Institute of Paper Science and Technology

ON-MACHINE SENSORS TO MEASURE PAPER MECHANICAL PROPERTIES

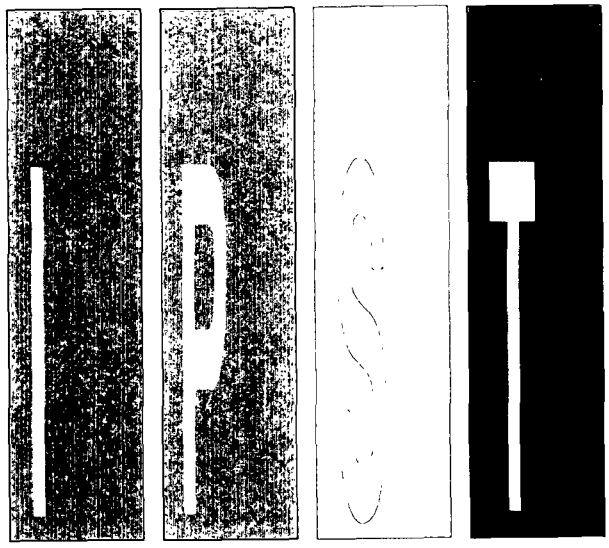
Project 3613/3332

Final Report

to

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

October 1993



Atlanta, Georgia

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INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

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Final Report

A Progress Report

to

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

By

Maclin S. Hall, Pierre H. Brodeur, and Theodore G. Jackson

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ABSTRACT

The measurement of the velocity of ultrasound provides a nondestructive means to characterize the elastic stiffness properties of paper. The objective of this project is to develop sensors capable of measuring the velocity of ultrasound in the thickness and in-plane directions of moving paper webs. On-machine measurements would allow continuous monitoring of product quality as well as provide data for controlling the papermaking process.

This final report first reviews the background and various technical approaches explored. Then the preferred configurations and examples of measurements on moving paper webs in the laboratory are presented and discussed. The report concludes with a summary of project results and recommendations for further developments.

Transducers mounted in fluid-filled wheels are used to make thickness direction, ZD, ultrasound velocity measurements on paper webs moving in the nip between two such wheels. Comparisons of the arrival times of echo and transmitted pulses with and without the paper web in the nip provide a measure of the transit time and caliper. Bimorph transducers mounted in an aluminum cylinder are used for machine direction (MD) and cross direction (CD) in-plane measurements. These ZD and in-plane sensors are mounted on a web handler in the IPST laboratory.

The ZD measurements are sensitive to temperature changes in the fluid-filled wheels. The time of flight in a delay line attached to the transmitting transducer provides a sensitive measure of temperature and basis for correcting the ZD data for system temperature changes. The use of pulse/echo driver 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.

A caliper measurement is required along with the transit time through the sample in order to calculate the ZD velocity of ultrasound. Either multireflected ultrasonic pulses in the fluid-filled wheels or an independent caliper gauge may be used to determine the web caliper. The main advantage of an independent gauge is that it is less sensitive to temperature changes. 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.

For in-plane measurements on moving paper webs in the laboratory, small bimorph, bender transducers are mounted in the surface of a 10-inch diameter aluminum cylinder. A special transducer housing and carrier are used to mount the transducers in the cylinder. Relatively weak spring loading is used in the carrier to minimize variation in the contact force between the transducers and the web.

In addition to various MD and CD longitudinal and shear measurement configurations, provision is also included in the cylinder to mount transducer sets at ±45 degrees to the machine direction. Data recorded for the MD and the ±45 degrees can be used to define an ellipse which provides a good approximation to the standard polar test for "polar angle" and polar plot area.

Both ZD and in-plane ultrasound velocity data have been collected in the laboratory on a variety of commercial paper grades. The ZD fluid-filled wheel sensor system is believed to be ready for engineering development into a prototype system for testing in a production environment. The in-plane cylinder-mounted system provides reliable measurements on moving webs in the laboratory. This, together with the web handling system, provide an excellent system to test and evaluate the performance of in-plane measurement prototypes for wide web scanning as they are developed.

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INTRODUCTION

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 reel will not be identified from end-of-reel tests until the tests are completed after reel turnup. Thus, a substantial amount of substandard material may be produced and require repulping and remanufacture to meet specifications.

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 paper and board production by the U.S. paper industry at 75 million tons/year, for each 1% of production that is substandard and reprocessed, the energy wasted would be 0.01 Quads (10,000,000,000,000 Btu) with an approximate value of $40,000,000 (@ $4/million Btu) annually.

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. If suitable means were developed to use such on-machine sensor data to control the process, the production of substandard material could be reduced further. Further 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.

Minimizing the need for repulping and remanufacture would reduce water utilization and provide consequential environmental benefits. The ability to control the process to a mechanical property specification may enable the product to be produced with a lower 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.

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 out-of-plane (ZD) velocities of ultrasound. IPST has developed instruments to measure MD, CD, and ZD ultrasound velocities and elastic stiffnesses in paper samples in the laboratory and demonstrated that elastic stiffnesses are measures of product quality and are sensitive to changes in paper machine operating variables.

With this background and the recognized potential for significant efficiency, energy, and environmental benefits from on-machine measurement and control of certain paper mechanical properties, the Department of Energy has supported research at IPST, through Contract DE-AC05-86CE40777, beginning October 1, 1986. This contract is now at an end.

This final report first reviews the background and various technical approaches explored. Then the preferred configuration and examples of measurements are presented and discussed. Finally, the report concludes with a summary of project results and recommendations for further developments.

OBJECTIVES

The primary objective of this project is to develop sensors capable of measuring the velocity of ultrasound in the in-plane and thickness directions of moving paper webs. A further objective is to use these sensors to demonstrate their ability to continuously monitor product quality as well as provide data that may be used to control the paper manufacturing process. The measurement of the velocity of ultrasound provides a nondestructive technique to characterize the mechanical properties of paper. Successful implementation of this technology would provide more effective utilization of raw materials and energy while producing products with improved uniformity and quality.

The initial emphasis of this project is specifically concerned with the development of a sensor to make measurements of elastic stiffnesses in the thickness direction (ZD) of a moving paper web. Then an appropriate in-plane sensor must be implemented to be used in combination with the ZD sensor. In order to separately identify the effects of refining, jet-to-wire speed ratios, wet pressing pressure, and draws (and the related 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.

BACKGROUND

Research at The Institute of Paper Chemistry (IPC) (Mann et al., 1979; Whitsitt, 1985) has demonstrated that ultrasound velocity techniques may be used to make nondestructive measurements of certain paper sheet properties 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.

Paper is normally treated as an orthotropic elastic material requiring nine elastic parameters to describe its mechanical behavior (Habeger et al., 1979). The three principal orthogonal directions are taken as the in-plane machine direction (MD), the in-plane cross machine direction (CD), and the out-of-plane or thickness direction (ZD). For convenience the MD, CD, and ZD directions are referred to as the 1, 2, and 3 directions, respectively. The elastic stiffnesses are fundamental parameters which describe the strains developed in the paper as it is subjected to various stresses. The nine elastic stiffnesses are the three values in the principal directions, C_{11}, C_{22}, C_{33}; the three shear values, C_{44}, C_{55}, and C_{66}; and the three off-diagonal values, C_{12}, C_{13}, and C_{23}.

Laboratory instrumentation has been developed to routinely measure seven of the nine elastic parameters using ultrasonic techniques (Baum and Bornhoeft, 1979; Mann et al., 1979; Mann et al, 1980; Habeger and Wink, 1986). The effects of machine and process variables on these seven parameters have been the subject of extensive staff and student research at the Institute of Paper Science and Technology (IPST). 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 and process variables. Thus, measurement of these parameters on the paper machine would provide a means to monitor any changes in manufacturing conditions.

Other research has shown these same parameters to be highly correlated with many measures of product quality now used to characterize paper for end-use performance and/or converting efficiency (Habeger and Whitsitt, 1983; Baum, 1984). For example, certain elastic parameters or combinations of parameters have been related to tensile strength in the MD, CD,

or ZD (internal bond strength), compressive strength in the MD and CD, fluteability of corrugating medium, MD and CD bending stiffness, and bursting strength.

The relationships that have been identified between the three-dimensional elastic behavior of the sheet and the product quality tests (measured off-machine) suggest that these tests may be replaced by a set of nondestructive measurements of elastic properties. Measurement of these elastic parameters on the paper machine would serve as a continuous record of product quality. Values for a number of the common end-use tests could then be predicted from the measured elastic parameters. Thus, on-machine measurement of paper mechanical properties would allow continuous monitoring of product quality, as well as provide the data on which to base control of the papermaking process.

Because of the sensitivity of the elastic stiffnesses to paper machine variables, and the desire to use the measurements to actually control the paper manufacturing process, sensors to measure the velocity of ultrasound would be mounted on the dry end of the paper machine just ahead of the reel. It is envisioned that these sensors would be mounted along with the basis weight gauge and moisture gauge now used on most paper machines and would scan the web just as those devices do. In fact, it would be desirable to have the basis weight and moisture at each location, so that the elastic stiffnesses may be adjusted to constant temperature and moisture content conditions. Such adjusted values could then be compared directly with values obtained independently in a conditioned test laboratory, if desired.

Ultrasonic sensor instrumentation capable of on-machine measurements of elastic stiffnesses in the plane of the paper was developed at IPC (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 successfully demonstrated that the correlations between elastic properties and "strength" properties observed in the laboratory also hold in a mill setting. The technology associated with the in-plane measurements has been licensed to a number of instrument manufacturers.

The above development was a major step forward in terms of on-machine monitoring of product quality. However, it was incapable of measuring out-of-plane (ZD) elastic properties. As noted above, it is important to be able to measure elastic stiffnesses in both the in-plane and out-of-plane directions in order to separate the effects of different paper machine variables and maximize the sensitivity to these variables for process control. Therefore, the initial emphasis

of this project has been on the development of a sensor to measure the ZD elastic stiffness of a moving web of paper. This sensor would then be combined with an appropriate in-plane sensor to provide a complete system to measure paper mechanical properties on the paper machine.

ZD Elastic Stiffnesses and Their Measurement

There are three different elastic stiffnesses of paper which involve the out-of-plane direction (ZD). They are the ZD longitudinal stiffness (C_{33}), the shear stiffness (C_{55}) in the plane determined by the machine direction (MD) and the ZD, and the shear stiffness (C_{44}) in the plane of the cross machine direction (CD) and the ZD. The ZD longitudinal stiffness is the ratio of ZD stress to ZD strain when no strain is permitted in the MD or the CD. This is a few percent greater than the ZD Young's modulus, which is the ratio of stress to strain in the absence of in-plane stresses. The shear ZD stiffnesses are identical to the ZD shear moduli.

These three ZD elastic parameters can be calculated from measurements of the velocities of a bulk longitudinal and two shear waves (one polarized in the MD and one in the CD) traveling in the ZD. The square of an ultrasound bulk velocity is equal to the corresponding elastic stiffness divided by the apparent density. Therefore, the quantities actually measured are the square roots of the "mass specific elastic stiffnesses." These measurements are made at frequencies of about 1 MHz. Since paper is a viscoelastic material, its mechanical properties depend on test frequency, and the ultrasonic stiffnesses are greater than would be determined in other experiments having longer time constants. The difference is on the order of 20-40% when compared with a 1 Hz (or approximately 1 second duration) test at standard conditions.

The degree of fiber-to-fiber bonding and the extent of ZD fiber orientation are the most important factors influencing the ZD stiffnesses. Since nearly all of fibers in a sheet of paper are oriented in the MD-CD plane, the ZD stiffnesses are roughly two orders of magnitude lower than the in-plane stiffnesses. In machine-made papers, C_{55} is significantly larger than C_{44}, and the ZD anisotropy ratio, C_{55}/C_{44}, is roughly equal to the square root of the in-plane stiffness ratio, C_{11}/C_{22}. As compared to in-plane properties, the ZD stiffnesses exhibit greater dependence on manufacturing process variations and are more sensitive to the moisture and temperature at the time of testing. It has been observed that the ZD stiffnesses increase upon refining and wet pressing (Fleischman et al., 1982; Berger and Baum, 1985) and decrease when wet straining (Fleischman et al., 1982), calendering (Berger, 1985), or supercalendering (Waterhouse and Charles, 1988) are performed. In addition, furnish (Habeger and Whitsitt, 1983) and yield (Berger and Baum, 1985) are known to affect ZD stiffnesses. It has also been

demonstrated that ZD stiffnesses can be useful as nondestructive indicators of strength properties. For example, the ZD longitudinal stiffness of single-ply sheets correlates with ZD tensile strength (Fleischman et al., 1982); ZD stiffnesses are important in modeling the in-plane compressive strength (Habeger and Whitsitt, 1983; Whitsitt, 1985) of paperboard; and ZD longitudinal stiffness correlates with the retention of medium compressive strength during corrugation (Whitsitt and Baum, 1987).

A laboratory instrument has been developed and is routinely used to make measurements of ZD shear stiffness. However, it is more difficult to couple ultrasonic energy into paper for ZD shear waves than for ZD longitudinal waves. Therefore, the development of transducers for on-line ZD measurement has been directed at the measurement of ZD longitudinal stiffness (C_{33}).

TRANSDUCER DEVELOPMENT FOR ON-LINE ZD MEASUREMENT

The first requirement for on-line ZD measurement is to devise a method of transmitting a pulse of ultrasonic energy through the thickness of paper while the paper web is moving. One must also develop a method to detect the arrival of the pulse on the opposite side of the moving web. A practical gauge would need to determine the pulse transit time with and without the web present. One would also need to measure the caliper of the paper web. Transducer design considerations and the first transducer developed were discussed in Report One (Hall and Habeger, 1988). For good resolution of the time-of-flight through thin samples, pulses having as high a frequency as practical should be used. For most paper samples, scattering of the ZD ultrasonic energy becomes prohibitive at frequencies above 2 MHz. The frequency used in the IPST laboratory ZD instrument is 1 MHz, and this is the frequency used for nearly all of our ZD measurements on moving webs.

From the experience with laboratory ZD instruments, we know a conformable coupling between the paper and the transducer is preferred for efficient transfer of energy in the thickness direction. We also know that this is simpler to achieve with longitudinal waves than with shear waves; therefore, all on-line ZD attempts were designed to generate longitudinal waves.

Three approaches for making measurements of the velocity of ultrasound in the thickness direction (ZD) of moving paper webs were examined. The first approach used ceramic disk transducers, mounted in 5-inch aluminum wheels. This is described briefly below with more detail in Report One (Hall and Habeger, 1988). A second approach, using IPST-made,

elastomer-faced, PVDF wheels, was the subject of more development and is reviewed below. Our recent work has concentrated on a third approach which uses modified, commercially available fluid-filled wheels. The details of this approach are reviewed below.

Ceramic Button-in-Wheel Transducers

The first ZD transducer for moving webs was made from a piezoelectric ceramic disk (1/10-inch thick P.Z.T. 5A) attached to a thin aluminum button. A 1/32-inch thick sheet of soft neoprene was fastened with epoxy to the face of this transducer to provide a conformable coupling to the paper web. Two of these ceramic disk transducers, each mounted in a 5-inch aluminum wheel, were tested on 42-lb linerboard and a low basis weight bond paper, using the web strainer in Appleton, Wisconsin. The signal, transmitted throught the paper from one wheel to the other, had excellent strength even at a web speed of 2000 ft/min. This demonstrated the feasibility of transmitting and detecting an ultrasonic signal in the thickness direction at line speed. However, the resonant frequency of the transducers was not as high as needed to resolve the time-of-flight of a longitudinal ZD pulse.

Elastomer-Faced PVDF Wheel Transducers

To overcome the frequency limitations of the ceramic button-in-wheel transducers described above, a much different design was chosen for experimental evaluation. This design was modeled after the low-impedance, broadband disk transducers which are key components in the IPST laboratory unit for static ZD measurements. The active piezoelectric elements in these transducers are polarized polyvinylidene fluoride (PVDF or Kynar) films. This design was extended to construct wheel transducers that are active around the entire circumference.

Several wheel-type transducers were constructed and evaluated. The construction techniques developed and properties observed provided the basis for the design and construction of serviceable wheel-type transducers for measurement of caliper and ZD velocity in the laboratory.

Two of these elastomer front-faced, PVDF wheel transducers were constructed and mounted in a specially designed wheel alignment apparatus. The top wheel is mounted on a slide so that it can move up and down as the caliper of the paper in the nip changes. A linear variable differential transformer (LVDT) is used to sense the movement of the slide relative to the stand and to determine sample caliper. Rotational alignment of the wheels to a standard position on their circumference is accomplished with a mechanism employing wheels and

slotted cams. The bottom wheel is driven by a computer-controlled stepping motor, allowing the sample to be transported between the wheel transducers. Pulleys were added to run a small belt sample of paper between the wheels for dynamic testing. The details of the mechanical mounting apparatus, the electronic instrumentation, the measurement procedures, and results are presented in Report One (Hall and Habeger, 1988).

The above set of PVDF wheel transducers provided encouraging results. It provided a laboratory instrument which can rapidly profile the out-of-plane velocity and soft-platen caliper of a sample running in the nip between two wheel transducers. With proper calibration, time-of-flight and caliper measurements were in agreement with the laboratory ZD instrument. Dynamic testing demonstrated that these measurements could be determined at the highest speed practical with the stepping motor apparatus (about 180 fpm). However, the design of these wheel transducers could not be expected to withstand the high speeds and temperatures routinely encountered on-line. Therefore, with the objective of designing and building more rugged elastomer-faced PVDF wheel-transducers, a second set was built.

The new wheel design uses harder, more durable rubber front-faces and higher temperature, more sensitive PVDF piezoelectric films. In addition, improvements were made in the uniformity of the piezoelectric element and the front-face. The wheel construction is essentially as before. A PVDF film is clamped between a Kynar core and an undersized Kynar ring, and an elastomer is applied to the contact surface of the Kynar ring. Instead of the standard PVDF film, a new experimental PVDF copolymer film (VF2-VF3 from Pennwalt Corp.) was used. This provides for higher temperature performance, as the film can be subjected to 100°C without significant depolarization. It also has approximately a 50% higher coupling coefficient. Two wheels were fabricated, one with a stack of two 220-micron thick films, and one with a stack of four 110-micron films.

A major challenge in the development of these wheel transducers is the fabrication of the elastomer front-faces. One needs a durable interface that efficiently couples acoustic energy between the wheels and paper. A hard polyurethane rubber, manufactured for repairing conveyor belts, was used. The elastomer coupling was formed on the wheel. This produced a seamless tire that was not subjected to nonuniform stresses during application and bonding. Much effort and skill were required to overcome a number of difficulties in perfecting a method for forming the polyurethane into a tough, uniform coupling layer free of air bubbles and well-bonded to the transducer.

The resulting wheels proved to have approximately the same sensitivity as the first set of

laboratory wheels. Mounting yokes that can be bolted to a frame were designed and built for these wheels. The frame was designed so that the bottom yoke would be rigid, and the top one would be mounted on a plate attached to a linear bearing. The top wheel would be loaded with a spring-dashpot combination to hold it in position with constant force against the paper and bottom wheel. This design is similar to the mounting used for the rotary laboratory apparatus. The frame design just described was not built. The parallel development of elastomer-faced PVDF wheels and the fluid-filled wheels was discontinued at this point in favor of the fluid-filled wheels.

Fluid-Filled Wheel Transducers

Fluid-filled ultrasonic wheel transducers are used commercially in testing railroad rails for flaws. We obtained one of these wheel search units on loan from Automation/Sperry to determine if such a wheel might couple an ultrasonic signal into paper. We were encouraged by an initial test and purchased two wheels. Early work with these wheels is reported in Report One (Hall and Habeger, 1988) and briefly reviewed here.

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.

The initially perceived advantages of this approach: (1) wheels can be modified for our purpose and obtained without extensive development, and (2) slip rings are not needed for electrical connection to the transducers since they are mounted on a shaft that is not rotating. Potential disadvantages: (1) the tire thickness and radius may vary around the circumference, making the measurements rotational position dependent; (2) the time delay in the fluid path depends on the sample caliper; and (3) the temperature dependent velocity of sound in the fluid is needed to determine time-of-flight.

For our initial experiments, the axles of the wheels were mounted, as illustrated in Fig. 1, so that the separation between transducers could be adjusted but held constant as samples were inserted in the nip. The transmitter is excited with a one-cycle, 1 MHz ultrasonic pulse. The time-of-flight between transmitter and receiver is measured without and with a sample in the nip. As shown in Fig. 2, the time-of-flight without a sample is t_1 and with a sample is $t_{1'}$. The difference in these two times,

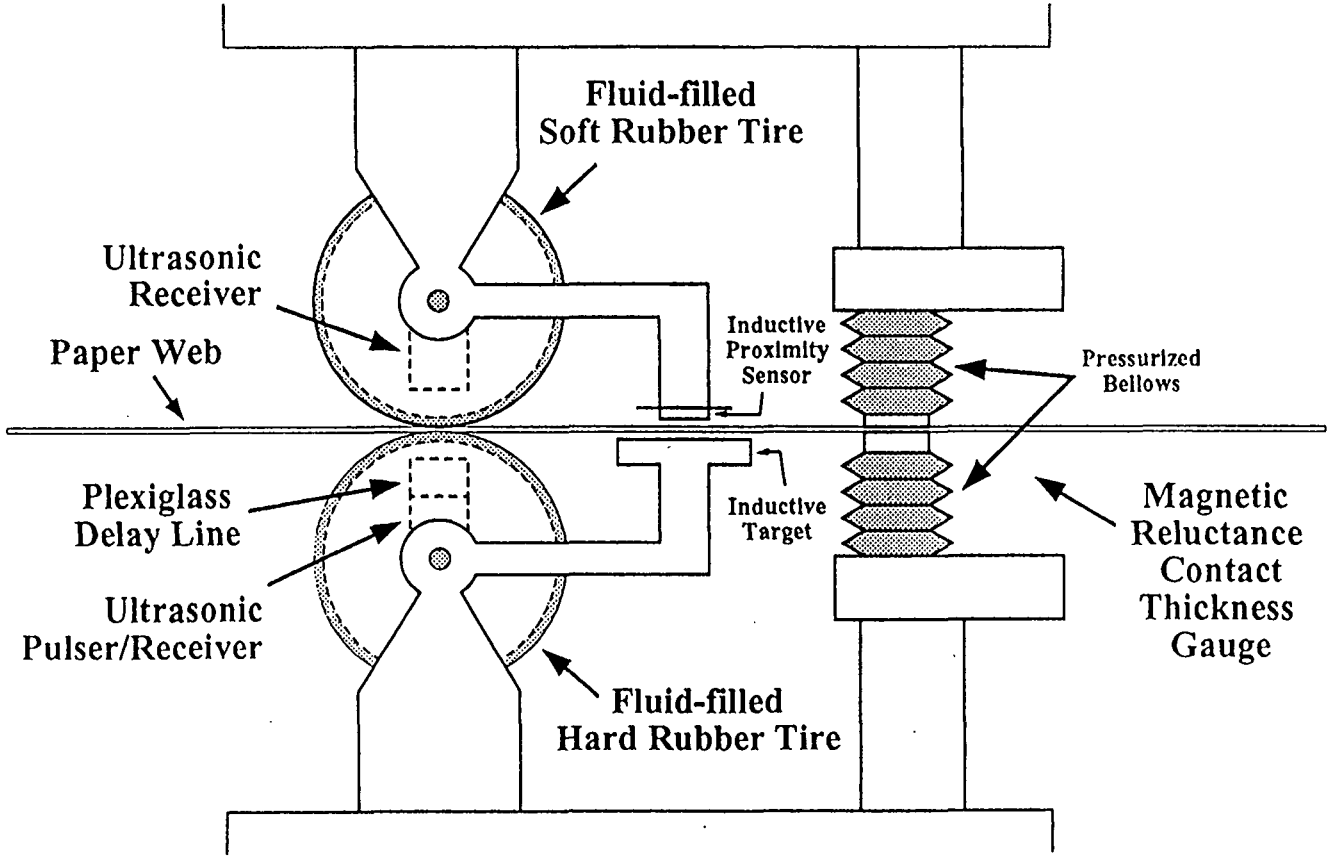


Figure 1. Illustration showing position of transducers in fluid-filled wheels, along with inductive displacement sensor and contact thickness gauge.

