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ON-LINE MEASUREMENT OF PAPER MECHANICAL PROPERTIES

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ABSTRACT

A sensor which determines the elastic properties of paper during manufacture is described. The sensor actually measures ultrasound velocities which are related to the elastic properties and sheet density. Since elastic properties are sensitive to machine operating conditions, the sensor could be used to monitor the machine performance and provide feedback for process control. In many cases, strength properties correlate with elastic properties; therefore, the sensor is also a product quality monitor. The operating principles are explained and the results of a mill trial are presented.

Introduction

A previous publication (1) discussed the importance of monitoring paper mechanical properties during the manufacturing process and described an ultrasonic sensor capable of making such measurements. This paper describes a new version of the sensor which was installed on an Owens-Illinois linerboard machine in Valdosta, GA, in December, 1982, and the results that were obtained over a two-year time period. This research was supported by the Fourdrinier Kraft Board Group (FKBG) of the American Paper Institute. The sensor developed under this project is therefore referred to in the following sections as the FKBG sensor.

The original sensor (1) and the FKBG sensor both use transducers mounted in wheels which are driven by the web. The piezoelectric transducer in each wheel is resonant at 80 kHz, a value well above most machine noise but below the point where the plate waves in paper become dispersive (2). The transducers are coupled to the rim of the wheel through an aluminum "button" which is mechanically isolated from the rest of the wheel. One wheel serves as a transmitter; two others act as receivers. One receiver is displaced in the machine direction (MD) from the transmitter, while the other is displaced in the cross-machine direction (CD). The transducer wheels are mechanically isolated from each other and from the supporting member (and thus from mill vibrations). The transducer wheels are synchronized so that the buttons contact the web at approximately the same time.

When the transducers contact the paper, the transmitter is excited with a burst of sine waves, and the vibrating transducer creates a mechanical disturbance in the moving paper web. This disturbance propagates away from the transmitter in all directions. The receiver wheels in the MD and CD directions detect the disturbance after some time has elapsed. The "time-of-flight" of the mechanical disturbance is measured and, using the separation distance of the wheels, the velocities of sound in the MD and CD of the paper web are calculated. The time-of-flight approach was used, rather than a continuous wave method, to avoid undesirable interferences in the received signals due to waves reflected from the edges of the web, between the wheels, and from rolls.

This basic description applies to either sensor. Significant improvements have been made in the FKBG sensor, however, in signal analysis techniques, transducer design and ruggedness, wheel position detection, and synchronization of the transmitter and receiver wheels for maximum signal output. The major difference between the FKBG system and the earlier version is the way in which the transit times are measured. In the original system the time-of-flight was recorded when the voltage of the received signal exceeded a set threshold level. Unfortunately, this technique was too sensitive to extraneous noise and a more sophisticated approach was needed. The operation of the FKBG sensor is discussed below.

The FKBG Sensor

The sensor mounted at the dry end of the paper machine is shown in Fig. 1. Figure 2 is a schematic of the FKBG sensor and support electronics for CD measurements. The magnetic Hall effect position detector pulses just before the transducer buttons contact the web. Using a phase lock loop circuit, a second pulse is produced after an electronically adjustable angle of wheel rotation. This pulse triggers a signal generator. A 400-volt pulse of sine waves is delivered to the transmitter wheel, and a mechanical disturbance is created in the paper. After about 100 μsec, the disturbance is detected by a receiver wheel in the cross machine (or machine) direction of the web. A preamplifier in each receiver wheel amplifies the signal immediately after it is received. Power to the preamplifier and the signal transmitted out of the wheel are passed through the same mercury slip-rings. The received signals are then passed through isolation transformers to reduce noise generated by ground loops. Line drivers transfer the signals over the 100 feet of 50-ohm coaxial cable between the sensor head and the central electronics cabinet.

[Figure 1 and 2 here]

The signals are digitized at a rate of five samples per microsecond by a Biomation Model 2805 high-speed waveform recorder. It is triggered at the same time as the transmitter and records the following 410 microseconds of received signal. After the analog-to-digital conversion, the digitized data is transferred to the microcomputer over a parallel interface. This transfer is made in less than one revolution of the wheel so that the Biomation is ready to accept a new signal at the next firing of the transmitter. In order to reduce noise and average out web variability, an adjustable number (1 to 100) of consecutive digitized signals are summed to produce a composite signal. Figure 3 shows a typical composite signal.

[Figure 3 here]

Each digitized receiver response has an initial portion, greater than 50 μsec, that contains only noise. This flat section (or baseline in Fig. 3) is analyzed to establish a zero signal level and a noise threshold. The software steps through the rest of the digitized composite signal, finds excursions from the baseline significantly greater than the noise threshold, and locates the descending crossing times (the times at which the waveform crosses zero moving downward, indicated by the solid circles). The transit times in the paper are determined from a zero crossing time. A calibration procedure, utilizing manual changes in the wheel separation distances, allows the nonpaper delay times to be calculated. By subtracting the nonpaper delay from the transit time, the time-of-flight in the paper is determined. The separation distances between the transmitter and receiver wheels are known, so the velocity of sound in the web is simply the ratio of distance to transit time. MD and CD measurements are made alternately. The microcomputer software, which is written in both Basic and an assembly language, is stored in EPROMs so that the program is not lost during power failure or shutdown.

The measured velocities are displayed on a CRT in the electronics console, printed out, and sent to an analog output for communication with other systems. The FKBG sensor measures a longitudinal velocity, V_L, in the machine direction of the web and a shear velocity, V_S, in the cross-machine direction of the web. These are related to the elastic parameters by the following equations:

$$V_L = [(E_1/\rho)(1 - v_{12}v_{21})]^{1/2} \quad \text{and} \tag{1}$$

$$V_S = [G_{66}/\rho]^{1/2}, \tag{2}$$

where ρ is the density, E_1 is Young's modulus in the paper machine direction*, G_{66} is the shear modulus in the 1-2 plane, and v_{12} and v_{21} are the two Poisson ratios in the 1-2 plane. In paper the product of the Poisson ratios is typically small [about 0.07, see Ref. (3)] so that it is convenient to rewrite Eq. (1) as $V_L \approx [E_1/\rho]^{1/2}$. The square of the measured sound velocities are thus mass

*Paper is usually described as an orthotropic elastic material (2). The machine direction is defined as the 1 (or x) direction, the cross machine direction as the 2 (or y) direction, and the thickness direction as the 3 (or z) direction.

specific elastic moduli. Any furnish or machine operating variable which affects the density or elastic properties of the paper will change the measured velocities.

