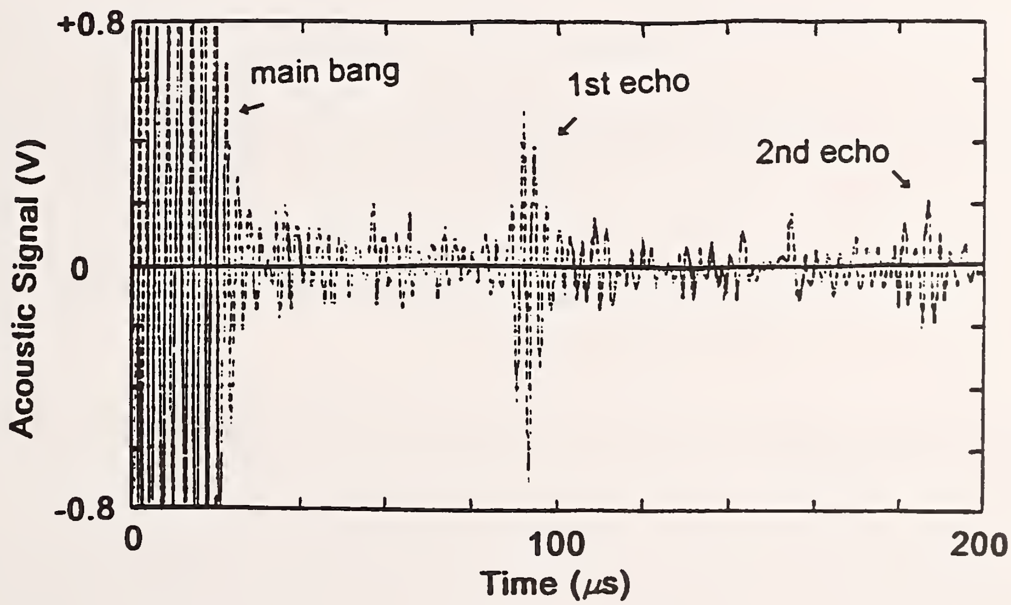

Figure 11. Raw acoustic signal, 2 MHz shear wave through the rim thickness, The first and second echoes are visible.

6. SOFTWARE

The pulser/receiver board comes with a program used to establish operational parameters (see Appendix IV). This system runs that program to establish the gated pulse amplification for the EMAT and then starts the package written for the rim stress. This applications package incorporates some software that came with the ADC to transfer data from the digitizer to the PC RAM.

The software language is BASIC. An outline and listings appear in Appendix V. Two capabilities here make operation possible:

a. Relay control (Appendix III) makes it possible to switch between coils and eliminate any mechanical rotation during a measurement; and
b. The ability to use digital signal data to measure timing with high precision without operator judgment or intervention.

As noted above, the ADC runs at only 40 MHz. At this rate, there is a trigger uncertainty of 25 ns. While this value alone would be unacceptable, the repeatability of the signal makes averaging a realistic possibility. As currently written, the software averages 36 signals for each polarization for each of 10 measurement sets, for a total of 360 signals. Statistically, this reduces the jitter to 25 ns/$\sqrt{360}$ = 1.3 ns, a satisfactory limit. The speed of the microprocessor makes it possible to collect this many waveforms in an acceptable time (<30 s).

The basic timing algorithm is to find the maximum of the first echo collected by the ADC. The program then looks for the two data points above and the two points below signal zero. It fits a straight line through these four points and calculates the zero crossing (Figure 12); this is taken to be the arrival time [10]. The search in all subsequent signals in a given measurement set is in the same time vicinity (for both polarizations). This prevents any cycle skipping, and is possible since no possible stress would shift the time by an amount as large as the cycle period of 500 ns. The range of measured times seen in Appendix VI shows that the standard deviation does approach the statistical possibility of 1.3 ns.

There are two variations (Appendix V) of the software. The basic operations are the same, but the presentations differ:

1. Shop version (SHOP.BAS). In each of 10 measurements, the number of signals averaged is fixed at 36, and the report on the screen contains only the final stress calculations rounded to the nearest 5 MPa or 1 ksi. The most significant calculations are the average of the ten measurements and the standard deviation; maximum and minimum values also help judge the quality of the test. A colored flag shows red

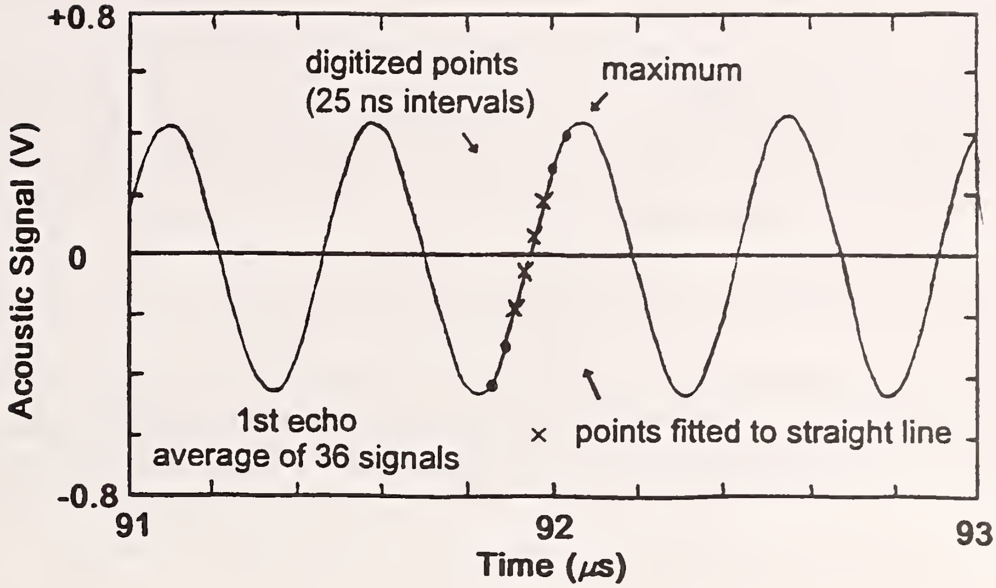

Figure 12. Expanded signal after 36 averages. The program fits a straight line to the four points immediately above and below the zero crossing. The intercept with the signal zero is the arrival time [10].

(tension) or green (compression). A yellow caution flag appears if the spread between the maximum and minimum is greater that a preset limit (currently 35 MPa or 5 ksi).

2. Detail version (DETAIL.BAS). The number of signals averaged is variable, and the report on the screen gives the measured times and calculated birefringences, as well as the stress.

7. OPERATION

As presently set up, the computer executes some batch files (Appendix V) at power-up. The pulser/receiver software requires a Q (quit) and O (okay) entry. The shop version of the data program then begins. Two lines are available for identification (e.g., operator, specimen)—or are skipped with an ENTER. When the transducer is in place, type S (as instructed by the bottom line) to begin the 10 sets of measurements (blue flag appears). When the measurements and calculations are complete (<30 s), the bottom line offers four options: paper hardcopy (P), continue to next specimen (M), record data on diskette (F), or exit the program (X).

The software has some built-in parameters:

B_0 = −2.1 × 10^{-4} (average value from heat-treated rimblocks),
C_A = −7.8 × 10^{-6} MPa^{-1},
Number of signal averages for each measurement pair = 36,
Number of measurement pairs = 10,
Red flag for tension (stress > 0),
Green flag for compression (stress < 0), and
Yellow flag for measurement spread > 35 MPa (5 ksi).

Two different programs read the data recorded on a diskette. FILE presents the data as does SHOP (stresses only), while FILEB gives all the detail of DETAIL (includes times and birefringence). These recorded versions note the values of B_0 and C_A used to calculate the stress.

At the C:\ prompt, the following batch programs are individually available:

PULSER — pulser/receiver control program,
SHOP — shop version of data collection (SHOP.BAS),
DETAIL — detailed version of data collection (DETAIL.BAS),
FILE — read diskette data and display as in shop version, and
FILEB — read diskette and display as in detail version.

While not fully tested, portable operation may be possible under power from a car/truck battery. Commonly available power inverters (≥500 W) generate 120 VAC from 12 VDC. The power, however, is quasi-sinusoidal; the stacked square waves have high-frequency components that may reach the ADC and distort the acoustic signal transferred to the computer. A large isolation transformer between inverter and computer seems to smooth out the 60 Hz power for satisfactory operation.

Additional improvements are always possible. Appendix VII lists a few of these.

8. CONCLUSIONS

In the present form, this ultrasonic instrumentation for stress measurement is

1. compact,
2. assembled of largely commercial electronics,
3. highly automatic, little training necessary,
4. easy to use, and
5. quantitative within useful uncertainties.

Two possible uses of this ultrasonic stress measurement system include:

1. Quality control at the wheel factory. This instrument has the precision to monitor stress changes in wheel rim stress to within <±28 MPa. Because of the speed and ease of measurement, nondestructive evaluation of the entire production becomes possible. Currently a significant fraction of production undergoes destructive testing.

2. Screening tool in a shop environment to evaluate in-service condition during routine maintenance and inspection. Accuracy restrictions imposed by possible texture variations increase possible error to <±60 MPa. With a realistic cutoff for tolerable stress, this would lead to quantitative and reliable decisions on wheel status. While insuring the removal of potentially dangerous wheels, testing would avoid the unnecessary condemnation of still-useful wheels. The economic incentive is strong.

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9. REFERENCES

1. Federal Railroad Administration, U.S. Dept. of Transportation, Code of Federal Regulations 49 CFR, 65, §215.03(h), 1985.

2. Office of Research and Development of the Association of American Railroads, *Wheel Failure Mechanisms of Railroad Cars*, Report TFR 53-82-C-00282, 1986.

3. R.E. Schramm, A.V. Clark, Jr., D.V. Mitraković, S.R. Schaps, and T.J. McGuire, "Report No. 23 - Residual Stress Detection in Railroad Wheels: An Ultrasonic System Using EMATs," NISTIR 3968, May 1991.