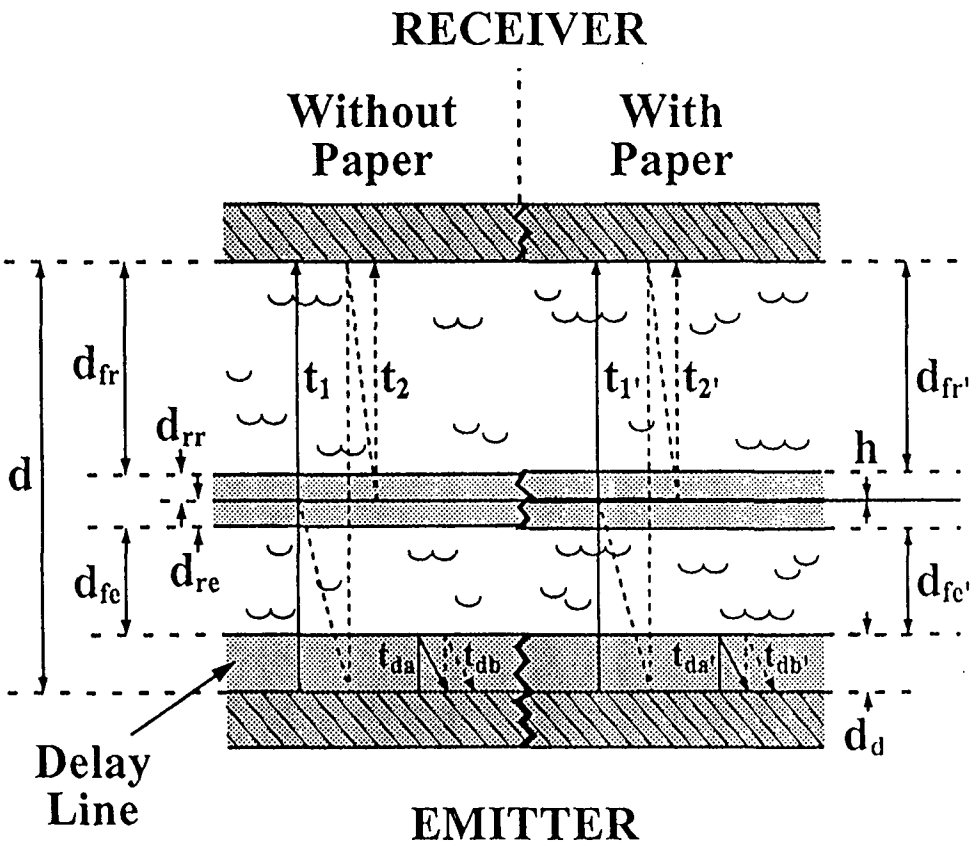


Figure 2. Sketch showing path of pulses without and with a paper sample between the wheels.

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

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

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

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

$$t_h = h/v_p = \Delta t_{1',1} + h/v_f. \quad (2)$$

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

At first, it seems that an independent measurement of caliper is necessary in order to obtain useful information from this approach. However, for on-line process and quality control, there may be ways to get around this requirement. If the basis weight of the sample is known, the acoustic impedance,

$$Z = \rho v_p, \quad (3)$$

(where ρ represents the density of the sample) can be calculated from the time-of-flight without any knowledge of the caliper. Since ρ is basis weight divided by caliper and time-of-flight is caliper divided by velocity, Z is simply the basis weight divided by time-of-flight. Impedance is equal to the mass per unit area traversed in unit time, and in order to calculate impedance instead of velocity, basis weight is merely exchanged for caliper. From the standpoint of providing a nondestructive test which is indicative of paper mechanical integrity, there is no apparent reason to prefer v_p over ρv_p. In fact, as basis weight is the better-defined, more fundamental property of paper, one may argue that the use of acoustic impedance is the better parameter since the determination of the caliper is avoided. These considerations apply to all ZD velocity determinations. The overriding question is, for the specific application, which measurement (caliper or basis weight) is more feasible. In the laboratory, the caliper measurement can be inexpensively integrated with the acoustic apparatus, and velocity is the preferred measurement. However, basis weight is routinely determined on-line and is usually available without added development. Therefore, it may be preferable, in the design of any on-line out-of-plane acoustic sensor, to evade the difficulties of caliper definition and determination by using an impedance measurement.

Even if mechanical impedance is used as the preferred acoustic measurement with the fluid-filled wheels technique, as demonstrated in Eqn. 2, caliper is needed just to calculate time-of-flight. However, caliper only enters in a correction term that accounts for about 20% of the time-of-flight, and a rough caliper determination could be sufficient.

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 in Fig. 2 is detected in the receiver, a number of reflection-delayed pulses are observed. The pulse whose travel time is noted as t_2 in Fig. 2 is of particular interest. With a fixed distance, d, 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 with a fixed d, 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

$$h = [(t_2 - t_1) - (t_{2'} - t_{1'})]v_f/2. \quad (4)$$

We had observed that the caliper and velocity values determined with the elastomer-faced PVDF wheels were sensitive to the dead weight load used. Therefore, it seems that a similar effect might be observed by changing the axle separation of the two fluid-filled wheels. However, the readings were insensitive to this adjustment since the contact area of the nip increased as separation decreased and loading pressure on the sample remained fairly constant. This is another potential advantage of the fluid-filled wheels.

The commercial transducers, originally used in the fluid-filled wheels, leaked fluid after prolonged encapsulation in the wheels. This degraded and, in some cases, completely destroyed their sensitivity. After discussions with the manufacturer, it was clear that the transducers were not designed for long-time immersion. We were careful to specify transducers designed for prolonged immersion after this experience.

We purchased two new fluid-filled wheels modified to our specifications from a second vendor (Dapco Industries). The tires on these wheels are 6.5 inches in diameter and 2.25 inches wide. These new wheels are an improvement in three areas. (1) They are easier to service and exchange transducers and/or tires. (2) The transducer position relative to the axle can be adjusted over a greater range than that possible in the old wheels. This provides more flexibility in minimizing interferences encountered when one signal begins before another signal ends. (3) The wheel design allows the installation of a thermocouple into the center of the wheel without affecting the bearing/seal arrangement of the tire.

One problem became evident with the tires of the new wheels. The shape of the signals received, though strong, did not appear as sharp as previous signals. We believed that a reflection from the rubber-liquid interface overlapped the signal of interest, changing its shape. Measuring the old tire and new tire thicknesses revealed that the new tires with a thickness of about 1/8 inch were slightly thinner than the old. Experiments with added rubber thickness indicated that these signals could be separated by using thicker tires. Tires with a thickness of about 3/8 inch were procured and provided the anticipated improvement in shape of signals. Three-eights (3/8) inch continues to be the preferred thickness for tires.

We have used two sets of "thick" (3/8 inch) tires. One set is made from a soft natural rubber, and the other is made from a harder polyurethane. There are advantages and disadvantages for each type. The "soft" tires are similar to the soft rubber that is used for soft platen caliper and for the transducers used in the IPST laboratory instrument for ZD measurements. Soft rubber is desirable for coupling ultrasound to paper for longitudinal ZD measurements. However, the soft tires are more susceptible to distortion as speed is increased.

The "hard" tires are quite stiff. Any out-of-roundness will cause a variation in pressure on the paper being measured and will make it more difficult to hold the variation of distance between wheel axles at a minimum. On the other hand, the hard tires do provide good signal strength, do not distort at higher speeds, and would be expected to wear better in use. A good compromise may be a combination, using a "hard" tire on one side of the web and a "soft" tire on the other.

Temperature Effects in Fluid-Filled Wheels

Temperature changes in the wheels due to friction-related heating effects and/or ambient temperature changes affect the pulse transit time measurements. A temperature change of one degree Centigrade in the fluid (water) changes the pulse propagation velocity by 2.4 meters/sec. Therefore, an effective method for temperature measurement and compensation is needed.

For our first attempt to monitor temperature, we mounted a thermocouple in one of the wheels. This was part of a digital thermometer that was interfaced to the computer over an GPIB bus. We found it necessary to sheath the thermocouple in a nylon tube and ground the shield to the frame in order to eliminate a high frequency, periodic noise that could not be eliminated by signal averaging. However, with the digital thermometer system working as designed, we found that its ability to read to the nearest 0.1 degree was not sensitive enough for our purposes.

The thermocouple approach was abandoned in favor of monitoring the changes in the transit time of ultrasonic pulses through a delay line. This method involves using an acrylic (Plexiglas) rod as a delay line butted against the face of the transmitting transducer inside one of the wheels. The time of flight within the delay line is proportional to the temperature of the delay line. We assume that the delay-line temperature is equal to the fluid temperature, and the delay-line flight time is used to determine the corrections required to compensate for changes in fluid temperature.

The assumption that the change in temperature of the delay line represents the change in temperature of the fluid-filled wheel system is good for steady state operation or gradual changes in speed. However, there is a lag in delay-line temperature with heat up or cool down with wheel speed changes. This is a problem for short runs in the laboratory, but we do not expect it to be a significant problem on-machine. The temperature of the system should stabilize on long runs, and references may be taken off the sheet frequently. Only the temperature change between off-sheet references and on-sheet readings affects the pulse transit time measurements.

Web Handling System and Test Stand

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. The reel-to-reel and endless loop web paths are illustrated in Fig. 3. 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 enables us to perform tests on 33-foot endless loops or reels on 3-inch cores up to 34 inches in diameter.

A test stand for mounting the fluid-filled wheels was designed and constructed to operate with the unwind/rewind web handling system, see Fig. 3. 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 wheel axle spacing (nip pressure) is adjustable.

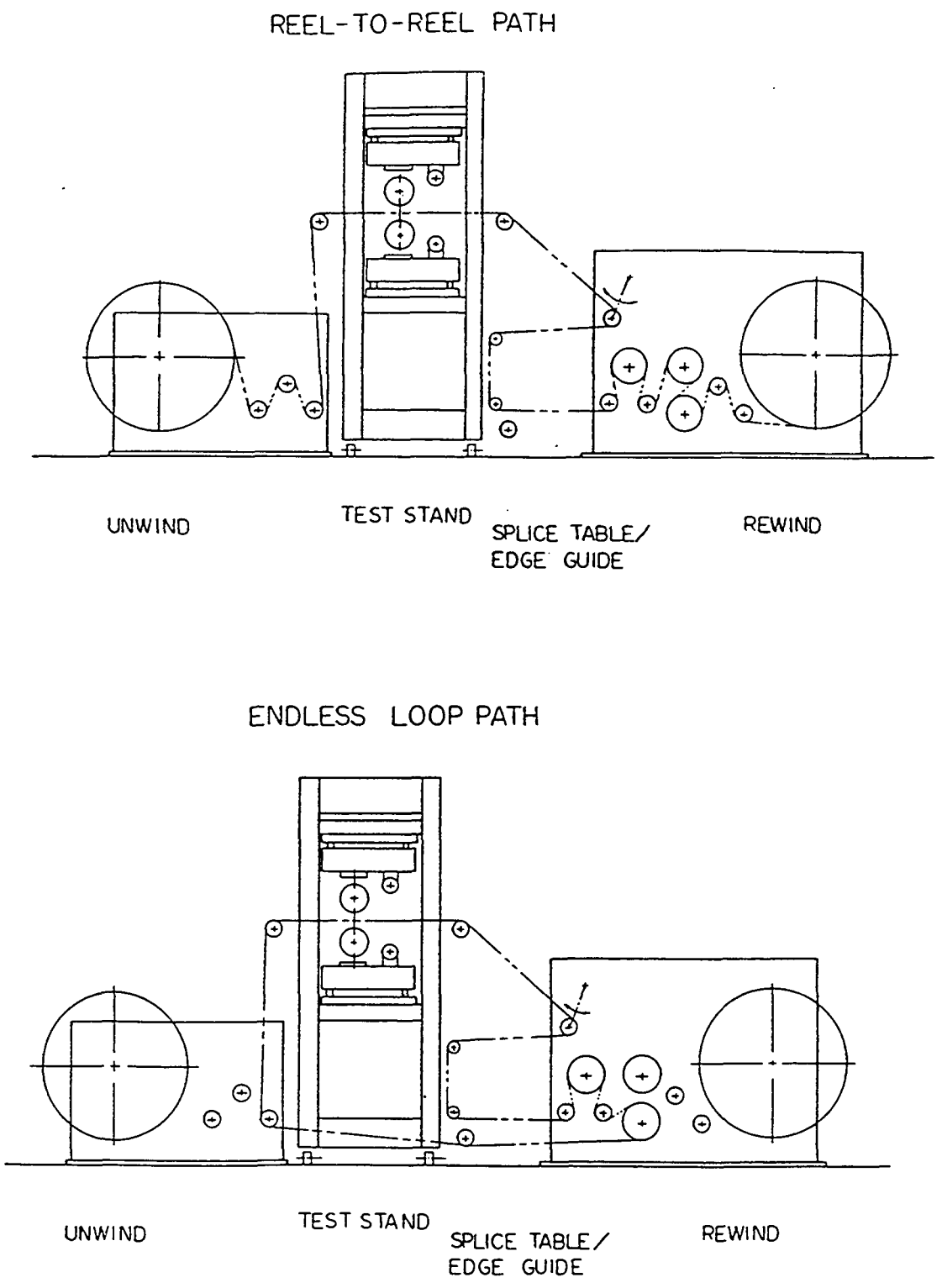


Figure 3. Reel-to-reel and endless loop paths in unwind/rewind web handling system.

We have found that the force provided by the air cylinders, used to extend and retract the wheels, is not sufficient to maintain a fixed axle distance with "stiff" or out-of-round tires. Small changes in transducer separation distance affect flight time measurements. To provide a means to measure the separation distance variation, an inductive distance measurement circuit has been added to the system. A conductive (aluminum) target is rigidly attached to the support of the transmitting tire and an inductive sensor (Kaman Instrumentation Corporation) is rigidly attached to the support of the receiving tire, as illustrated in Fig. 1. This circuit is insensitive to the presence of paper between the target and sensor. The circuit is calibrated in volts versus distance between the inductive sensor and the target. Readings from the circuit provide dynamic corrections for variation in the axle or transducer separation distance, increasing the accuracy of the calculated velocities. In addition, for some experiments the wheels are mechanically blocked in the closed position.

Electronics and Software

We began our work with a 286-type computer and programmed our own Pascal-based interface software. We changed our computer as upgrades became available first to a 386 and currently to a 486-type computer. After spending much effort in developing software we purchased a software package (WAVE) which became available for use with the 386-type computer. This package is specially designed for manipulating and analyzing digitized waveform data. This package has significantly increased the convenience and efficiency in preparing the software necessary to support both ZD and in-plane moving web data collection.

We initially used a Tektronix model 2432 digitizing oscilloscope which has a record length of 1024 samples per channel and performs well for recording short time intervals. In order to determine the caliper with the fluid-filled wheels, we need to record a pulse-train signal extending over as much as 100 microseconds. The entire pulse-train must be acquired following the scope trigger. The time between digitizing samples is highly precise, but the time between the trigger and the first digitizing sample, "trigger jitter," is variable up the sampling interval. We use a long sampling interval (50 to 100 nanoseconds) for faster signal averaging and analysis. A LeCroy 7200 Precision Digital Oscilloscope with 7242 plug-in modules was acquired. This digital oscilloscope has the capability of capturing a 50,000 point record length allowing the acquisition of pulse trains exceeding 100 microseconds. The LeCroy 7200 provides a number of on-board data collection and analysis options. This enables us to experiment with a variety of combinations while looking for the best compromise between measurement precision and sampling rate.

ZD MEASUREMENTS WITH FLUID-FILLED WHEEL TRANSDUCERS

The ZD measurement system must be capable of measuring ZD pulse flight times through paper with near nanosecond accuracy. A number of techniques have been developed to compensate for the effects due to temperature changes and to physical limitations of the measurement apparatus itself.

Some of the pulses critical to ZD velocity measurement may be very weak and degraded substantially by noise. The noise is effectively overcome by averaging a number of pulse sets produced by a sequence of excitation pulses sent to the transmitter. The received pulse sets are captured and averaged using a LeCroy 7242 plug-in module in a LeCroy 7200 digital oscilloscope. The averaged waveform is transferred to a 486-type computer where second-order interpolation and cross correlation are employed to determine pulse time differences with great accuracy and high noise immunity. In fact, a digitization rate of only 100 nanoseconds/point (10 Msamples/second) can yield time difference measurements with near nanosecond accuracy when second-order interpolation is used in conjunction with cross correlation. The low digitization rate also allows extremely fast averaging (approximately 500 pulse sets averaged per second). This is important because small but significant variations in tire thickness lead to corresponding variations in pulse flight times. In order to eliminate these variations, pulse sets are averaged while the tires turn exactly one or two rotations.

The equipment arrangement for averaging pulse sets during integral rotations is shown in Fig. 4. A square wave generator produces a continuous train of pulses. These pulses are fed to the input of a 3-channel analog multiplexer. A 4-state roll-around counter determines which multiplexer output is addressed to the input. The counter is clocked each time a metallic target, fixed to the transmitter tire, moves with tire rotation into the immediate vicinity of an inductive proximity sensor. One of the multiplexer outputs is coupled to the trigger input of a pulse/echo box. This device has a dual-purpose I/O line which outputs a short-duration ultrasonic pulse in response to an external trigger (the rising edge of the square wave), then changes state to act as an input, accepting ultrasonic echo pulses and enabling the transmitter to be a receiver as well. The echoes are available at the box's signal output line. The pulse/echo box is incorporated into the design for the purpose of temperature compensation mentioned above. The pulses that are reflected back from the delay line/water boundary to the transmitter are captured to relate the transit time in the delay line to the temperature of the fluid-filled wheels. The multiplexer/counter arrangement passes triggers to the pulse/echo box during every fourth rotation of the transmitter tire, minimizing the effect of variations in tire uniformity and leaving three "dead" count states available for wave transfer, cross correlation,

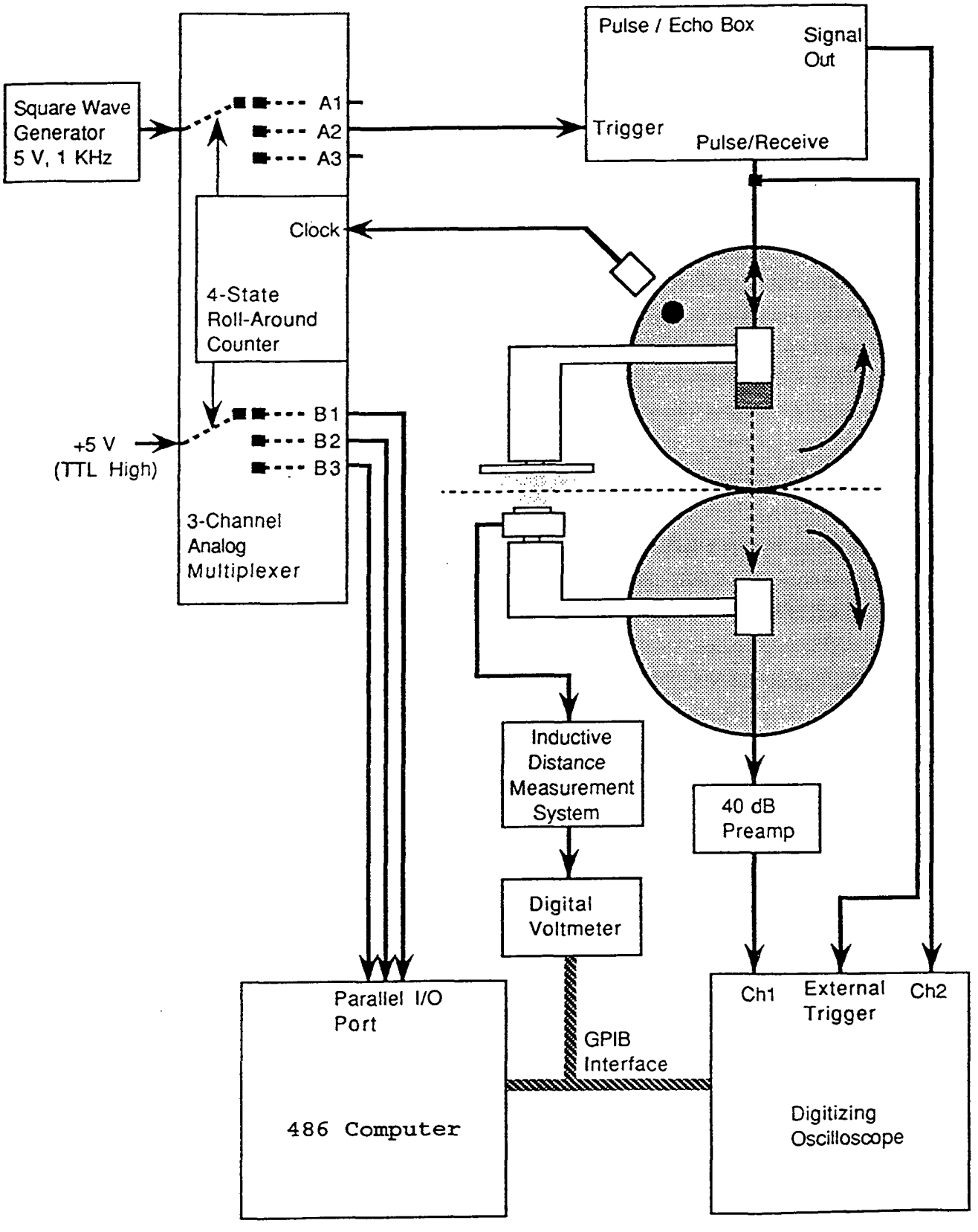


Figure 4. ZD measurement system for averaging pulse sets during integral wheel rotations.

and preparation for the next acquisition. The computer monitors the count state in order to synchronize acquisition and GPIB communication with tire rotation.

Static Measurements with Fluid-Filled Wheels

Early results of a comparison of the caliper and velocity as determined from the fluid-filled wheels and the standard out-of-plane laboratory instrument were presented in Report One (Hall and Habeger, 1988). The results of a more extensive study were presented at the 1991 Ultrasonic International Conference (Brodeur et al., 1991). This study presented the results for 29 paper specimens from 50 to 1750 μm in thickness. The values of caliper and velocity determined with the fluid-filled wheels are in good agreement with soft-platten measurements made with the laboratory instrument.

Immersion Transducers

With the ability to more accurately capture and analyze pulses and their time-of-flight differences, we observed that the reflected pulse shape (frequency content) from the fluid/transducer surface was somewhat broader. This affected the accuracy of the time difference measurement and in turn the value obtained for caliper. Standard immersion transducers are made with a one-quarter wavelength plastic cover. We experimented with transducers in a water tank and tried several techniques to provide a suitable reflective surface. We found that short acrylic rods positioned against each transducer gave fairly "sharp" reflected pulses.

This was the initial motivation and start of our using acrylic delay lines in the fluid-filled wheels. We subsequently purchased special transducers made with a cover of the minimum thickness needed for a water seal. The cover on these "thin cap" transducers is about one-fifth the thickness of the conventional quarter-wave cover. Since we found that the delay-line transit time can be use as a "thermometer" to correct for temperature changes in the wheels, we have continued to use a delay line with the transmitting transducer as discussed previously.