Paper is a viscoelastic material and its mechanical properties are sensitive to temperature and moisture content. Therefore, to use the measured sound velocities to predict product quality it is necessary to take these factors into consideration. Based on experiments performed at The Institute of Paper Chemistry on mill samples, correction formulae were developed for moisture content and temperature. These formulae were linear within the ranges of values experienced in the mill. The corrections would differ with furnish, but were not very grade sensitive. The sound velocities measured with the FKBG sensor were corrected to a moisture content of 7% and a temperature of 25°C. The temperature and moisture content values were available from the Measurex process control equipment in the mill. These corrections were made in the Measurex process control computer and displayed on their color CRT display.

The Measurex CRT display is shown in Fig. 4. The main title "STRENGTH" is misleading since most entries are elastic parameters rather than strength parameters. The top line gives the company initials, mill location, machine number, the grade currently being manufactured, the date, and time of day. The bottom of the display gives the slice number (position across the width of the paper machine) at which the FKBG sensor is located, and the values of basis weight (lb per 1000 ft^2), web temperature (°F), and web moisture content (%) at that location. The last two values are used to correct the measured specific stiffnesses to constant temperature and moisture. They are measured by the Measurex scanner (see Fig. 1) and are actually a weighted average of a number of CD scans. They are updated approximately every two minutes.

[Figure 4 here]

The variables in the NOW column are updated about every 45 seconds. The top two values are the specific elastic stiffness in the MD ($E_1 \rho \approx V_L^2$) and the specific shear stiffness ($G_{66}/\rho = V_s^2$), both corrected for temperature and moisture. MD EXT STIFF and SHEAR STIFF are obtained by multiplying the first two entries, respectively, by the basis weight. The CD EXT STIFF is the extensional stiffness in the cross direction and is computed from the MD extensional stiffness and the shear stiffness using an empirical relationship that applies to most Fourdrinier papers (3). Paper squareness, SQUARENESS, is a measure of the anisotropy in the plane of the paper and is the ratio of MD to CD extensional stiffnesses. RING CRUSH, MULLEN, and STFI COMPRS are tests of paper strength commonly measured on linerboard grades. The displayed values are predicted from the extensional and shear elastic stiffness values. The prediction algorithm was derived from tests conducted at IPC on mill samples. The average, AVG, and two standard deviation spread, SPREAD(2S), give the average and two sigma spread of the measured values beginning at the start of the construction of the current reel. Like the NOW column, these values are updated every 45 seconds. During reel turn-ups the Measurex scanner is removed from the web; therefore, velocities cannot be corrected for the environment at the time of turn-up.

The values shown in Fig. 4 provide a continuous record of the quality of the paper being manufactured and give an immediate warning when a problem arises. This is important to the papermaker, since, without an indication of mechanical integrity, a large quantity of substandard material can be produced before a problem is detected from tests taken at the end of the reel. The sensor can also be used to "fine-tune" the paper machine to produce a product of more uniform quality and/or optimum specifications.

Test results

In order to study the response of the FKBG sensor to machine operating variables, the paper machine variables were changed one at a time. The variables studied were wet pressing pressure, stock consistency to the headbox, refining level, rush-drag ratio (jet-speed to wire-speed), wet pressing pressure, and wet straining in the draws. In all instances the measured elastic properties behaved as expected from laboratory studies, confirming that the sensor is capable of monitoring paper quality. The results, obtained from trend plots, are shown in Fig. 5-9.

[Figures 5-9 here]

Figure 5 shows the results of the change in the wet pressing pressure. The second wet press was unloaded at 10:20. The decrease in pressing pressure produced a drop in the specific extensional stiffness, the shear stiffness, and the predicted CD ring crush, all as expected. When the pressing pressure was returned to normal, the values returned to their previous levels.

As shown in Fig. 6, the rush-drag ratio was reduced in two separate steps and later returned to normal in one step. Decreasing rush-drag causes a smaller fiber orientation preference for the mechanical direction. Notice that there were no significant changes in shear velocity as a result of the rush-drag alterations. This is as expected, since the shear modulus is relatively insensitive to fiber alignment. However, the MD longitudinal velocity, as anticipated, decreased with lower rush-drag ratio, since less fiber alignment in the

MD decreases the MD modulus. This is particularly evident in the abrupt changes in MD longitudinal velocity occurring about one minute after the 9:01 and 9:20 changes. Since reel 6 turned up at a low rush-drag setting and reel 7 at a normal one, these effects could be checked by laboratory tests on the grab samples. The laboratory MD longitudinal velocity at reel 6 was 8% below the daily average of the grab samples. The corresponding number for reel 7 was 1% below average. The ratio of MD to CD longitudinal velocities squared is 20% below average for reel 6 and 5% over average for reel 7.

Changes in refining level were made by varying the current to the refiners. The sensor outputs were not very sensitive to these changes made in the refiner current. The only event that was related to the refining changes was a drop in both velocity signals about six minutes after a 20% decrease in refiner current (see Fig. 7). The lack of a strong response is attributed to the small effect of these refiner current changes on the paper properties. This interpretation is supported by the laboratory results which showed little variation in end-of-reel grab samples taken during the refining test. Also, O.I. personnel made hourly checks of pulp freenesses, and the 11:00 values (which should be high) are not significantly different than the daily average.

Figure 8 presents some of the trend plot results for changes in wet-straining. The results of doubling and then restoring to normal the strain in the draw between the second press and the dryer section are shown. As expected, the MD longitudinal velocity responded abruptly to the change in draws about 30 seconds after initiation. Increased wet-straining produces a stiffer sheet in the MD. The effects on the shear velocity are not as pronounced, but shear velocity does appear to correlate positively with tension in the draws for this on-line test. There were no reel turn-ups at the abnormal settings of the draws; therefore it was not possible to investigate the effects by testing grab samples.

The consistency of the stock to the wire was changed by adjusting the turbine speed. A decrease in turbine speed caused an increase in consistency. Figure 9 records the changes due to three successive reductions in the turbine speed. The behavior of V_{MD}^2 and V_S^2 during this time was to decrease with decreasing turbine speed but then to recover somewhat after 6 or 7 minutes. Apparently, some other machine variable was being adjusted which tended to compensate for the consistency changes and bring the sheet properties back toward their usual values. Reel 16 turned up at about 13:31, while the turbine speed was about 7% below normal. The grab sample from this reel had V_{MD}^2 about 6% below normal, consistent with the trend plots in Fig. 9.