4. R.E. Schramm, A.V. Clark, Jr., and T.J. McGuire, "Ultrasonic Measurement of Residual Stress in Railroad Wheel Rims," in *Tenth International Wheelset Congress*, Institution of Engineers, Australia, 11 National Circuit, Barton, ACT, pp. 151-155 (1992).

5. R.E. Schramm, J. Szelążek, and A.V. Clark, Jr., "Report No. 28 - Residual Stress in Induction-Heated Railroad Wheels: Ultrasonic and Saw Cut Measurements," NISTIR 5038, May 1995.

6. R.E. Schramm, J. Szelążek, and A.V. Clark, Jr., "Ultrasonic Measurement of Residual Stress in the Rims of Inductively Heated Railroad Wheels." *Materials Evaluation*, Vol. 54, August 1996, pp. 929-934.

7. R.E. Schramm, J. Szelążek, and A.V. Clark, Jr., "Report No. 30 - Dynamometer-Induced Residual Stress in Railroad Wheels: Ultrasonic and Saw Cut Measurements," NISTIR 5043, March 1996.

8. R.E. Schramm, A.V. Clark, and J. Szelążek, "Ultrasonic Measurement of Residual Stress in Cast Steel Railroad Wheels," in *Determining Material Characterization: Residual Stress and Integrity with NDE*, PVP-Vol. 276, NDE-Vol. 12, The American Society of Mechanical Engineers, NY, pp. 157-162 (1994).

9. R.E. Schramm, A.V. Clark, and J. Szelążek, "Safety Assessment of Railroad Wheels by Residual Stress Measurements," in *Nondestructive Evaluation of Aging Railroads*, Donald E. Gray, Daniel Stone, eds., Proc. SPIE 2458, pp. 97-108 (1995).

10. P.A. Fuchs, A.V. Clark, M.G. Lozev, U. Halabe, P. Klinkhachorn, S. Petro, and H. GangaRao, "Ultrasonic Instrumentation for Measuring Applied Stress on Bridges," submitted to *Journal for Nondestructive Testing*, November 1997.

APPENDIX I: Commercial Systems Available or in Development

We are aware of three ultrasonic systems currently available on the commercial market. While the principle of operation is the same, there are differences in implementation.

1. DEBRO from the Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland.

   - Based on piezoelectric transducers requiring fluid couplants.
   - Small, compact, can use batteries for portable operation.

2. Institut für zerstörungsfreie Prüfverfahren (IzfP), Saarbrücken, Germany.
   - Based on EMATs.
   - Very large, with electromechanical operations for very detailed inspections/analyses.

3. CISE SpA, Milan, Italy
   - Based on EMATs.
   - Recently released, no further information.

The NIST/FRA system, for comparison:
- Based on EMATs.
- Compact, but not currently operating on batteries.
- Reliable screening (stress is compressive or tensile) in about 30 s.

Within the last few months, two companies have notified us that they have started preliminary development of EMAT systems intended for stress measurements in railroad wheel rims. Their work stems, at least in part, from the NIST program.

1. International Electronic Machines Corporation
   60 Fourth Ave.
   Albany, NY 12202-1924

2. Sonic Force Company
   30 Adrian Ct.
   Burlingame, CA 94010

APPENDIX II: Commercial Equipment Used in this Instrument

The identification of companies, products, or tradenames in no way implies endorsement or approval by NIST; these are included in this report only for complete documentation of apparatus we found adequate or useful. Other products may exist which are equally acceptable.

Three commercial products make up the bulk of the electronics in this ultrasonic package.

1. Personal Computer, 100 MHz, Pentium-type:

   Virtually any PC can serve as a platform. The only requirements are the availability of two, full-length plug-in slots and a power supply with a minimum capacity of 250 W. A faster CPU will result in shorter measurement time, but, after 100 MHz, the main limit is probably the transfer time from the ADC to the main RAM.

2. The software used here explicitly incorporates the WAAG II ADC, 40 MHz, 8 bit:

   Markenrich Corp.
   1812 Flower Ave.
   Duarte, CA 91010

   Several digitizers with sampling rates of 50 or 100 MHz are now on the market. The WAAG III at 50 MHz has superseded the WAAG II.

3. To the best of our knowledge, the only integrated pulser/receiver currently available on a single PC plug-in card is the Matec TB1000, 450 W (p-p) power, 70 dB gain:

   Matec Instrumentation, Inc.
   56 Hudson St.
   Northborough, MA 01532

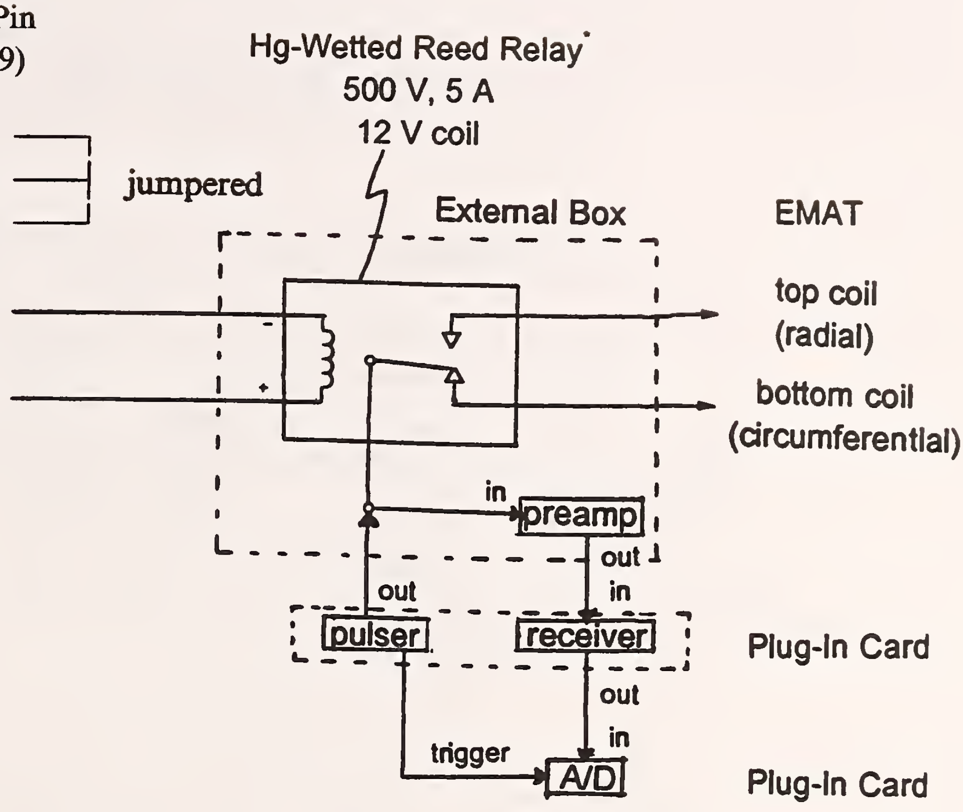
   While this integration is not necessary, it does allow the stress-measurement system to reside in a consolidated box.

APPENDIX III: External Box: Relay, Preamp, and Cable

The RS-232 connectors (D-subminiature) are 25-pin at the computer and 9-pin at the external box. Jumpers connect three pins, and two pins provide the drive for the coil switching relay. While we found a relay that will operate directly from the bus, it would be better to have a driver for the relay. The following schematic shows the connections and a proposed driver.

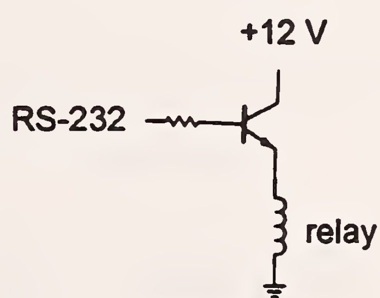
RS-232

Computer Pin (DB25)		Box Pin (DB9)
20	—	4
6	—	6
4	—	8
2	—	3
4	—	7



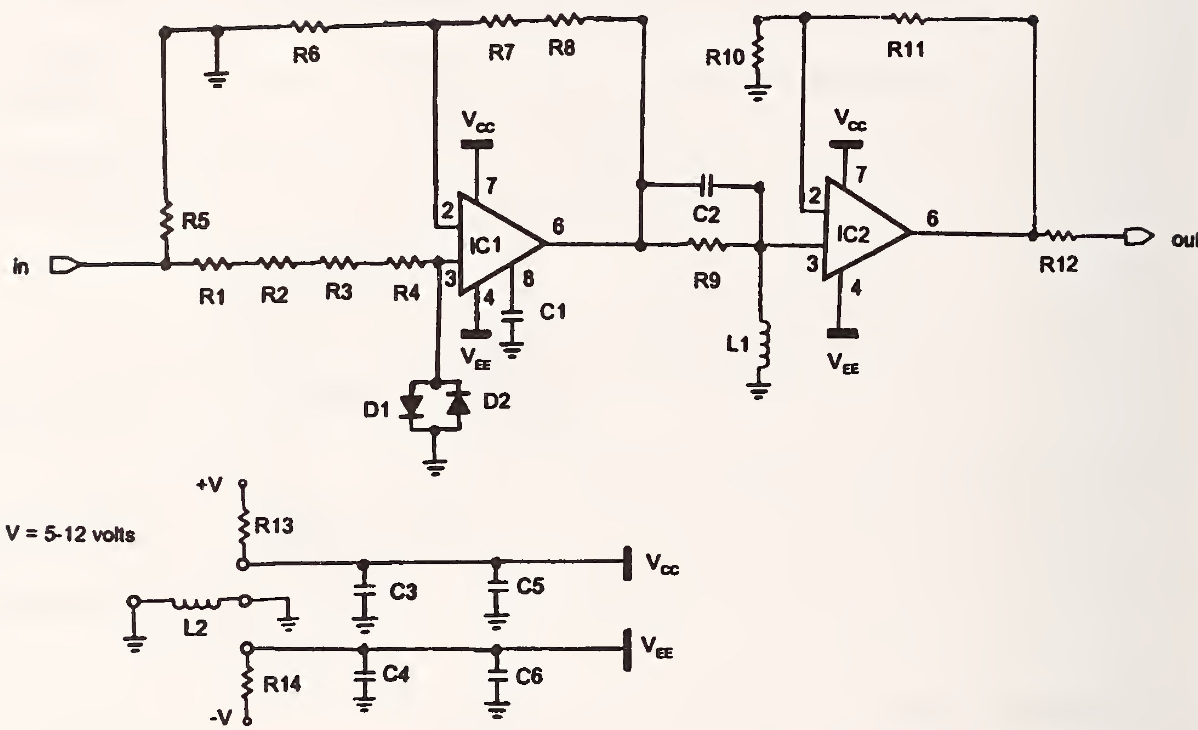
e.g., CP Clare, HGWM51111P00

A possible relay driver:



The following schematic is the preamplifier in the external box. We estimate the gain to be 55 dB to 60 dB. Note that R1 - R4 with D1 and D2 constitute a diode limiter that protects the preamp from the very large gated signal that powers the EMAT. Preamp power comes from the computer. R13 and R14 are current-limiting resistors to protect the power supply. L2 helps protect against ground-loop noise.

