INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

COMMERCIALIZATION OF ON-MACHINE SENSORS TO MEASURE PAPER MECHANICAL PROPERTIES

Project 3869/3332

Final Report

A Progress Report

to the

U.S. DEPARTMENT OF ENERGY
AND THE
MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

By

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September 1994

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Work Performed Under Cooperative Agreement No. DE-FC05-93CE40006

Institute of Paper Science and Technology
Atlanta, Georgia

Project No. 3869/3332

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ABSTRACT

The objective of this project is to develop sensors capable of measuring the velocity of ultrasound in the thickness and in-plane directions of a moving paper web as it is being produced on the paper machine. The velocity of ultrasound can be used to determine various mechanical properties of paper, e.g., the square of the velocity times the basis weight is a measure of the extensional stiffness. On-machine measurements would allow continuous monitoring of product quality as well as provide data for controlling the papermaking process.

This report summarizes work supported by Cooperative Agreement No. DE-FC05-93CE40006, U.S. Department of Energy (DOE), and by the member companies of the Institute of Paper Science and Technology (IPST). The central purpose of this grant, effective from October 1, 1993, through June 30, 1994, was to establish a plan: to develop a commercially viable system for on-machine, out-of-plane, and in-plane measurements of ultrasonic velocities; install a working system on a paper machine in a host paper mill; demonstrate the system's capabilities and benefits to the paper manufacturing industry; and have a vendor committed to providing and supporting the system.

This work followed previous work supported by the IPST membership and by DOE Contract No. DE-AC05-86CE40777. The details of the previous work are recorded in a final report dated October 1993.

This report first presents a review of the background and potential benefits of on-line ultrasonic velocity measurements. Then the results of the work supported by the previous contract are summarized followed by additional measurements on moving webs in the laboratory. Out-of-plane (ZD) and in-plane ultrasonic velocity data for 26-lb medium and 42-lb liner samples are presented and discussed, illustrating the type of data that will be available from on-machine measurements. Finally, the status of the plans and support for continued work toward commercialization is reviewed.

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INTRODUCTION

This report summarizes work supported by Cooperative Agreement Grant No. DE-FC05-93CE40006 from the U.S. Department of Energy (DOE) and by the member companies of the Institute of Paper Science and Technology (IPST). The central purpose of this grant, effective from October 1, 1993, through June 30, 1994, was to support IPST in its efforts to establish a working alliance with a vendor to develop a plan to commercialize on-machine in-plane and ZD ultrasonic velocity measurements.

This work followed previous work supported by the IPST membership and by DOE Contract No. DE-AC05-86CE40777. The details of the previous work are recorded in a final report dated October 1993.

This report first presents a review of the background and potential benefits of on-line ultrasonic velocity measurements along with a summary of the results of the work supported by the previous contract. Additional experimental measurements on moving webs in the laboratory illustrate the type of data that will be available from on-machine measurements. Finally, the status of the plans and support for work toward commercialization is reviewed.

BACKGROUND

Most paper grades have some type of mechanical property specification which must be met for satisfactory performance in end-use applications. Mechanical tests used for quality control are usually destructive and must be made off the paper machine on samples taken from the end of the reel. Thus, tests made on several square feet of material provide the only mechanical property information available for the thousands of square feet making up the reel. Variations within the reel are missed, and a substandard product will not be identified until the tests are completed after reel turn up. Thus, a substantial amount of substandard material may be produced and require repulping and remanufacture to meet specifications.

A sensor capable of monitoring mechanical properties continuously on the machine during production would immediately identify substandard material, and steps could be taken to correct the problem. With suitable means to use such on-machine sensor data to control the process, the production of substandard material could be reduced further. Additional energy benefits would result from optimum utilization of energy intensive processes, such as refining, and from efficiency improvement in subsequent converting processes as a result of improved product uniformity.

The in-plane and out-of-plane elastic stiffnesses are fundamental parameters related to the mechanical properties of paper. The elastic stiffnesses can be determined nondestructively by measuring the in-plane machine direction (MD) and cross direction (CD) and the out-of-plane (ZD) velocities of ultrasound. The square of the ultrasonic velocity is equal to the corresponding elastic stiffness divided by the apparent density. IPST has developed instruments to measure MD, CD, and ZD ultrasonic velocities through paper samples in the laboratory. It has been demonstrated that ultrasonic velocity techniques may be used to make measurements that are indicators of product quality and also can be correlated with end-use strength specifications (e.g., extensional stiffness, STFI short-span compression, ring crush) used in the paper industry (Mann et al., 1979; Whitsitt, 1985).

The sensitivity of elastic parameters to yield, refining, fiber orientation, wet pressing pressure, wet straining, and drying restraints has been studied (Baum et al., 1981; Fleischman et al., 1982; Baum et al., 1983; Berger and Baum, 1985). These studies have demonstrated that elastic parameters are particularly sensitive indicators of changes in furnish (the mixture of pulp and additives used) and process variables. Thus, measurement of these parameters on the paper machine would provide a means to continuously monitor product quality and to actually control the paper manufacturing process. The sensors to measure the velocity of ultrasound would be mounted at the dry end of the paper machine just ahead of the reel. These sensors would be mounted along with the basis weight, moisture, and caliper gauges now used on most paper machines and would scan the web just as those devices do. The basis weight, temperature, and moisture measurements would be used to adjust the elastic stiffness measurements to constant temperature and moisture content conditions for comparison with laboratory measurement and for appropriate use in control algorithms.

BENEFITS

Industry "needs or wants lists" always rank near the top the on-machine measurement of the physical properties of paper. A workshop, "Research Needs in the Pulp and Paper Industry," sponsored by the National Science Foundation at the University of Maine, July 12-13, 1988, put *elastic stiffnesses* high on the sensor priority list. This high priority need was reaffirmed at an Industry Needs Meeting, May 1992, in Syracuse, New York, sponsored by the TAPPI Process Control Committee. On-machine measurement of the MD, CD, and ZD stiffnesses continued to have high priority on the paper industry's "needs list" at the DOE/OIT sponsored "Pulp and Paper Mill of the Future Workshop, held in Reston, Virginia, February 3-5, 1993.

A mechanical instrument has been developed by Measurex to make on-line strain/stress in-plane measurements. Off-line ultrasonic velocity instruments are used to measure MD/CD ratio and stiffness orientation (polar angle) of end-of-reel cut samples. However, these measurements are not yet used or useable for closed-loop control of the papermaking process.

For products requiring specific mechanical "strength" properties for end-use, a nondestructive measurement of elastic stiffnesses would permit the manufacturing process to be controlled to stiffness targets rather than a basis weight target. This could reduce the amount of pulp required, since the specified "strength" might be achieved with a reduced basis weight.

The principal users of on-line ultrasonic velocity technology would be manufacturers of the heavier weight grades, packaging paper, and paperboard. These are primarily the linerboard and mediums used to make corrugated boxes. Well-controlled, uniform properties in rolls of paper available to the corrugated box plants would have a significant impact on their production efficiency through improved runnability and reduced warp.

Other potential users of this technology would be the paper companies producing printing and copy papers and newsprint. These products also have mechanical property specifications which are important to their end-use performance.

Energy Benefits

On-line ultrasonic velocity measurement instrumentation should enable more effective use of raw materials and minimize waste of energy while producing products with improved uniformity and performance.

It requires the equivalent of approximately 30 million Btu per ton to produce pulp and paper from wood. The ability to measure product quality on-line and control the manufacturing process to stiffness targets could reduce the tonnage required to meet current product specifications, providing further savings in energy. Furthermore, such monitoring would permit increased use of recycled fiber, which may reduce the energy required for some products.

Energy waste is avoided by minimizing the amount of substandard product which must be repulped and remanufactured. Further energy savings result from production efficiency improvement in subsequent converting processes as a result of uniformity of the paper properties. Additional savings may be obtained from the optimum utilization of energy intensive processes, such as refining. Refining requires approximately 200 kWh/ton, which is equivalent to 2.1 million Btu/ton. This presents significant opportunity for reducing energy use by controlling the amount of refining used to meet product specifications. It is speculative to quantify the potential productivity improvement and energy savings in refining and subsequent converting processes. However, we do have a basis for estimating the reduction in energy wasted by the production of substandard paper that must be reprocessed.

Repulping and remanufacture require about 13.5 million Btu/ton (Hersh, 1981). The electrical usage for repulping and paper machine operation is approximately 520 kWh per ton. With approximately 10,500 Btu required to produce one kWh of electrical energy, the electrical usage is equivalent to about 5.5 million Btu/ton. In addition, steam usage by the paper machine is approximately 8 million Btu/ton. Thus, the energy wasted by substandard production is approximately 13.5 million Btu/ton. With packaging paper and board production by the U.S. paper industry at 32 million tons/year, for each 1% of production that is substandard and reprocessed, the energy wasted would be 4.32 trillion (4,320,000,000,000) Btu/year with an approximate value of $17,000,000 (@ $4/million Btu) annually. Assuming that substandard production is 5% (Orloff and Lindsay, 1993), this amounts to 1.6 million tons/year. This presents an energy waste reduction opportunity of 21.6 trillion Btu/year or 0.02+ quad with an approximate value of $86,000,000 annually.

Environmental Benefits

The ability to control the process to a mechanical property specification may enable the product to be produced with a lower grammage (grams/square meter) or basis weight and/or lower quality fiber. This would not only provide the potential environmental benefit of using less pulp and fewer trees, but also would encourage a higher utilization of recycled fiber. The paper manufacturer would be able to monitor the effect of recycled fiber utilization on product quality and thus could use higher percentages of recycled fiber with confidence that the product remains within specifications.

Minimizing the need to repulp and remanufacture reduces water utilization and provides consequential benefits to the environment. An additional waste that is difficult to quantify is the "waste" of fiber quality that occurs each time the fibers are dried and rewet. This type of waste is avoided by making quality paper the first time through the paper machine.

REVIEW OF PREVIOUS WORK

Instrumentation capable of on-machine measurements of in-plane ultrasonic velocity in moving paper webs was developed at The Institute of Paper Chemistry (IPC), now IPST, (Baum and Habeger, 1980; Baum and Habeger, U.S. Patent 4,291,577; Habeger and Baum, 1986). This equipment was tested in a linerboard mill at Valdosta, Georgia, from January 1983, to July 1985, under a research program supported by the Fourdrinier Kraft Board Group (FKBG) of the American Paper Institute (Baum and Habeger, Project 2692-4, 1985). The research demonstrated that the correlation between elastic properties and "strength" properties observed in the laboratory also hold in a mill setting.

With the above background and the recognized potential for significant efficiency, energy, and environmental benefits, the Office of Industrial Technologies of the U.S. Department of Energy supported a research project at IPST titled, "On-Machine Sensors to Measure Paper Mechanical Properties," through Contract DE-AC05-86CE40777, from October 1, 1986, through May 31, 1993. During this period, this project was supported by $1,380,000 from DOE and by $880,000 from the member companies of IPST.