In summary, the on-line sensor was capable of following the changes in properties due to the machine variables studied. In each case the changes were in the directions predicted by laboratory experiments. Most of the changes in machine variables were modest; that is, the machine operator selected a range where he knew he could still make paper. The concomitant changes in the measured elastic stiffnesses (or strengths predicted from them) are thus not much larger than the random variations in the sheet. This is true, even though each on-line sensor reading was an average of 50 separate tests taken about one foot apart. We think that these large, random, variations of mechanical properties make it impossible to judge the quality of an entire reel with traditional mechanical tests on grab samples at reel turn-ups. A monitor that can measure mechanical integrity over the full length of paper on the reel is necessary.

Paper mechanical properties can vary considerably across the width of the paper machine, even though the basis weight and moisture content profiles are uniform. Figure 10 shows a CD profile of about one-fourth of the width of the web on the backside of the paper machine, obtained by scanning the sensor across the web. The decrease in mechanical properties near the edge of the sheet results in a bell-shaped distribution in properties across the full width of the machine. This behavior usually can be traced to a nonuniform shrinkage of the paper web in the CD. Such measurements suggest that the sensor will be useful for monitoring the CD properties of the web, and eventually lead to ways to control them.

[Figure 10 here]

Conclusions

The on-machine ultrasonic sensor successfully measures ultrasound velocities and thus the specific elastic properties of the moving paper web. The sensor is valuable as a product quality monitor and as a process control sensor. The latter application requires that suitable means be found for controlling MD and CD paper machine variables. The device is useful now for tuning the paper machine and providing an indication in real time of the quality of the paper being manufactured. It has been licensed to two process control equipment manufacturers, Accuray and Measurex, and the first prototype units are expected to be available by the summer of 1985.

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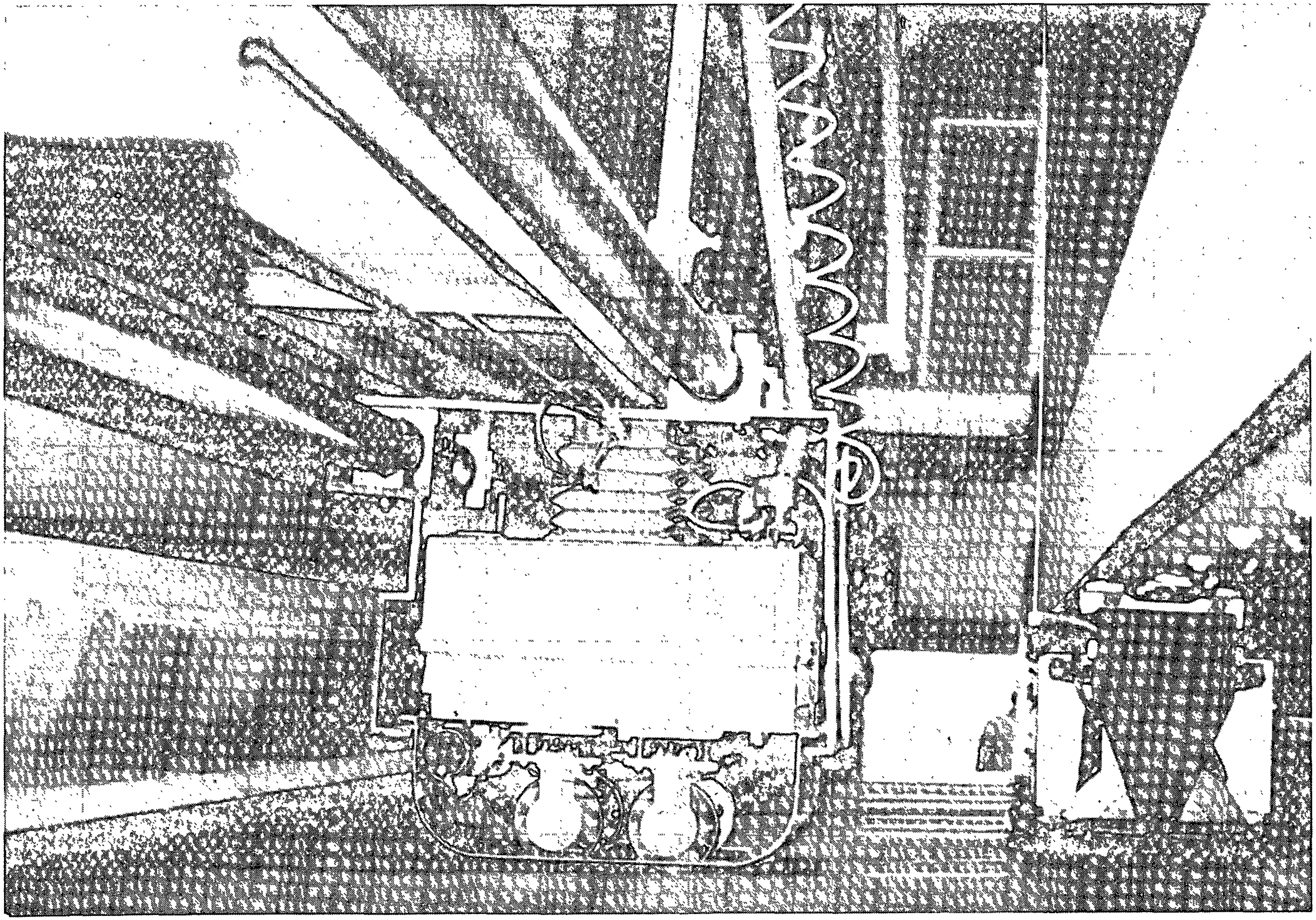


Fig. 1. Ultrasonic sensor mounted next to a Measurex Scanner at dry end of paper machine.