EMAT PREAMPLIFIER
(2 MHz)



PARTS LIST

R1 - R4	100 Ω, 1%, 1/8 W, metal film	C1	33 pF
R5	6.8 k, 1%, 1/8 W, metal film	C2	56 pF
R6	10 Ω, 1%, 1/8 W, metal film	C3 - C4	0.1 µf
R7	5.11 k, 1%, 1/8 W, metal film	C5 - C6	1 µf, 50 V
R8	4.75 k, 1%, 1/8 W, metal film	D1 - D2	1N4148
R9	47.5 k , 1%	L1	100 µH
R10 - R11	100 Ω, 1%	L2	22 mH
R12	49.9 Ω, 1%, 1/8 W metal film	IC1	AD797
R13 - R14	100 Ω, 1 W, carbon	IC2	CLC425

The 2 m long EMAT cable contains six pairs of 24 AWG wire, with a foil shield around each pair; an external wire braid and then a polymer braid covers the cable. The connectors at each end have a heavy aluminum case with a screw-on shell to ensure stable, enclosed contacts. Since this was still a research project, the box contains parallel feeds through BNC connectors and a DPDT switch to reverse the connections to the two EMAT coils.

APPENDIX IV: Pulser/Receiver Operational Parameters

To operate the pulser/receiver board, a menu of parameters available. Those used here are:

Rep Rate	=	10 ms (repetition rate = 100 Hz)
Receiver Gain	=	25 dB (adjustable 0 dB to 70 dB)
Frequency	=	2 MHz (20 MHz maximum)
Trigger	=	+Int
Width	=	4 μs (8 cycles/pulse)
Vsel	=	High (also can switch to low or zero voltage)
X/R	=	Tx ("through transmission" normally for pitch-catch)
Rectify	=	None (look at rf signal)
HPF	=	1 MHz (high pass filter)
LPF	=	2.25 MHz (low pass filter)

Unless changed during startup, these parameters remain fixed.

APPENDIX V: Software Listings

The software written for this program is in BASIC and will run in QBASIC or GWBASIC; when it is run in the latter, use the /d switch (see batch files below) to activate double precision capability necessary for the statistical calculations.

Table 1. Software Summary

Directory	Contents	Purpose
STRESS	SHOP, DETAIL, FILE, FILEB (all as .BAS and .TXT)	Data collection and display programs
TB1000	Matec software	Pulser/receiver operation and control
BATCH	SHOP, DETAIL, FILE, FILEB (all as .BAT)	Call software (directory in PATH statement of AUTOEXEC.BAT)

Software Outline

1. Enter identification (or just ENTER twice for blank lines)
   - A. Work-session parameters (e.g., operator name, location, etc.)
   - B. Specimen parameters (e.g., wheel ID, rim location, etc.)

2. Switch relay to radial polarization
   - A. Digitize first round-trip echo at 40 MHz (25 ns/point)
   - B. Transfer 512 points to computer RAM (85 μs to 97.8 μs)
   - C. Repeat signal capture (A and B) 36 times
   - D. Calculate average of the 36 signals

3. Signal timing
   - A. Find signal maximum (N.B., do this for only the first echo captured, then use this same time point for all subsequent signals. This assures measuring the same cycle on each echo, i.e., prevents cycle skipping.)
   - B. Find the first zero crossing before the maximum from A
   - C. Fit (least squares) a straight line to the two points above and the two points below this zero crossing
   - D. The intercept of this line with the zero ordinate is the time

4. Switch relay to hoop polarization, repeat 2 and 3

5. Calculate stress
   - A. B from the relative time change between polarizations
   - B. B_0 and C_A material constants

6. Report stress (MPa and ksi) on computer screen

7. Repeat 2 through 6, 10 times

8. Statistics calculated from the 10 sets of measurements
   - A. Average and standard deviation
   - B. Data spread (maximum and minimum)

9. Options
   - A. Printer copy of screen display
   - B. Floppy disk copy of raw data (can be used to display stresses any time later)
   - C. Go to next measurement (1.B.)
   - D. Exit program and conclude session