In order to separately identify the effects of refining, jet-to-wire speed ratios, wet pressing pressure, draws, and drying restraints on paper properties, the elastic stiffnesses in both the in-plane and thickness directions should be measured. This would provide the maximum sensitivity to the effects of the various paper machine variables for machine control. Therefore, the initial project emphasis specifically concerned the development of a sensor to make measurements of the ultrasonic velocity in the thickness direction (ZD) of a moving paper web. Then an appropriate in-plane sensor would be used in combination with the ZD sensor to provide a complete system to measure paper mechanical properties on the paper machine. The details of the previous work are recorded in a report, dated October 1993. The principal results are reviewed below.

WEB HANDLING SYSTEM

In order to evaluate the sensor developments on moving webs in the laboratory, an unwind/rewind web handling system was designed and purchased. This web handling system includes a web guide and a splicing station. It can operate at speeds up to 2500 feet per minute, running in either an endless loop or a reel-to-reel mode. A dancer arm provides adjustable tension in the loop mode, and tension is automatically controlled in the reel-to-reel mode. The system is able to handle webs up to 14 inches in width with tension controllable from 0.5 to 4 pounds per linear inch. This system may be used to perform tests on 33-foot endless loops or reels on 3-inch cores up to 34 inches in diameter.

ZD MEASUREMENTS WITH FLUID-FILLED WHEEL TRANSDUCERS

Fluid-filled wheel ultrasonic transducers, similar to those used commercially in testing railroad rails for flaws, are modified for our application. Each wheel is constructed with an ultrasonic transducer mounted to a fixed axle. Bearings are used to mount a hollow rubber tire on the axle. Fluid is pumped into the tire, and all air bubbles are carefully removed. In our application, the paper runs in the nip between two such wheels, and acoustic energy is transmitted from the transducer in one wheel through the paper to the transducer in the other wheel.

A test stand for mounting the fluid-filled wheels was designed and constructed to operate with the unwind/rewind web handling system. This test stand has cross-web positioning in 1-inch increments. The wheel mounts are extended and retracted by air cylinders. Motors are provided to drive the wheels to match wheel-to-web speed before closing the wheels onto the web.

The tires on the fluid-filled wheels must be of sufficient thickness, about 3/8 inch, to avoid a change of shape in the pulse used for measurement. The effect of variations in the tire around its circumference is minimized by averaging multiple pulse trains during an integral rotation of the wheel.

The time-of-flight between the transmitter and receiver is measured without and with a sample in the nip. The difference in the time-of-flight without a sample, t_1, and with a sample, $t_{1'}$, or

$$\Delta t_{1'1} = t_{1'} - t_1,$$

is equal to the caliper of the sheet, h, times the inverse of the velocity of ultrasound in the sample, v_p, less the inverse of the velocity of ultrasound in the fluid, v_f, or

$$\Delta t_{1'1} = h(1/v_p - 1/v_f). \tag{1}$$

Therefore, a measurement of caliper is needed to find the time-of-flight, $t_h = h/v_p$, through the paper, which from Eqn. 1 is

$$t_h = h/v_p = \Delta t_{1'1} + h/v_f. \tag{2}$$

The velocity of ultrasound in the fluid is of the order of five times greater than the velocity of ultrasound in the thickness direction of paper, v_p, and the value of h/v_f is about 20% of $\Delta t_{1'1}$.

It so happens that the caliper of the sheet can be determined from the acoustic pulses transmitted between these wheels. After the first straight-through pulse with a travel time t_1 is detected in the receiver, a number of reflection-delayed pulses are observed. One of these pulses with a travel time t_2 is of particular interest. With a fixed distance between transducers, the time of arrival for this pulse is independent of any variation of the pass line between the two wheels. When a paper sample is inserted in the nip, the path length change in the fluid for this pulse is equal to two times the paper thickness. Using the time difference with and without a sample in the nip, the caliper or paper thickness, h, can be calculated

$$h = [(t_2 - t_1) - (t_{2'} - t_{1'})]v_f/2. \tag{3}$$

Either the multireflected ultrasonic pulses described above or an independent caliper gauge may be used to determine the web caliper. The principal advantage of the use of the multireflected pulses is that the data are collected at the same sample locations and with the same sample compression as the transit time data. The ZD measurements are sensitive to temperature changes in the fluid-filled wheels. The main advantage of determining caliper with an independent gauge is that the measurement is less sensitive to temperature changes. A temperature change of one degree Centigrade in the fluid (mostly water) changes the pulse propagation velocity by approximately 2.4 meters/second. It was found that the time of flight in a delay line attached to the transmitting transducer provides a sensitive measure of temperature. The current transit times must be compared with the "reference" values that would be measured at the current system temperature. This can be achieved by frequent off-web "reference" determination when the temperature of the system remains stable. Also, the temperature-dependent "reference" values can be determined as a function of the temperature-dependent, delay-line transit time. These relationships can then be used to correct the "reference" values to the current system temperature.

A pulser/receiver was first introduced to measure the delay-line travel time in the echo signal rather than in the signal transmitted through the sample to the receiver. The use of pulse/echo in combination with the delay line also provides an appropriate set of pulses to permit time difference measurements without "trigger jitter." The pulse trains are digitized at a rate of 10 Msamples/second (100 nanoseconds/point) to allow fast averaging (approximately 500 pulse trains averaged per second). By using second-order interpolation of the digitized waveforms and then using cross-correlation, time differences within averaged pulse trains can be determined with near nanosecond accuracy.

IN-PLANE MEASUREMENT SYSTEM FOR MOVING WEB

The in-plane measurement system for moving webs is based on a set of wideband bimorph bender ultrasonic transducers similar to those developed for the in-plane laboratory instruments. The transducers are mounted in the surface of a 10-inch diameter aluminum cylinder. The cylinder is mounted in the web handling system. The transducers are oriented outward so that each active element protrudes slightly outside the circumference of the cylinder. The transducer housing and the carrier are designed to minimize variation in the contact force between the transducers and the web. Part of the housing is square in cross section and slides freely in a square hole in the carrier. This maintains the rotational alignment of the bender transducer. Relatively weak springs hold the transducer in light contact with the paper sample or with the cap on the carrier when there is no paper. A technique was developed to adhere a metal wire or cap to the tip of the transducer to provide a more durable wear surface.

The transducers are used in sets of three. One transducer serves as a transmitter, and the other two transducers are used as receivers. The transducers may be oriented and aligned to operate in the longitudinal or shear mode in the MD or CD directions. For example, a transmitter positioned to excite longitudinal waves in the MD direction of the web also excites shear waves in the CD direction. Four transducers may be positioned relative to this transmitter into two sets of receivers. For both sets, the receivers are positioned at different distances (NEAR and FAR) from the transmitter in order to create a path length difference from transmitter to receivers. This path length difference is divided by the measured difference in pulse flight times for the calculation of in-plane velocities.

The web is wrapped part way around the cylinder. The portion of a rotation within which a set of transducers is in contact with the web is the active measurement period for that set. During this active period, the transmitter is excited by single-cycle, 80 kHz, ultrasonic pulses spaced at approximately 1 millisecond intervals. The pulse interval is just long enough to allow time for the waves propagating within the web from the previous excitation to die out. Each excitation causes the transmitter to produce in-plane waves that propagate in all directions. The receivers convert the waves back into electrical signals which are captured by a digitizing oscilloscope. After averaging a number of waves within the active period of rotation, the oscilloscope takes time measurements of corresponding half-cycle peaks. The difference in peak times for each receiver set is determined and sent to the 486 computer for velocity calculations.

POLAR ANGLE DETERMINATION FOR MOVING WEBS

Provision is also included in the cylinder to mount transducer sets at plus and minus 45 degrees to the machine direction. These two measurements at $\pm$ 45 degrees provide an indication of the in-plane stiffness alignment relative to the machine direction. For example, the difference divided by the average,

$$\frac{2[(V_{+45})^2 - (V_{-45})^2]}{[(V_{+45})^2 + (V_{-45})^2]}$$

may be used to infer the direction of maximum stiffness relative to the machine direction.

In-plane polar specific stiffness measurements are now routinely performed on cut samples in the laboratory, wherein velocity readings are recorded at every 5 or 10 degrees. The polar stiffness plot may be in the shape of a peanut, but the polar velocity plot may be closely approximated by an ellipse at angles away from the vicinity of the CD. Since any ellipse may be uniquely defined by three distinct points, two points at $\pm$45 degrees and one point in the MD (zero degrees) are sufficiently removed from the CD to define an ellipse. This ellipse provides a good approximation to the standard polar test for both polar angle and area.

ADDITIONAL EXPERIMENTAL MEASUREMENTS

To demonstrate the type of data that will be available to the papermaker from on-line ZD and in-plane ultrasonic velocity measurements, additional experiments were completed with the results discussed below.

26-LB MEDIUM

A roll was made by splicing together 2000 feet each of the following 26-lb mediums: Caustic Carbonate (CC), Green Liquor (GL), Neutral Sulfite Semichemical (NSSC), and Old Corrugated Containers (OCC). A leader of flat multiwall was used at each end of the roll.

Figure 1 shows the caliper in microns as measured with a Measurex (MX) caliper gauge. The dotted lines show the maximum and minimum values measured with a hard platen gauge on an 8" by 8" sample. The effect of sample roughness is apparent.

Figure 2 shows the ZD velocity in meters per second. The term "MX Velocity" indicates that the ZD velocity was calculated using the MX caliper with the time-of-flight of ultrasound through the thickness of the web. The dotted lines indicate the maximum and minimum ZD velocity measured with the laboratory ZD instrument on an 8" by 8" sample of each medium. Two data collection runs are presented in Fig. 2. One set was taken with a soft, natural rubber tire above the web and a hard, polyurethane tire below. For the other set of data, a hard, polyurethane tire was used for both fluid-filled wheels. It appears that either tire combination provides acceptable performance.

Figure 3 shows the in-plane MD longitudinal and CD shear velocities for the 4-section 26-lb medium roll. Figure 4 shows the in-plane MD shear and CD longitudinal velocities for the 4-section 26-lb medium roll.