Pulse-Echo

We continued to use a function generator (WAVETEK, Model 143) to send pulses to the transmitter when a delay line was first introduced. We collected and analyzed only the transmitted pulses. Referring to the lower half of Fig. 5, the first pulse, w_1, is the first

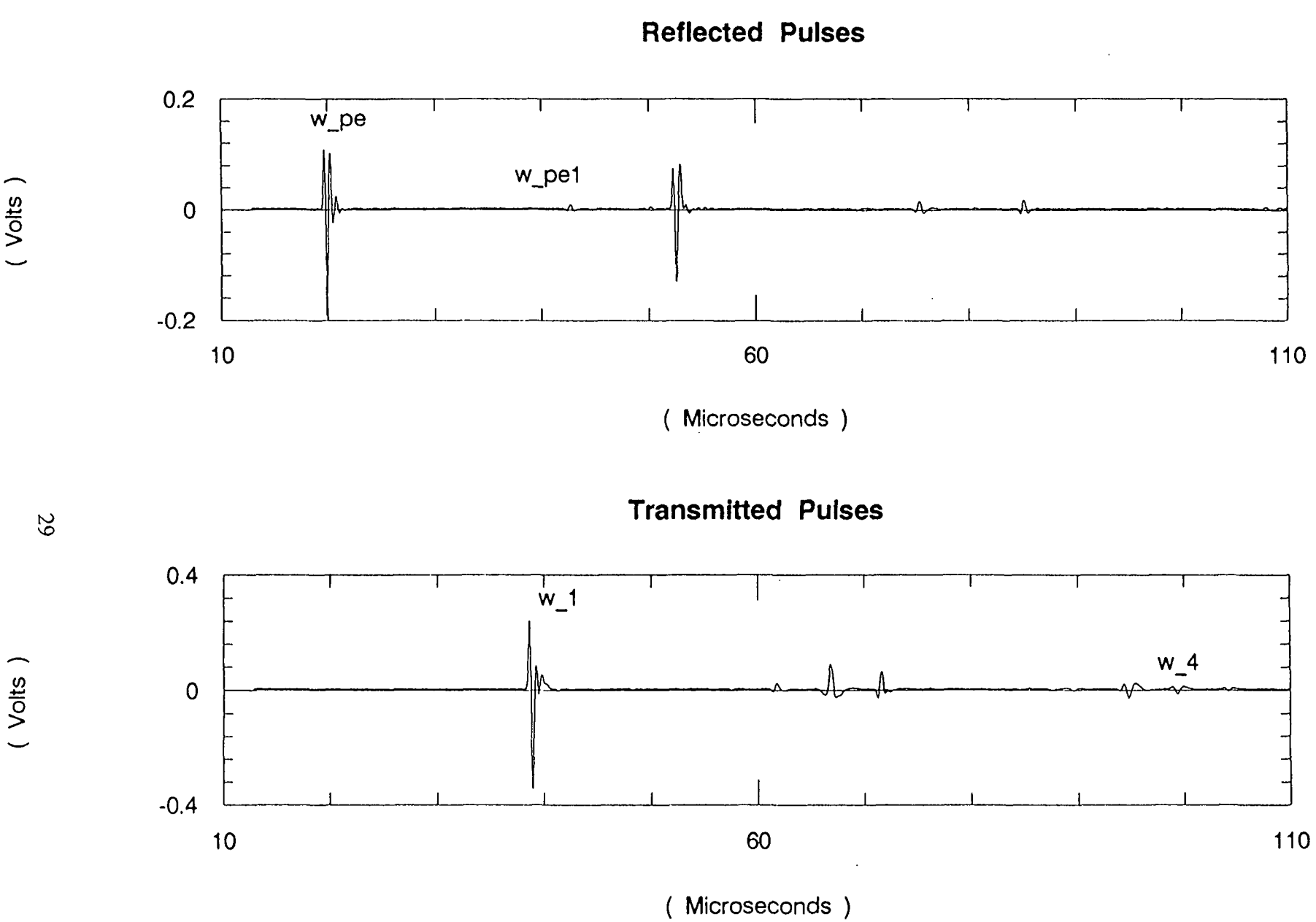


Figure 5. Reflected pulse train and transmitted pulse train.

pulse through. The next small pulse has reflected from the delay-line/fluid interface back to the transmitting transducer and then through to the receiver. Therefore, the time difference between these two pulses is equal to the pulse travel time in the delay line. In the process of developing techniques to use the delay-line travel time for temperature correction, we observed that the values determined from the transmitted pulse sets were sensitive to paper sample differences. Small changes in the shape of the pulses reduced the precision needed for temperature correction.

Data taken on a two-segment belt of different 42-lb liner are shown in Fig. 6. Data recordings were initiated by a trigger mark at the beginning of each segment. The plot on the left is the delay-line travel time for 100 readings. One can observe the time variation from segment to segment. We believed this effect to be due to pulse shape differences after going through the different samples. This would affect the time difference determined by cross correlation of the pulses of different shapes. The plot on the right in Fig. 6 was taken at the same time as that on the left and is the first pulse through, w_1, cross correlated with the same pulse that had been recorded without a sample as a reference. The slope of the data in the two plots shows the effect of temperature change in the wheels during the run.

After the above observation, we replaced the function generator with a pulser/receiver (Panametrics 5055PR) and used a cross correlation of the pulses noted as w_pe and w_pe1 in the reflected pulse set illustrated in the upper half of Fig. 5. This eliminated delay-line travel time sensitivity to samples in the nip.

Trigger Jitter

Initially, pulses taken during the measurement process were cross correlated against corresponding reference pulses taken without the presence of the paper web. As the accuracy of the measurements was improved, it became apparent that the time between trigger arrival at the oscilloscope and the onset of digitization contains a small degree of unpredictability. This can be seen in Fig. 7. With no sample and no wheel movement, the plot on the left shows the time variation of the pulse echo from the delay-line/water interface for 10 successive acquisitions when cross correlated with a stored reference of the same pulse. The plot on the right was recorded at the same time and cross correlated with a stored reference for w_1, the first pulse to the receiver. The time variation in the two plots is of the same shape and magnitude, demonstrating scope "trigger jitter" when current waveforms are cross correlated with stored reference waveforms.

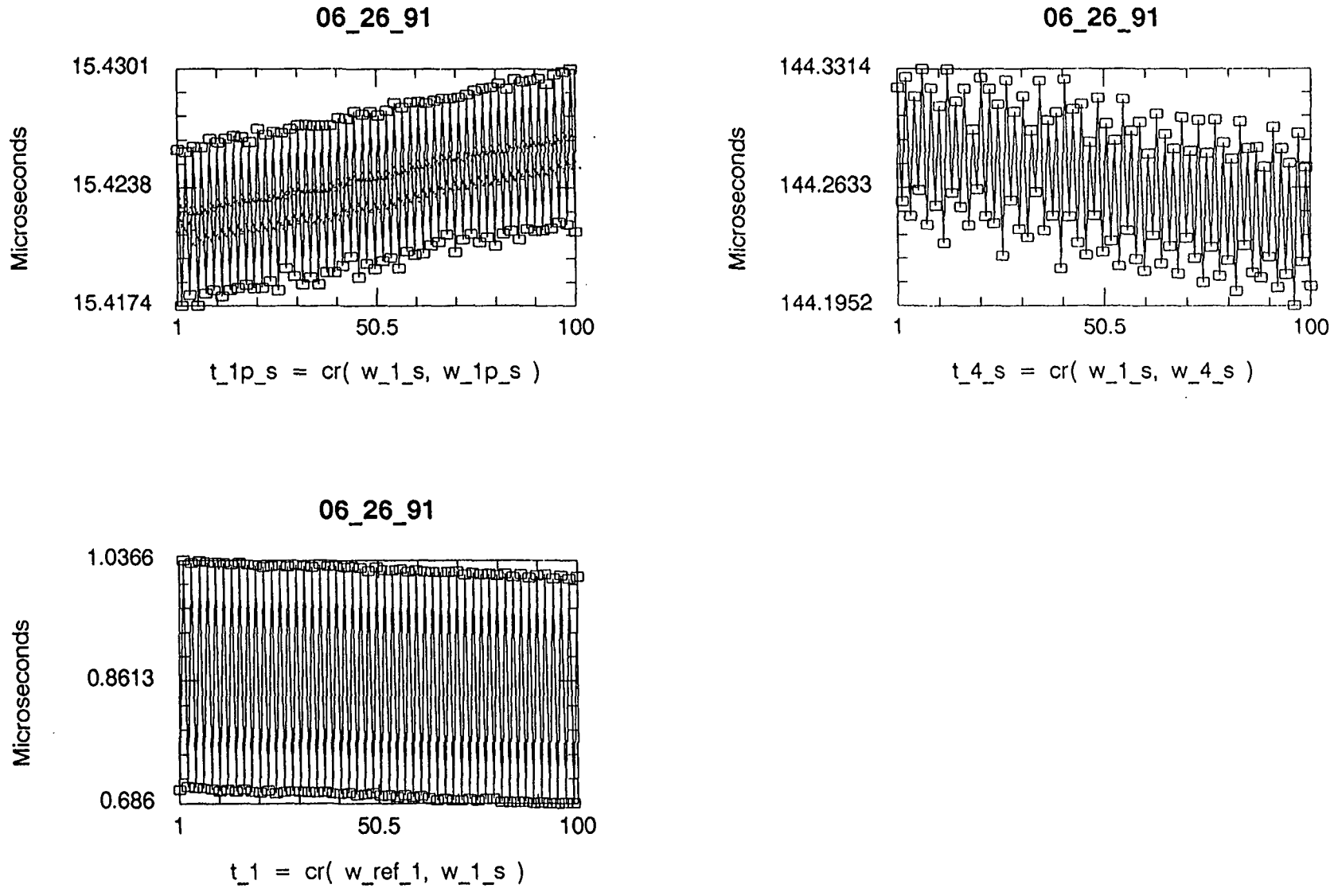


Figure 6. Data taken on a belt spliced with two segments of different 42-lb liners. Data collection initiated by trigger mark at beginning of each segment. Illustrates undesirable sensitivity of delay-line time (t_1p_s) to sample properties when delay-line time is determined from transmitted signal.

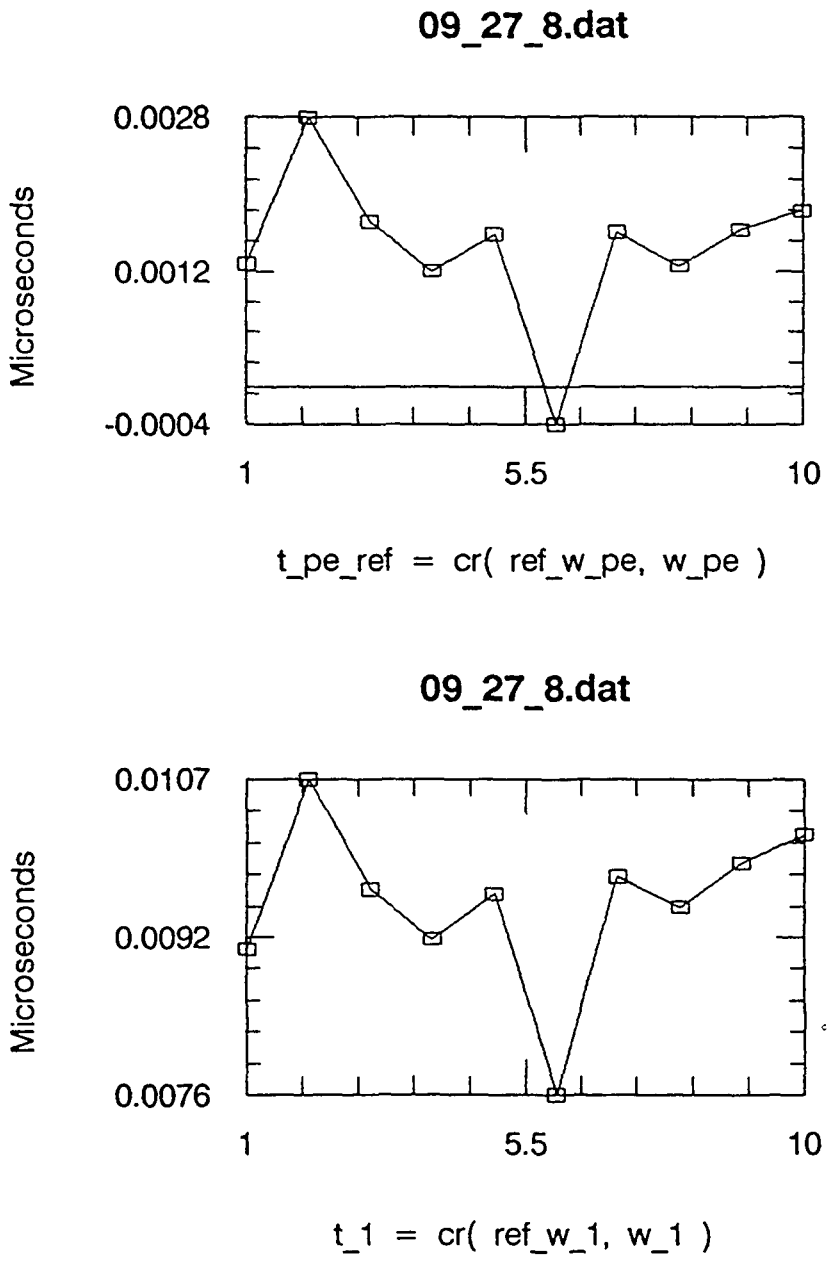


Figure 7. Illustrates scope "trigger jitter" when current waveforms are cross correlated with stored reference waveforms.

This "trigger jitter," though always less than the digitization period of the acquisition, is significant for a 50 or 100 nanoseconds/point digitization rate. The time between points of a digitized waveform is free of the jitter, since the sampling frequency is driven by a crystal oscillator. By cross correlating only pulses within the presently acquired pulse train, the problem of trigger jitter is overcome. This necessitates a different choice of pulses for cross correlation, since stored reference pulses cannot be used. With the use of pulse echo, an appropriate set of pulses is available, as illustrated in Fig. 5. For the delay-line flight time used in temperature correction, the pulse that reflects from the delay-line/water boundary and back to the transmitter (w_pe) is cross correlated against the pulse that reflects back from the transmitter face to the delay-line/water boundary and back a second time (w_pe1). More precisely, since w_pe1 is inverted relative to w_pe, w_pe1 is negated before cross correlation. The cross correlation gives the travel time within the delay line, t_pe_s, without trigger jitter. The notations in the next few paragraphs are those used in the WAVE computer program and are used here to coincide with the notations in accompanying figures where the plots were generated by the WAVE program.

In a manner similar to the above, trigger jitter is eliminated from the measurement of change in transit time from transmitter to receiver with and without a paper sample between the wheels. The primary pulse, w_1, is cross correlated with the echo pulse, w_pe, first without a sample for a reference value and then with the sample. The difference in these values, t_pe_1_del, is then used to determine the ZD transit time through the paper,

$$\text{del\_ts} = \text{t\_pe\_1\_del} + \text{del\_d} / \text{f\_vel}, \tag{5}$$

where del_ts is the transit time through the sample; del_d is the thickness or caliper of the sample; and f_vel is the effective fluid velocity.

The caliper, del_d, may be determined by cross correlating pulses w_1 and w_4, represented by ref_t_4_1 = cr(ref_w_1, ref_w_4) without a sample and then cross correlating the same pulses with a sample, represented by t_4_s = cr(w_1, w_4). The caliper is then calculated

$$\text{del\_d} = (\text{ref\_t\_4\_1} - \text{t\_4\_s})\ \text{f\_vel} / 2. \tag{6}$$

In this notation the velocity in the sample, vel_s, is then calculated using Eqns. 5 and 6,

$$\text{vel\_s} = \text{del\_d}/\text{del\_ts}. \tag{7}$$

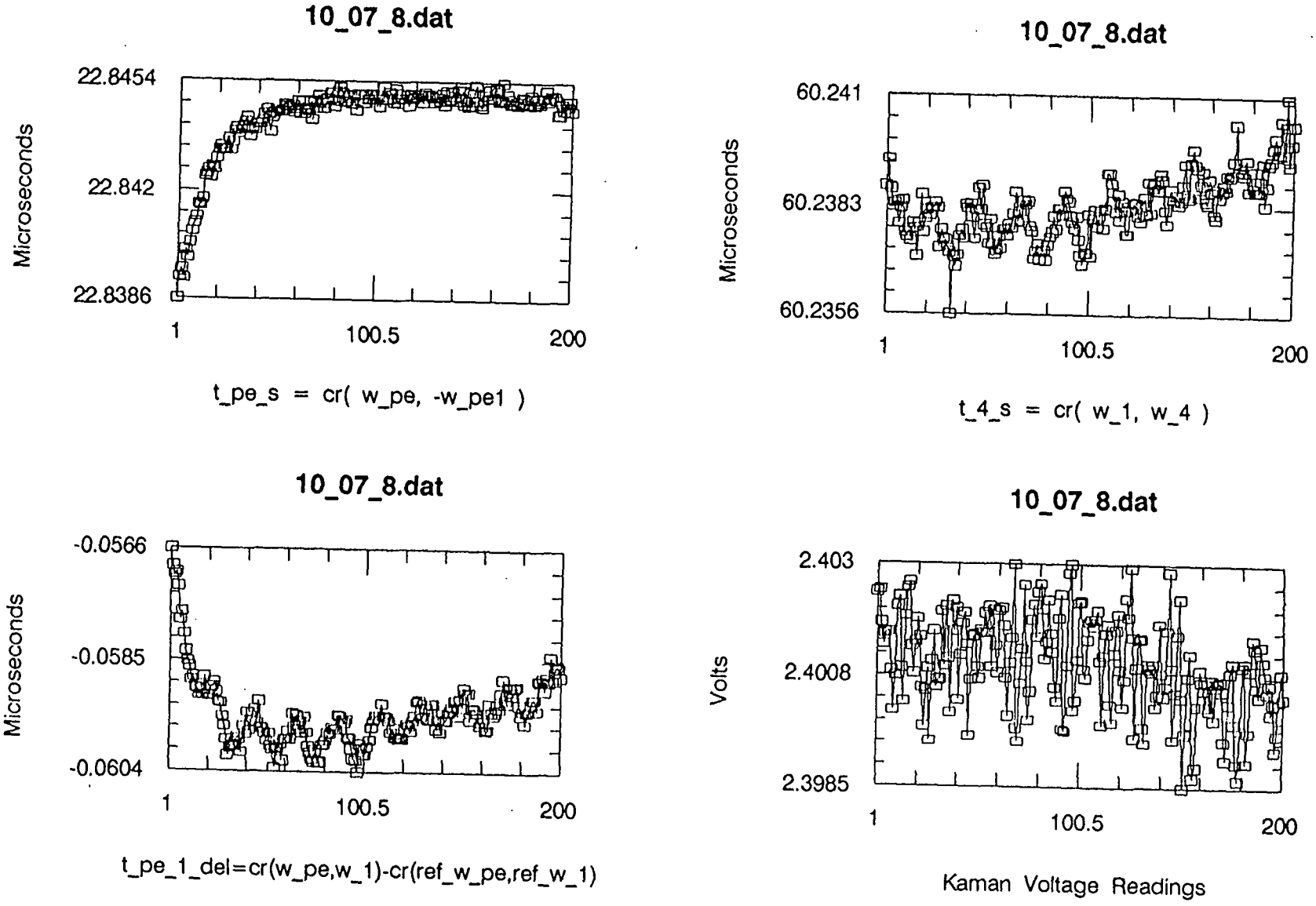


Figure 8. Wheels cooling @ 60 fpm, no sample; pulses averaged for one wheel rotation. Illustrates residual effects in time measurements due to variations around the circumference of the tire set.

Measurement Results with Fluid-Filled Wheels

Figure 8 illustrates the residual variation in the time measurements if we use pulse averaging during one wheel rotation. These data were taken with no sample in the nip. The wheels were turned at a higher speed and then run at a speed equivalent to 60 fpm while these data were recorded. In the upper left quadrant, we see the change in delay-line flight time as the temperature is decreasing in the wheels. The lower left quadrant shows the variation of the time difference between the echo pulse, w_pe, and the primary pulse, w_1, measured with cross correlation. The WAVE program automatically selects the maximum and minimum values for the range os axis values when generating plots. The time range on the y-axis is 3.8 nanoseconds. Similarly, the upper right quadrant shows the variation of the time difference between w_1 and w_4. This measure is used to determine fluid-filled wheel (FFW) caliper. The time range on the y-axis in this plot is 5.4 nanoseconds, including a "glitch" that adds about 1.5 nanoseconds to the range. The timing target for synchronizing the averaging with one wheel rotation is located on the upper tire. The circumference of the lower tire is slightly less than the upper so that the relative rotational phase of the two tires will cycle. The tires may also vary slightly in thickness and/or radius. This is the cause of periodic variation seen in the data. This in turn may cause a variation in the axle spacing. The lower right quadrant of Fig. 8 shows cycling in the Kaman voltage. The y-axis range is equivalent to 4.5 microns. Nevertheless, we can conclude from this data that the time measurements are repeatable to nanosecond accuracy, and the effect of tire dimension variation is minimized by fast averaging for integral wheel rotations.

In order to compare ZD readings for different papers, a roll was assembled with six 500-foot sections. The six sections were: 42-lb liner (A), 42-lb liner (B), 69-lb liner, 42-lb liner (C), 26-lb medium, and 42-lb liner (A). Figure 9 shows the temperature corrected caliper, del_d; the transit time in the sample, del_ts; and the ZD velocity in the paper sample, vel_s. Also shown in the lower right quadrant is the ZD velocity squared, vel2_s, the measurement of ZD specific elastic stiffness. The technique for temperature correction will be reviewed below.

Figures 10 and 11 are examples of ZD data similar to Fig. 9. Figure 10 shows data recorded for a 1800-foot roll of C2S (coated 2 side) free sheet, 70 lb/3300 sq.ft. Figure 11 shows data recorded for approximately 8500 feet of 26-lb/1000-sq.ft. liner.

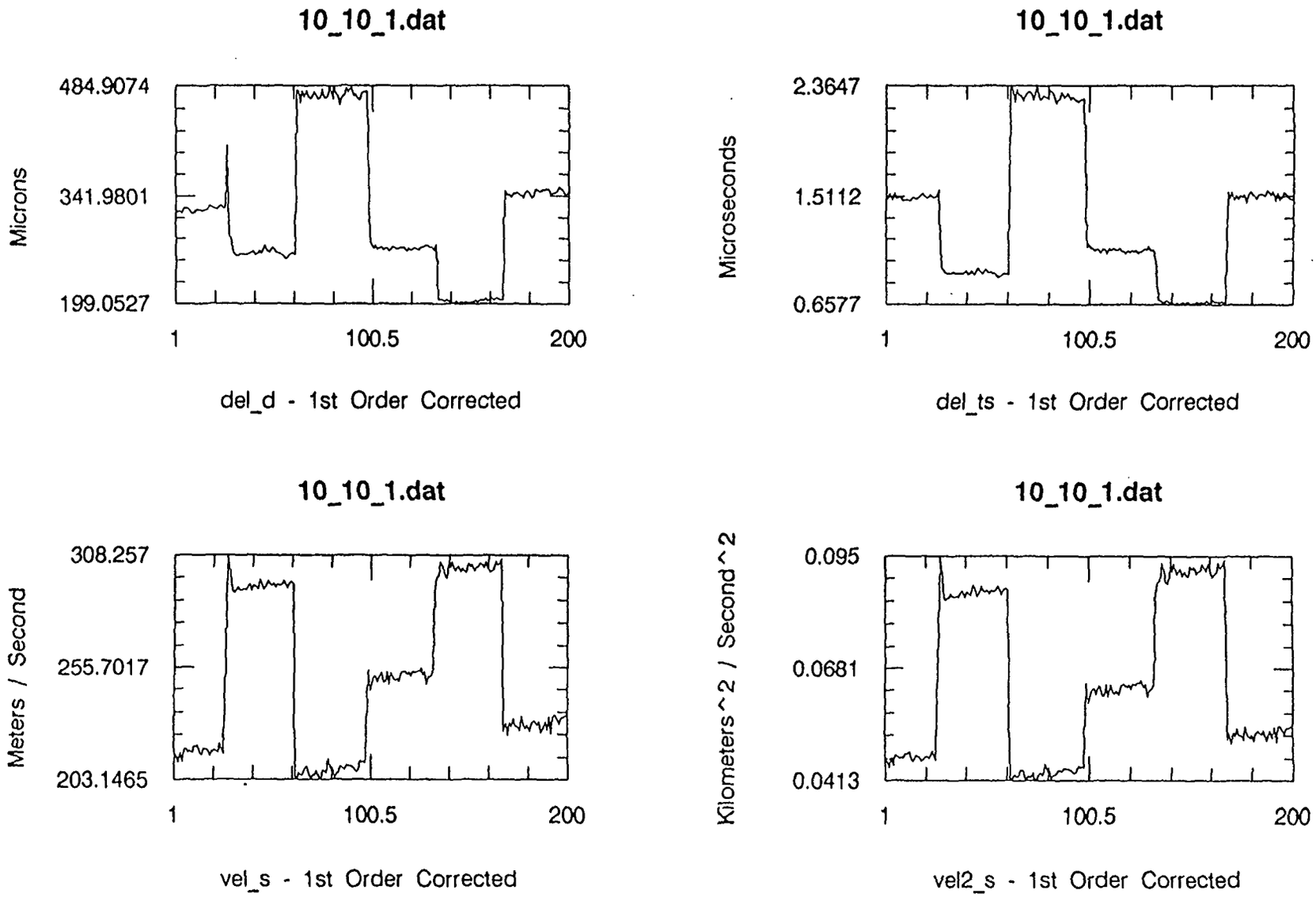


Figure 9. Roll spliced with six 500-foot sections: 42-lb liner (A), 42-lb liner (B), 69-lb liner, 42-lb liner (C), 26-lb medium, and 42-lb liner (A). This shows: the temperature corrected caliper, del_d; the transit time in the sample, del_ts; the ZD velocity in the paper sample, vel_s; and the ZD velocity squared, vel2_s, the ZD specific elastic stiffness.