SHOP.BAS -- BASIC listing of the program that displays only the calculated stress.


```
100 '  SHOP   12/8/97  Mon      Ray S.
110 '    automatic switching between coils - connects to COM2
120 '    calculate echo arrival times for radial & circum. polarizations
130 '    time by straight line extrapolation - cf. Paul Fuchs (4 points)
140 '    average AV signals  - 10 tests - colored flags
150 '    calculate stress only (default B0 & CA)
160 '      also calculate avg. & std. dev.
170 '  (Load interpreter as GWBASIC/D to get double precision for std. dev.)
180 '    2 MHz signals digitized @ 40 MS/s  (WAAG) 512 pts start @ 85 us (OS ns)
190 '       @ 25 ns/pt, this is 12.8 us (thickness range about 136-156 mm)
200 '    find index of max for 1st sig - same for 2nd sig & subsequent 10 tests
205 '    options for printer and floppy disk file (use FILE or FILEB to read)
210 '
500 REM    ******************    Program Constants    *********************
510 '
520 AV=36                        ' # of signals captured for average
530 LF=4                         ' # of points for straight line fit (could be 2)
540 ALARM=0                      ' alarm leve (red square) for stress report
550 KSI=6.894757                 ' conversion, ksi to MPa
560 WIDE=5*KSI                   ' max stress spread (yellow square) in MPa (=5ksi)
570 BF=-2.1                      ' texture birefringence (in 10^-4)
580 CF=-7.8                      ' stress acoustic constant (in 10^-6/MPa)
590 DS=10                        ' # of data sets collected
600 OS=85000!                    ' digital offset in ns = start of data
610 DT=25                        ' digitizing time in ns for 40 MS/s A/D
620 '
700 REM   *****************     Set Up      ********************************
710 '
720 SCREEN 8                     ' change screen
730 COLOR 7,1                    ' white on blue
750 DIM Y%(512)
760 FOR I=1 TO 2                 ' cycle coil relay 2 times
770 OPEN "COM2:" FOR RANDOM AS #3: '  switch to radial
780 FOR J=1 TO 60000!:NEXT J  ' delay
790 CLOSE #3: '   switch to circumferential
800 FOR J=1 TO 60000!:NEXT J  ' delay
810 NEXT I
820 GOSUB 4000        ' set up WAAG
830 CLS : PRINT "Information for EVERY data set (e.g., operator) --": INPUT OP$
840 IF ID$ = "" THEN 890
850 CLS : PRINT ID$: PRINT : PRINT : PRINT "Use SAME identification or type in a
 NEW one? (Type S or N)"
860 Z$ = INPUT$(1): IF Z$ = "S" OR Z$ = "s" THEN 1020
870 IF Z$ = "N" OR Z$ = "n" THEN 890
880 GOTO 860
890 CLS : PRINT "Identification for THIS data set (DATE$ & TIME$ added) --": INP
UT ID$
900 '
1000 REM    ***************      Start Test     ****************************
1010 '
1020 CLS : ' print heading
1030 PRINT ID$; "--"; OP$; "  "; DATE$; "  "; TIME$
1040 LOCATE 3,1
1050 PRINT "Test           Stress"
1060 PRINT "Num         MPa      ksi"
1070 F$ = "###       +####     +###"
1080 PRINT : L = 5: ID = 1
1090 SM1# = 0: SM2# = 0: SE1# = 0: SE2# = 0
1100 GOSUB 10000:PRINT "  Type S to start data collection.  ";
1110 Z$ = INPUT$(1)
```

```
1120 IF Z$ = "S" OR Z$ = "s" THEN 1140
1130 GOTO 1110
1140 GOSUB 10000: PRINT "Now collecting";DS;"sets of data.";
1150 GOSUB 9600                ' turn on blue flag
1160 POL=1:OPEN "COM2:" FOR RANDOM AS #3: '  switch to radial
1170 GOSUB 4200: R = T:TR(ID)=R+OS    ' READ RADIAL TIME
1180 POL=2:CLOSE #3: '   switch to circumferential
1190 GOSUB 4200: C = T:TC(ID)=C+OS    ' READ CIRCUM TIME
1200 GOSUB 1250: LOCATE L,1: PRINT USING F$; ID; 5*CINT(SM/5); SE: L = L + 1
1210 T1(ID) = R + OS: T2(ID) = C + OS: S1(ID) = SM: S2(ID) = SE: ID = ID + 1
1220 SM1# = SM1# + SM: SM2# = SM2# + SM ^ 2: SE1# = SE1# + SE: SE2# = SE2# + SE
^ 2
1230 IF ID = DS+1 THEN 2200: '  average & statistics
1240 GOTO 1160
1250 '
2000 REM   ***************  Calculations   ---   Stress, Max, Min   **********
2010 '
2020 BO = BF * 10 ^ -4: ' Birefringence due to texture
2030 CA = CF * 10 ^ -6: ' Stress acoustic constant in 1/MPa
2040 B = (R - C) / (OS+(R + C) / 2): ' Measured birefringence
2050 SM = (B - BO) / CA: ' Stress in MPa
2060 SE = SM / KSI: '  Stress in ksi
2070 IF ID > 1 THEN 2090
2080 SMAX = SM: SMIN = SM: RETURN
2090 IF SM > SMAX THEN SMAX = SM
2100 IF SM < SMIN THEN SMIN = SM
2110 RETURN
2120 '
2200 REM  ***********     AVERAGE & STATISTICS     ***********************
2210 '
2220 ID = ID - 1: IF ID < 2 THEN 2360
2230 SM1# = SM1# / ID: SM2# = SQR((SM2# - ID * SM1# ^ 2) / (ID - 1))
2240 SE1# = SE1# / ID: SE2# = SQR((SE2# - ID * SE1# ^ 2) / (ID - 1))
2250 F$ = "\  \      +####     +###"
2260 LOCATE L + 1,1: PRINT USING F$; "Avg"; 5*CINT(SM1#/5); SE1#
2270 F$ = "\  \        ###       ###"
2280 PRINT USING F$; "S.D."; 5*CINT(SM2#/5); SE2#: PRINT
2290 F$ = "\  \      +####     +###"
2300 PRINT USING F$; "Max"; 5*CINT(SMAX/5); SMAX / KSI
2310 PRINT USING F$; "Min"; 5*CINT(SMIN/5); SMIN / KSI
2320 IF SM1#>=ALARM GOTO 2340 ' test for bad stress
2330 GOSUB 9700: GOTO 2350    ' green flag
2340 GOSUB 9800               ' red flag
2350 IF SMAX-SMIN>WIDE THEN GOSUB 9900   ' yellow flag
2360 'LOCATE 22: F$ = "                                  ": F$ = F$ + F$ + F$: PRINT F$:
PRINT F$
2370 GOSUB 10000: PRINT "PRINT this screen (P), MORE data (M), SAVE to floppy (S
), or EXIT program (X)?";
2380 Z$ = INPUT$(1)
2390 IF Z$ = "X" OR Z$ = "x" THEN SYSTEM
2400 IF Z$ = "M" OR Z$ = "m" THEN 840
2405 IF Z$ = "S" OR Z$ = "s" THEN 5000
2410 IF Z$ = "P" OR Z$ = "p" THEN 2430
2420 GOTO 2380
2430 '
2600 REM   ***********      PRINT SCREEN       ***********************
2610 '
2620 LPRINT CHR$(27); CHR$(120); CHR$(1): '  turn on NLQ on LX-800 printer
2630 LPRINT CHR$(27); CHR$(107); CHR$(1): '  select sans serif font on LX-800 pr
inter
```

```
2640 SC = SC + 1: '  screen counter
2650 LPRINT ID$: LPRINT OP$; "  "; DATE$; "  "; TIME$: LPRINT
2660 LPRINT "Test         Stress"
2670 LPRINT "Num       MPa      ksi"
2680 F$ = "###     +####     +###"
2690 FOR I = 1 TO ID: LPRINT USING F$; I; 5*CINT(S1(I)/5); S2(I): NEXT I
2700 LPRINT
2710 F$ = "\  \    +####     +###"
2720 LPRINT USING F$; "Avg"; 5*CINT(SM1#/5); SE1#
2730 F$ = "\  \      ###      ###"
2740 LPRINT USING F$; "S.D."; 5*CINT(SM2#/5); SE2#: PRINT
2750 F$ = "\  \    +####     +###"
2760 LPRINT : LPRINT USING F$; "Max"; 5*CINT(SMAX/5); SMAX / KSI
2770 LPRINT USING F$; "Min"; 5*CINT(SMIN/5); SMIN / KSI
2775 LPRINT : LPRINT "B0 ="; BF; " x 10^-4    and    CA = "; CF; " x 10^-6/MPa"
2790 LPRINT : LPRINT : LPRINT : IF SC < 2 THEN 2810
2800 SC = 0: LPRINT CHR$(12): '  form feed printer after 2 screen prints
2810 GOSUB 10000:PRINT "MORE data (M), SAVE to floppy (S), or EXIT program (X)?"
;
2820 Z$ = INPUT$(1)
2830 IF Z$ = "X" OR Z$ = "x" THEN SYSTEM
2835 IF Z$ = "S" OR Z$ = "s" THEN 5000
2840 IF Z$ = "M" OR Z$ = "m" THEN 840
2850 GOTO 2820
2860 '
3000 REM  *****************        Start Processing          ******************
3010 '
3020 FOR I=0 TO 511:Y%(I)=Y%(I)-AV*128:NEXT I
3030 IF POL=2 THEN 3070
3040 IF ID>1 THEN 3070
3050 GOSUB 3280          '  find peak of 1st signal
3060 GOTO 3080
3070 GOSUB 3460
3080 T=REF(LF)*10^3':PRINT T:RETURN       '  LF (= 2 or 4) point fit for time
3090 RETURN
3100 '
3200 REM  ***************   Linear Fit of N points, starting @ point K  **
3210 '  calculate slope & intercept to get 0 crossing
3220 SX#=0:SY#=0:SXY#=0:SX2#=0
3230 FOR K=I TO I+N-1
3240 SX#=SX#+K:SX2#=SX2#+K^2:SY#=SY#+Y%(K):SXY#=SXY#+K*Y%(K):NEXT K
3250 SL#=(N*SXY#-SX#*SY#)/(N*SX2#-SX#^2)                       '  slope
3260 IN#=(SX2#*SY#-SX#*SXY#)/(N*SX2#-SX#^2)                    '  intercept
3270 X0#=-IN#/SL#:RETURN           '  0 crossing  (time=0.025 us * X0#)
3280 '
3400 REM   *******    Find 0 Crossing - acoustic signals                    ***
3410 '
3420 MAX=Y%(0):P=0          'find signal peak
3430 FOR I=1 TO 511
3440 IF MAX<Y%(I) THEN MAX=Y%(I):P=I
3450 NEXT I
3460 GOSUB 3510         '  points about 0
3470 FOR N=2 TO 4 STEP 2      '  fit to 1 & 2 point pairs
3480 I=I-1:GOSUB 3200    '  linear LS fit
3490 REF(N)=X0#*.025:NEXT N          '  reference times in us
3500 RETURN
3510 '
3600 REM   ********  Find 1st Point Above Baseline   *******
3610 '
3620 I=P-2
```

```
3630 IF Y%(I)<0 THEN 3650
3640 I=I-1:GOTO 3630
3650 I=I+1:RETURN           '  I = 1st # above baseline
3660 '
4000 REM  ***************  Set Up WAAG Card  ********************************
4010 '
4020 SEGMENT% = &HD000            'WAAG II data segment
4030 PORT0% = &H178               'Default setting, all switches are off
4040 PORT1% = &H179
4050 PORT2% = &H17A
4060 PORT3% = &H17B
4070 '
4080 DEF FN LOBT(X%) = X% AND &HFF                        'Define low byte
4090 DEF FN HIBT(X%) = ((X% AND &HFF00) \ 256) AND &HFF  'Define high byte
4100 '
4110 COUNT%=4096                  'Record length  (102.4 us @ 0.025 us/point)
4120 CONTROL% = &H800C            'Control word, 40 Mhz clock (single channel)
4130 TOFFSET% = 140               'Trigger offset value
4140 '
4150 RETURN
4160 '
4200 REM  ************     Digitize Signal     ****************************
4210 '
4220 FOR I=0 TO 511:Y%(I)=0:NEXT I                  'clear array
4230 FOR M=1 TO AV                                  'average AV pulses
4240 GOSUB 4400                                     'Load trigger offset
4250 GOSUB 4600                                     'Data acquitition
4260 '
4270 START = TRIG * 2             'Valid address of trigger point
4280 DEF SEG = SEGMENT%           'Define data segment
4290 GOSUB 4800                   'add up files
4300 DEF SEG                      'Restore data segment
4310 NEXT M
4320 GOSUB 2860
4330 RETURN
4340 '
4400 REM ********** Load Trigger offset subroutine ************************
4410 '
4420 DEF SEG = SEGMENT%                  'Define WAAG II segment
4430 OUT PORT3%,&HC0: OUT PORT2%,&H6F    'Enable trigger offset
4440 POKE 0,TOFFSET%                     'Load offset value
4450 OUT PORT3%,&H80: OUT PORT2%,&H6F    'Reset control register
4460 DEF SEG                             'Restore data segment
4470 RETURN
4480 '
4600 REM **********  Data acquisition subroutine *************************
4610 '
4620 OUT PORT3%,&H80: OUT PORT2%,&H6F   'Initialize control regs
4630 OUT PORT1%,&HFF: OUT PORT0%,&HFF   'Clear counter
4640 OUT PORT1%,&HFF: OUT PORT0%,&HFF
4650 N% = -(COUNT% + &HFF)              'Correct count
4660 OUT PORT1%,FN HIBT(N%): OUT PORT0%,FN LOBT(N%)     'Load count
4670 OUT PORT1%,FN HIBT(N%): OUT PORT0%,FN LOBT(N%)
4680 N1% = CONTROL% AND &HBFFC
4690 OUT PORT3%,FN HIBT(N1%): OUT PORT2%,FN LOBT(N1%)   'Start sampling
4700 IF INP(PORT2%)<>249 THEN 4700      'WAIT PORT2%,1    -    wait for busy
4710 OUT PORT3%,&H80: OUT PORT2%,&H6F                   'Enable WAAG II ram
4720 TRIG = INP(PORT0%) + (INP(PORT1%) AND &H3F)*256    'Read trigger value
4730 RETURN
4740 '
```

```
4800 REM **************  Sum Files   ********************************************
4810 '
4820 IA=START
4830 FOR I=0 TO 511                          '  12.8 us = 512*25 ns/pt
4840 Y%(I)=Y%(I)+PEEK(IA+I+OS/DT):NEXT I 'add sigs, start @ OS ns, DT increments
4850 RETURN
4860 '
5000 REM   **********************   Write time data on floppy  *************
5010 '
5020 GOSUB 10000
5030 PRINT"Insert floppy into DRIVE A:  --  FILE name (.DAT added) = ";
5040 INPUT DN$:DN$="A:"+DN$+".DAT"
5050 OPEN "O",#1,DN$
5060 PRINT#1,ID$:PRINT#1,OP$
5070 PRINT#1,CHR$(34);TIME$;CHR$(34);CHR$(34);DATE$;CHR$(34);CHR$(34);STR$(BF);C
HR$(34);CHR$(34);STR$(CF);CHR$(34);CHR$(34);STR$(DS);CHR$(34)
5080 FOR I=1 TO DS:PRINT#1,CHR$(34);STR$(TR(I));CHR$(34);CHR$(34);STR$(TC(I));CH
R$(34):NEXT I
5090 CLOSE#1
5100 LOCATE 22: F$ = "                         ":F$=F$+F$+F$:PRINT F$:PRINT F$
5110 GOSUB 10000:PRINT"PRINT this screen (P), MORE data (M), or EXIT program (X)
?";
5120 Z$=INPUT$(1)
5130 IF Z$="X" OR Z$="x" THEN SYSTEM
5140 IF Z$="M" OR Z$="m" THEN 840
5150 IF Z$="P" OR Z$="p" THEN 2600
5160 GOTO 5120
5170 '
9500 REM   ****************    Colored Flags    ******************************
9600 '
9610 ' Light Blue Square  ---  TESTING
9620 LINE(500,120)-(600,170),2,B        'green border - only thing that works
9630 PAINT(525,137),3,2                 'light blue square
9640 LOCATE 19,66:PRINT"WORKING":RETURN
9650 '
9700 '
9710 ' Green Square  ---  GOOD
9720 PAINT(525,137),2,2                 'green square
9730 LOCATE 19,66:PRINT"  GOOD ":RETURN
9740 '
9800 '
9810 ' Red Square  ---  BAD
9820 PAINT(525,137),4,2                 'red square
9830 LOCATE 19,66:PRINT"  BAD  ":RETURN
9840 '
9900 '
9910 ' Yellow Square  ---  WIDE STRESS RANGE
9920 LINE(500,50)-(600,100),2,B         'green border - only thing that works
9930 PAINT(525,75),14,2                 'yellow square
9940 LOCATE 9,67:PRINT" WIDE "
9950 LOCATE 10,67:PRINT"STRESS"
9960 LOCATE 11,67:PRINT"RANGE ":RETURN
9970 '
10000 REM   ***************        Response Bar - Bottom of Screen   *******
10010 '
10020 LINE(0,170)-(640,195),5,BF
10030 LOCATE 23,1:RETURN
10040 '
```