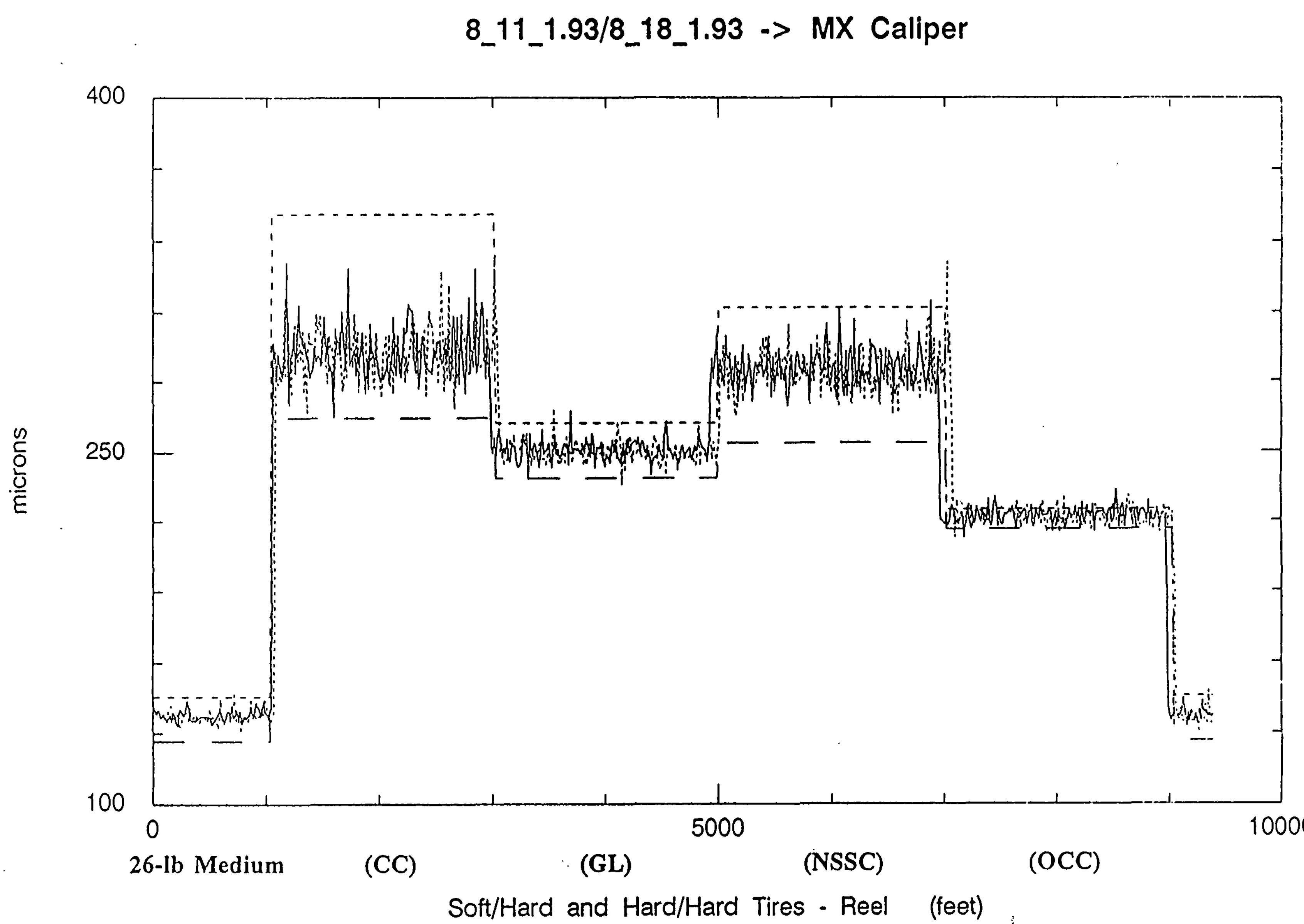


Figure 1. MX Caliper of 26-lb medium with 2000 feet from each of four different sources.

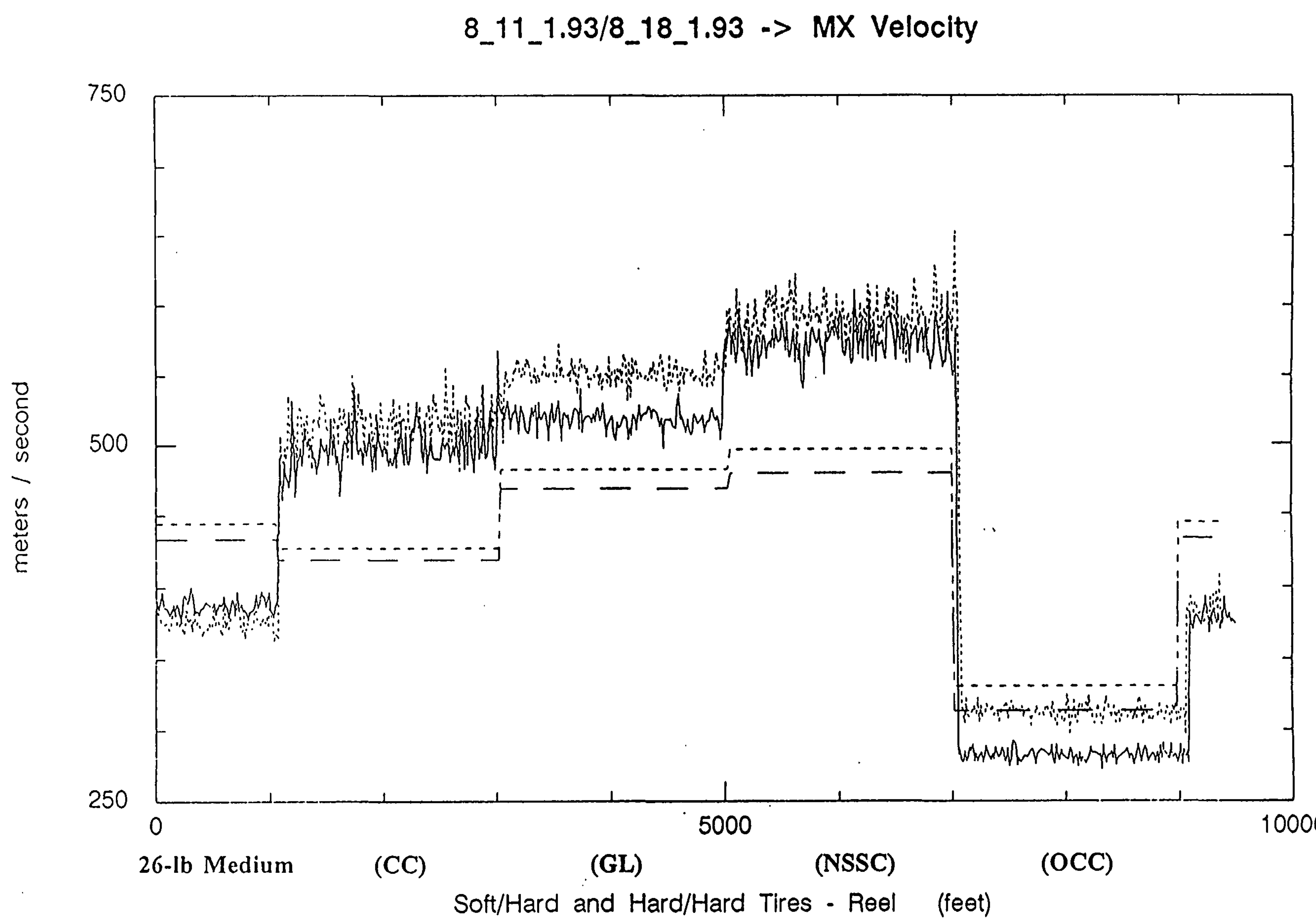


Figure 2. ZD velocity for the 4-section 26-lb medium, determined using the MX caliper.

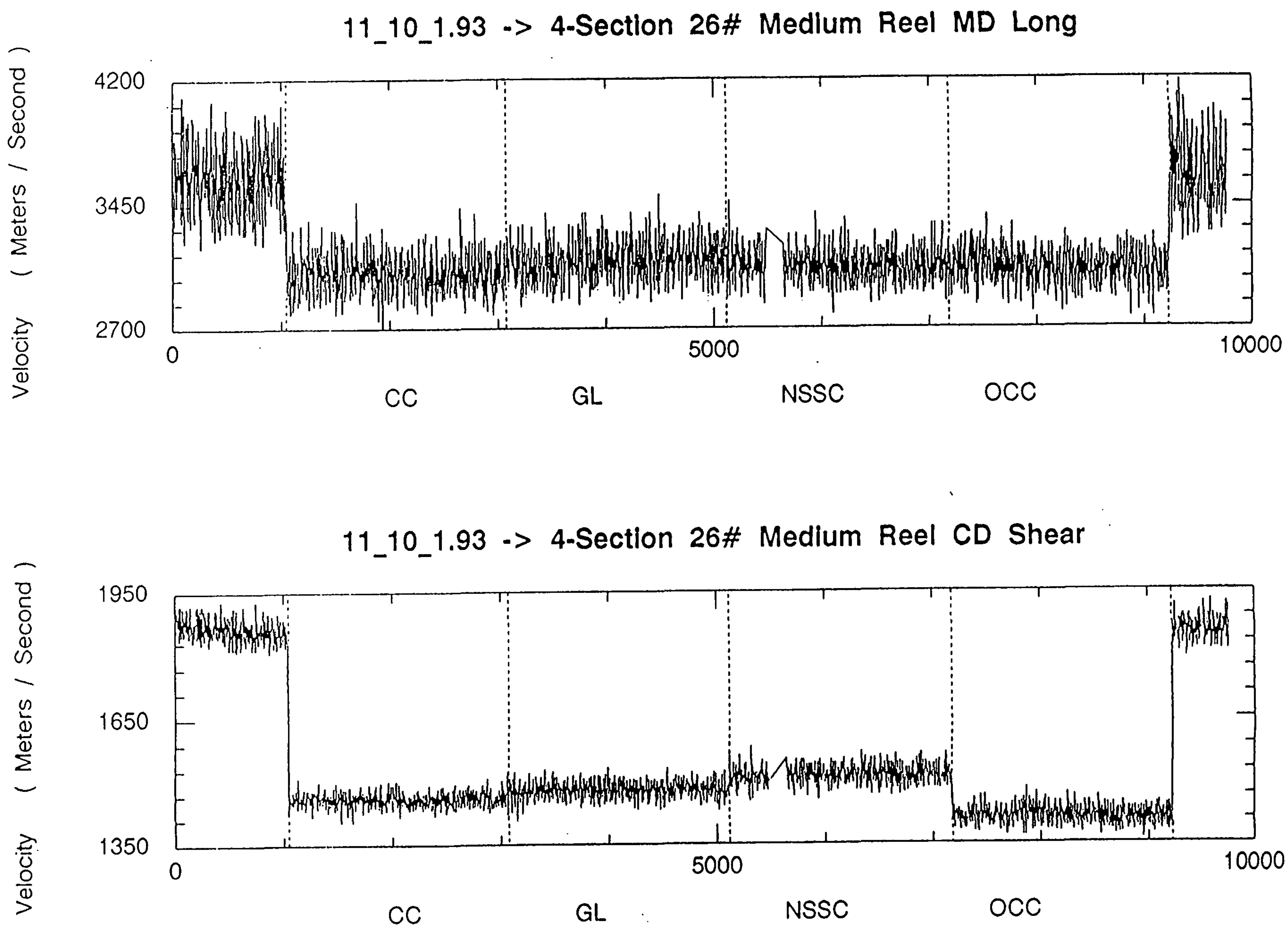


Figure 3. In-plane MD longitudinal and CD shear velocities for the 4-section 26-lb medium roll.