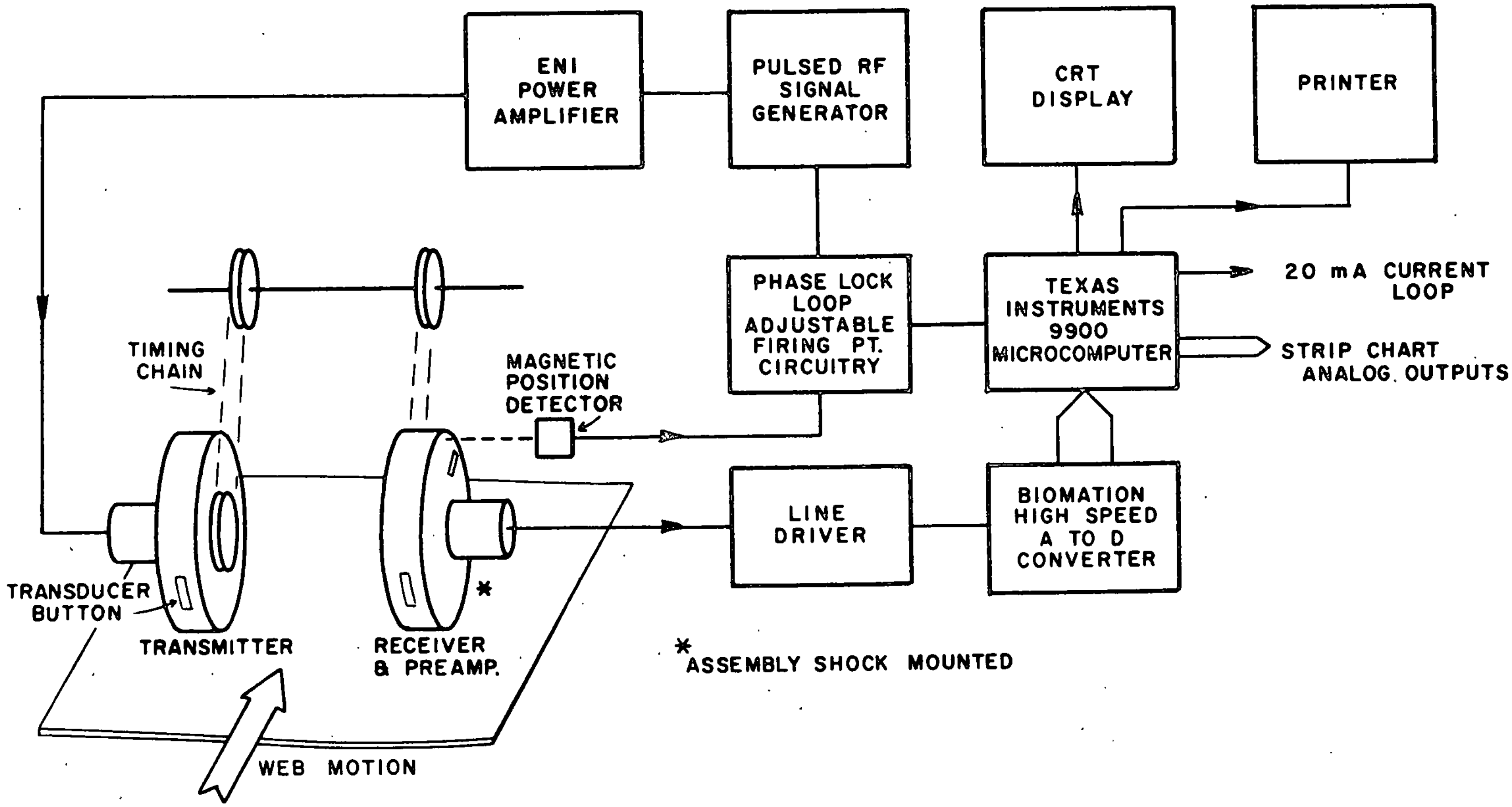
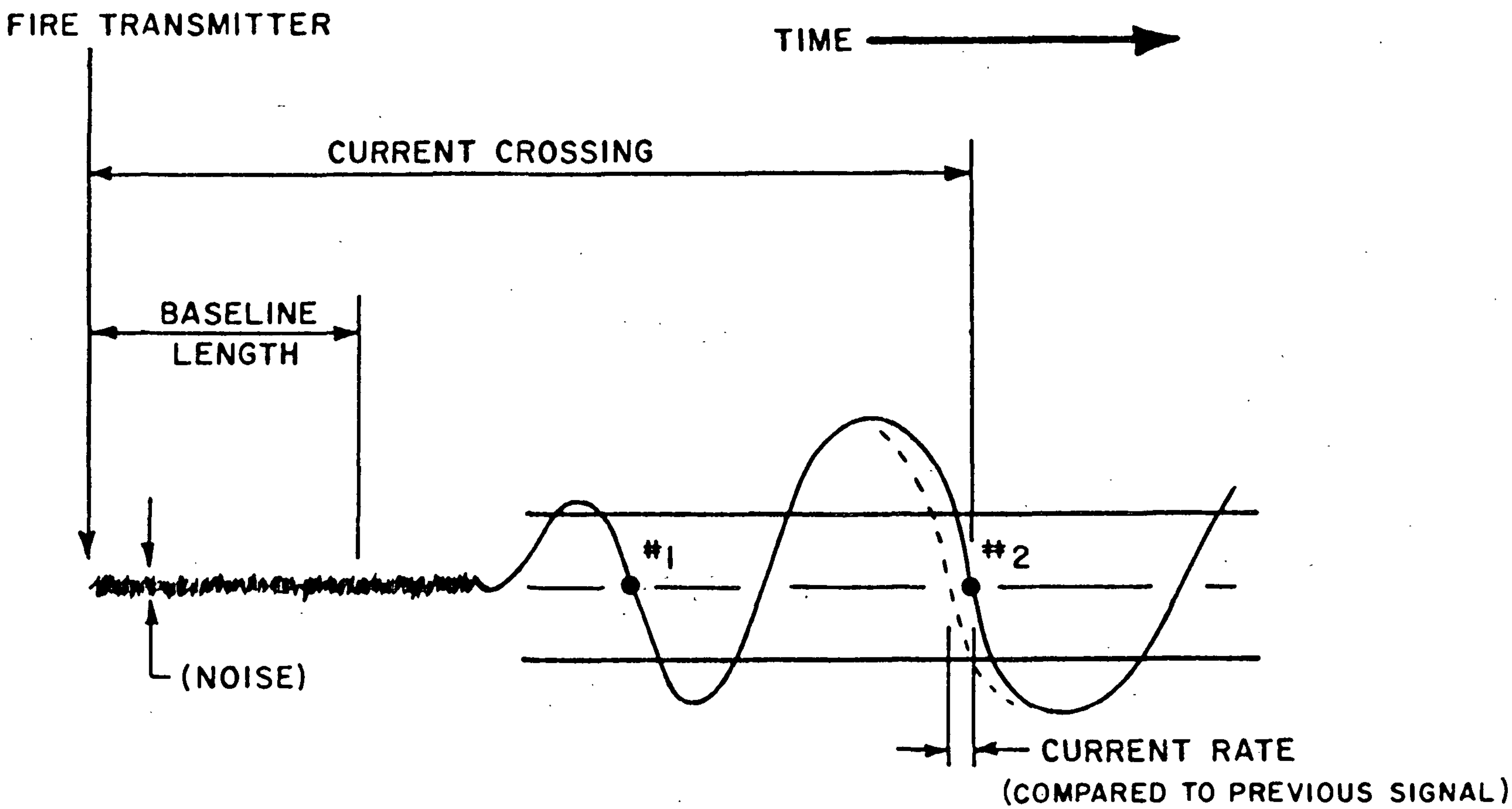


Fig. 2. Block diagram of the ultrasonic stiffness gage. Wheel transducers shown are for cross machine direction measurements.



$$\text{VELOCITY} = \frac{\text{WHEEL SPACING}}{\text{CURRENT CROSSING} - \text{DEAD TIME USED}}$$

Fig. 3. A typical averaged composite signal.