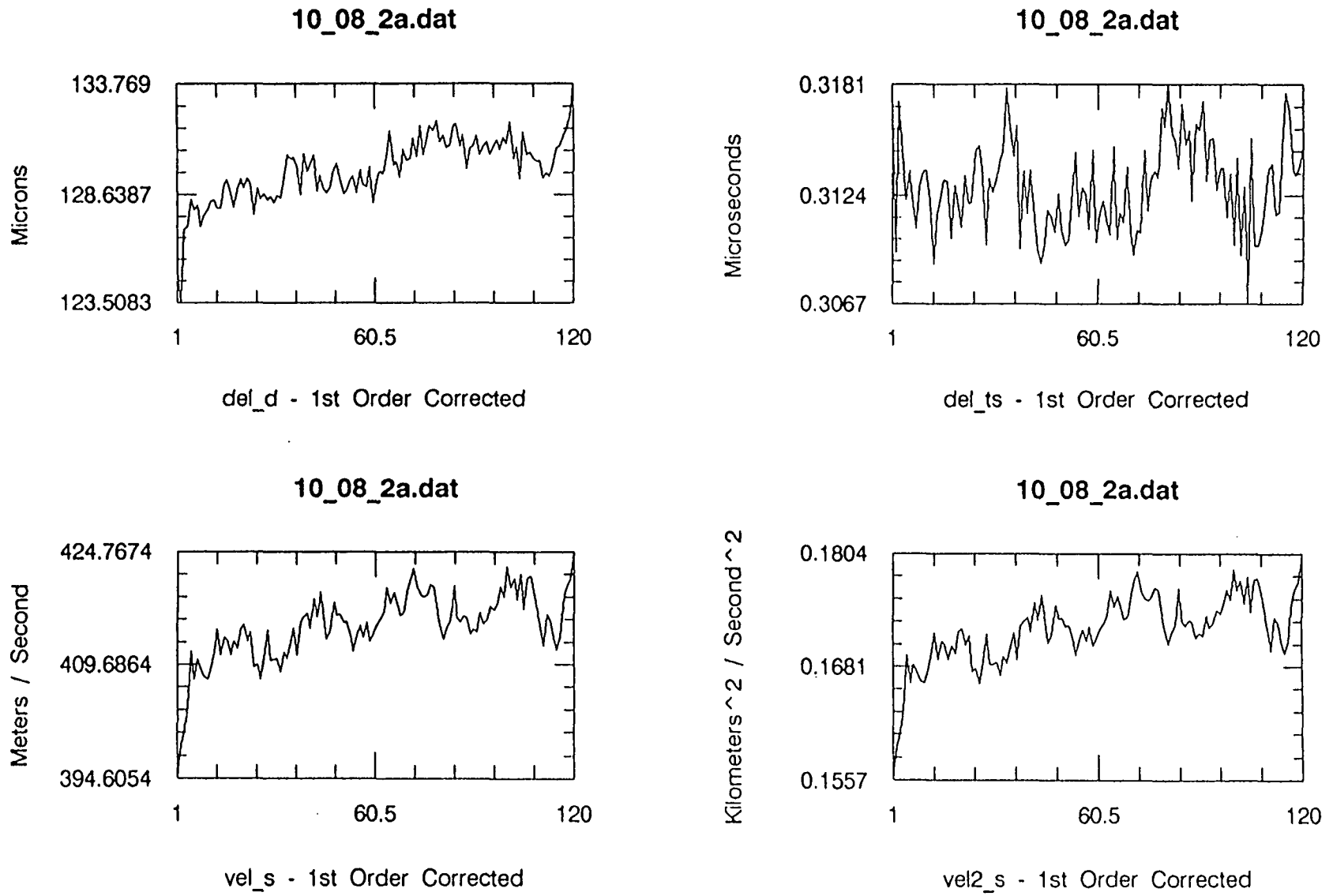


Figure 10. ZD data recorded for a 1800-foot roll of C2S (coated 2 side) free sheet, 70 lb/3300 sq.ft. Similar to Fig. 9, this shows: the temperature corrected caliper, del_d; the transit time in the sample, del_ts; the ZD velocity in the paper sample, vel_s; and the ZD velocity squared, vel2_s, the ZD specific elastic stiffness.

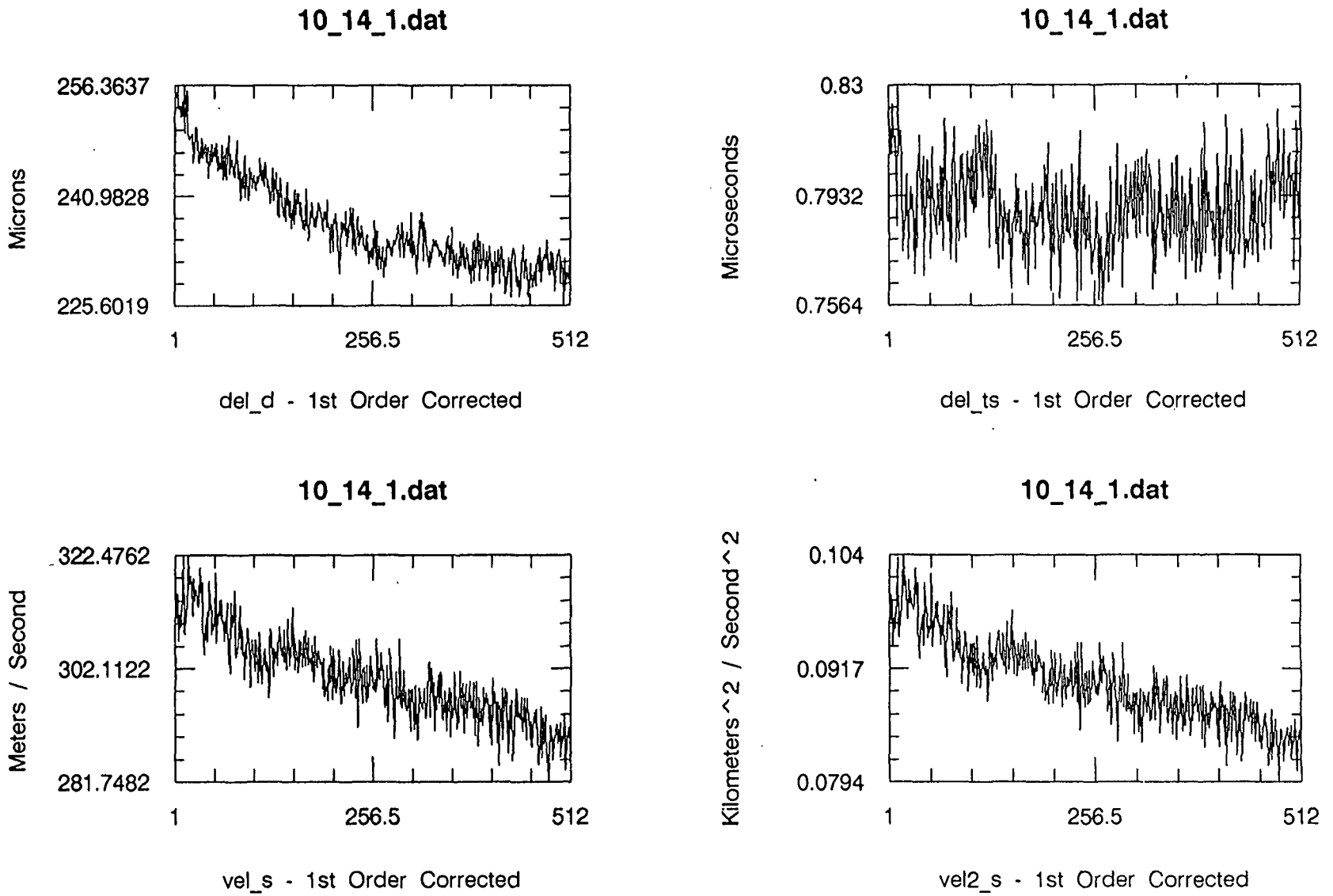


Figure 11. ZD data recorded for approximately 8500 feet of 26-lb/1000-sq.ft. liner. Similar to Fig. 9 and 10, this shows: the temperature corrected caliper, del_d; the transit time in the sample, del_ts; the ZD velocity in the paper sample, vel_s; and the ZD velocity squared, vel2_s, the ZD specific elastic stiffness.

Independent Caliper Measurement

A web caliper measurement is required to calculate the out-of-plane (ZD) velocity of ultrasound through the web. We have demonstrated the use of the multireflected pulses described above to determine the web caliper. However, an independent caliper measuring instrument may be used in conjunction with the fluid-filled wheels. Potential advantages are: the positioning of the transducer and delay line in the tires is less critical because one does not need to be concerned about reflected pulse overlap and interference; the analysis rate may be increased because the amount of data to be transferred and cross correlated is reduced; the multireflected pulse is weak and more difficult to use as sample thickness increases; and the temperature sensitivity of the multireflected pulse time requires careful correction, since it has a fairly long travel path. Potential disadvantages of using a separate caliper gauge are: the sample locations at which the transit times are determined are not exactly the same as those at which the thickness is measured; the compression of the sample for transit time and thickness measurement will not be the same; and the caliper gauge will give a "hard platen" caliper, whereas the wheels with soft rubber tires will be essentially a "soft platen" caliper.

We have mounted a Measurex contact caliper gauge on our test stand in line with the fluid-filled wheels. The measurement results obtained are in reasonable agreement with the FFW caliper determined with the multireflected pulses in the wheels and with the laboratory ZD instrument. The sampling rate is also increased. Using a fast average of 500 pulse trains per sample, the free run (not controlled by integral tire rotations) time per sample is approximately 4 seconds, versus 5 seconds per sample if caliper is determined with multireflected pulses in the fluid-filled wheels.

Figure 12 shows a comparison of the temperature effect on the fluid-filled wheel (FFW) caliper and the Measurex (MX) caliper. A two-section belt spliced with two different 42-lb liners was used. The temperature effect on the FFW caliper is apparent from the slope of the data. The FFW data have not been corrected for temperature, which accounts for a major part of the difference in the caliper values. The cycling in the FFW data for each liner is no doubt due to residual effects of tire dimension variation. The cycling in the MX caliper data is thought to be due to small caliper variations with lateral movement of the belt by the web guide.

Figure 13 shows a run of the same six-section roll used for the Fig. 9 data. In this case the caliper is recorded with the Measurex contact caliper gauge. This caliper, del_d_mx, is then used with the transit time through the sample, del_ts, to calculate the velocity through the

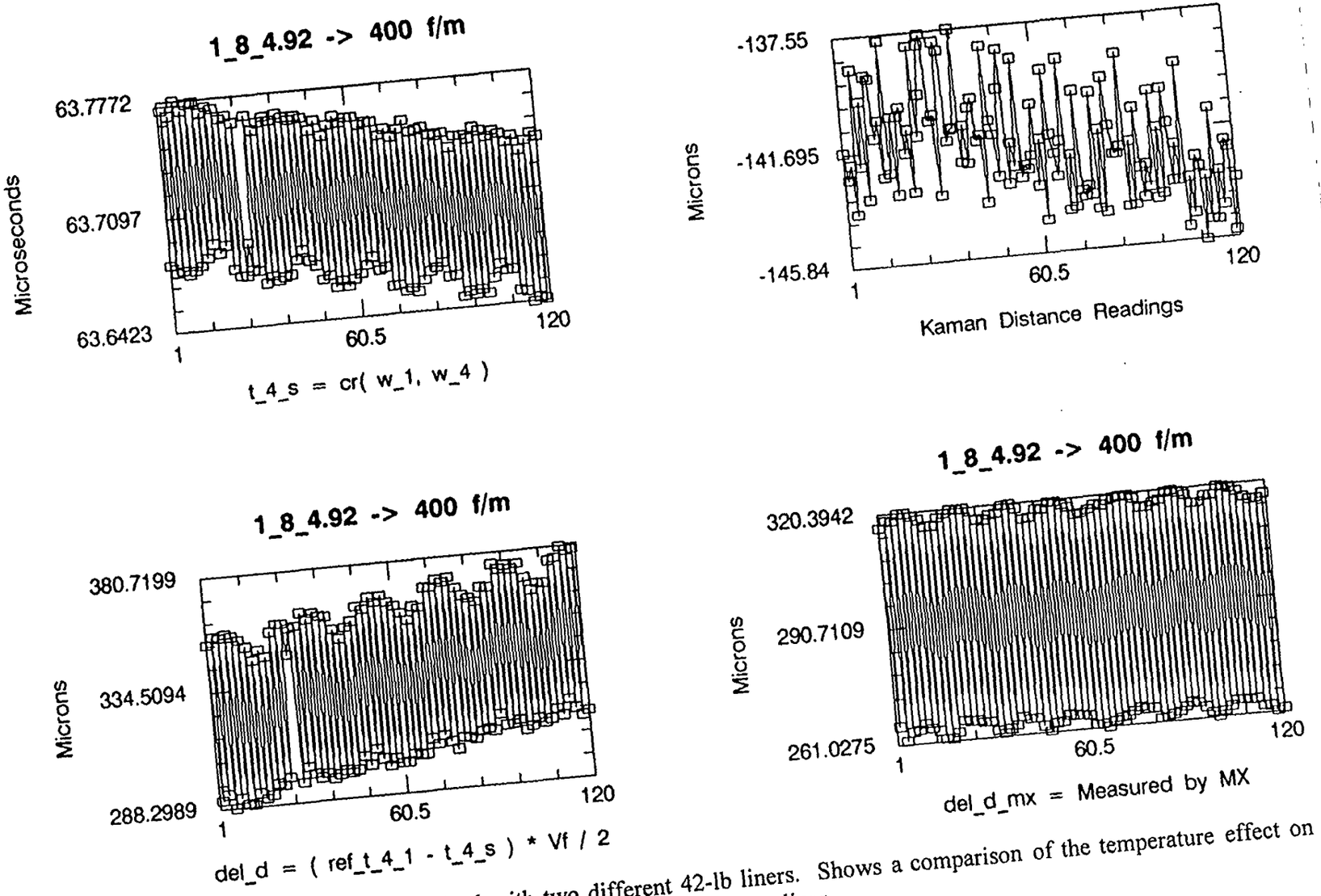


Figure 12. ZD data. Two section belt spliced with two different 42-lb liners. Shows a comparison of the temperature effect on the fluid-filled wheel (FFW) caliper and the Measurex (MX) caliper.

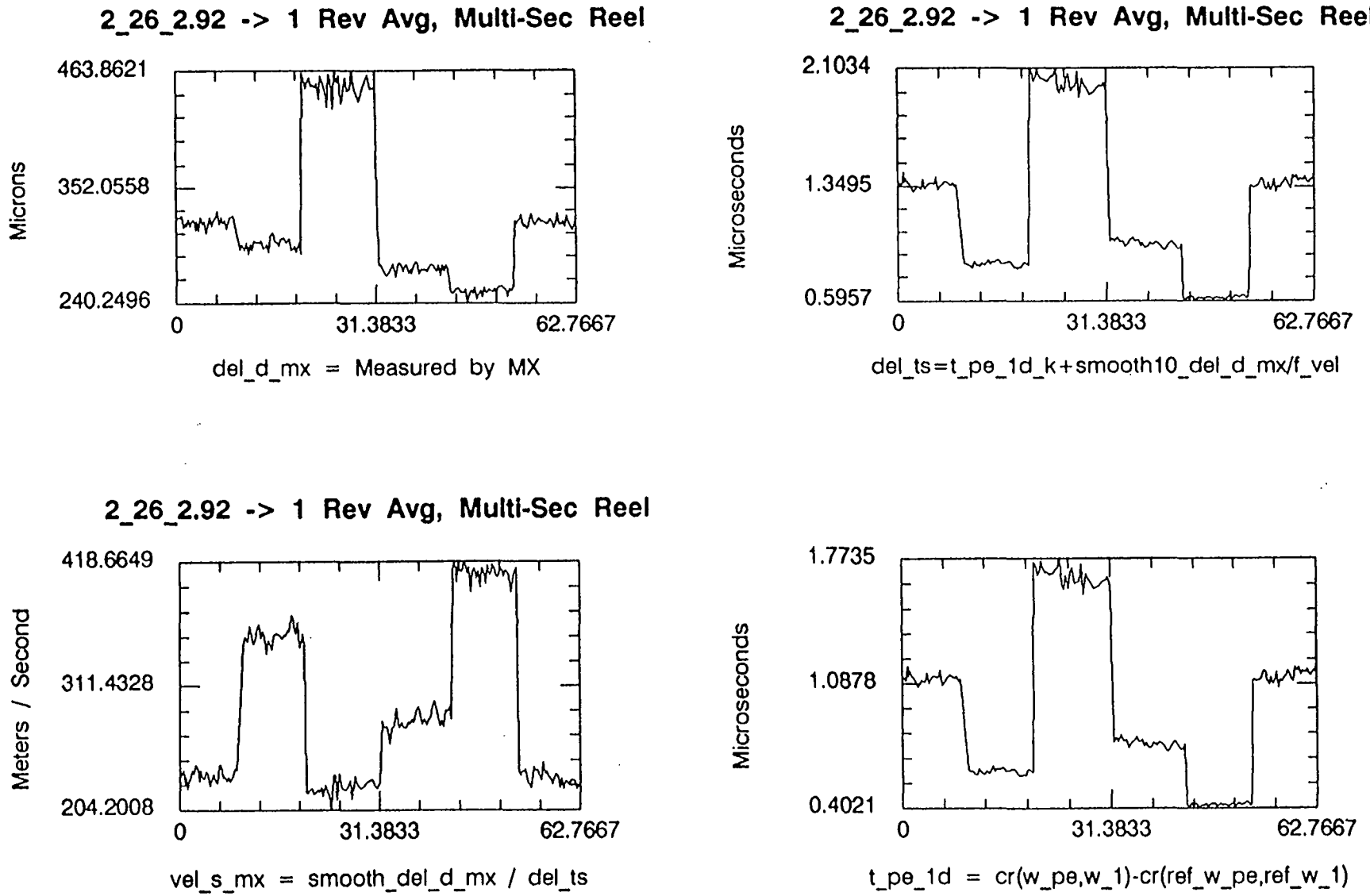


Figure 13. ZD data for the same six-section roll used for Fig. 9. Six 500-foot sections: 42-lb liner (A), 42-lb liner (B), 69-lb liner, 42-lb liner (C), 26-lb medium, and 42-lb liner (A). The Measurex caliper, del_d_mx, is used with the transit time through the sample, del_ts, to calculate the velocity through the paper, vel_s_mx.

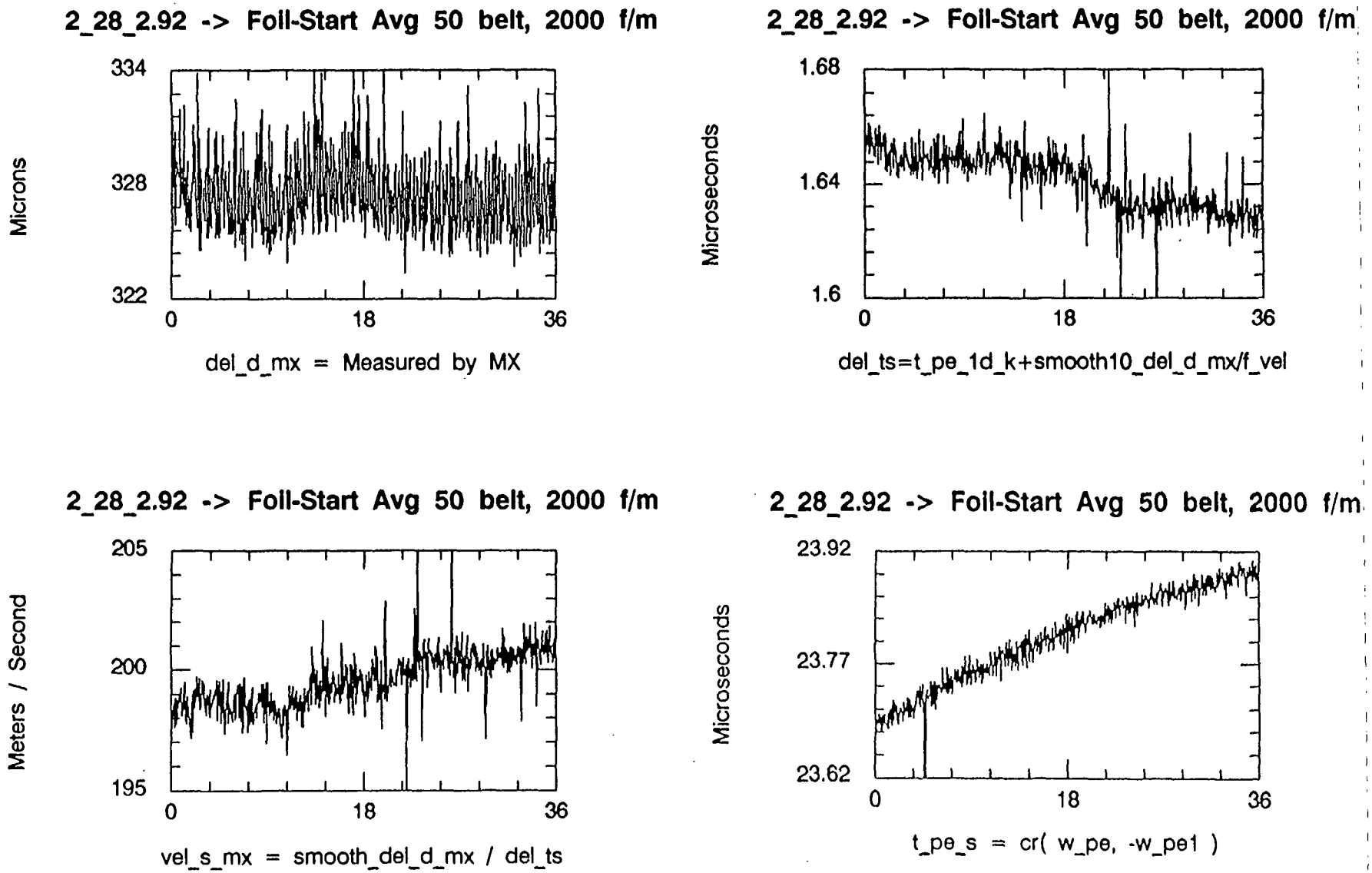


Figure 14. A 36-minute record of ZD data collected for a 42-lb liner belt running at 2000 fpm. No temperature correction. Delay-line transit time, t_pe_s, shows temperature change during run.

paper, noted as vel_s_mx. ZD velocity determined using the MX caliper is much less sensitive to temperature changes than when FFW caliper is used without appropriate temperature compensation. However, the contact caliper gauge determines caliper values similar to a hard platen gauge. Therefore, surface roughness of the samples will have a greater effect on the MX caliper readings than on FFW readings.