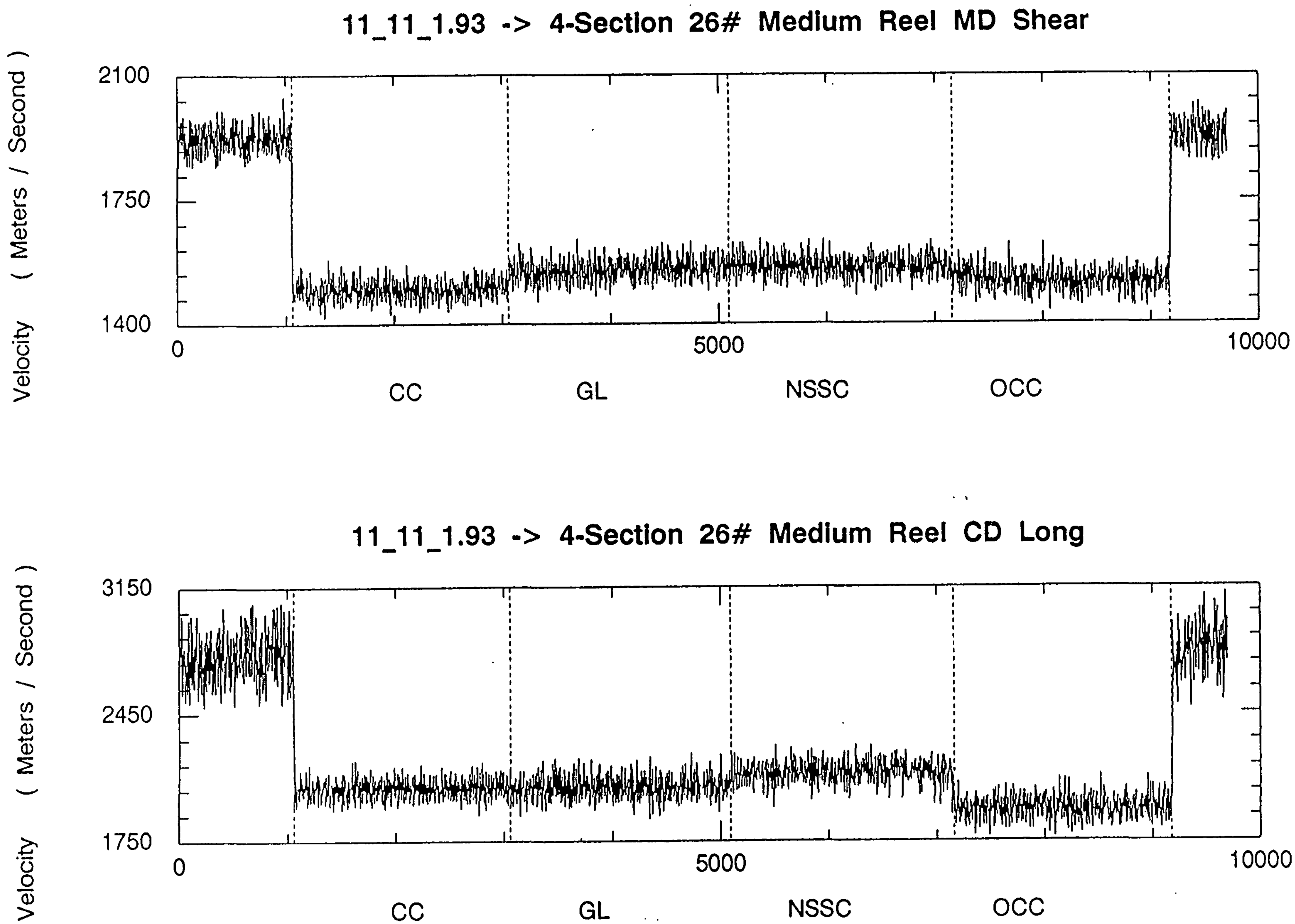


Figure 4. In-plane MD shear and CD longitudinal velocities for the 4-section 26-lb medium roll.

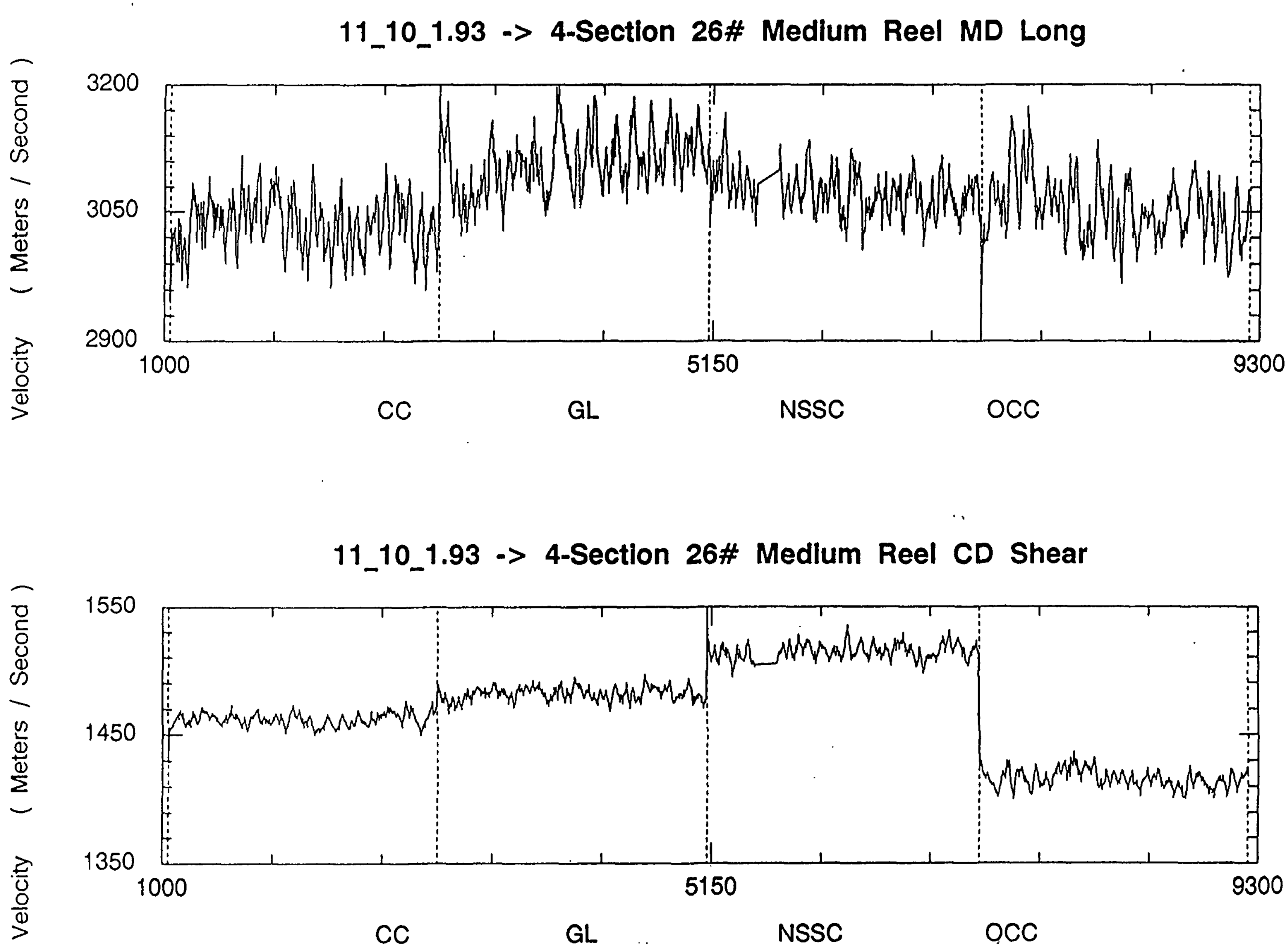


Figure 5. "Smoothed" replot of the MD longitudinal and CD shear velocity data of Fig. 3.

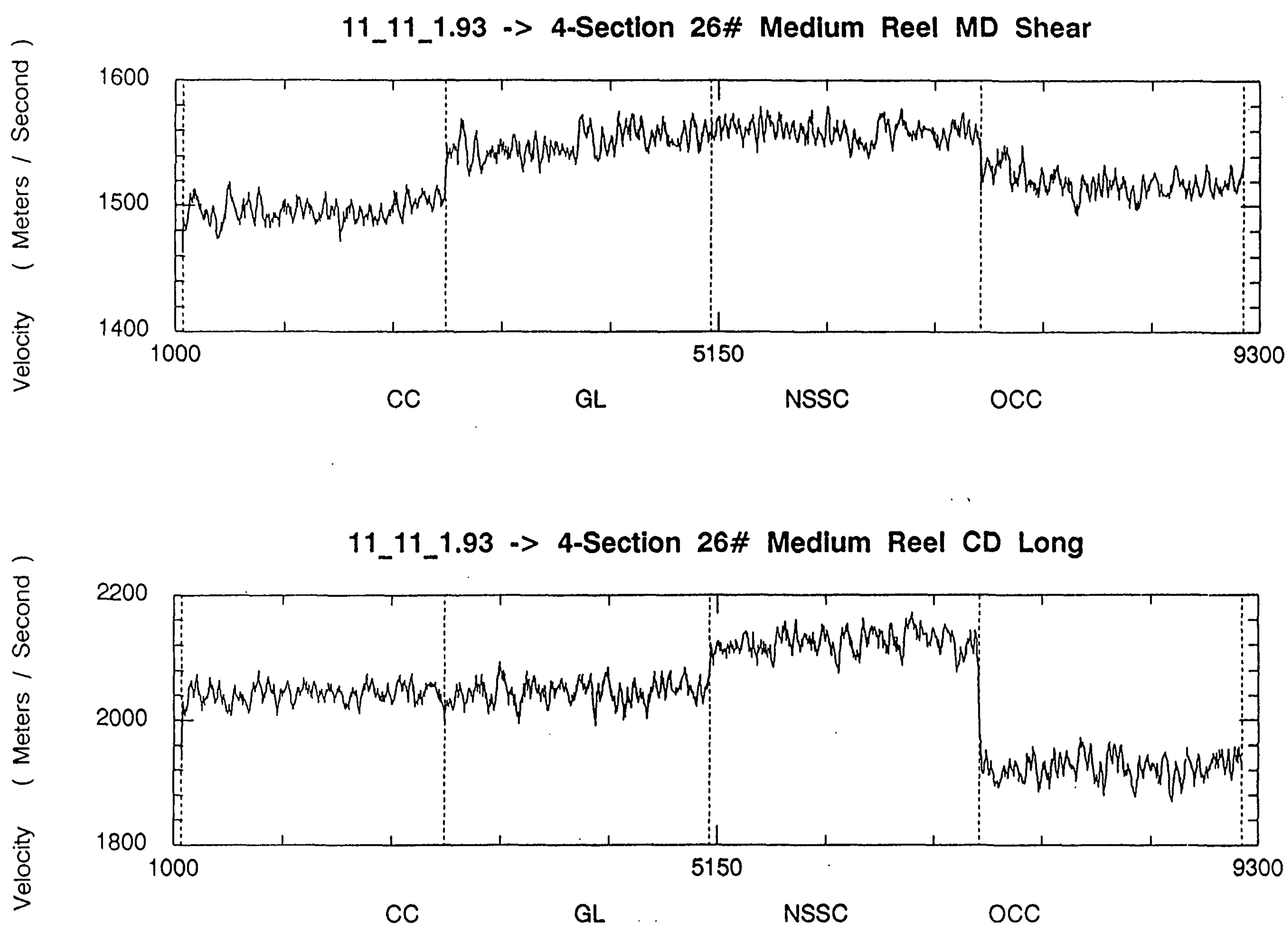


Figure 6. "Smoothed" replot of the MD shear and CD longitudinal velocity data of Fig. 4.