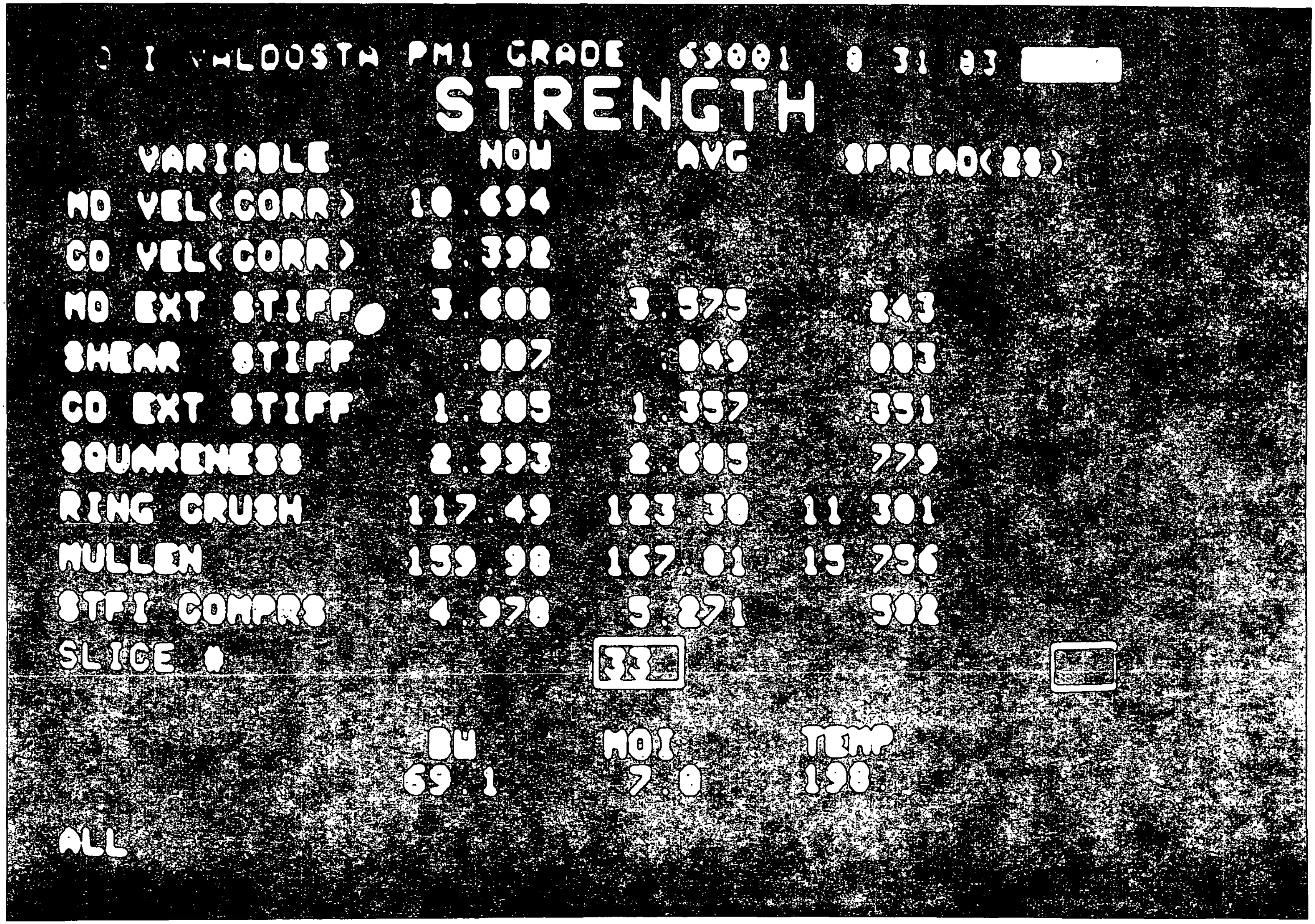


Fig. 4. The Measurex CRT display.