With a belt of paper mounted on the web handling system in the laboratory, we have demonstrated the feasibility of measuring the ZD ultrasound velocity with paper webs moving at high web speeds for several hours. Figure 14 shows a 36-minute record of ZD data collected for a 42-lb liner belt running at 2000 fpm. Each reading was initiated by a trigger from a target on the belt, followed by a fast average of 50 pulses. These data have not been corrected for temperature. The delay-line transit time shown in the lower right quadrant shows that the temperature of the system had not stabilize during this run. Long runs and references taken off the sheet periodically may eliminate the need for temperature correction. The ZD velocity in Fig. 14 ranges from 198 to 202 meters/second. This range of ± 1% is small and would be reduced by applying a calibrated temperature correction using the delay-line data.

Correction for Temperature Changes in Fluid-Filled Wheels

Referring again to Fig. 2 and using the notations used there, the temperature-dependent transit times for the directly transmitted and the reflection-delayed pulses in the reference (without paper) configuration are:

$$t_1(T) = d_d/v_d(T) + [d_{fe} + d_{fr}]/v_f(T) + d_{te}/v_{te}(T) + d_{tr}/v_{tr}(T) \quad (8)$$

$$t_2(T) = 3\{d_d/v_d(T) + [d_{fe} + d_{fr}]/v_f(T) + d_{te}/v_{te}(T) + d_{tr}/v_{tr}(T)\} \quad (9)$$

in which $v_d(T)$, $v_f(T)$, $v_{te}(T)$, and $v_{tr}(T)$ represent the sound velocity at temperature T in the delay line, the fluid, the emitter tire, and the receiver tire, respectively. Similarly, transit times for the directly transmitted and reflection-delayed pulses in the specimen (with paper) configuration are:

$$t_{1'}(T) = d_d/v_d(T) + [d_{fe'} + d_{fr'}]/v_f(T) + d_{te}/v_{te}(T) + d_{tr}/v_{tr}(T) + t_h(T) \quad (10)$$

$$t_{2'}(T) = 3\{d_d/v_d(T) + [d_{fe'} + d_{fr'}]/v_f(T) + d_{te}/v_{te}(T) + d_{tr}/v_{tr}(T)\} + t_h(T) \quad (11)$$

where t_h is the traveling time in paper. From Eqns. 8, 9, 10, and 11, we get:

$$\Delta t_{21}(T) = t_2 - t_1(T) = 2\{d_d/v_d(T) + [d_{fe} + d_{fr}]/v_f(T) + d_{te}/v_{te}(T) + d_{tr}/v_{tr}(T)\} \quad (12)$$

$$\Delta t_{2',1'}(T) = t_{2'} - t_{1'}(T) = 2\{d_d/v_d(T) + [d_{fe'} + d_{fr'}]/v_f(T) + d_{te}/v_{te}(T) + d_{tr}/v_{tr}(T)\}. \quad (13)$$

Subtracting Eqn. 13 from Eqn. 12,

$$\Delta t_{21}(T) - \Delta t_{2',1'}(T) = 2\{[d_{fe} + d_{fr}] - [d_{fe'} + d_{fr'}]\}/v_f(T) \quad (14)$$

where with fixed axle distance, d,

$$[d_{fe} + d_{fr}] - [d_{fe'} + d_{fr'}] = h. \quad (15)$$

Therefore, from Eqn. 14 the paper thickness is

$$h = v_f(T)[\Delta t_{21}(T) - \Delta t_{2',1'}(T)]/2. \quad (16)$$

The transit time through the sample, t_h, could be calculated by subtracting Eqn. 8 from Eqn. 10,

$$t_h = t_{1'}(T) - t_1(T) + h/v_f(T) = \Delta t_{1',1}(T) + [\Delta t_{21}(T) - \Delta t_{2',1'}(T)]/2. \quad (17)$$

However, $t_{1'}(T)$ and $t_1(T)$ are determined at different times and are subject to variation in the analog-to-digital conversion in the oscilloscope (see trigger jitter discussion above). In order to eliminate this possible timing error, we take advantage of the echo pulse in the delay line, represented by t_{da} in Fig. 2, since this is recorded at the same time as the primary pulse to the receiver, t_1. Thus, using the delay-line transit times, $t_{da}(T)$ for the "reference" (without paper) and $t_{da'}(T)$ when measuring with paper, $\Delta t_{1',1}(T)$ is computed as follows:

$$\Delta t_{1',1}(T) = [t_{1'}(T) - t_{da'}(T)] - [t_1(T) - t_{da}(T)] = \Delta t_{1',d'}(T) - \Delta t_{1d}(T) \quad (18)$$

Thus, the preferred equation for the sample transit time is

$$t_h = \Delta t_{1',d'}(T) - \Delta t_{1d}(T) + [\Delta t_{21}(T) - \Delta t_{2',1'}(T)]/2. \quad (19)$$

The transit time in the delay line can be determined by cross correlating the first and second echo pulses from the delay-line/water interface. This transit time, $\Delta t_{ba}(T)$, is

$$\Delta t_{ba}(T) = t_{db}(T) - t_{da}(T) = t_{db'}(T) - t_{da'}(T). \quad (20)$$

The transit time in the delay line will depend upon the temperature and not upon the presence or absence of a paper sample in the nip between the wheels, as observed in earlier trails. Therefore, the delay-line transit time may be used as a measure of the temperature of the system, and Eqns. 16 and 17 may be rewritten as

$$h = v_f(\Delta t_{ba}(T)[\Delta t_{21}(T) - \Delta t_{2'1'}(T)]/2, \quad (21)$$

$$t_h = \Delta t_{1'd'}(\Delta t_{ba}) - \Delta t_{1d}(\Delta t_{ba}) + [\Delta t_{21}(\Delta t_{ba}) - \Delta t_{2'1'}(\Delta t_{ba})]/2. \quad (22)$$

The thickness direction (ZD) longitudinal sound velocity through the paper, v_p, is then calculated using Eqns. 21 and 22,

$$v_p = h/t_h. \quad (23)$$

The off-web relationships for v_f, $\Delta t_{1d}(T)$, and $\Delta t_{21}(T)$ as a function of Δt_{ba} can be determined, i.e.,

$$v_f = f(\Delta t_{ba}); \quad \Delta t_{1d}(T) = f(\Delta t_{ba}); \quad \text{and } \Delta t_{21}(T) = f(\Delta t_{ba}). \quad (24)$$

These relationships can then be used to correct the "reference" values in Eqns. 21 and 22 to the current system temperature. Thus, the measurements of the ZD sound velocity, v_p, are corrected for any temperature change between the time the reference data were recorded and the current readings.

ULTRASONIC MEASUREMENT OF IN-PLANE ELASTIC STIFFNESSES

Robot-Based In-Plane Laboratory Instruments

IPST has conducted research on the use of ultrasound to characterize the in-plane mechanical properties of paper since the late 1970s. The early work was done with hand-operated transducer holders. The transit time of the ultrasound signal from transmitter to receiver was recorded for several transducer spacings (Baum and Habeger, 1981). The velocity was calculated by determining the slope of the distance versus the transit time data. This technique avoided the need to correct the time measurement for nonpaper delays. This philosophy has been continued in the subsequent instrument developments where accuracy is considered more important than speed of measurement.

The first automatic instrument developed by the Institute is described in detail in the literature (Van Zummeren et al., 1987). This computer-controlled instrument automatically selected the near or far separation of the transducers and raised and lowered them onto the sample. The computer determined the time-of-flight difference for the near and far transducer spacings by cross correlation. The sample was attached to a turntable driven by a stepping motor. In addition to determining shear velocity and the machine direction (MD) and the cross machine direction (CD) longitudinal velocities, this instrument could measure velocities as a function of angle from the MD. The velocity squared values (specific stiffnesses) and a "polar plot" of the results were displayed and printed.

The above instrument was superseded by a robot-based instrument (Habeger et al., 1989). A Mitsubishi RM-501 robot arm with a special "end effector" was used to position the transducers in the desired orientations on the sample. The instrument could be programmed to test up to four samples positioned around the robot. New miniature bender transducers were designed for this instrument to provide greater bandwidth and modal purity and improved sensitivity. Transducers with this design continue to be used in our present instrumentation.

The present robot-based instrument uses an Adept 604-S robot. This is a 4-axis robot and is more conveniently modified in its positioning program for single-plane movements than the 5-axis arm of the RM-501. The same end effector and bender transducers noted above are used. Up to five 20-cm by 20-cm samples positioned around the robot or a 30-cm by 60-cm strip may be tested without operator intervention. This instrument is very versatile for in-plane ultrasonic testing and research, having a wide effective measurement envelope.

The above development of in-plane laboratory instruments has provided background for in-plane sensor development for moving webs. The robot-based instrument also provides data for comparison with moving web measurements. The miniature bender transducers developed for the laboratory instruments are described in detail by Habeger et al. (1989). The basic design of these wideband, bimorph transducers was adapted for the present in-plane ultrasonic measurements on moving paper webs.

In-Plane Measurement System for Moving Webs

Rather than repeat the previous in-plane system design demonstrated on-line in Valdosta, Georgia (Baum and Habeger, 1985), we pursued the following approach. In this project, the system to measure the in-plane velocity of ultrasound in moving webs is based on using wideband, bimorph, bender transducers similar to those developed for in-plane measurements in the laboratory instruments. 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 mounted in the surface of a 10-inch diameter aluminum cylinder in special spring-loaded holders. Provision is made in the web handling system to mount this drum. The transducers are oriented outward so that each active element protrudes slightly outside the circumference of the cylinder.

The transducers are used in sets of three. One transducer serves as a transmitter and may be positioned at either end of the set or in between two transducers 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.

One receiver set, aligned in the CD direction and oriented to transmit and detect CD shear waves, has a CD NEAR distance of 46 mm, and the CD FAR is 82 mm for a path difference of 36 mm. The other set, aligned in the MD direction and oriented to transmit and detect MD longitudinal waves, has a MD NEAR distance of 66 mm, and the MD FAR is 101 mm for a path difference of 35 mm. Similarly, the transducers may be oriented to make longitudinal measurements in the cross direction and shear measurements in the machine direction.

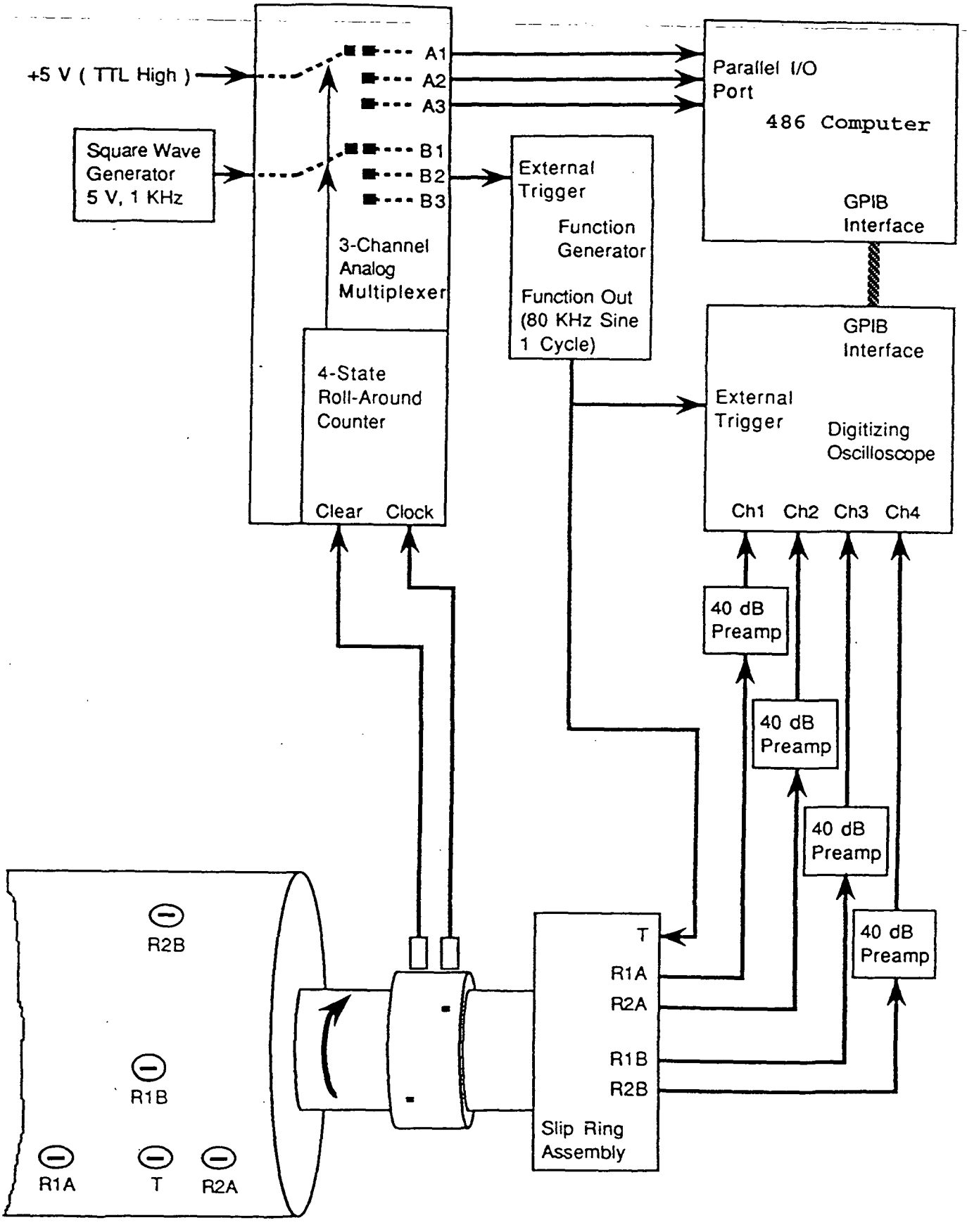


Figure 15. Schematic of measurement system for averaging in-plane ultrasonic pulses.

The web contacts a portion of the circumference of 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 ring for a few cycles, producing 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 pulse trains within the active period of rotation, the oscilloscope takes time measurements of corresponding half cycle peaks. The differences in these peak times for each receiver set are sent to the 486 computer for velocity calculations.

A schematic for the pulse averaging measurement system is shown in Fig. 15. Pulse excitations are sent to the transmitter only during the active measurement period. A square wave generator sends a continuous train of pulses to the input of a 3-channel analog multiplexer. A 4-state roll-around counter determines which multiplexer output is addressed to the input. Two metallic targets are fixed to the cylinder. One target is positioned at the beginning of the active region to trigger an inductive proximity sensor, which clears the multiplexer/counter circuit. The other target, located at the end of the active region, clocks the counter. Excitation pulses are passed by the multiplexer to the transmitter only during the zero state of the counter. Thus, 80-kHz, one-cycle sine pulses are sent to the transmitter only while the transducers are in contact with the web. The signals detected by the four receiver transducers are captured and processed by a 4-channel digitizing oscilloscope.

The transducer housing and the carrier for mounting the transducers in the cylinder are designed to minimize variation in the contact force between the transducers and the web (see Fig. 16). 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. The spring loading is designed to minimize variation in the contact force between the transducers and the web. The caps are held in place with screws and can be removed to replace or reposition the transducers from outside the cylinder without removing the main body of the carrier.

With one transducer set positioned to measure in the CD longitudinal mode and another set positioned in the CD shear mode, data may be collected with the web in light tangential contact with the cylinder. With tangential contact only one longitudinal pulse set and one

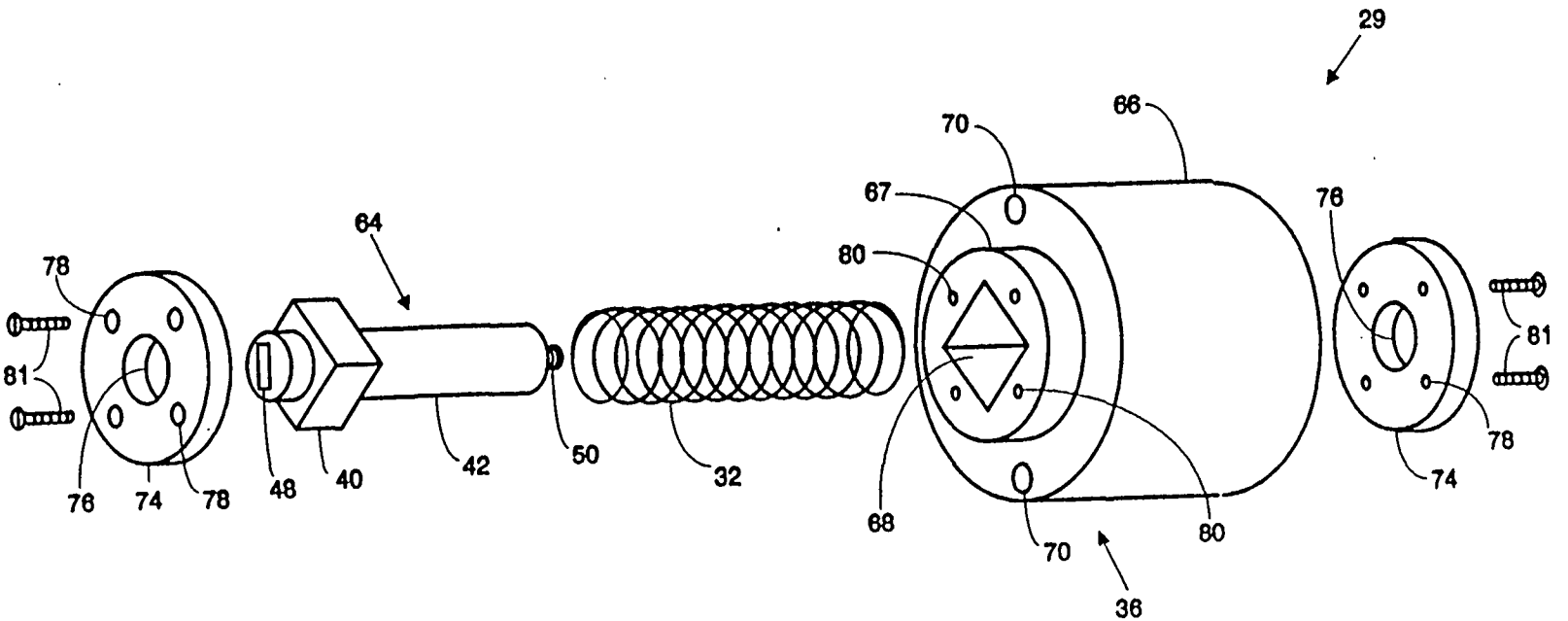


Figure 16. Transducer housing and carrier for mounting the in-plane transducers in the cylinder.

shear pulse set are captured during each cylinder rotation, whereas with partial wrap the transducers are in contact with the web long enough to permit measurement by averaging several pulses each cylinder rotation. The results are essentially the same; however, with tangential contact it may be necessary to average the data from several rotations of the cylinder to obtain good signal-to-noise data. Wrapping the web around part of the cylinder is preferable because good signal-to-noise data can be obtained by signal averaging within one cylinder rotation.

In-Plane Measurement Results

In-plane CD shear and MD longitudinal data have been taken on rolls of paper representing a variety of commercial grades. The data are in general agreement with cut samples measured with the laboratory in-plane ultrasonic instrument. Examples of recorded in-plane data are shown in the accompanying figures:

Figure 17 shows the as-collected in-plane data for the CD shear velocity and for the MD longitudinal velocity for 3200 feet of 42-lb liner. A datum point for each is recorded with each rotation of the cylinder, which has a circumference of 2.618 feet. Thus, there are more than 1200 data points in each of these plots, which have been generated by the WAVE program used with the computer.

The top plot in Fig. 18 repeats the MD longitudinal velocity of Fig. 17, but here the data have been smoothed with a running average of 11 points. This minimizes the short-range variation and shows the trends more clearly. The bottom plot in Fig. 18 shows data for a repeat run of the rewound roll. A comparison of the values and shape of the variations provides confidence in the repeatability of the measurements.

Figure 19 shows smoothed data for the CD shear velocity and MD longitudinal velocity for 3000 feet of 69-lb liner.

Figure 20 shows smoothed data for the MD longitudinal and CD shear velocities for 9600 feet of 26-lb liner.

Figure 21 shows smoothed data for the CD shear and MD longitudinal velocities for 5360 feet of 60-lb/3000-sq.ft. extensible sack kraft.

Figure 22 shows smoothed data for the CD shear and MD longitudinal velocities for

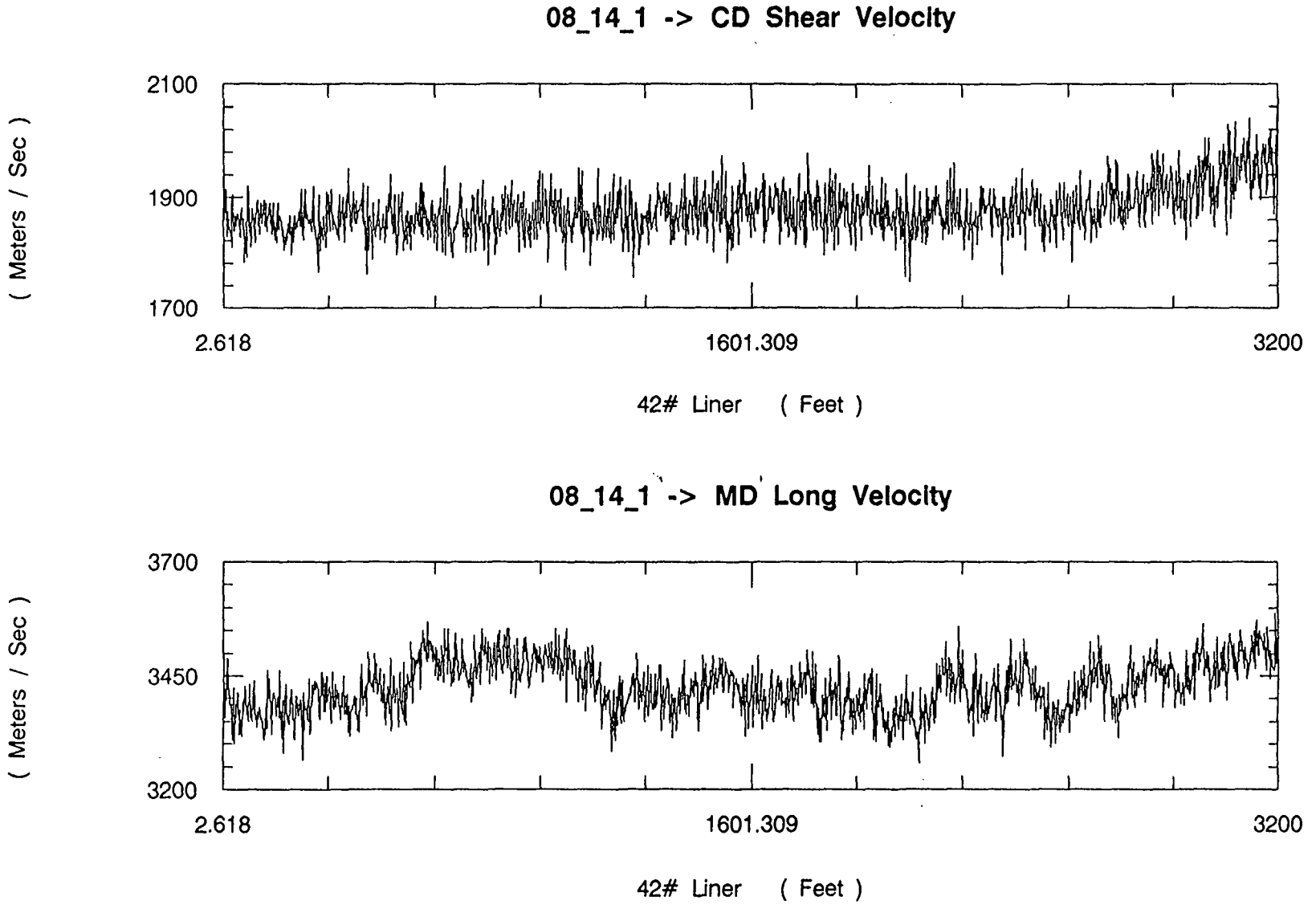


Figure 17. As-collected in-plane data for the CD shear velocity and for the MD longitudinal velocity for 3200 feet of 42-lb liner.