Figure 5 shows a "smoothed" replot of the MD longitudinal and CD shear data of Fig. 3. Figure 6 shows a "smoothed" replot of the MD shear and CD longitudinal data of Fig. 4.

The in-plane transducers are in contact and move with a particular segment of the web hile ultrasonic pulse transit times are measured. Thus, in-plane velocity readings may be recorded each rotation of the cylinder for segments along the web every 2.6 feet (the circumference of the cylinder). Figures 3 and 4 present such data recorded each rotation of the cylinder. While variation in the data may, in part, be due to variations in transducer contact to the web, most of the variation is believed to be due to variations in web properties that affect the velocity of ultrasound. Thus, the variation of this in-plane data may provide a measure of the uniformity of the web. A tabulation of the Mean, Standard Deviation, and Coefficient of Variation for the in-plane velocities measured on the 4-section reel of 26-lb medium and plotted in Figs. 3 and 4 is presented below.

	V_{MD} ⇔ *MD Longitudinal Velocity*			$V_{SH,CD}$ ⇔ *CD Shear*		
	Mean	*Standard Deviation*	*Coefficient of Variation*	*Mean*	*Standard Deviation*	*Coefficient of Variation*
CC	3036.06	110.354	0.036	1462.28	15.991	0.011
GL	3108.51	106.815	0.034	1481.40	18.057	0.012
NSSC	3072.59	92.296	0.030	1514.39	19.721	0.013
OCC	3053.74	95.289	0.031	1415.29	18.865	0.013
	$V_{SH,MD}$ ⇔ *MD Shear*			V_{CD} ⇔ *CD Longitudinal*		
	Mean	*Standard Deviation*	*Coefficient of Variation*	*Mean*	*Standard Deviation*	*Coefficient of Variation*
CC	1496.41	25.014	0.017	2042.70	49.178	0.024
GL	1550.14	27.269	0.018	2045.43	55.804	0.027
NSSC	1559.50	26.174	0.017	2123.97	52.678	0.025
OCC	1519.06	28.511	0.019	1923.56	55.588	0.029

The in-plane shear velocity should be the same whether measured in the MD or CD. We note a small difference in the average shear velocities, perhaps due to an error in the determination of transducer spacing in the cylinder.

Several studies (Baum et al., 1981; Whitsitt, 1985; Vahey, 1987) have noted and made use of empirical relationships between shear and longitudinal ultrasonic velocities. One such relationship is

$$(V_{SH,MDorCD})^2 = k_1 [(V_{MD})(V_{CD})].$$

Using the velocities tabulated above, a calculation of k_1 for this relationship is tabulated below. If one measures two of these velocities, this relationship may be used to calculate the third velocity.

	$V_{MD}V_{CD}/(V_{SH,MD})^2$	$V_{MD}V_{CD}/(V_{SH,CD})^2$	$V_{MD}V_{CD}/(V_{SH,AV})^2$
CC	2.770	2.900	2.834
GL	2.646	2.897	2.767
NSSC	2.683	2.846	2.763
OCC	2.546	2.933	2.729

Other empirical relationships between shear and longitudinal ultrasonic velocities noted in the literature (Whitsitt, 1985) are;

$$(V_{SH,MD\text{-}ZD})^2 = k_2 [(V_{MD})(V_{ZD})], \quad \text{and} \quad (V_{SH,CD\text{-}ZD})^2 = k_3 [(V_{CD})(V_{ZD})].$$

Thus, the simultaneous measurement of the ZD longitudinal ultrasonic velocity with the in-plane ultrasonic velocities may provide an on-line measure of ZD shear stiffnesses.

42-LB LINER

To illustrate the type of cross-direction data that on-line ultrasonic velocity measurements will provide by scanning across the moving web at the dry end of the paper machine, two machine-width (20 feet) samples, approximately 40 feet long, were obtained. The samples were two-ply 42-lb liner with the primary ply containing approximately 80% of the basis weight. The significant process difference between the two samples made on the same machine was that one, designated "regular," was made with a rush/drag of -74.2 ft/min for the primary ply, and the other, designated "high ring," was made with a rush/drag of -41.0 ft/min for the primary ply.

The samples were separated into four segments across the width for transport to IPST. The samples were unrolled, marked, and cut into one-foot wide strips. The separations of the cross-machine segments did not run parallel to the edges of the sheet. Only one-foot wide strips that could be cut parallel to the edge from one end of the sample to the other were used. Consequently, 16 one-foot wide strips were obtained from the "high ring" sample, and only 12 one-foot strips could be cut from the "regular" sample. A roll was constructed by splicing the one-foot wide strips in a machine back-to-front sequence, starting with a 42-lb leader, then the "regular" samples followed by a leader and the "high ring" samples and ending with a leader.

ZD velocity measurements were made on the roll of samples by repeated runs, "front to back." The cross-web position of the fluid-filled wheels in the test stand is marked in one-inch increments. The 12-inch web was centered on position 9. The repeat runs were made with the wheels in positions 5, 7, 9, 11, and 13, i.e., in 2-inch increments across the samples. Because it requires approximately 7 seconds to acquire and process one data point, the web was run at 35 to 40 feet/minute so that 7 to 9 measurements were made within each 40-foot strip. Figure 7 shows a plot of the data from the run with ZD wheels in "position 7."

The values of the measurements along each 40-foot strip were averaged. The averages for each cross-web position are plotted in Figs. 8, 9, 10, and 11. Figures 8 and 9 compare the caliper versus the position across the web for the "high ring" and "regular" samples. The notations along the x-axis mark the distance in inches from the front edge of the web. The range of caliper values is approximately 25 microns across a web sample, and a few cross-machine locations show a difference of as much as 25 microns between the two samples.

Figures 10 and 11 compare the ZD velocity versus position across the web for the "high ring" and "regular" samples. The range of the cross-machine variation of the ZD velocity values is greater for the "high ring" web sample than for the "regular" sample, ~60 meters/second versus ~40 meters/second. There is little difference between the two samples near the front edge, but other cross-machine locations show differences of as much as 25 meters/second. The cross-machine variations within the samples are greater than the differences between samples at given locations.

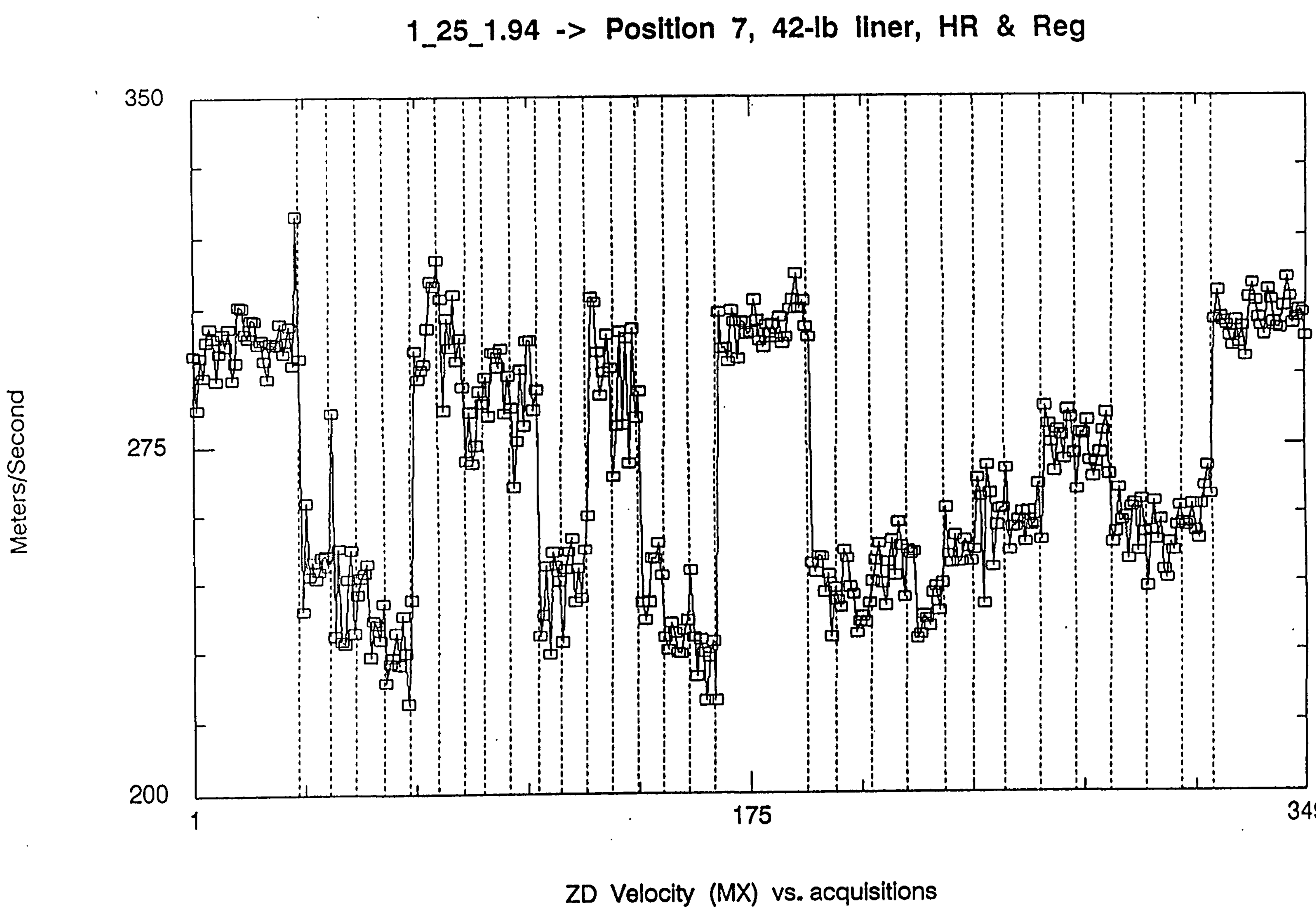


Figure 7. ZD velocity data recorded in position 7 for "High Ring" and "Regular" 42-lb liner samples.