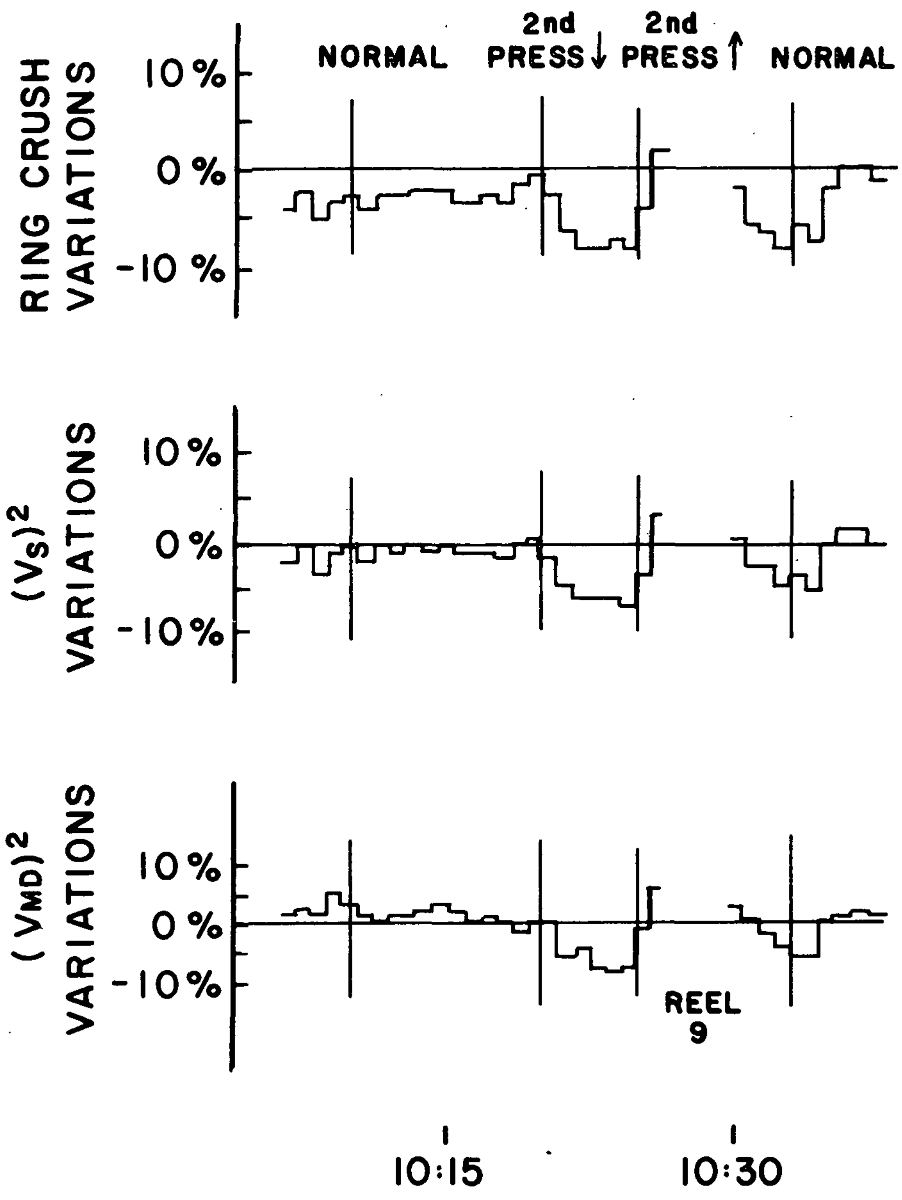


Fig. 5. Wet pressure results.

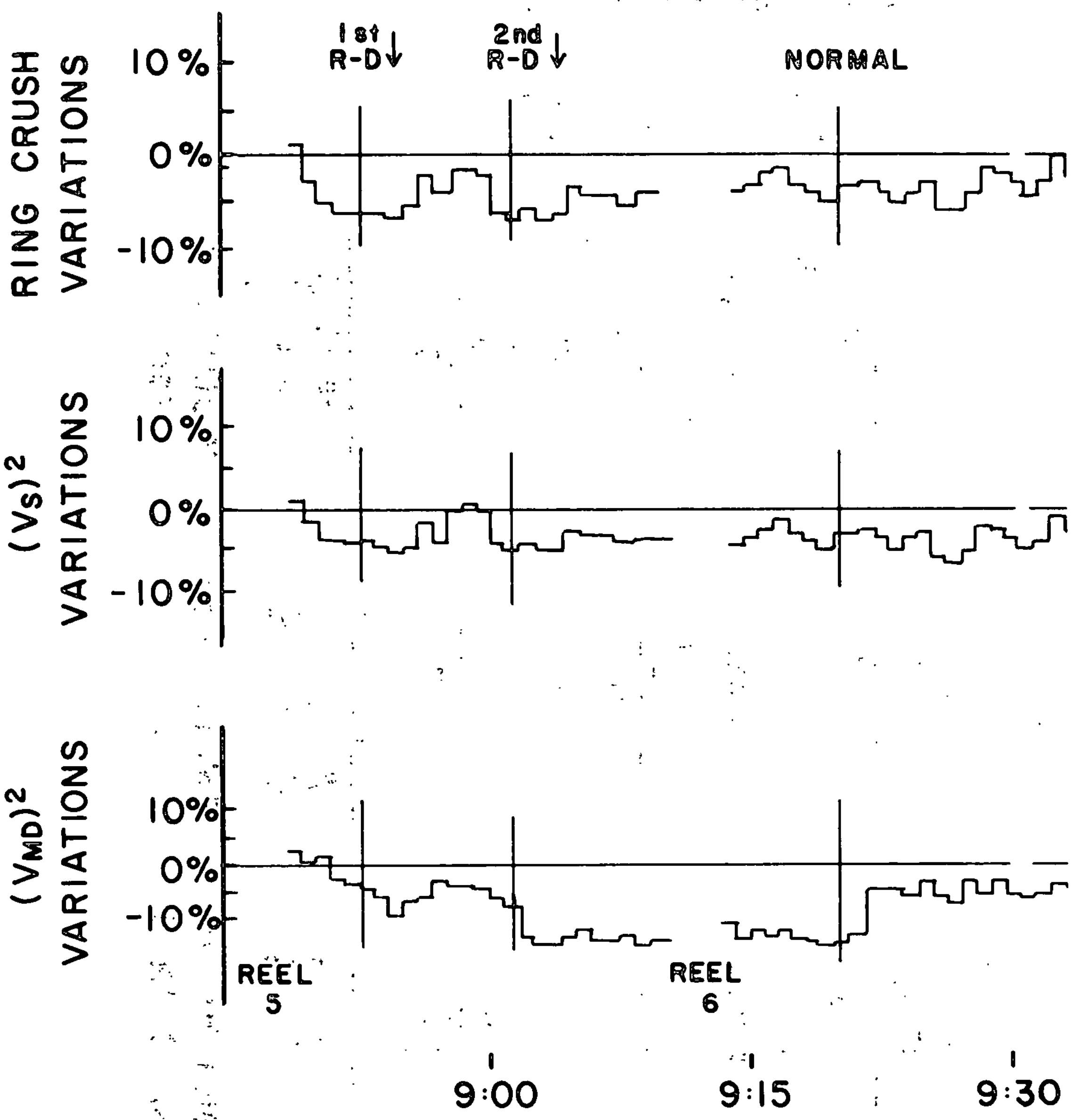


Fig. 6. Rush-drag results.