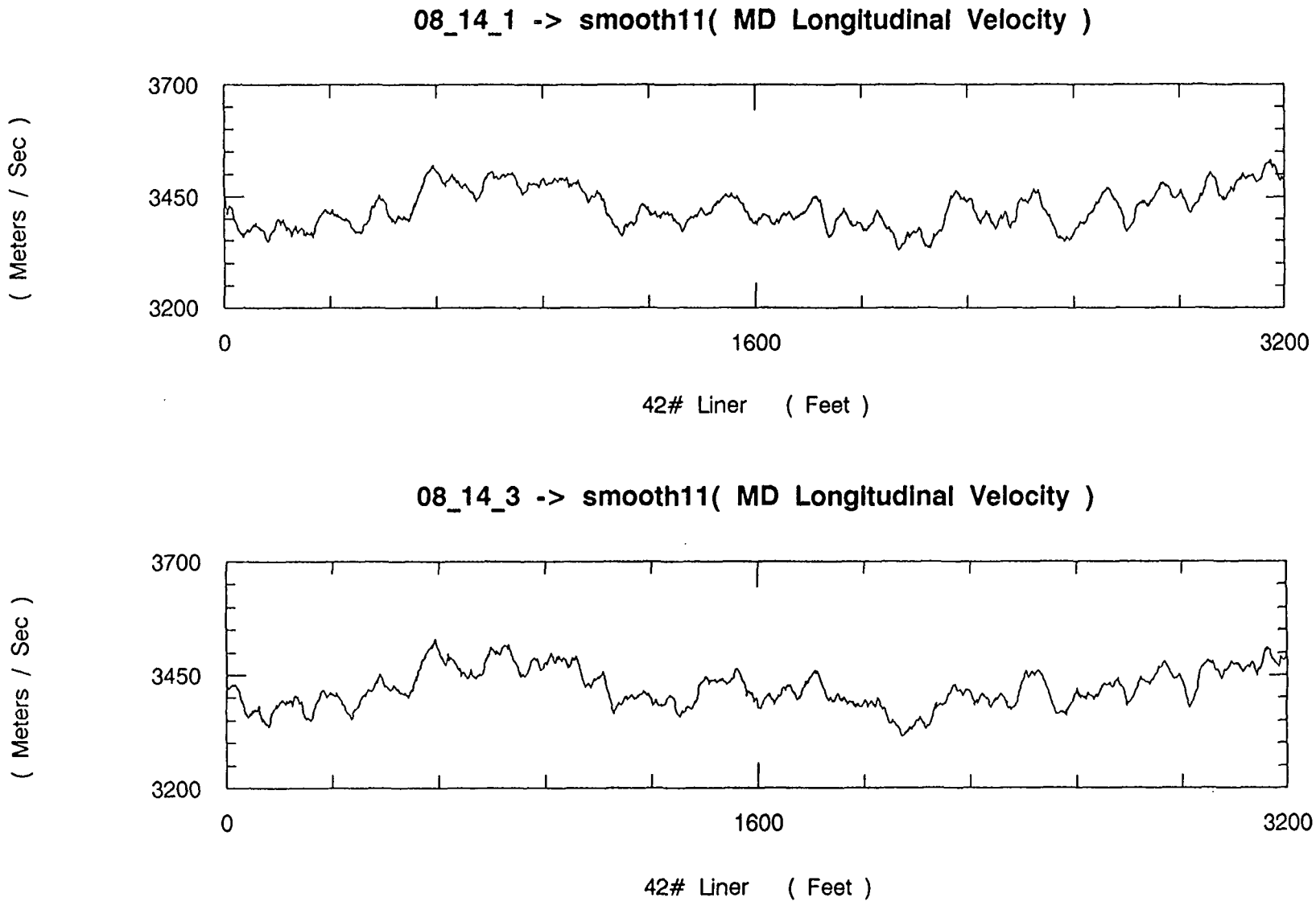


Figure 18. The top plot shows smoothed MD longitudinal velocity for the same data shown in Fig. 17. The bottom plot shows similar data for a repeat run of the same 3200 feet of 42-lb liner.

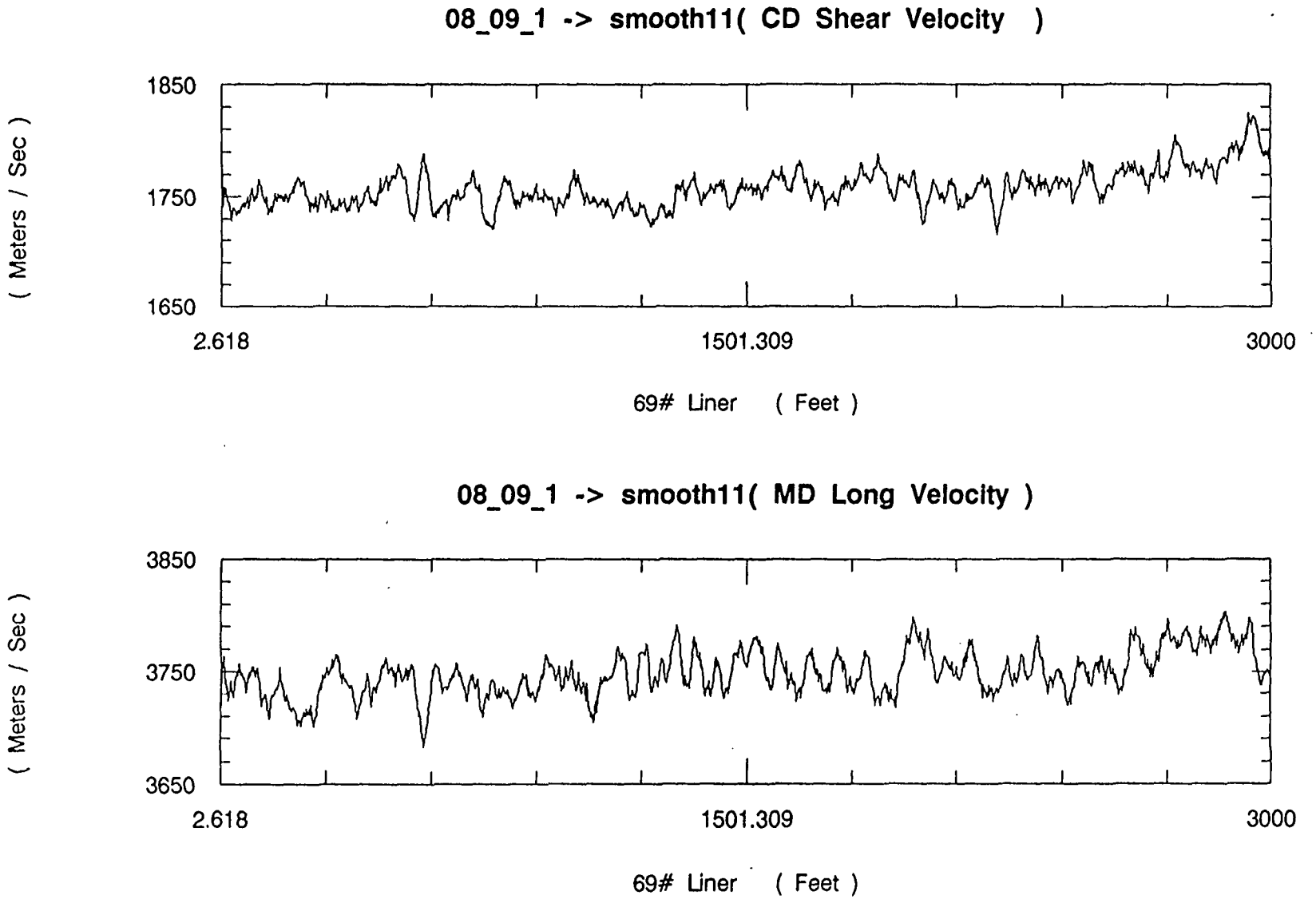


Figure 19. Smoothed data for the CD shear velocity and MD longitudinal velocity for 3000 feet of 69-lb liner.

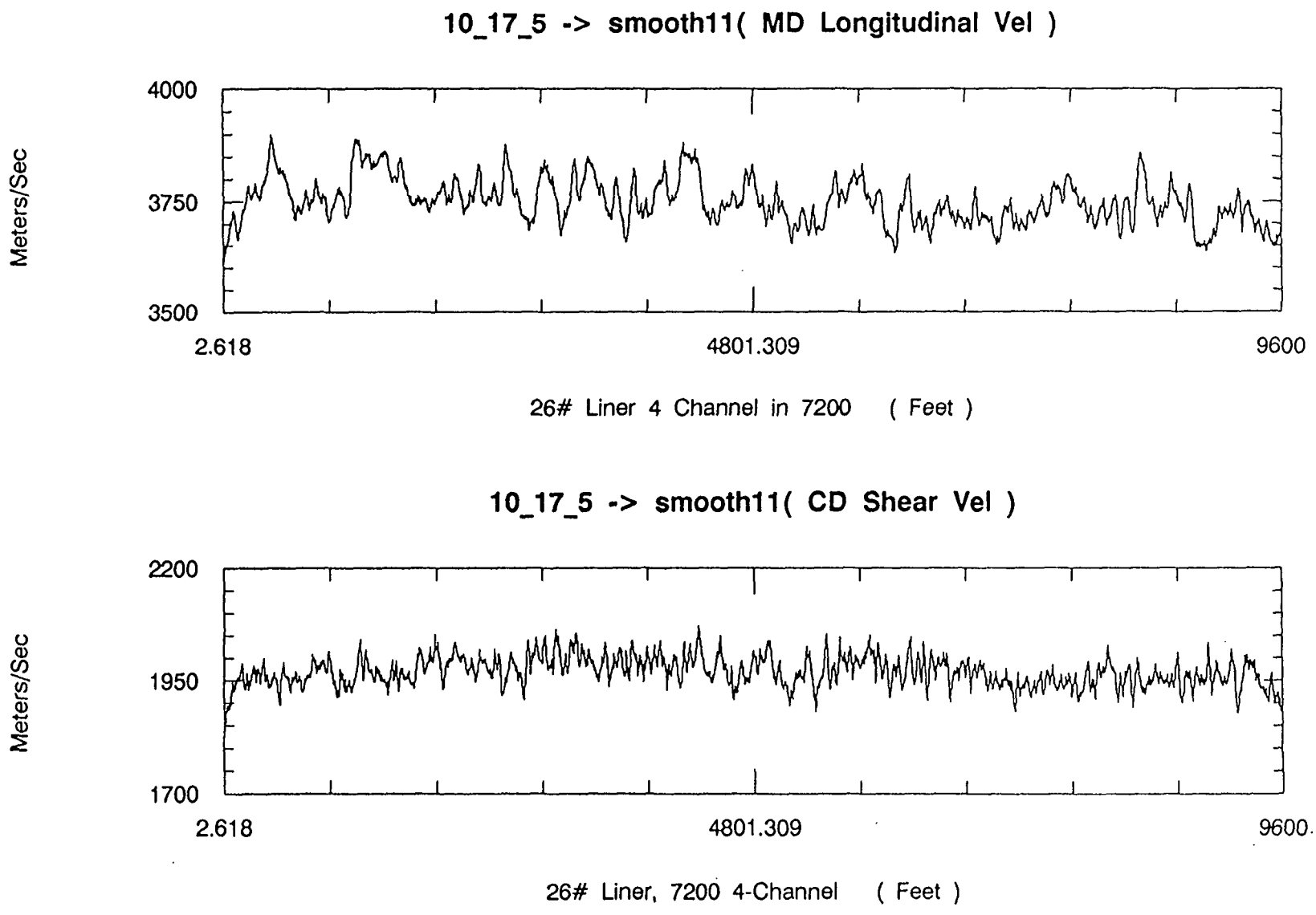


Figure 20. Smoothed data for the MD longitudinal and CD shear velocities for 9600 feet of 26-lb liner.

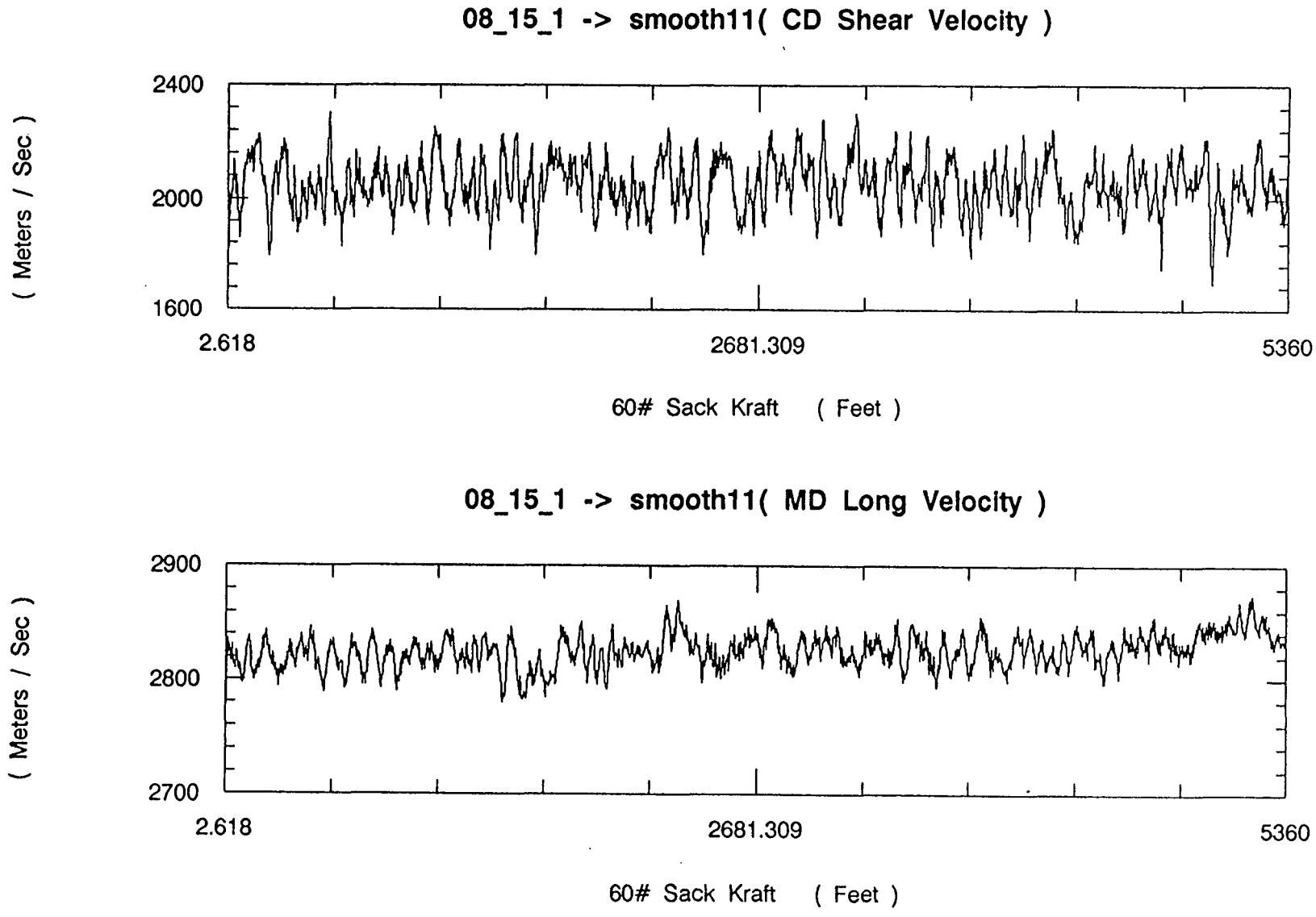


Figure 21. Smoothed data for the CD shear and MD longitudinal velocities for 5360 feet of 60-lb/3000-sq.ft. extensible sack kraft.

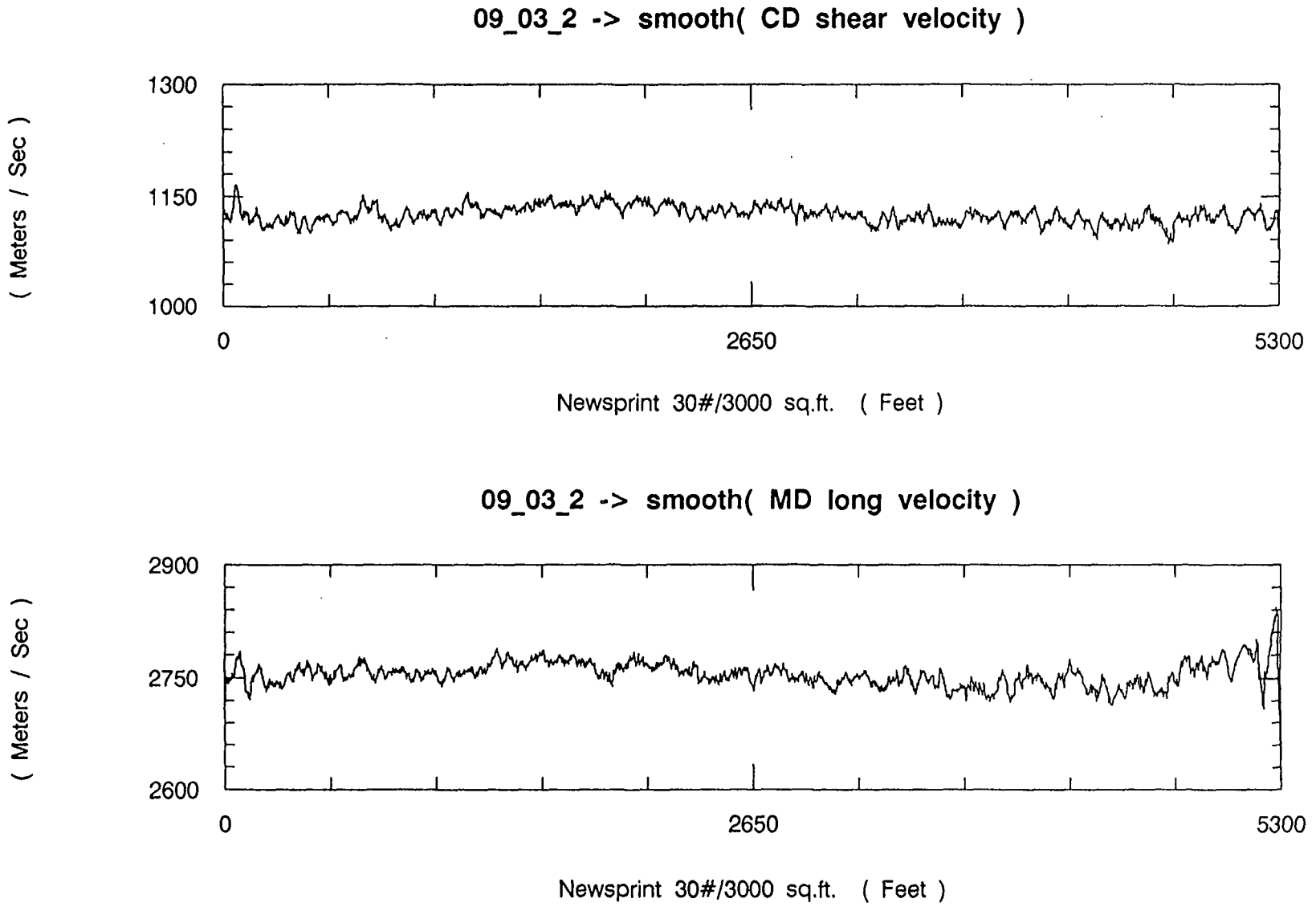


Figure 22. Smoothed data for the CD shear and MD longitudinal velocities for 5300 feet of 30-lb/3000-sq.ft. newsprint.

5300 feet of 30-lb/3000-sq.ft. newsprint.

Figure 23 shows smoothed data for the CD shear and MD longitudinal velocities for 5360 feet of stamp paper measured from the glue side.

Figure 24 shows the as collected data for the CD shear and MD longitudinal velocities for 5200 feet of 26-lb medium.

Figure 25 repeats the data of Fig. 24, but here plots the squares of the smoothed CD shear and MD longitudinal velocities, i.e, the respective specific stiffnesses for the 5200 feet of 26-lb medium.

Further examples of data analysis possible with the in-plane data are shown in Fig. 26 and 27. One can apply Fourier transform analysis to the measurements to determine whether there may be periodic effects in the data. Figure 26 shows the FFT power spectrum of the stamp paper data shown in Fig. 23. The x-axis in this plot is in reciprocal feet (1/feet). The double peaks near 0.2 are an artifact of the transform. The peak at 0.095 (near 0.1) in the CD shear velocity data indicates a 10.5-foot cycle. Peaks in the MD longitudinal velocity data at 0.04 and 0.17 indicate periods of 25 and 5.9 feet, respectively. Figure 27 shows the FFT power spectrum of the 26-lb medium data shown in Fig. 24. There is no significant peak in the CD shear velocity data, but peaks in the MD longitudinal velocity data at 0.064 and 0.127 indicate a fundamental and a harmonic of approximately 15.7 and 7.85 feet, respectively.

Another example of the type of information contained in the moving-web, in-plane velocity data is presented in Fig. 28. Here MD longitudinal velocity data are plotted for 3000 feet of data selected from longer runs of two different stamp papers. The plots use the same scale on the y-axis. A comparison shows that in addition to the average values of the velocities being different, the magnitude of the variation is much greater for Lot C than for Lot B. This suggests that the coefficient of variation of the in-plane velocity data may be useful as a measure of paper quality. Perhaps this is related to formation. This may be a fruitful area for further study.

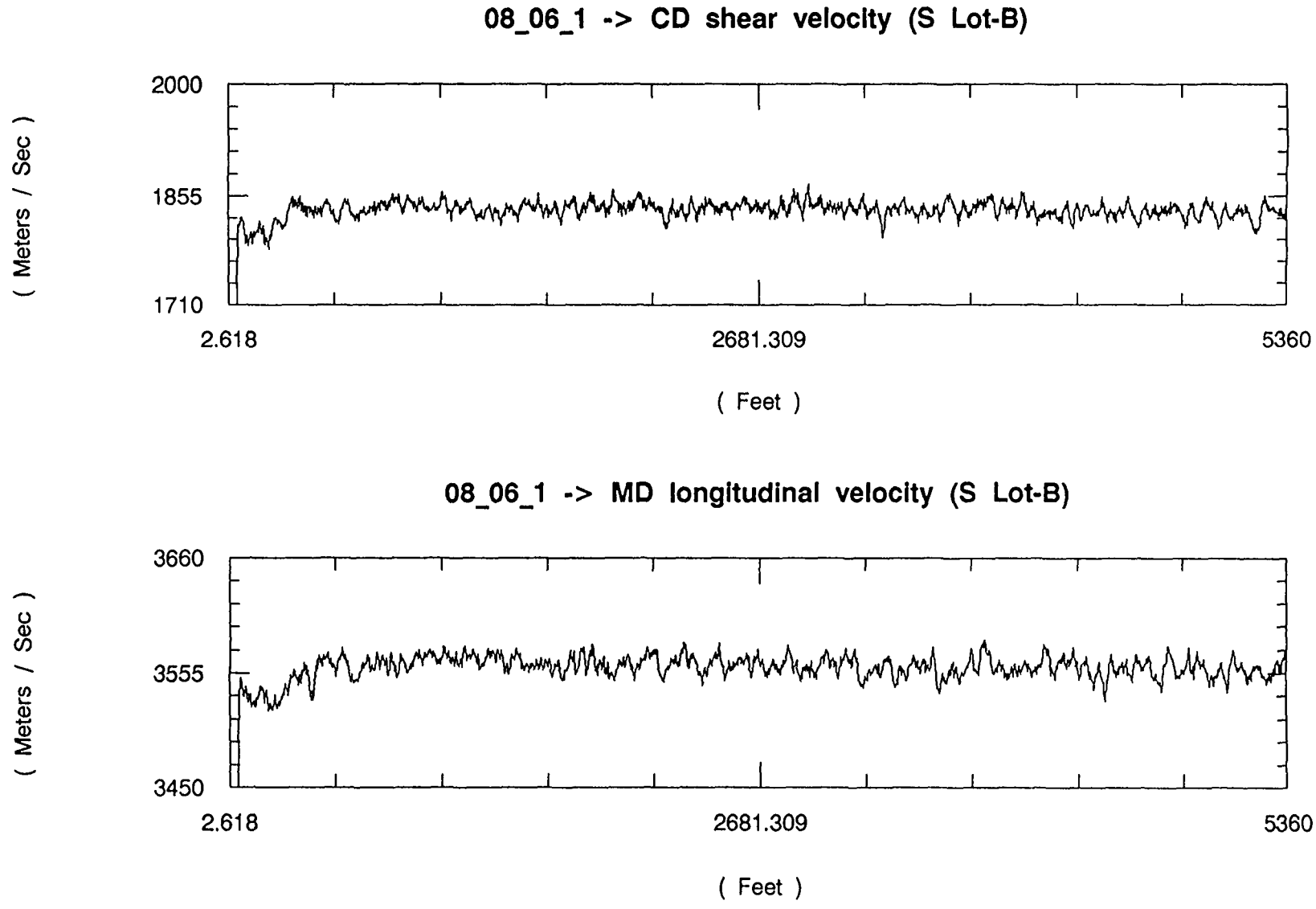


Figure 23. Smoothed data for the CD shear and MD longitudinal velocities for 5360 feet of stamp paper measured from the glue side.