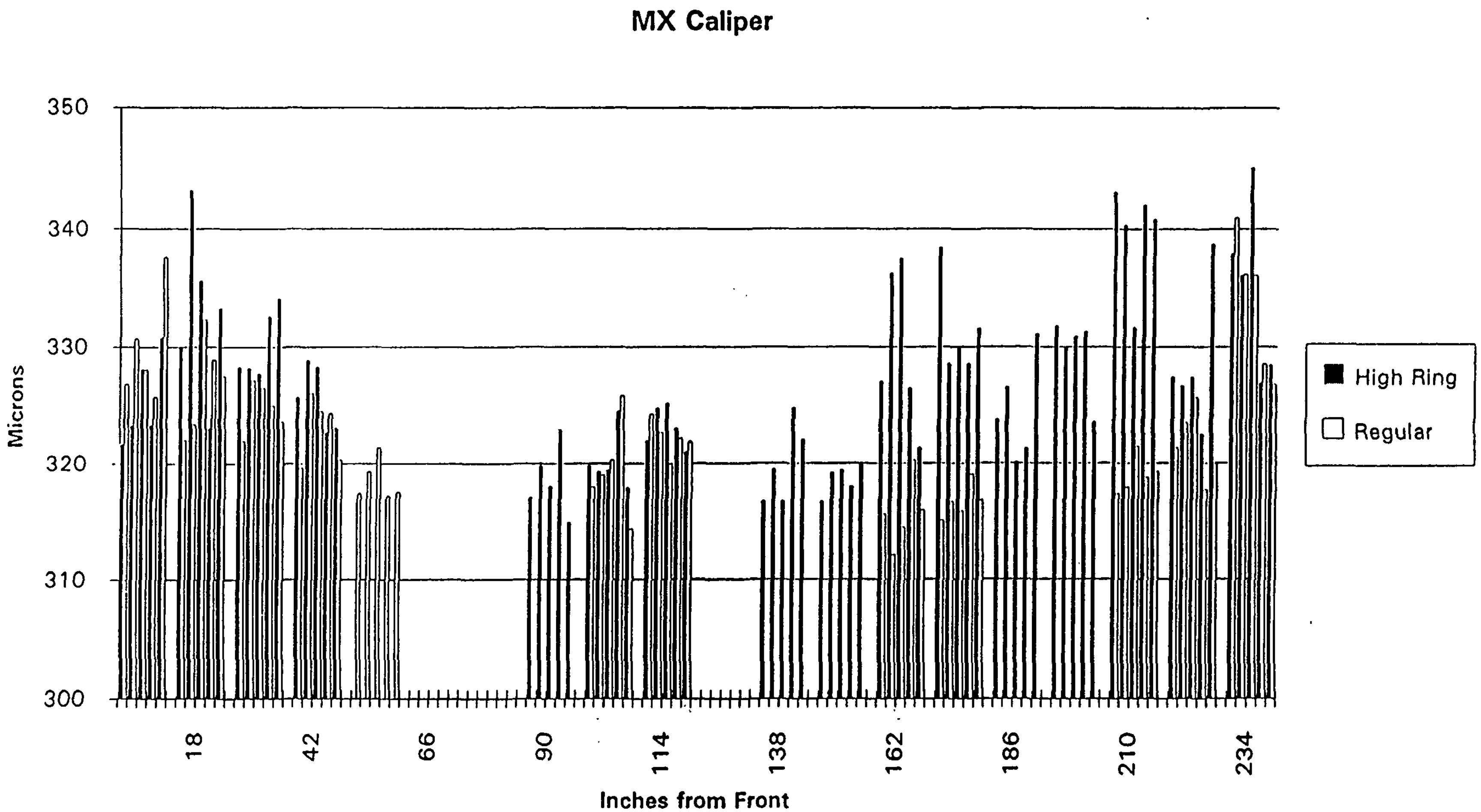


Figure 8. Average MX caliper in microns versus cross-web position in inches from the front edge for the "High Ring" and "Regular" 42-lb liner samples.

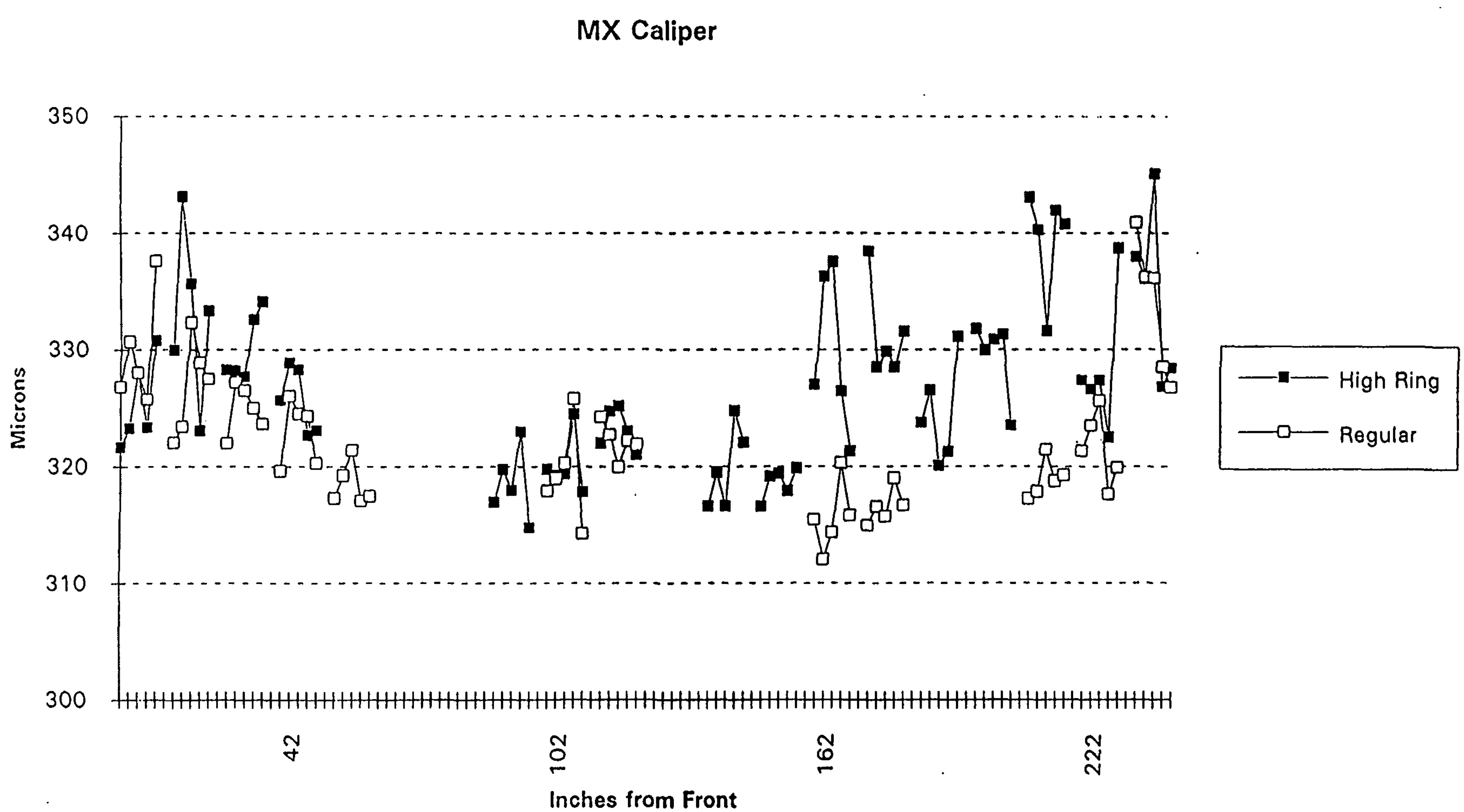


Figure 9. The average MX caliper data of Fig. 8 replotted as a point chart rather than a bar chart.

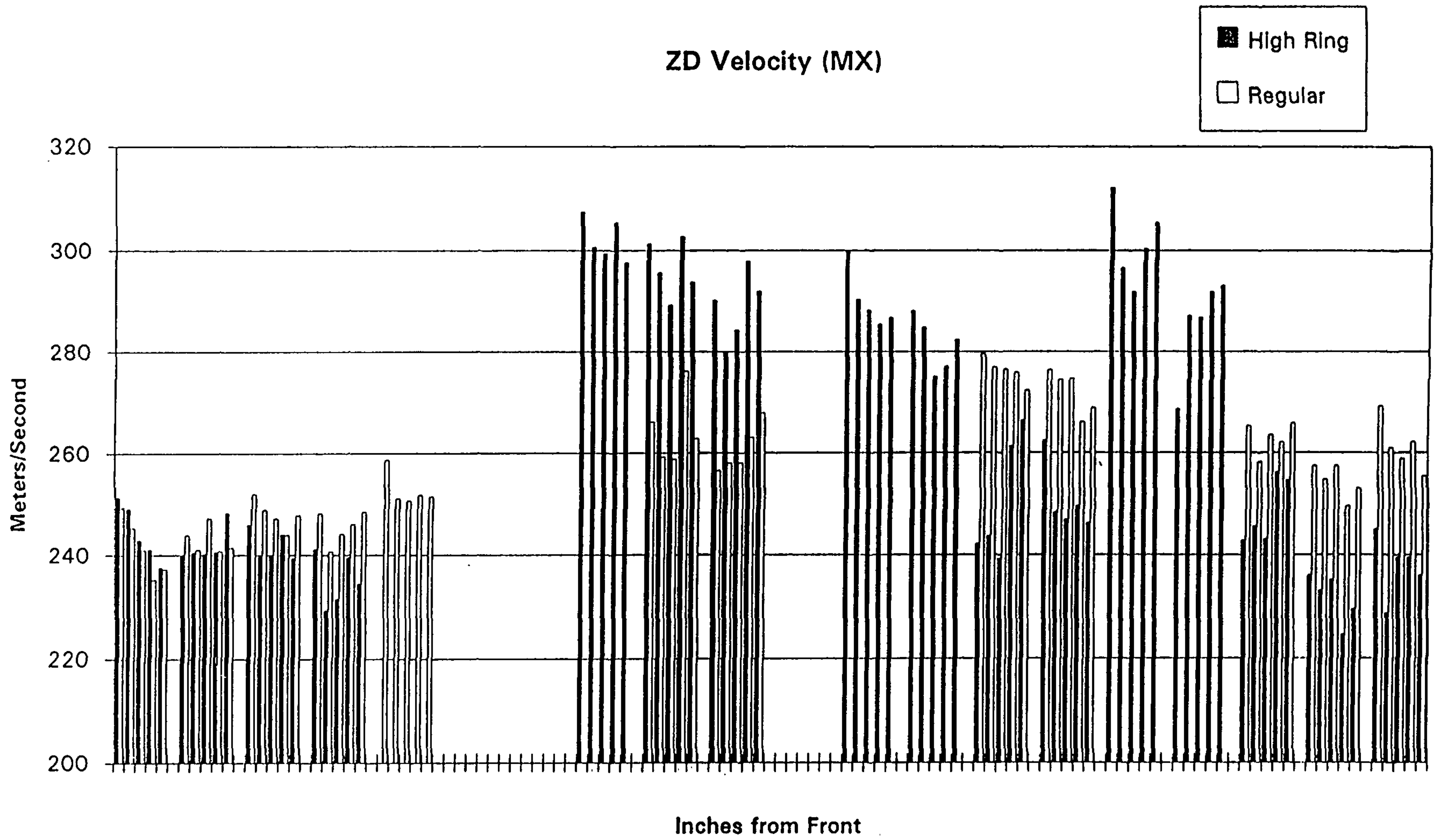


Figure 10. Average ZD velocity in meters/second versus cross-web position in inches from the front edge for the "High Ring" and "Regular" 42-lb liner samples.