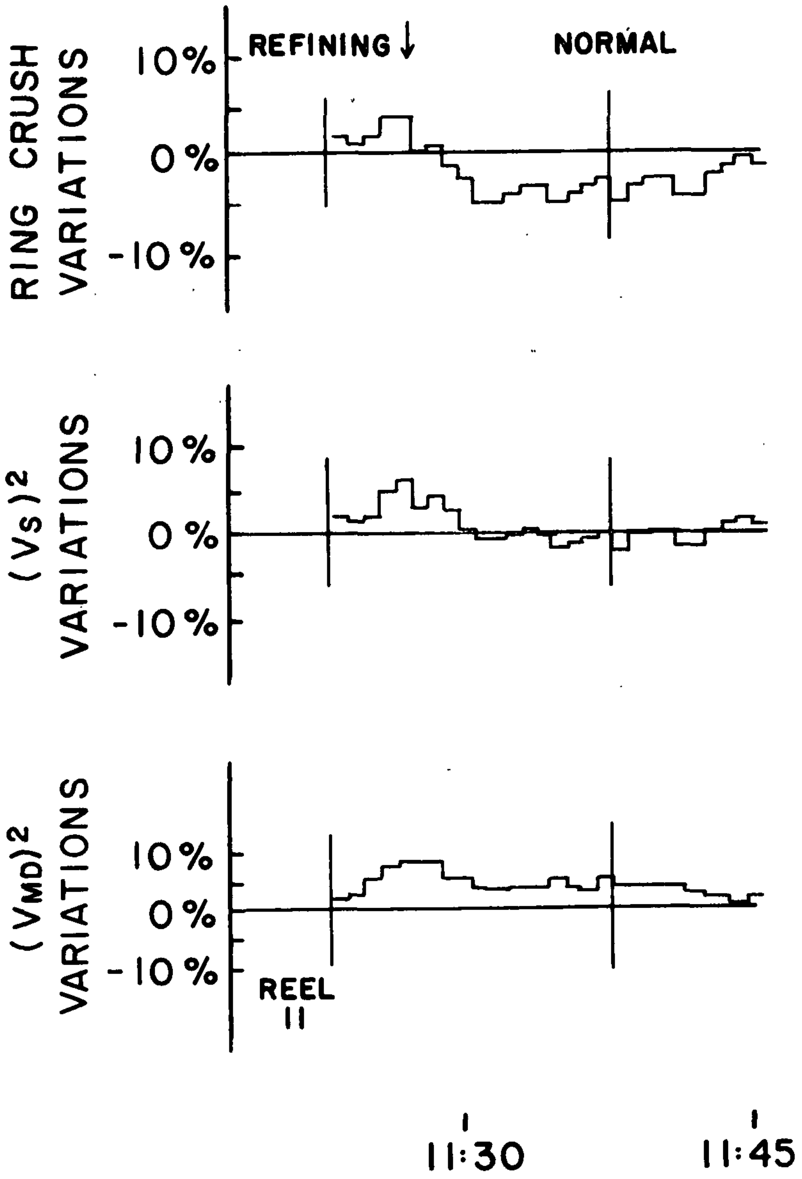


Fig. 7. Refining results.

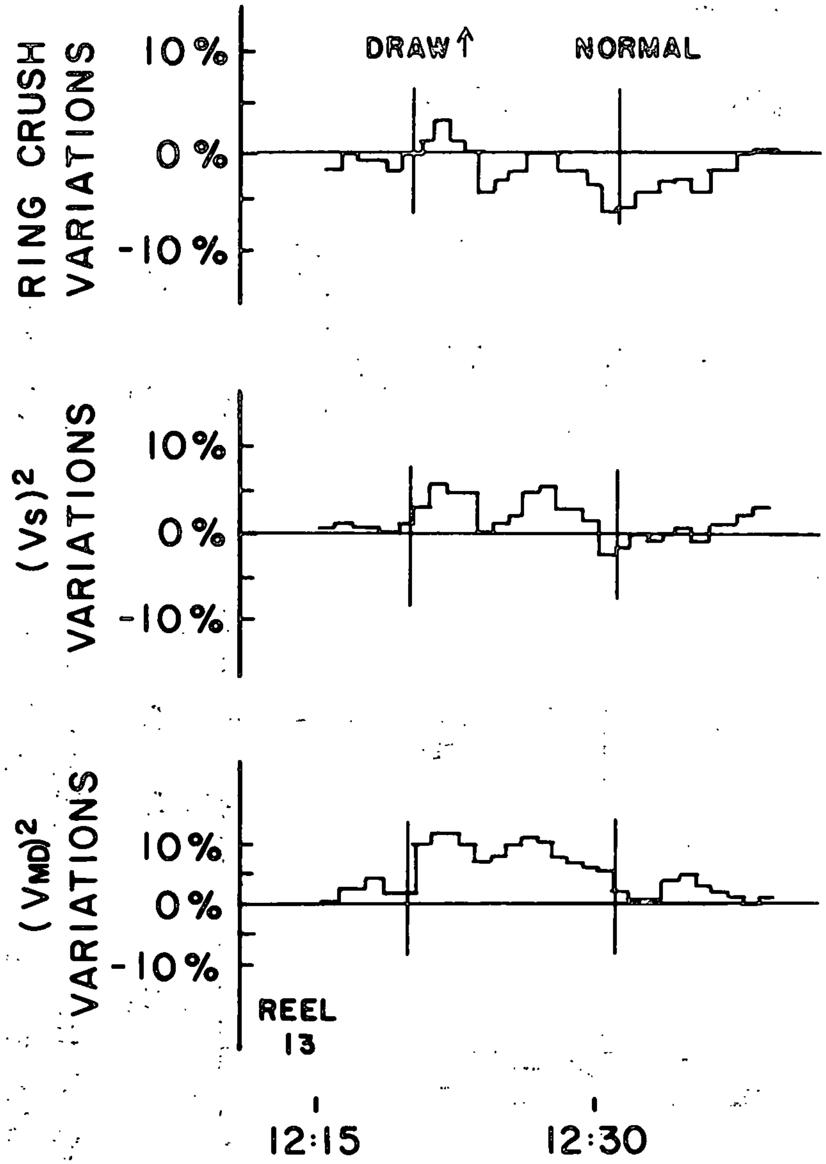


Fig. 8. Wet straining results.