DETAIL.BAS -- BASIC listing of the program that displays arrival times and birefringence with calculated stress.


```
100 '  DETAIL   12/8/97  Mon      Ray S.
110 '    automatic switching between coils - connects to COM2
120 '    read in echo arrival times for radial & circum. polarizations
130 '    calculate biref & stress  (default B0 & CA in 2480 or read file)
140 '      also calculate avg. & std. dev.
160 '  (Load interpreter as GWBASIC/D to get double precision for std. dev.)
170 '
180 '    2 MHz signals digitized @ 40 MS/s  (WAAG) 512 pts start @ 85 us
190 '    time by straight line extrapolation - cf. Paul Fuchs
200 '    uses both 1 & 2 pairs of points about baseline
210 '    find index of max for 1st sig - same for 2nd sig
215 '      options for printer and floppy file (read with FILE or FILEB)
220 '
230 BF = -2.1:CF = -7.8              '  stress parameters
240 CLS
255 DIM Y%(512)
260 FOR I=1 TO 2          ' cycle coil relay 2 times
270 OPEN "COM2:" FOR RANDOM AS #3: '  switch to radial
280 FOR J=1 TO 60000!:NEXT J    'delay
290 CLOSE #3: '   switch to circumferential
300 FOR J=1 TO 60000!:NEXT J    'delay
310 NEXT I
330 GOSUB 9014       ' set up WAAG
340 PRINT"Number of traces for average = ";: INPUT AV
410 CLS: 'PRINT"Check EMAT control box:"
500 DS=10: 'number of data sets for each measurement
570 CLS : PRINT "Information for EVERY data set (e.g., operator) --": INPUT OP$
580 IF ID$ = "" THEN 630
590 CLS : PRINT ID$: PRINT : PRINT : PRINT "Use SAME identification or type in a
 NEW one? (Type S or N)"
600 Z$ = INPUT$(1): IF Z$ = "S" OR Z$ = "s" THEN 640
610 IF Z$ = "N" OR Z$ = "n" THEN 630
620 GOTO 600
630 CLS : PRINT "Identification for THIS data set (DATE$ & TIME$ added) --": INP
UT ID$
640 CLS : ' print heading
650 PRINT ID$; "--"; OP$; "  "; DATE$; "  "; TIME$
660 LOCATE 3
670 PRINT "Test   Radial Time    Circum Time      B (x10^4)          Stress"
680 PRINT "Num        (ns)           (ns)                           MPa      ksi"
690 F$ = "###        ######         ######        +###.##        +####    +###.#"
700 PRINT : L = 5: ID = 1
710 R1# = 0: R2# = 0: C1# = 0: C2# = 0: B1# = 0: B2# = 0: SM1# = 0: SM2# = 0: SE
1# = 0: SE2# = 0: OS=85000! 'digital offset in ns
1000 '
1010 ' MASTER CONTROL
1020 '
1030 LOCATE 22
1040 PRINT "Type S to start data collection.    "                             "
1050 LOCATE 23: Z$ = INPUT$(1)
1060 IF Z$ = "S" OR Z$ = "s" THEN 1080
1070 GOTO 1050
1080 LOCATE 22: PRINT "Now collecting";DS;"sets of data.              "
1090 POL=1:OPEN "COM2:" FOR RANDOM AS #3: '  switch to radial
1100 GOSUB 9080: R = T   ' READ RADIAL TIME
1110 POL=2:CLOSE #3: '   switch to circumferential
1120 GOSUB 9080: C = T   ' READ CIRCUM TIME
1130 GOSUB 1200: LOCATE L: PRINT USING F$; ID; R + OS; C + OS; B * 10 ^ 4; SM; S
E: L = L + 1
1150 T1(ID) = R + OS: T2(ID) = C + OS: BR(ID) = B * 10 ^ 4: S1(ID) = SM: S2(ID)
```

```
= SE: ID = ID + 1
1160 R1# = R1# + R: R2# = R2# + R ^ 2: C1# = C1# + C: C2# = C2# + C ^ 2: B1# = B
1# + B * 10 ^ 4: B2# = B2# + (B * 10 ^ 4) ^ 2
1170 SM1# = SM1# + SM: SM2# = SM2# + SM ^ 2: SE1# = SE1# + SE: SE2# = SE2# + SE
^ 2
1180 IF ID = DS+1 THEN 2000: '  average & statistics
1190 GOTO 1090
1200 '
1210 '  Calculations
1220 '
1230 B0 = BF * 10 ^ -4: ' Birefringence due to texture
1240 CA = CF * 10 ^ -6: ' Stress acoustic constant in 1/MPa
1250 B = (R - C) / (OS+(R + C) / 2): ' Measured birefringence
1260 SM = (B - B0) / CA: ' Stress in MPa
1270 KSI = 6.894757: SE = SM / KSI: '  Stress in ksi
1280 IF ID > 1 THEN 1300
1290 RMAX = R: RMIN = R: CMAX = C: CMIN = C: BMAX = B: BMIN = B: SMAX = SM: SMIN
 = SM: RETURN
1300 IF R > RMAX THEN RMAX = R
1310 IF R < RMIN THEN RMIN = R
1320 IF C > CMAX THEN CMAX = C
1330 IF C < CMIN THEN CMIN = C
1340 IF B > BMAX THEN BMAX = B
1350 IF B < BMIN THEN BMIN = B
1360 IF SM > SMAX THEN SMAX = SM
1370 IF SM < SMIN THEN SMIN = SM
1380 RETURN
2000 '
2010 ' AVERAGE & STATISTICS
2020 '
2040 ID = ID - 1: IF ID < 2 THEN 2170
2050 R1# = R1# / ID: R2# = SQR((R2# - ID * R1# ^ 2) / (ID - 1))
2060 C1# = C1# / ID: C2# = SQR((C2# - ID * C1# ^ 2) / (ID - 1))
2070 B1# = B1# / ID: B2# = SQR((B2# - ID * B1# ^ 2) / (ID - 1))
2080 SM1# = SM1# / ID: SM2# = SQR((SM2# - ID * SM1# ^ 2) / (ID - 1))
2090 SE1# = SE1# / ID: SE2# = SQR((SE2# - ID * SE1# ^ 2) / (ID - 1))
2100 F$ = "\  \       ######       ######        +###.##       +####    +###.#"
2110 LOCATE L + 1: PRINT USING F$; "Avg"; R1# + OS; C1# + OS; B1#; SM1#; SE1#
2120 F$ = "\  \       ###.##       ###.##         ##.###        ##.##    ##.###"
2130 PRINT USING F$; "S.D."; R2#; C2#; B2#; SM2#; SE2#: PRINT
2140 F$ = "\  \       ######       ######        +###.##       +####    +###.#"
2150 PRINT USING F$; "Max"; RMAX + OS; CMAX + OS; BMAX * 10 ^ 4; SMAX; SMAX / KS
I
2160 PRINT USING F$; "Min"; RMIN + OS; CMIN + OS; BMIN * 10 ^ 4; SMIN; SMIN / KS
I
2170 LOCATE 22: F$ = "                           ": F$ = F$ + F$ + F$: PRINT F$: P
RINT F$
2180 LOCATE 22: PRINT "PRINT this screen (P), MORE data (M), SAVE to floppy (S),
or EXIT program (X)?"
2190 Z$ = INPUT$(1)
2200 IF Z$ = "X" OR Z$ = "x" THEN SYSTEM
2205 IF Z$ = "S" OR Z$ = "s" THEN 5000
2210 IF Z$ = "M" OR Z$ = "m" THEN 580
2220 IF Z$ = "P" OR Z$ = "p" THEN 4000
2230 GOTO 2190
4000 '
4010 'PRINT SCREEN
4020 '
4030 LPRINT CHR$(27); CHR$(120); CHR$(1): '  turn on NLQ on LX-800 printer
4040 LPRINT CHR$(27); CHR$(107); CHR$(1): '  select sans serif font on LX-800 pr
```

```
inter
4050 SC = SC + 1: '  screen counter
4060 LPRINT ID$: LPRINT OP$; "  "; DATE$; "  "; TIME$: LPRINT
4070 LPRINT "Line   Radial Time    Circum Time      B (x10^4)          Stress"
4080 LPRINT "Num        (ns)           (ns)                            MPa      ksi
"
4090 F$ = "###       ######         ######        +###.##       +####    +###.#"
4100 FOR I = 1 TO ID: LPRINT USING F$; I; T1(I); T2(I); BR(I); S1(I); S2(I): NEX
T I
4110 LPRINT
4120 F$ = "\  \      ######         ######        +###.##       +####    +###.#"
4130 LPRINT USING F$; "Avg"; R1# + OS; C1# + OS; B1#; SM1#; SE1#
4140 F$ = "\  \      ###.##         ###.##          ##.###       ##.##    ##.###"
4150 LPRINT USING F$; "S.D."; R2#; C2#; B2#; SM2#; SE2#: PRINT
4160 F$ = "\  \      ######         ######        +###.##       +####    +###.#"
4170 LPRINT : LPRINT USING F$; "Max"; RMAX + OS; CMAX + OS; BMAX * 10 ^ 4; SMAX;
 SMAX / KSI
4180 LPRINT USING F$; "Min"; RMIN + OS; CMIN + OS; BMIN * 10 ^ 4; SMIN; SMIN / K
SI
4190 LPRINT : LPRINT "B0 ="; BF; " x 10^-4    and    CA = "; CF; " x 10^-6/MPa"
4200 LPRINT : LPRINT : LPRINT : IF SC < 2 THEN 4220
4210 SC = 0: LPRINT CHR$(12): '  form feed printer after 2 screen prints
4220 LOCATE 22: PRINT "PRINT this screen (P), MORE data (M), SAVE to floppy (S),
or EXIT program (X)?"
4230 Z$ = INPUT$(1)
4240 IF Z$ = "X" OR Z$ = "x" THEN SYSTEM
4245 IF Z$ = "S" OR Z$ = "s" THEN 5000
4250 IF Z$ = "M" OR Z$ = "m" THEN 580
4255 IF Z$ = "P" OR Z$ = "p" THEN 4000
4260 GOTO 4230
5000 REM   **********************   Write time data on floppy  *************
5010 '
5030 PRINT"Insert floppy into DRIVE A:  --  FILE name (.DAT added) = ";
5040 INPUT DN$:DN$="A:"+DN$+".DAT"
5050 OPEN "O",#1,DN$
5060 PRINT#1,ID$:PRINT#1,OP$
5070 PRINT#1,CHR$(34);TIME$;CHR$(34);CHR$(34);DATE$;CHR$(34);CHR$(34);STR$(BF);C
HR$(34);CHR$(34);STR$(CF);CHR$(34);CHR$(34);STR$(DS);CHR$(34)
5080 FOR I=1 TO DS:PRINT#1,CHR$(34);STR$(T1(I));CHR$(34);CHR$(34);STR$(T2(I));CH
R$(34):NEXT I
5090 CLOSE#1
5100 LOCATE 22: F$ = "                              ":F$=F$+F$+F$:PRINT F$:PRINT F$
5110 PRINT"PRINT this screen (P), MORE data (M), or EXIT program (X)?";
5120 Z$=INPUT$(1)
5130 IF Z$="X" OR Z$="x" THEN SYSTEM
5140 IF Z$="M" OR Z$="m" THEN 580
5150 IF Z$="P" OR Z$="p" THEN 4000
5160 GOTO 5120
5170 '
8000 REM  ******************************************************************
8010 FOR I=0 TO 511:Y%(I)=Y%(I)-AV*128:NEXT I
8012 IF POL=2 THEN 8017
8013 IF ID>1 THEN 8017
8014 GOSUB 8047        '  find peak of 1st signal
8015 GOTO 8018
8017 GOSUB 8052
8018 T=REF(4)*10^3':PRINT T:RETURN      '  4 point fit for time
8019 RETURN
8020 REM  ***************************************************************
8021 '
```

```
8039 REM ****************   Linear Fit of N points, starting @ point K  **
8040 '  calculate slope & intercept to get 0 crossing
8041 SX#=0:SY#=0:SXY#=0:SX2#=0
8042 FOR K=I TO I+N-1
8043 SX#=SX#+K:SX2#=SX2#+K^2:SY#=SY#+Y%(K):SXY#=SXY#+K*Y%(K):NEXT K
8044 SL#=(N*SXY#-SX#*SY#)/(N*SX2#-SX#^2)                  '  slope
8045 IN#=(SX2#*SY#-SX#*SXY#)/(N*SX2#-SX#^2)               '  intercept
8046 X0#=-IN#/SL#:RETURN         '  0 crossing  (time=0.025 us * X0#)
8047 REM   *******    Find 0 Crossing - acoustic signals               ***
8048 MAX=Y%(0):P=0           'find signal peak
8049 FOR I=1 TO 511
8050 IF MAX<Y%(I) THEN MAX=Y%(I):P=I
8051 NEXT I
8052 GOSUB 8058        '  points about 0
8053 FOR N=2 TO 4 STEP 2     '  fit to 1 & 2 point pairs
8054 I=I-1:GOSUB 8039    '  linear LS fit
8055 REF(N)=X0#*.025:NEXT N          '  reference times in us
8057 RETURN
8058 REM   ********  Find 1st Point Above Baseline   *******
8059 I=P-2
8060 IF Y%(I)<0 THEN 8062
8061 I=I-1:GOTO 8060
8062 I=I+1:RETURN           '  I = 1st # above baseline
8063 '
9014 REM ****************  Set Up WAAG Card  *********************************
9015 SEGMENT% = &HD000             'WAAG II data segment
9016 PORT0% = &H178                'Default setting, all switches are off
9017 PORT1% = &H179
9018 PORT2% = &H17A
9019 PORT3% = &H17B
9020 '
9021 DEF FN LOBT(X%) = X% AND &HFF                         'Define low byte
9022 DEF FN HIBT(X%) = ((X% AND &HFF00) \ 256) AND &HFF  'Define high byte
9023 '
9024 COUNT%=4096                   'Record length  (102.4 us @ 0.025 us/point)
9025 CONTROL% = &H800C             'Control word, 40 Mhz clock (single channel)
9026 TOFFSET% = 140                'Trigger offset value
9027 '
9030 RETURN
9031 REM ******************************************************************
9032 '
9080 '   Digitize signal
9090 FOR I=0 TO 511:Y%(I)=0:NEXT I                'clear array
9100 FOR M=1 TO AV                                'average AV pulses
9105 GOSUB 9180                                   'Load trigger offset
9110 GOSUB 9225                                   'Data acquitition
9115 '
9120 START = TRIG * 2              'Valid address of trigger point
9125 DEF SEG = SEGMENT%            'Define data segment
9140 GOSUB 9305                    'add up files
9145 DEF SEG                       'Restore data segment
9150 NEXT M
9160 GOSUB 8000
9165 RETURN
9166 '
9170 REM ******************************************************************
9175 '
9180 REM ********** Load Trigger offset subroutine ************************
9185 DEF SEG = SEGMENT%                     'Define WAAG II segment
9190 OUT PORT3%,&HC0: OUT PORT2%,&H6F    'Enable trigger offset
```

```
9195 POKE 0,TOFFSET%                          'Load offset value
9200 OUT PORT3%,&H80: OUT PORT2%,&H6F    'Reset control register
9205 DEF SEG                              'Restore data segment
9210 RETURN
9215 REM ******************************************************************
9220 '
9225 REM **********  Data acquisition subroutine ************************
9230 OUT PORT3%,&H80: OUT PORT2%,&H6F   'Initialize control regs
9235 OUT PORT1%,&HFF: OUT PORT0%,&HFF   'Clear counter
9240 OUT PORT1%,&HFF: OUT PORT0%,&HFF
9245 N% = -(COUNT% + &HFF)              'Correct count
9250 OUT PORT1%,FN HIBT(N%): OUT PORT0%,FN LOBT(N%)     'Load count
9255 OUT PORT1%,FN HIBT(N%): OUT PORT0%,FN LOBT(N%)
9260 N1% = CONTROL% AND &HBFFC
9265 OUT PORT3%,FN HIBT(N1%): OUT PORT2%,FN LOBT(N1%)   'Start sampling
9270 IF INP(PORT2%)<>249 THEN 9270       'WAIT PORT2%,1    -     wait for busy
9280 OUT PORT3%,&H80: OUT PORT2%,&H6F                   'Enable WAAG II ram
9285 TRIG = INP(PORT0%) + (INP(PORT1%) AND &H3F)*256    'Read trigger value
9290 RETURN
9295 REM *****************************************************************
9300 '
9305 REM **************  Sum Files   ******************************************
9310 IA=START
9315 FOR I=0 TO 511
9320 Y%(I)=Y%(I)+PEEK(IA+I+3400):NEXT I   'add files, starting @ 85 us
9325 RETURN
9330 REM ********************************************************************
9335 '
```