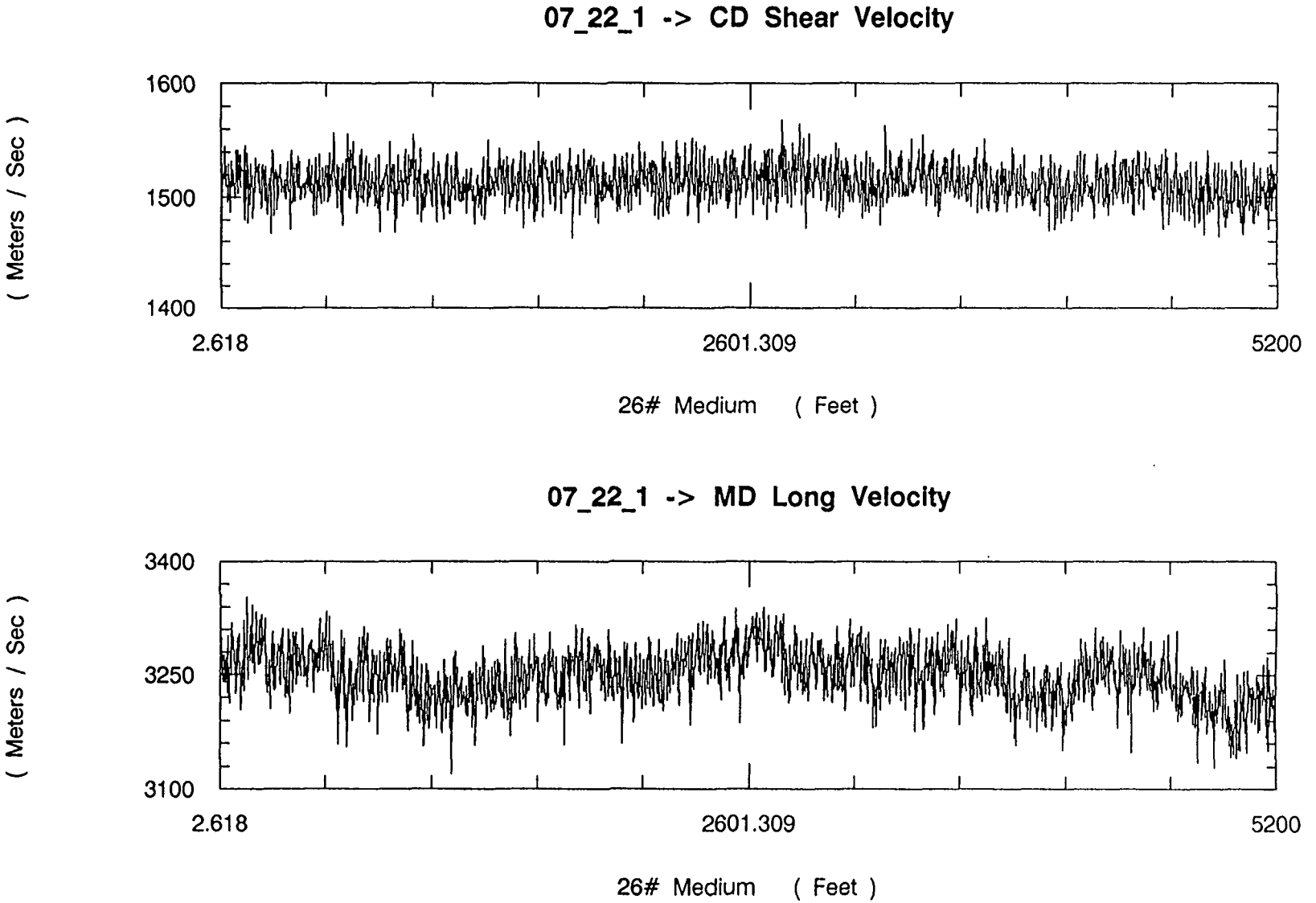


Figure 24. As-collected data for the CD shear and MD longitudinal velocities for 5200 feet of 26-lb medium.

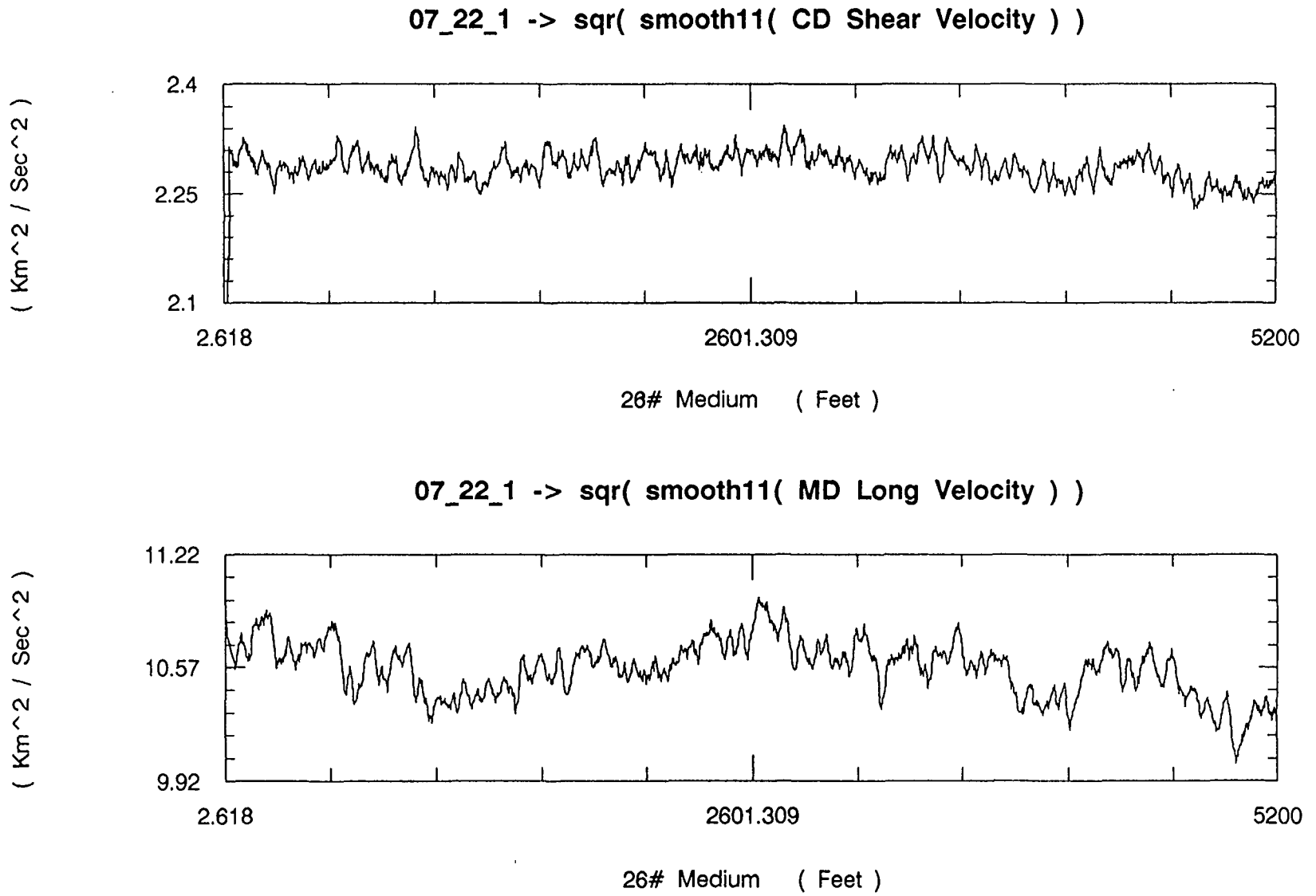


Figure 25. Repeat of the data of Fig. 24, but here the plots are squares of the smoothed CD shear and MD longitudinal velocities, i.e, the respective specific stiffnesses for the 5200 feet of 26-lb medium.

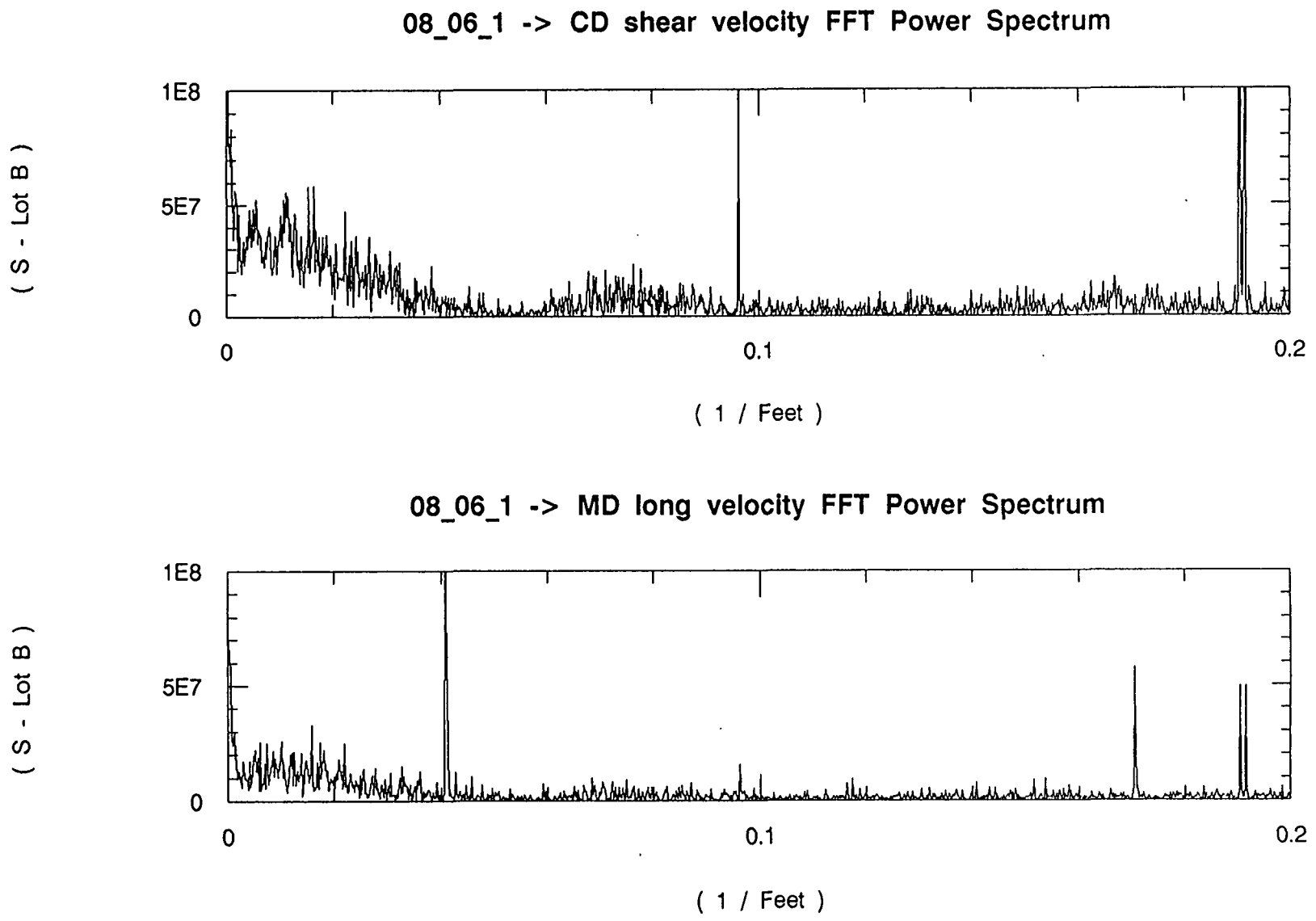


Figure 26. The FFT power spectrum of the data for the CD shear and MD longitudinal velocities shown in Fig. 23 for stamp paper.

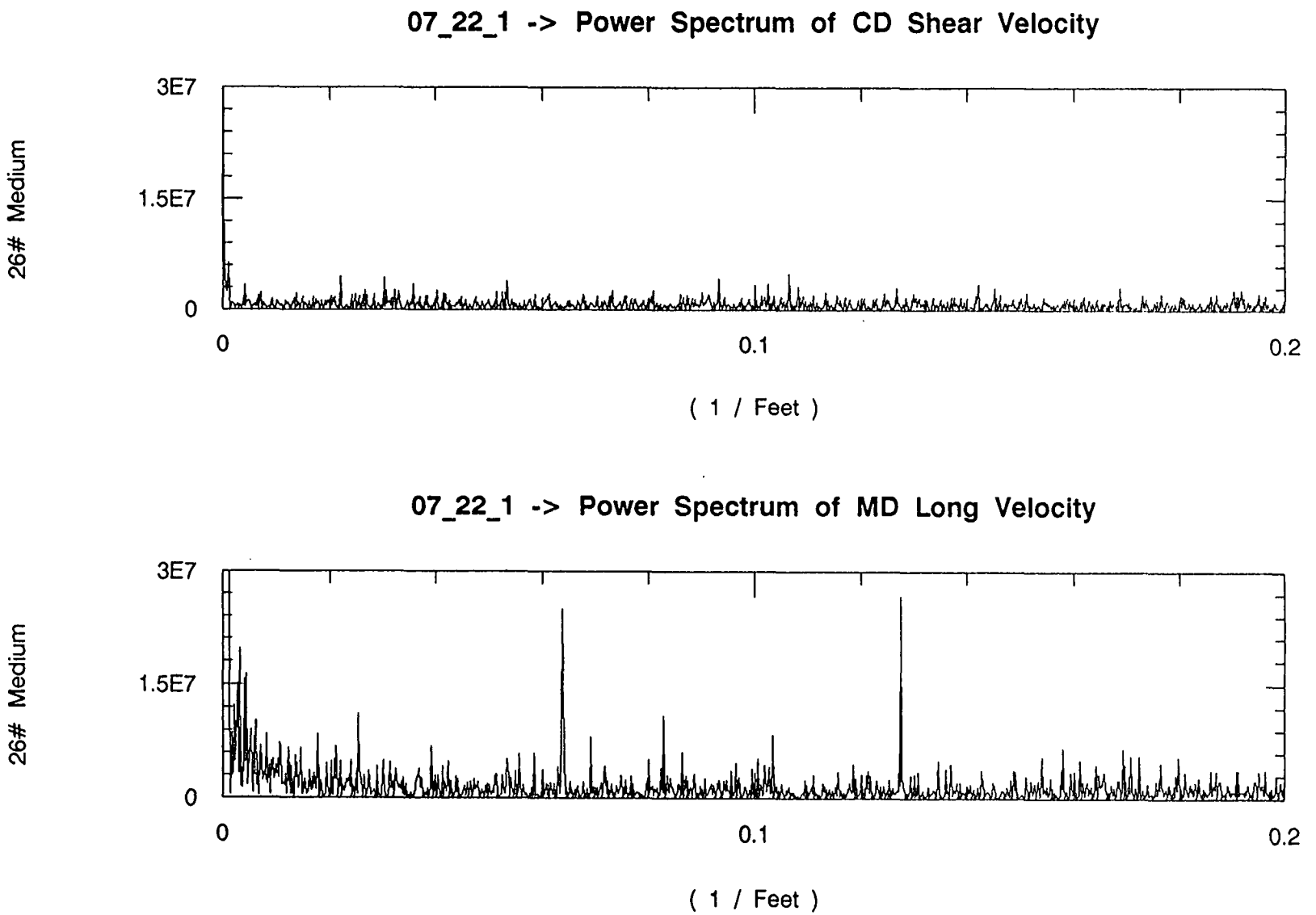
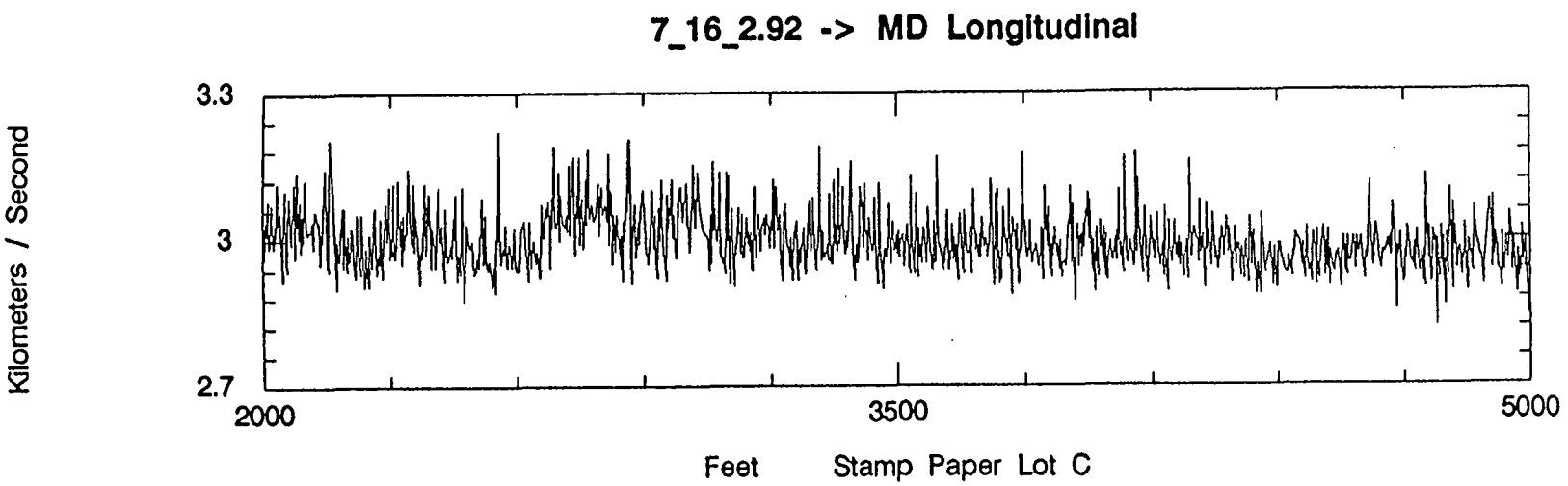


Figure 27. The FFT power spectrum of the 26-lb medium data shown in Fig. 24. The peaks in the MD longitudinal velocity data at 0.064 and 0.127 indicate a fundamental and a harmonic of approximately 15.7 and 7.85 feet, respectively.



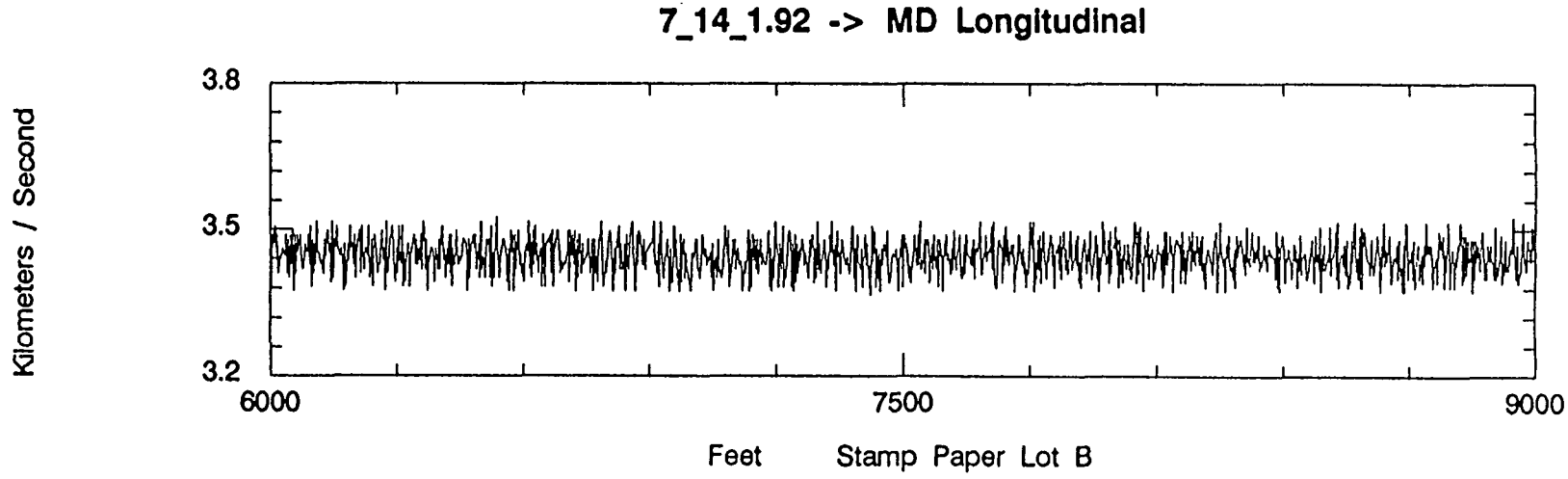


Figure 28. MD longitudinal velocity data plotted for 3000 feet selected from longer runs of two different stamp papers. The plots use the same scale on the y-axis. A comparison shows differences in the average values of the velocities, and the magnitude of the variation in velocity is much greater for Lot C than for Lot B.

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. Two sets of transducers were mounted at ±45 degrees and oriented to operate in the longitudinal mode. These two measurements at ±45 degrees are not sufficient to determine the exact "polar angle" (the angle of the direction of maximum stiffness relative to the MD), but do provide an indication of the in-plane stiffness alignment relative to the machine direction. The velocity ratio,

$$(V_{+45})/(V_{-45}), \tag{25}$$

or the difference of the squared velocities divided by their average,

$$2[(V_{+45})^2 - (V_{-45})^2] \,/\, [(V_{+45})^2 + (V_{-45})^2] \tag{26}$$

may be used to infer the "polar angle."

The ±45-degree transducer arrangement was used to take data on various rolls of paper. Figure 29 shows the longitudinal velocities measured at ±45 degrees for a roll of 69-lb liner. The x-axis is in data acquisitions or cylinder rotations (cylinder circumference = 2.618 feet), so the data cover 885 feet. The plot at the bottom of Fig. 29 shows the ratio of the +45 and -45 measurements. The ratio would be 1.0 for a "polar angle" of zero.

Figure 30 shows the ±45-degree data as recorded for the same six-section roll for which ZD data are presented in Fig. 9 and 13. The six 500-foot sections were: 42-lb liner (A), 42-lb liner (B), 69-lb liner, 42-lb liner (C), 26-lb medium, and 42-lb liner (A). There are a couple of "glitches" in the as-recorded data for the third and fourth sections. Figure 31 shows the smoothed (moving average) ratio, $(V_{+45})/(V_{-45})$, for the six-section roll.