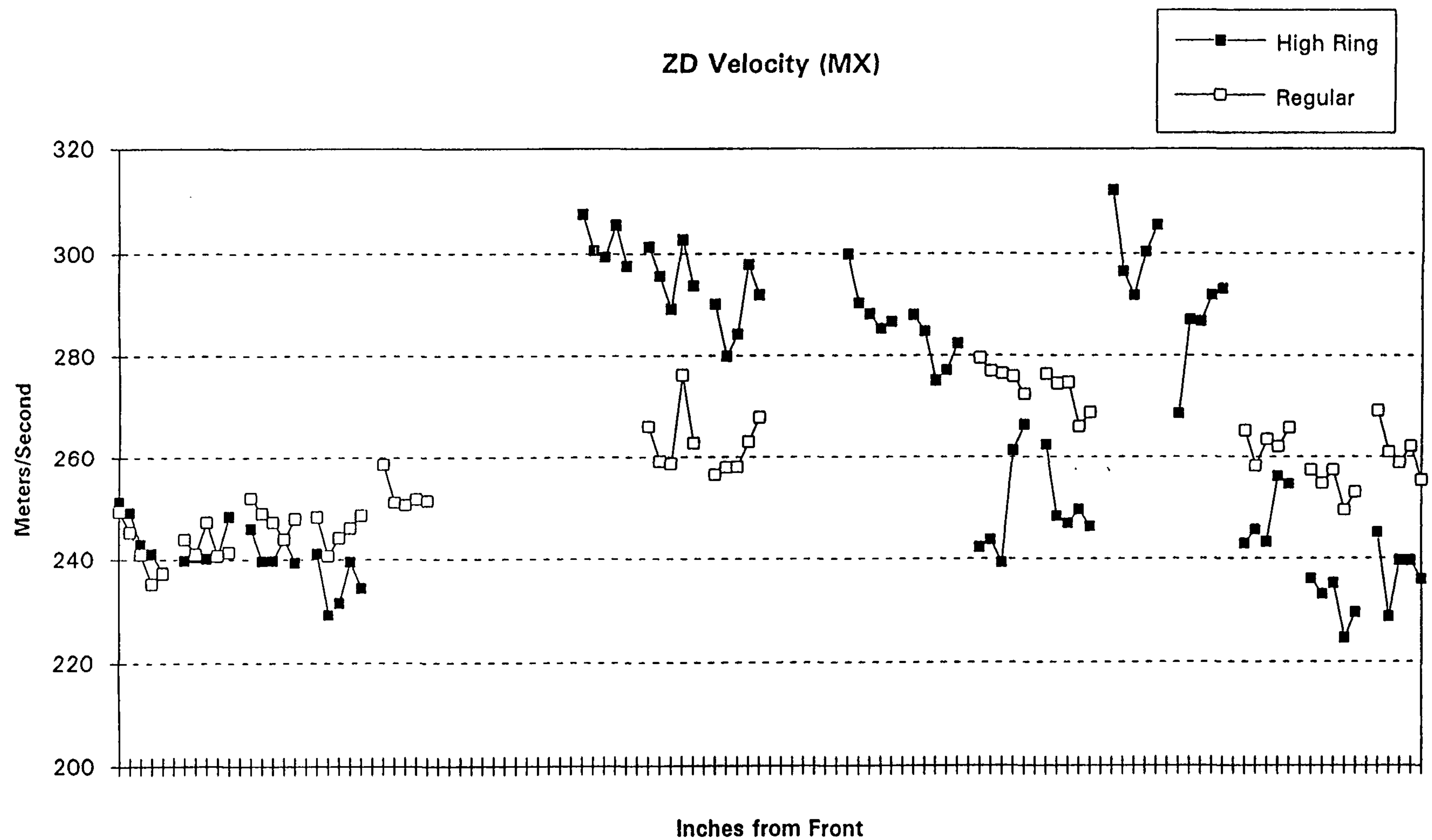


Figure 11. The average ZD velocity data of Fig. 10 replotted as a point chart rather than a bar chart.

POLAR ANGLE DETERMINATION

Transducers were mounted in the cylinder with receivers at ±45 degrees to the machine direction relative to a single transmitter. With this arrangement the pulse transit times at +45 degrees (t_1) and at -45 degrees (t_2) can be recorded and compared. Data were recorded for the 42-lb liner roll described above which was constructed by splicing the 1 by 40-foot strips of the "regular" and "high ring" samples.

The in-plane stiffness alignment relative to the machine direction, i.e., the polar angle, may be approximated by a constant, k, times the difference in pulse transit times at +45 and -45 degrees and dividing by their average,

$$k * 2[(t_1) - (t_2)] / [(t_1) + (t_2)].$$

Figures 12 and 13 show the results compared with the data taken at the mill on cross-reel strips for these samples using a Lorentzen & Wettre (L&W) Isotuner ultrasonic velocity instrument. The constant, k, was chosen to match one of the data sets at 10 degrees. The figures show that the ± 45 degree cross-web shape is similar to the L&W data. These results indicate that on-line "polar angle" determination may become a reality with ultrasonic velocity instrumentation.

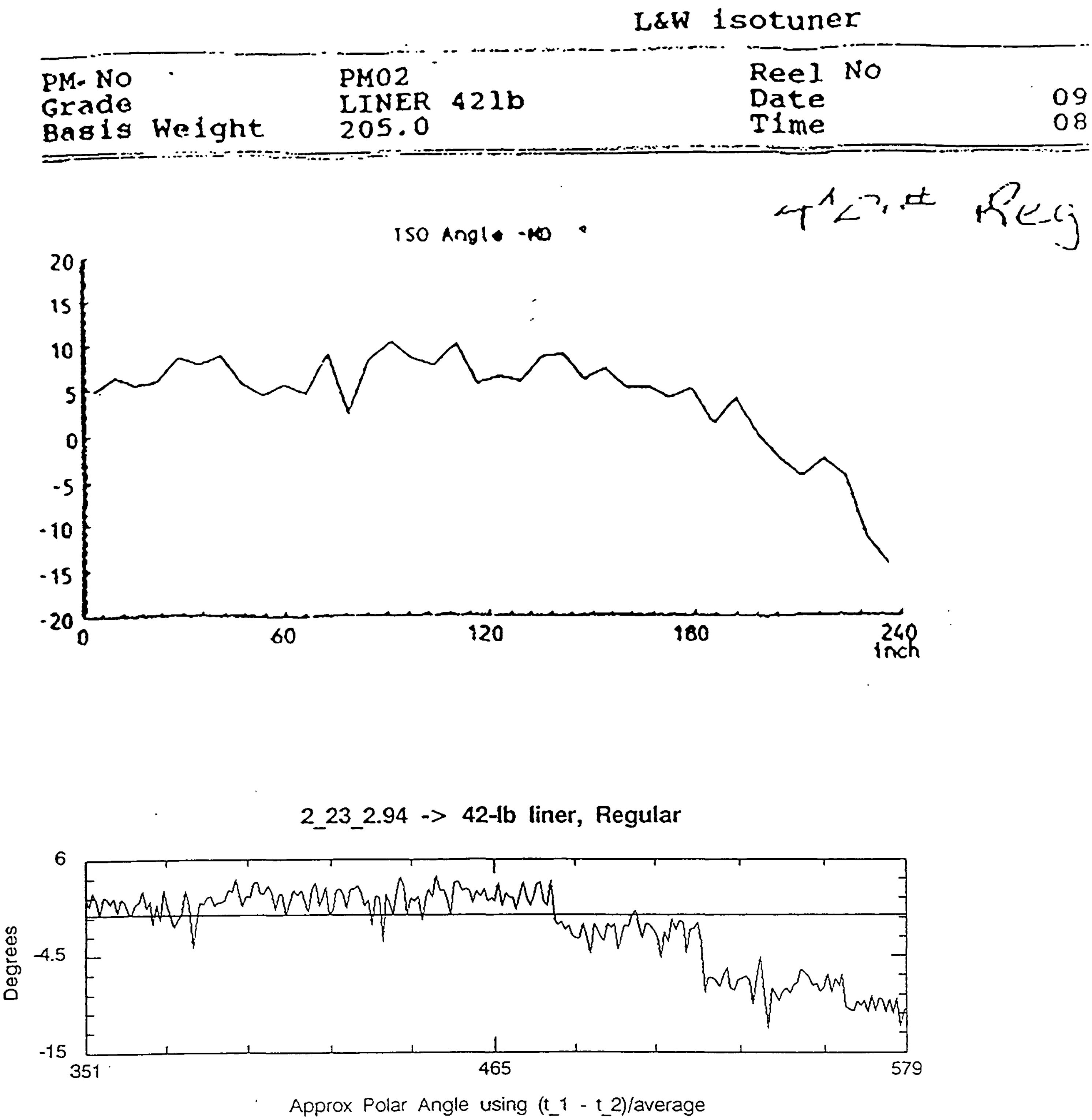
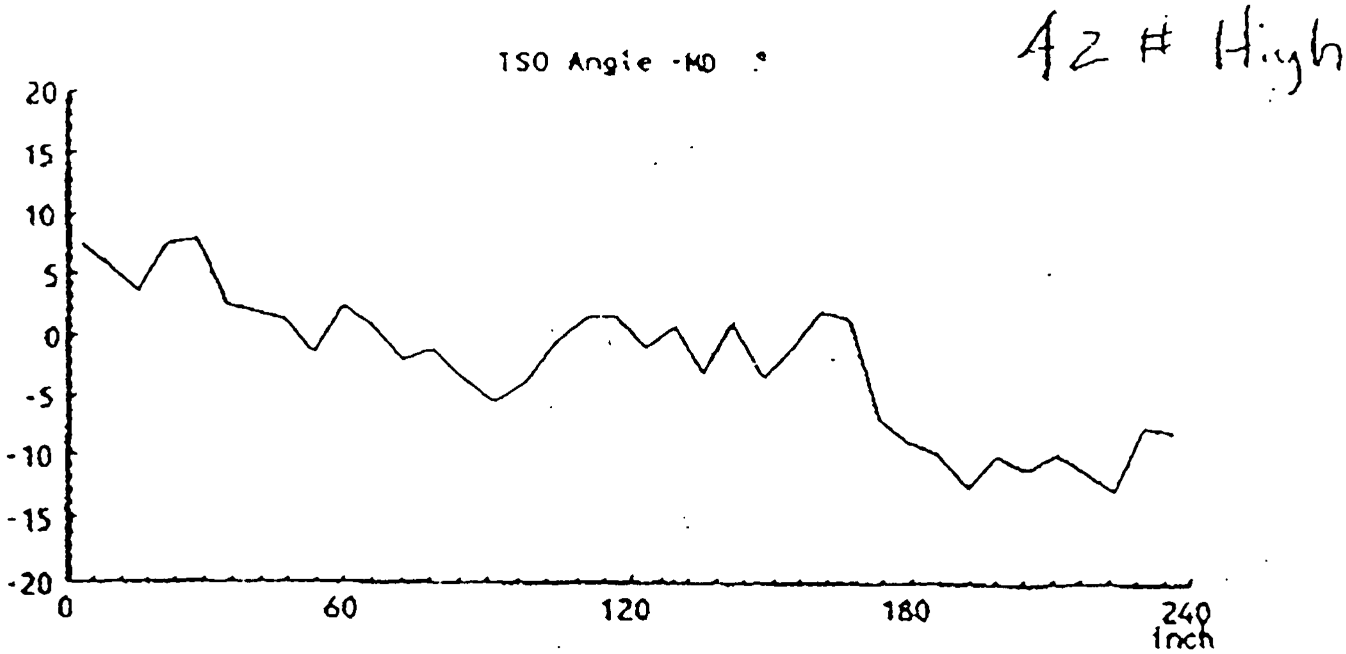


Figure 12. Polar angle approximated from pulse transit times at ±45 degrees compared with L&W Isotuner data on cross-reel strip for "Regular" 42-lb liner sample.