FILE.BAS -- BASIC listing of the program that reads stored data from a floppy and displays the calculated stress.


```
100 '   FILE     12/5/97   Fri   Ray S.
110 '      read files from floppy in drive A:  --  ID, parameters, time pairs
120 '      calculate stresses & statistics for screen display
130 '      option for hard copy
140 '   (Load interpreter as GWBASIC/D to get double precision for std. dev.)
150 '     files created by SHOP or DETAIL
200 '
210 SCREEN 8                 ' change screen
220 COLOR 7,1                ' white on blue
230 OS = 85000!              ' signal time offset in ns
240 KSI = 6.894757           ' conversion, ksi to MPa
250 ALARM=0                  ' alarm level (red square) for stress report
260 WIDE=5*KSI               ' max stress spread (yellow square) in MPa (=5 ksi)
300 '
5000 REM   ************   Read time data from Floppy   *************
5010 '
5020 CLS
5030 INPUT "Insert floppy into DRIVE A: and type FILE name (.DAT added) = ";DN$
5040 DN$ = "A:"+ DN$ + ".DAT"
5050 OPEN "I",#1,DN$
5060 INPUT#1, ID$: INPUT#1, OP$: INPUT#1, TIM$, DAT$, BF$, CF$, DS$
5065 BF=VAL(BF$): CF=VAL(CF$): DS=VAL(DS$)
5070 FOR I=1 TO DS: INPUT#1, R$, C$: TR(I) = VAL(R$): TC(I) = VAL(C$): NEXT I
5080 CLOSE#1:GOSUB 9600:GOSUB 6000
5100 GOSUB 10000:LOCATE 23: PRINT"PRINT screen (P), another data FILE (F), or EX
IT program (X)?";
5110 Z$ = INPUT$(1)
5120 IF Z$ = "X" OR Z$ = "x" THEN SYSTEM
5130 IF Z$ = "F" OR Z$ = "f" THEN 5000
5140 IF Z$ = "P" OR Z$ = "p" THEN 6400
5150 GOTO 5110
5160 '
6000 REM  *********   SCREEN print   **************************
6005 '
6010 PRINT ID$; "--"; OP$; "  "; DAT$; "  "; TIM$
6020 LOCATE 3,1
6030 PRINT "Test            Stress"
6040 PRINT "Num          MPa       ksi"
6050 F$ = "###       +####     +###"
6060 PRINT : L = 5: ID = 1
6070 SM1# = 0: SM2# = 0: SE1# = 0: SE2# = 0
6080 FOR K=1 TO DS: C = TC(K) - OS: R = TR(K) - OS
6090 GOSUB 6150: LOCATE L,1: PRINT USING F$; K; 5*CINT(SM/5); SE: L = L + 1
6100 S1(K) = SM: S2(K) = SE
6110 SM1# = SM1# + SM: SM2# = SM2# + SM ^ 2: SE1# = SE1# + SE: SE2# = SE2# + SE
^ 2
6120 NEXT K
6130 GOTO 6280       '   average and statistics
6140 '
6150 REM   ***************  Calculations   ---   Stress, Max, Min   **********
6160 '
6165 'BF=-2.1        forced value of B0 - remove eventually
6170 B0 = BF * 10 ^ -4: ' Birefringence due to texture
6180 CA = CF * 10 ^ -6: ' Stress acoustic constant in 1/MPa
6190 B = (R - C) / (OS+(R + C) / 2): ' Measured birefringence
6200 SM = (B - B0) / CA: ' Stress in MPa
6210 SE = SM / KSI: '  Stress in ksi
6220 IF K> 1 THEN 6240
6230 SMAX = SM: SMIN = SM: RETURN
6240 IF SM > SMAX THEN SMAX = SM
```

```
6250 IF SM < SMIN THEN SMIN = SM
6260 RETURN
6270 '
6280 REM  ***********     AVERAGE & STATISTICS      ***********************
6290 '
6300 SM1# = SM1# / DS: SM2# = SQR((SM2# - DS * SM1# ^ 2) / (DS - 1))
6310 SE1# = SE1# / DS: SE2# = SQR((SE2# - DS * SE1# ^ 2) / (DS - 1))
6320 F$ = "\  \      +####     +###"
6330 LOCATE L + 1,1: PRINT USING F$; "Avg"; 5*CINT(SM1#/5); SE1#
6340 F$ = "\  \       ###       ###"
6350 PRINT USING F$; "S.D."; 5*CINT(SM2#/5); SE2#: PRINT
6360 F$ = "\  \      +####     +###"
6370 PRINT USING F$; "Max"; 5*CINT(SMAX/5); SMAX / KSI
6380 PRINT USING F$; "Min"; 5*CINT(SMIN/5); SMIN / KSI
6382 IF SM1#>=ALARM GOTO 6386 ' test for bad stress
6384 GOSUB 9700: GOTO 6388    ' green flag
6386 GOSUB 9800               ' red flag
6388 IF SMAX-SMIN>WIDE THEN GOSUB 9900   ' yellow flag
6390 RETURN
6395 '
6400 REM   ***********      PRINT SCREEN       ***********************
6410 '
6420 LPRINT CHR$(27); CHR$(120); CHR$(1): '  turn on NLQ on LX-800 printer
6430 LPRINT CHR$(27); CHR$(107); CHR$(1): '  select sans serif font on LX-800 pr
inter
6440 SC = SC + 1: '  screen counter
6445 LPRINT "File:  ";DN$
6450 LPRINT ID$: LPRINT OP$; "  "; DAT$; "  "; TIM$: LPRINT
6460 LPRINT "Test          Stress"
6470 LPRINT "Num        MPa      ksi"
6480 F$ = "###     +####     +###"
6490 FOR I = 1 TO DS: LPRINT USING F$; I; 5*CINT(S1(I)/5); S2(I): NEXT I
6500 LPRINT
6510 F$ = "\  \    +####     +###"
6520 LPRINT USING F$; "Avg"; 5*CINT(SM1#/5); SE1#
6530 F$ = "\  \      ###      ###"
6540 LPRINT USING F$; "S.D."; 5*CINT(SM2#/5); SE2#: PRINT
6550 F$ = "\  \    +####     +###"
6560 LPRINT : LPRINT USING F$; "Max"; 5*CINT(SMAX/5); SMAX / KSI
6570 LPRINT USING F$; "Min"; 5*CINT(SMIN/5); SMIN / KSI
6580 LPRINT : LPRINT "B0 ="; BF; " x 10^-4    and    CA = "; CF; " x 10^-6/MPa"
6590 LPRINT : LPRINT : LPRINT : IF SC < 2 THEN 6610
6600 SC = 0: LPRINT CHR$(12): '  form feed printer after 2 screen prints
6610 GOTO 5100
6620 '
9500 REM   ****************     Colored Flags     ****************************
9600 '
9610 ' draw square
9620 LINE(500,120)-(600,170),2,B       'green border - only thing that works
9640 RETURN
9650 '
9700 '
9710 ' Green Square   ---   GOOD
9720 PAINT(525,137),2,2              'green square
9730 LOCATE 19,66:PRINT"  GOOD ":RETURN
9740 '
9800 '
9810 ' Red Square   ---   BAD
9820 PAINT(525,137),4,2               'red square
9830 LOCATE 19,66:PRINT"  BAD  ":RETURN
```

```
9840 '
9900 '
9910 ' Yellow Square   ---   WIDE STRESS RANGE
9920 LINE(500,50)-(600,100),2,B       'green border - only thing that works
9930 PAINT(525,75),14,2               'yellow square
9940 LOCATE 9,67:PRINT" WIDE "
9950 LOCATE 10,67:PRINT"STRESS"
9960 LOCATE 11,67:PRINT"RANGE ":RETURN
9970 '
10000 REM    ****************         Response Bar - Bottom of Screen   *******
10010 '
10020 LINE(0,170)-(640,195),5,BF
10030 LOCATE 23,1:RETURN
10040 '
```