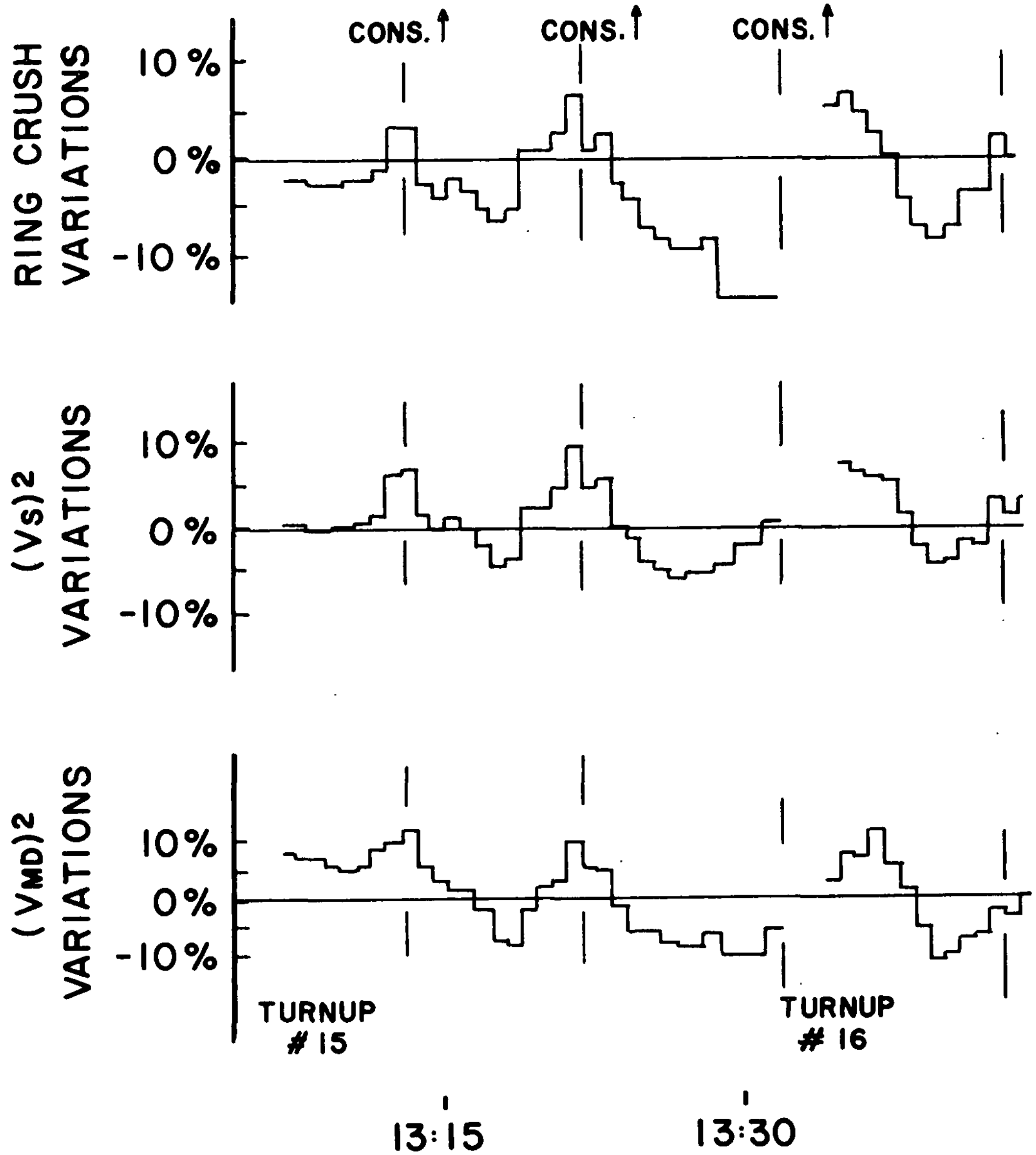


Fig. 9. Consistency results.

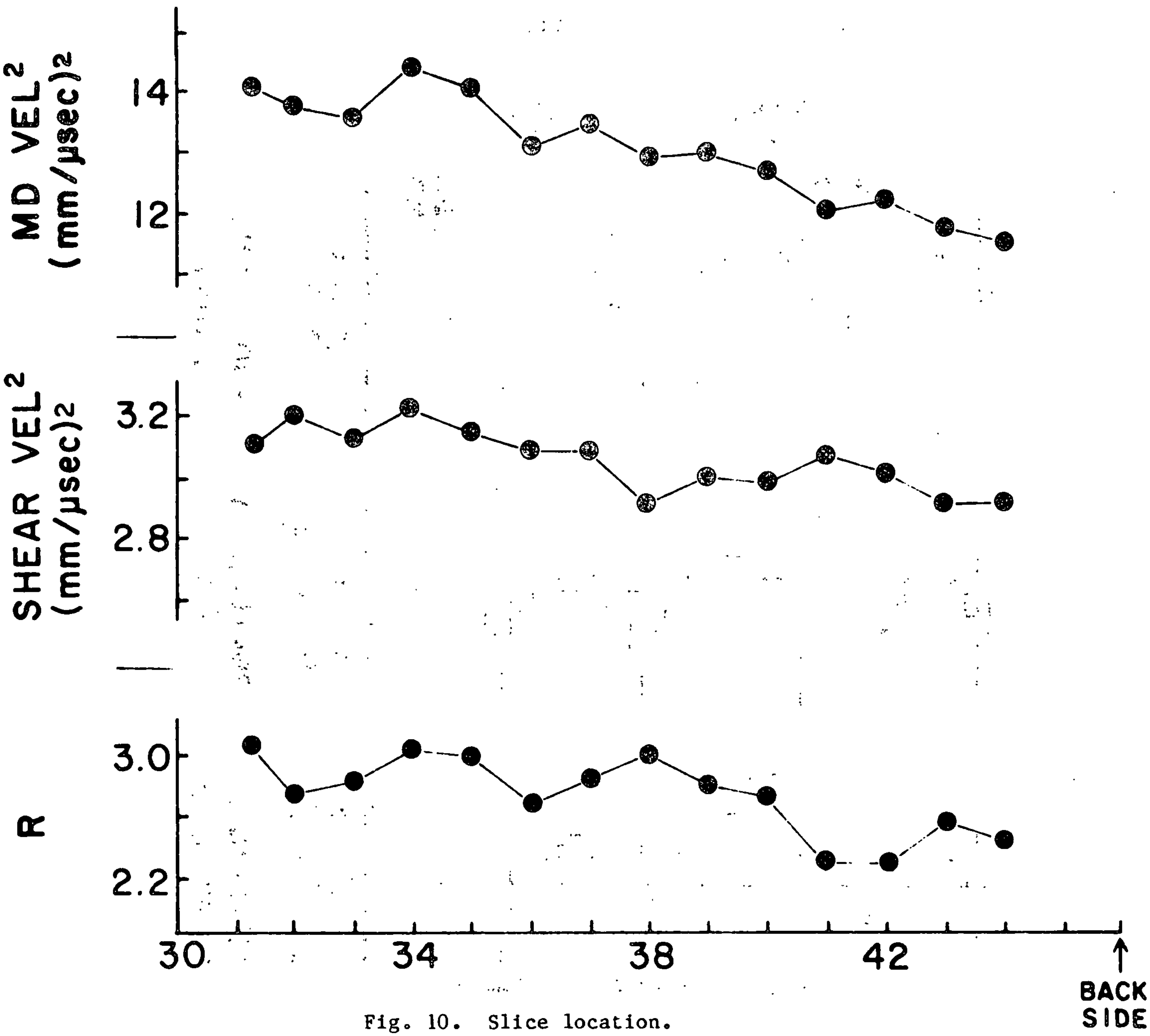


Fig. 10. Slice location.

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