L&W isotuner

PM-No	PM02	Reel No	
Grade	LINER 42lb	Date	0
Basis Weight	205.0	Time	0



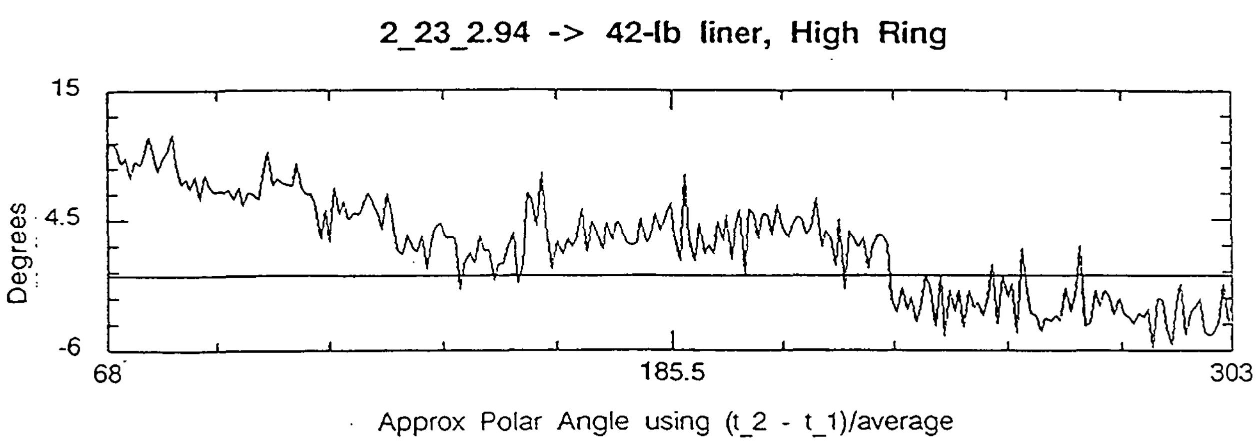


Figure 13. Polar angle approximated from pulse transit times at ±45 degrees compared with L&W Isotuner data on cross-reel strip for "High Ring" 42-lb liner sample.

TOWARD COMMERCIALIZATION

In view of the potential benefits and status of this technology, activities were directed at finding a path toward commercialization of on-machine ultrasonic velocity measurement. An essential step was the establishment of a working relationship with a vendor of instrumentation and control systems for paper machines. The various vendors were contacted in 1992. ABB Industrial Systems Inc. (ABB) of Columbus, Ohio, was the only vendor that expressed a willingness to participate.

ABB (formerly AccuRay) had licensed the IPST patent in 1982, and has made significant investments over the past 10 years in the development of ultrasonics technology, focusing on the introduction of products to measure the in-plane ultrasonic velocities in the machine direction and cross direction. In the late 1980s, ABB introduced a product that utilized a "rolling drum" concept for coupling ultrasonic energy into moving webs. However, this product had a number of technical problems, and was subsequently withdrawn.

During the last four years, ABB has continued to develop in-plane ultrasonic velocity instrumentation. The developments have hinged on the evolution of sensor designs and on the utilization of a specialized signal processing system, which has been developed for high-speed data acquisition. The combination of these developments has produced a pilot-scale Engineering Prototype probe ready for testing.

At IPST, both ZD and in-plane ultrasonic velocity data have been collected in the laboratory on a variety of commercial paper grades. The in-plane cylinder-mounted system provides reliable measurements on moving webs in the laboratory. This, together with the web handling system, provides an excellent system to test and evaluate performance of in-plane measurement prototypes for wide web scanning as they are developed. The ZD fluid-filled wheel sensor system is believed to be ready for engineering development into a prototype system on the path toward commercialization. Continued development of the ZD sensor should include incorporating the data collection and data processing hardware and software of the vendor.

The Department of Energy (DOE) Office of Industrial Technologies (OIT) sponsored a solicitation for Cooperative Agreements as part of its Industrial Waste Reduction Program in September 1993. This solicitation was focused on the metals industry and the pulp and paper industry. The program targeted key waste reduction opportunities that offered significant material, energy and cost savings, and environmental benefits. The solicitation required industry participation and 50% cost sharing. Working with ABB and with the concurrence of the Herty Foundation Center in Savannah, Georgia, a plan to aggressively pursue commercialization was prepared, and IPST submitted a cost-share proposal to DOE by the solicitation due date, December 2, 1993.

PROPOSED PROGRAM, "On-Machine Ultrasonic Sensors for Paper Stiffness"

The proposed program involves a cooperative effort between the Institute of Paper Science and Technology (IPST) and ABB Industrial Systems Inc. (ABB), a vendor of measurement and control instrumentation to the paper industry. Additional participants will be the Herty Foundation Research and Development Center with sensor and system testing on its new pilot paper machine and a paper manufacturing company selected to provide a Host Mill with a paper machine and support for "Beta Site" evaluation of the developed sensors and instrumentation.

Pilot-scale prototype and full-scale proof-of-principle units, for both in-plane ultrasonic velocity measurements and out-of-plane (ZD) ultrasonic velocity measurements, will be built and tested. Packaging paper and paperboard are the principal target applications because mechanical properties are of primary importance in the end-use of these products. The pilot-scale prototype units will be tested at IPST and at Herty. The full-scale proof-of-principle units will be verified at IPST and Herty and demonstrated on a paper machine in an actual commercial production environment in a Host Mill.

The ultimate objective is to commercialize on-line ultrasonic velocity sensors to provided real-time data for improved control of the papermaking process, and thereby reduce energy consumption and energy waste from reprocessing. Upon successful completion of the program, the capabilities and benefits of the on-machine sensors and instrumentation will have been demonstrated to the paper manufacturing industry, and ABB will be prepared to provide and support the systems commercially.

Extensive on-machine testing and performance demonstration is anticipated as a requirement to gain acceptance by the paper industry. A 4-year development and testing program was proposed to ensure that the developed measurement and control instrumentation is a commercially viable system. Funds were requested from DOE for the 4-year program with cost-sharing by IPST, ABB, Herty, and the Host Mill, such that DOE's share would not exceed 50%.

Status

In June 1994, IPST was informed that its proposal submitted in response to DOE Solicitation No. DE-SC02-94CE41064 was selected for negotiation of a cooperative agreement, titled, "On-Machine Ultrasonic Sensors for Paper Stiffness," for a project expected to start on or about October 1, 1994.

REFERENCES

Baum, G.A., and Habeger, C.C., "On-line Measurement of Paper Mechanical Properties," *Tappi J.* 63(7):63(1980).

Baum, G.A., Brennan, D.C., and Habeger, C.C., "Orthotropic Elastic Constants of Paper," *Tappi J.* 64 (8):97(1981).

Baum, G.A., and Habeger, C.C., "On Line Ultrasonic Velocity Gauge," U.S. Patent 4,291,577, September 29, 1981.

Baum, G.A., Habeger, C.C., and Fleischman, E.H., "Measurement of the Orthotropic Elastic Constants of Paper," presented at Fundamental Research Symposium, Cambridge, 1981, Mechanical Engineering Publications, Ltd., London, 1983.

Baum, G.A., and Habeger, C.C., "On-Line Measurement of Paper Mechanical Properties," Project 2692-4, Report One, A Progress Report to the Fourdrinier Kraft Board Group of the API (May 15, 1985).

Berger, B.F., and Baum, G.A., "Z-direction Properties - The Effects of Yield and Refining," Proceedings of the Eighth Fundamental Research Symposium held at Oxford, edited by V. Punton Mechanical Engineering Publications Limited: 339(1985).

Fleischman, E.H., Baum, G.A., and Habeger, C.C., "A Study of the Elastic and Dielectric Anisotropy of Paper," *Tappi J.* 65(10):115(1982).

Habeger, C.C., and Baum, G.A., "On-line Measurement of Paper Mechanical Properties," *Tappi J.* 69(6): 106(1986).

Hersh, H.N., "Energy and Material Flows in the Production of Pulp and Paper," Argonne National Laboratory, ANL/CNSV-16 (1981).

Mann, R.W., Baum, G.A., and Habeger, C.C., "Elastic Wave Propagation in Paper," *Tappi J.* 62(8):115(1979).

Orloff, D.I., and Lindsay, J.D., "Advances in Wet Pressing," PaperAge:14(January 1993).

Vahey, D.W., "An Ultrasonic-based Strength Sensor for On-line Measurements," *Tappi J.* 70(3):79(1987).

Whitsitt, W.J., "Relationships Between Elastic Properties and End-Use Performance," Project 2695-23, Report One, A Progress Report to the Fourdrinier Kraft Board Group of the API (January 30, 1985).

Presentations reviewing work supported in part by this Cooperative Agreement No. DE-FC05-93CE40006:

DOE/Industry Advanced Sensors Technical Conference, Atlanta, Georgia, November 1-2, 1993.

Hall, M.S., "On-Machine Sensors to Measure Paper Mechanical Properties," Industrial Energy Technology Conference, Houston, Texas, April 13-14, 1994.

ACKNOWLEDGMENTS

The work reported here was supported by the member companies of the Institute of Paper Science and Technology and by the U.S. Department of Energy. We thank IPST and DOE, and in particular, thank Stanley F. Sobczynski, Program Manager, Office of Industrial Technologies, U.S. Department of Energy, for this support.

We again wish to thank those acknowledged in the final report for DOE Contract No. DE-AC05-86CE40777 for their many contributions. In addition, we wish to thank those at ABB who have made it possible to plan and propose a cost-share program with DOE, in particular, Robert Pfeifer, Donald Hart, Paul Williams, and Brad Pankonin. We also wish to thank Michael Kocurek and the senior staff at the Herty Foundation for their interest in participating in our proposed program.

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