FILEB.BAS -- BASIC listing of the program that reads stored data from a floppy and displays the arrival times and birefringences with the calculated stress.


```
100 '   FILEB    12/5/97   Fri   Ray S.
110 '      read files from floppy in drive A:  --  ID, parameters, time pairs
120 '      calculate stresses & statistics for screen display
130 '      option for hard copy
140 '   (Load interpreter as GWBASIC/D to get double precision for std. dev.)
150 '     files created by SHOP or DETAIL
200 '
230 OS = 85000!             ' signal time offset in ns
240 KSI = 6.894757          ' conversion, ksi to MPa
300 '
5000 REM   *************   Read time data from Floppy   *************
5010 '
5020 CLS
5030 INPUT "Insert floppy into DRIVE A: and type FILE name (.DAT added) = ";DN$
5040 DN$ = "A:"+ DN$ + ".DAT"
5050 OPEN "I",#1,DN$
5060 INPUT#1, ID$: INPUT#1, OP$: INPUT#1, TIM$, DAT$, BF$, CF$, DS$
5065 BF=VAL(BF$): CF=VAL(CF$): DS=VAL(DS$)
5070 FOR I=1 TO DS: INPUT#1, R$, C$: TR(I) = VAL(R$): TC(I) = VAL(C$): NEXT I
5080 CLOSE#1:GOSUB 6000
5100 LOCATE 23: PRINT"PRINT screen (P), another data FILE (F), or EXIT program (
X)?";
5110 Z$ = INPUT$(1)
5120 IF Z$ = "X" OR Z$ = "x" THEN SYSTEM
5130 IF Z$ = "F" OR Z$ = "f" THEN 5000
5140 IF Z$ = "P" OR Z$ = "p" THEN 6400
5150 GOTO 5110
5160 '
6000 REM  *********   SCREEN print   **************************
6005 '
6010 PRINT ID$; "--"; OP$; "  "; DAT$; "  "; TIM$
6020 LOCATE 3,1
6030 PRINT "Test   Radial Time    Circum Time      B (x10^4)          Stress"
6040 PRINT "Num        (ns)           (ns)                          MPa       ksi"
6050 F$ = "###       ######         ######        +###.##       +####    +###.#"
6060 PRINT : L = 5: ID = 1
6070 R1# = 0: R2# = 0: C1# = 0: C2# = 0: B1# = 0: B2# = 0: SM1# = 0: SM2# = 0: S
E1# = 0: SE2# = 0
6080 FOR K=1 TO DS: C = TC(K) - OS: R = TR(K) - OS
6090 GOSUB 6150: LOCATE L: PRINT USING F$; K; R + OS; C + OS; B * 10 ^ 4; SM; SE
: L = L + 1
6100 TR(K) = R + OS: TC(K) = C + OS: BR(K) = B * 10 ^ 4: S1(K) = SM: S2(K) = SE
6105 R1# = R1# + R: R2# = R2# + R ^ 2: C1# = C1# + C: C2# = C2# + C ^ 2: B1# = B
1# + B * 10 ^ 4: B2# = B2# + (B * 10 ^ 4) ^ 2
6110 SM1# = SM1# + SM: SM2# = SM2# + SM ^ 2: SE1# = SE1# + SE: SE2# = SE2# + SE
^ 2
6120 NEXT K
6130 GOTO 6280       '   average and statistics
6140 '
6150 REM   ****************  Calculations   ---   Stress, Max, Min   **********
6160 '
6165 'BF=-2.1      forced B0 - remove eventually
6170 B0 = BF * 10 ^ -4: ' Birefringence due to texture
6180 CA = CF * 10 ^ -6: ' Stress acoustic constant in 1/MPa
6190 B = (R - C) / (OS+(R + C) / 2): ' Measured birefringence
6200 SM = (B - B0) / CA: ' Stress in MPa
6210 SE = SM / KSI: '  Stress in ksi
6220 IF K> 1 THEN 6231
6230 RMAX = R: RMIN = R: CMAX = C: CMIN = C: BMAX = B: BMIN = B: SMAX = SM: SMIN
 = SM: RETURN
```

```
6231 IF R > RMAX THEN RMAX = R
6232 IF R < RMIN THEN RMIN = R
6233 IF C > CMAX THEN CMAX = C
6234 IF C < CMIN THEN CMIN = C
6235 IF B > BMAX THEN BMAX = B
6236 IF B < BMIN THEN BMIN = B
6240 IF SM > SMAX THEN SMAX = SM
6250 IF SM < SMIN THEN SMIN = SM
6260 RETURN
6270 '
6280 REM  ***********     AVERAGE & STATISTICS     ***********************
6290 '
6292 R1# = R1# / DS: R2# = SQR((R2# - DS * R1# ^ 2) / (DS - 1))
6294 C1# = C1# / DS: C2# = SQR((C2# - DS * C1# ^ 2) / (DS - 1))
6296 B1# = B1# / DS: B2# = SQR((B2# - DS * B1# ^ 2) / (DS - 1))
6300 SM1# = SM1# / DS: SM2# = SQR((SM2# - DS * SM1# ^ 2) / (DS - 1))
6310 SE1# = SE1# / DS: SE2# = SQR((SE2# - DS * SE1# ^ 2) / (DS - 1))
6320 F$ = "\  \      ######          ######         +###.##       +####    +###.#"
6330 LOCATE L + 1: PRINT USING F$; "Avg"; R1# + OS; C1# + OS; B1#; SM1#; SE1#
6340 F$ = "\  \      ###.##          ###.##         ##.###        ##.##    ##.###"
6350 PRINT USING F$; "S.D."; R2#; C2#; B2#; SM2#; SE2#: PRINT
6360 F$ = "\  \      ######          ######         +###.##       +####    +###.#"
6370 PRINT USING F$; "Max"; RMAX + OS; CMAX + OS; BMAX * 10 ^ 4; SMAX; SMAX / KS
I
6380 PRINT USING F$; "Min"; RMIN + OS; CMIN + OS; BMIN * 10 ^ 4; SMIN; SMIN / KS
I
6390 RETURN
6395 '
6400 REM  ***********     PRINT SCREEN      ***********************
6410 '
6420 LPRINT CHR$(27); CHR$(120); CHR$(1): '  turn on NLQ on LX-800 printer
6430 LPRINT CHR$(27); CHR$(107); CHR$(1): '  select sans serif font on LX-800 pr
inter
6440 SC = SC + 1: '  screen counter
6445 LPRINT "File:  ",DN$
6450 LPRINT ID$: LPRINT OP$; "  "; DAT$; "  "; TIM$: LPRINT
6460 LPRINT "Test   Radial Time    Circum Time      B (x10^4)          Stress"
6470 LPRINT "Num        (ns)            (ns)                             MPa      ksi
"
6480 F$ = "###       ######          ######         +###.##       +####    +###.#"
6490 FOR I = 1 TO DS: LPRINT USING F$; I; TR(I); TC(I); BR(I); S1(I); S2(I): NEX
T I
6500 LPRINT
6510 F$ = "\  \      ######          ######         +###.##       +####    +###.#"
6520 LPRINT USING F$; "Avg"; R1# + OS; C1# + OS; B1#; SM1#; SE1#
6530 F$ = "\  \      ###.##          ###.##         ##.###        ##.##    ##.###"
6540 LPRINT USING F$; "S.D."; R2#; C2#; B2#; SM2#; SE2#: PRINT
6550 F$ = "\  \      ######          ######         +###.##       +####    +###.#"
6560 LPRINT : LPRINT USING F$; "Max"; RMAX + OS; CMAX + OS; BMAX * 10 ^ 4; SMAX;
 SMAX / KSI
6570 LPRINT USING F$; "Min"; RMIN + OS; CMIN + OS; BMIN * 10 ^ 4; SMIN; SMIN / K
SI
6580 LPRINT : LPRINT "B0 ="; BF; " x 10^-4    and    CA = "; CF; " x 10^-6/MPa"
6590 LPRINT : LPRINT : LPRINT : IF SC < 2 THEN 6610
6600 SC = 0: LPRINT CHR$(12): '  form feed printer after 2 screen prints
6610 GOTO 5100
6620 '
```

Batch Files:
The purpose of these files is to simplify the calling of several programs. To use these files, type the name (e.g., SHOP, the .BAT extension is not necessary) at the C:\ prompt.

1. **SHOP.BAT**

```
cd tb1000
matec
cd\
cd stress
gwbasic shop/d
cd\
```

This turns on the pulser/receiver board. (It will be necessary to type **Q O** to continue.) The standard operating program (stresses only) will start.

2. **DETAIL.BAT**

```
cd\
cd stress
gwbasic detail/d
cd\
```

This program reports the details of arrival times and birefringences with the stresses.

3. **PULSER.BAT**

```
cd tb1000
matec
```

This starts the software for the pulser/receiver. This controls operation (Appendix IV).

4. **FILE.BAT**

```
cd stress
gwbasic file/d
cd\
```

This reads data stored on a floppy and displays the calculated stress.

5. **FILEB.BAT**

```
cd stress
gwbasic fileb/d
cd\
```

This reads data stored on a floppy and displays time, birefringence, and stress.

Modifications to the AUTOEXEC.BAT file include:

1. Adding the STRESS and BATCH directories to the PATH (PATH C:\STRESS;C:\BATCH), and
2. Adding the command SHOP as the last line; this batch file automatically starts operation on power up.

APPENDIX VI: Sample Output

These are printouts of the screens produced by the two collection programs.

SHOP

242B--reference block 12-23-1997 15:45:33

Test	Stress	
Num	MPa	ksi
1	+5	+1
2	-10	-1
3	-10	-1
4	-15	-2
5	-5	-1
6	+5	+1
7	+5	+1
8	+0	-0
9	+5	+1
10	-5	-0
Avg	-5	-0
S.D.	5	1
Max	+5	+1
Min	-15	-2

GOOD

PRINT this screen (P), MORE data (M), SAVE to floppy (S), or EXIT program (X)?

DETAIL

reference block--multi-wear 12-23-1997 15:53:06

Test Num	Radial Time (ns)	Circum Time (ns)	B (x10^4)	Stress MPa	Stress ksi
1	94178	94138	+4.28	-82	-11.9
2	94179	94136	+4.62	-86	-12.5
3	94182	94138	+4.75	-88	-12.7
4	94189	94138	+5.44	-97	-14.0
5	94185	94135	+5.28	-95	-13.7
6	94182	94137	+4.81	-89	-12.8
7	94186	94138	+5.12	-93	-13.4
8	94183	94137	+4.87	-89	-13.0
9	94179	94135	+4.68	-87	-12.6
10	94182	94138	+4.66	-87	-12.6
Avg	94183	94137	+4.85	-89	-12.9
S.D.	3.32	0.18	0.343	4.40	0.638
Max	94189	94138	+5.44	-82	-11.9
Min	94178	94135	+4.28	-97	-14.0

PRINT this screen (P), MORE data (M), SAVE to floppy (S),or EXIT program (X)?

APPENDIX VII. Possible Future Modifications

Some changes that might lead to improvements include:

1. Printed-circuit coils might replace the current hand-wound wire coils. This would likely be more precise and repeatable.

2. A narrower EMAT case with only one ear would reduce bulk and possible fit a wider range of wheel sizes more precisely. However, there is a possibility that with only one ear, it may be necessary to be very careful to assure proper placement on the wheel face.

3. More power from the pulser is always desirable to increase the signal-to-noise ratio. (The voltage will be limited by dielectric breakdown in the EMAT coil.)

4. The electronics and connections in the small external box should be incorporated into the on-board electronics inside the computer. (This assumes no additional problems arising from electromagnetic interference.)

5. A driver for the delay (Appendix III) would be desirable.

6. Developing the software into a compiled form would speed execution slightly (most time now goes to signal digitization and transfer).

7. Control software for the pulser/receiver should be integrated into the measurement programs.

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