In-plane polar specific stiffness measurements are now routinely performed on cut samples with the robot-based laboratory instrument, wherein velocity readings are recorded at every 5 or 10 degrees. The polar stiffness plot is normally 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 closely approximated from three distinct points, two points at ±45 degrees and one point in the MD 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. This was demonstrated by hand positioning a cross-reel strip (42-lb liner) over the in-plane drum and recording the MD and ±45 degree data at 2-inch intervals. The

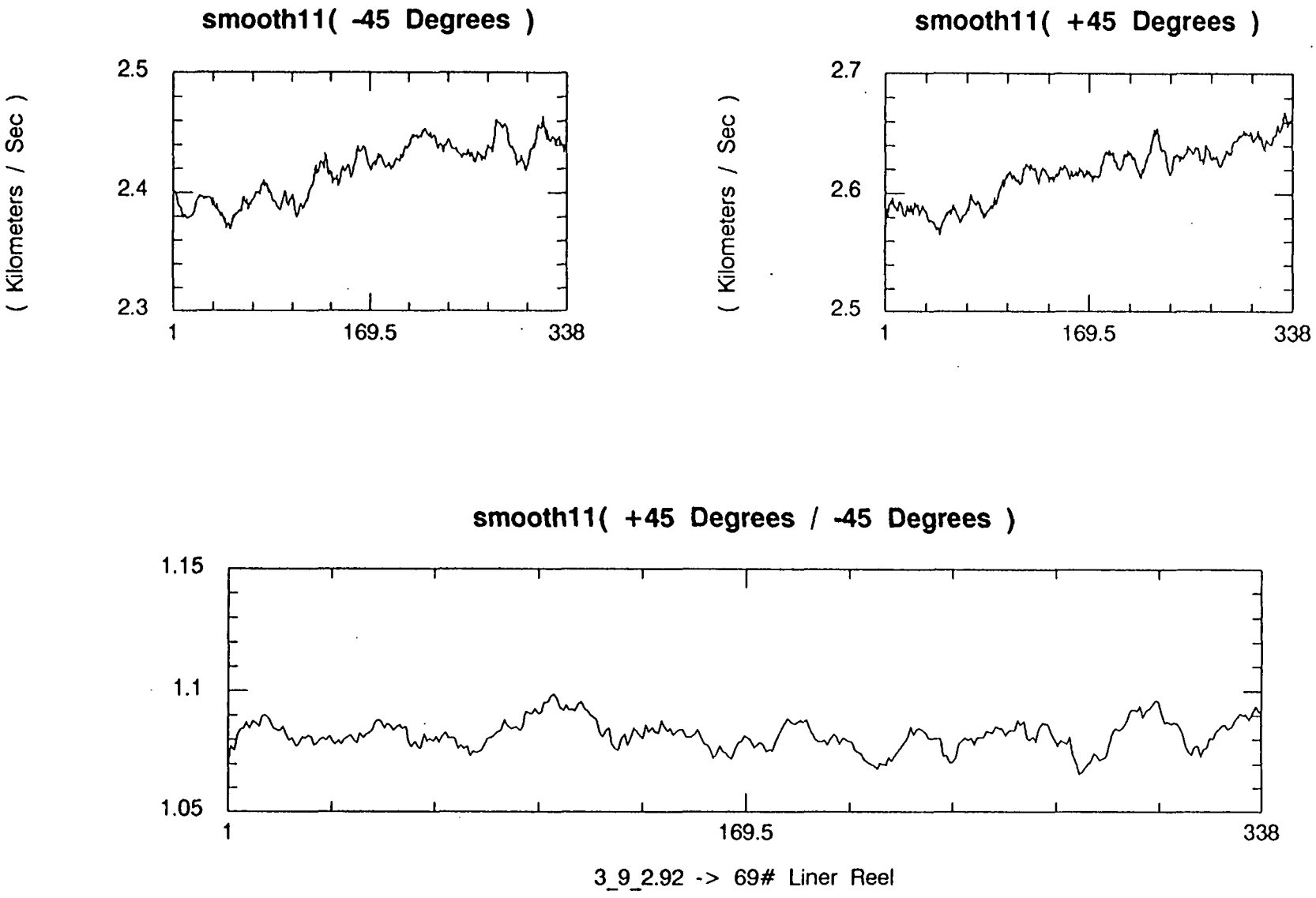
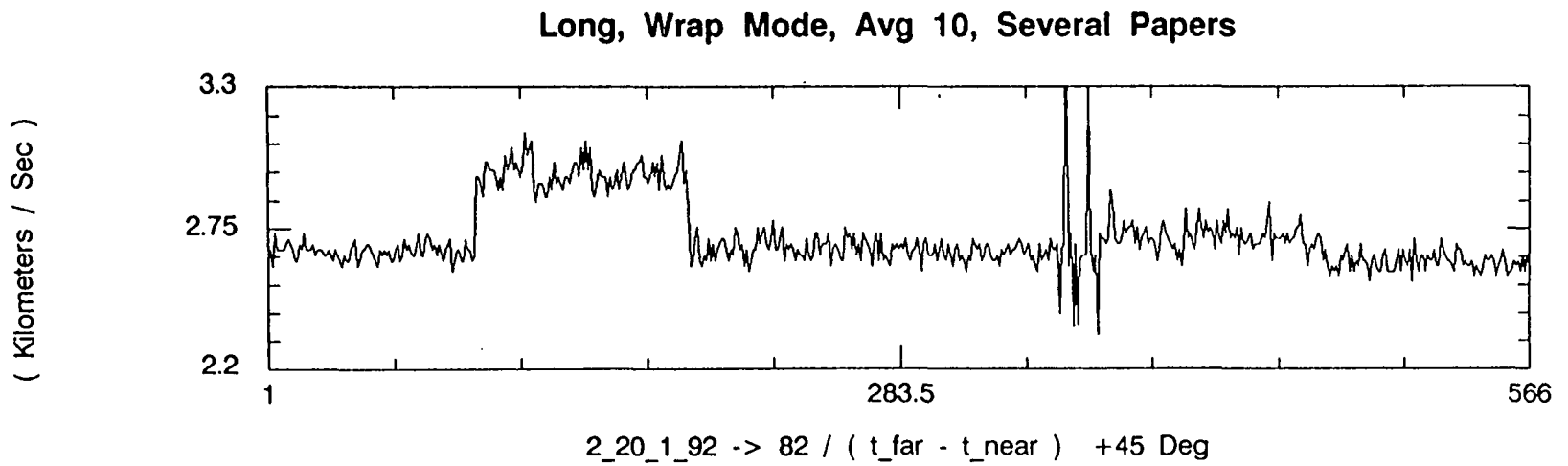


Figure 29. In-plane data showing the smoothed longitudinal velocities measured at ±45 degrees for a 885-foot roll of 69-lb liner. The bottom plot shows the ratio of the +45 and -45 measurements, which would be 1.0 for a "polar angle" of zero.



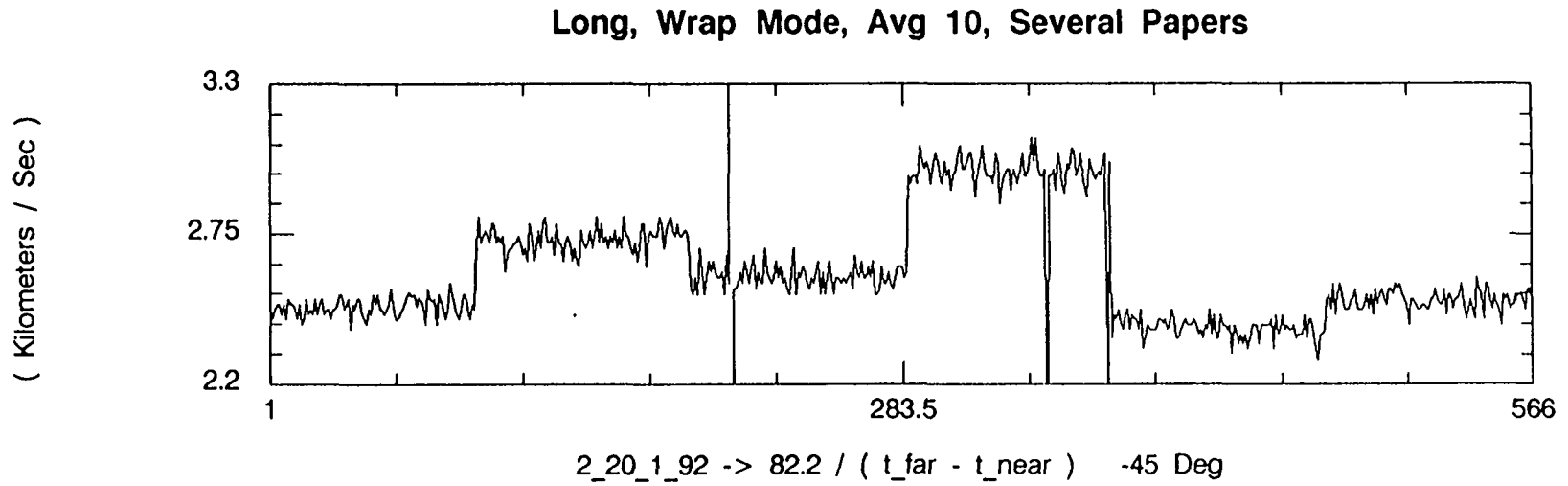


Figure 30. The ±45 degree data for the roll of six 500-foot sections: 42-lb liner (A), 42-lb liner (B), 69-lb liner, 42-lb liner (C), 26-lb medium, and 42-lb liner (A).

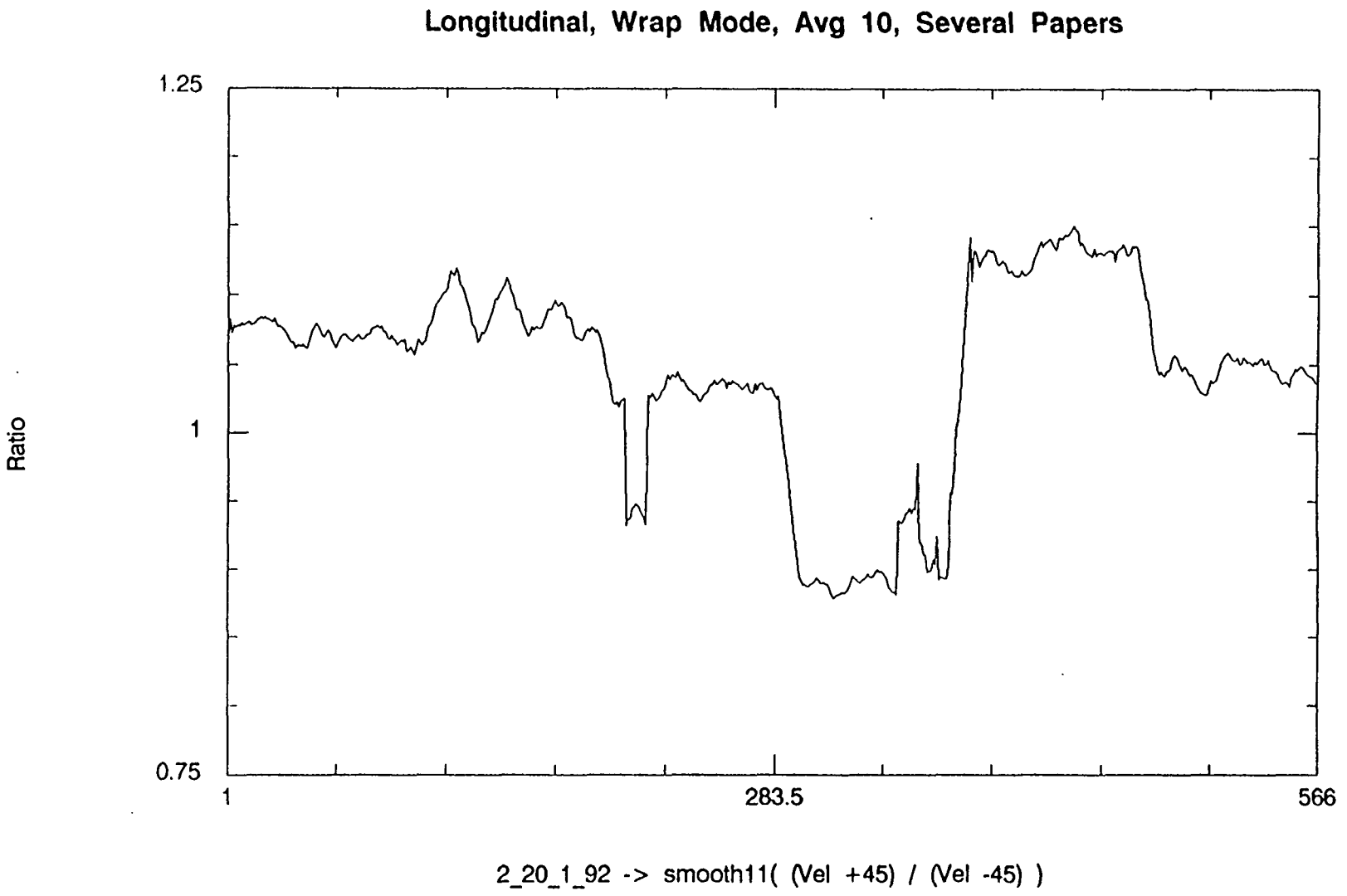


Figure 31. The smoothed (moving average) ratio, $(V_{+45})/(V_{-45})$, for the six-section roll data shown in Fig. 30.

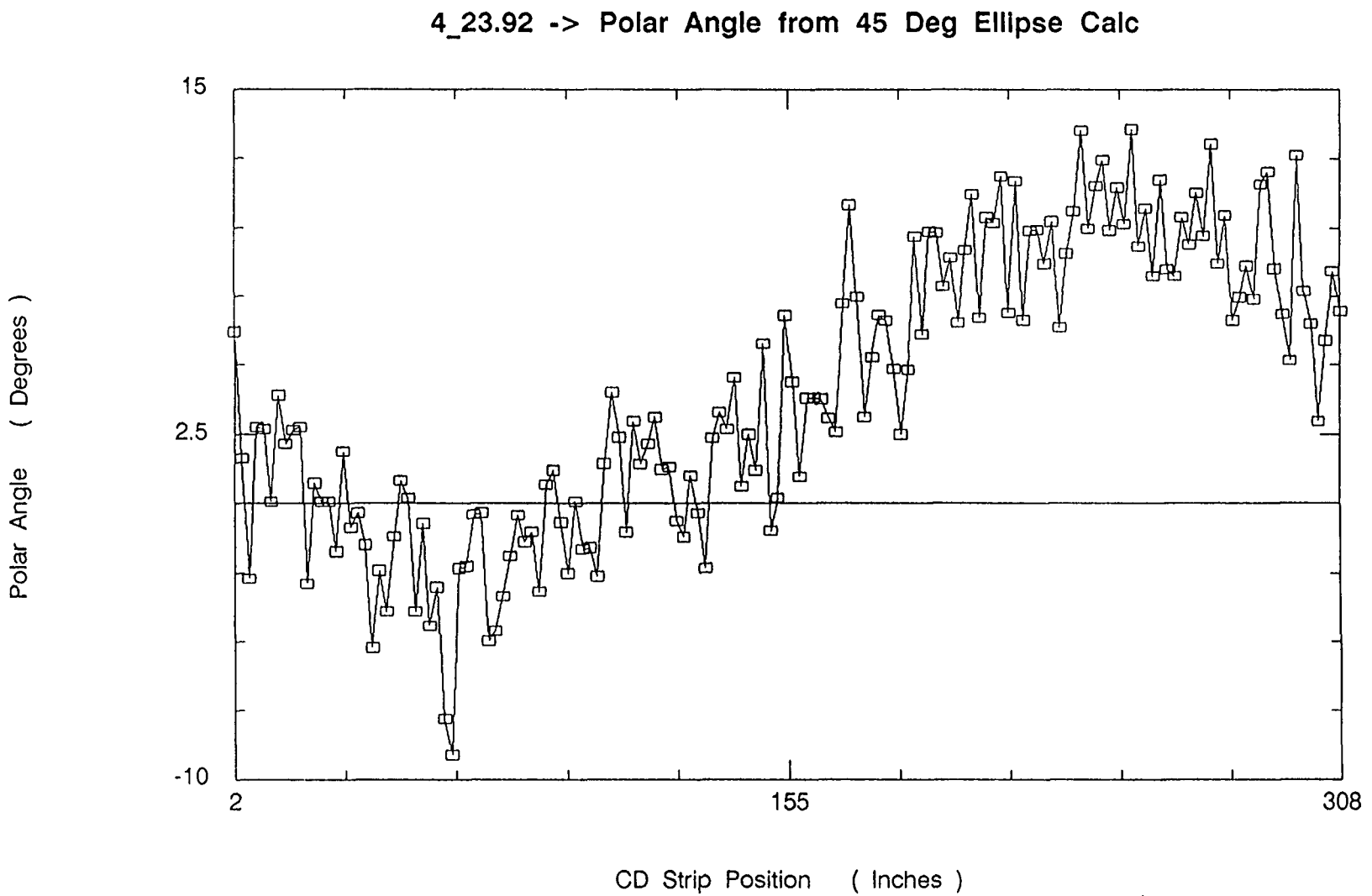


Figure 32. Polar angle data at 2-inch intervals for a cross-reel strip (42-lb liner), determined by fitting an ellipse to measurements in three in-plane directions, the MD, and ±45 degrees.

results are plotted in Fig. 32 to illustrate the type of data that could be obtained with on-line implementation.

The cylinder described above depends upon partial wrap and friction contact with the web in order to move at web speed. A system which would drive the above cylinder at web speed would have advantages over a friction-driven system. A synchronous system would place no inertial load on the web. Therefore, it may be useable with very thin papers. In addition, transducer life should be much longer, since the transducers would not be abraded by a possible web-to-transducer speed difference.

Synchronously Driven Wheels

The cylinder system with a partial wrap is appropriate for use with narrow webs. However, this system would not be useable in a scanning system for wider webs. The partial wrap system would be limited to applications where it is practical to use multiple transducer sets in a cylinder with a length greater than the width of the web (Burk, 1988). The following describes a system design, illustrated in Fig. 33, which provides the required interface of the transducers to a moving web in an embodiment suitable for scanning across a wide web.

This system includes three wheels, nominally 25 mm wide and 160 mm in diameter. The three wheels are positioned to contact the web tangentially, with two wheels placed above or on one side of the web and the third wheel placed below or on the other side of the web. The contact point of the third wheel is in line and preferable between the contact points of the two wheels above the web.

Each of the transducer wheels is driven by a servomotor with a control system to maintain rotational synchronization of the wheels. An encoder is used to measure the speed of the web as input to the control system to match the speed of the transducer wheels to the speed of the web.

Two wideband, bimorph, bender transducers, the same or similar to those described above, are mounted in each wheel in special spring-loaded carriers. The transducers are mounted 180 degrees apart within each wheel, with one transducer oriented to produce/receive longitudinal waves in the direction of rotation (MD) and the other oriented for shear waves. The transducers are mounted so that each active element protrudes slightly outside the circumference of the wheel. The spring loading is designed to minimize the variability in the contact force between the transducers and the web.

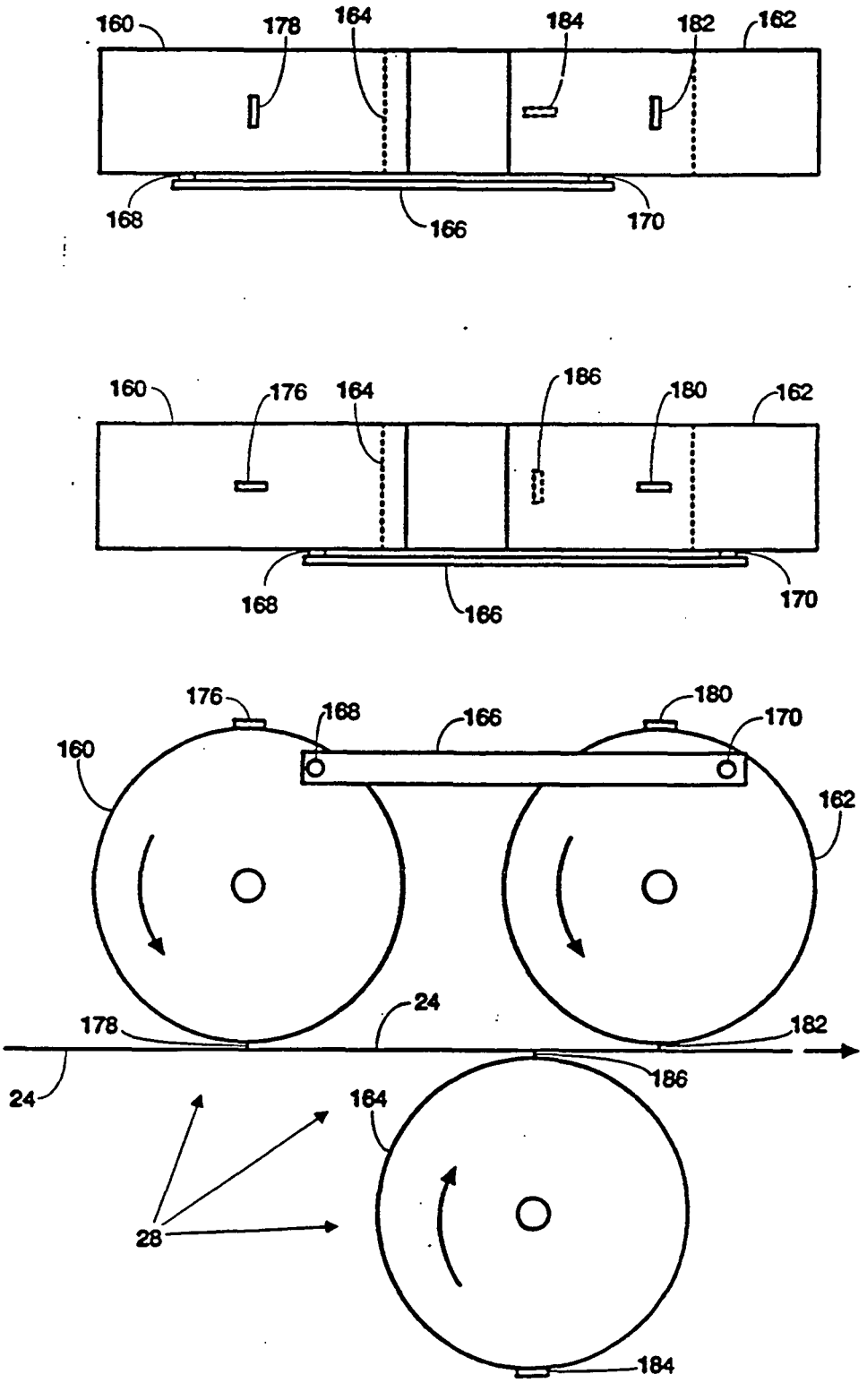


Figure 33. System design to interface the in-plane transducers to a moving web in a configuration suitable for scanning across a wide web.

The synchronous system may be mounted on an O-frame or C-frame instrument platform for cross-web scanning -- something not practical with a wrapped cylinder. Provision may be made to bring the transducers into or out of contact with the web by an appropriate extension/retraction mechanism. This permits the system to be scanned over the web from an off-web position, and then extended to contact the web with the wheels rotating at web speed.

The drive system functions such that the longitudinally oriented transducers in the three wheels are in contact with the web simultaneously during rotation, and the three shear-oriented transducers are in contact simultaneously one-half rotation later. The drive system matches the speed of the web without loading the web.

One could add two wheels to the shaft of one of the wheels or replace one of the wheels with a cylinder. Two sets of three transducers could then be aligned on opposite sides of this wheel set. These would enable one to make CD shear and CD longitudinal velocity measurements. In addition, MD longitudinal and MD shear velocities could be measured, and the web pass line would be maintained while scanning. However, for moving web measurements, it should be only necessary to measure the most convenient two of the following three: the CD longitudinal velocity (V_{CD}), the MD longitudinal velocity (V_{MD}), and the shear velocity (V_{SH}). The third velocity can be calculated using the empirical relationship (Baum et al., 1981),

$$(V_{SH})^2 = 0.387\ (V_{MD})(V_{CD}). \tag{27}$$

The above configuration has several advantages over the Microscan Sensor (Vahey, 1987). First, wideband, bender transducers rather than the larger 1-inch by 0.25-inch resonant transducers (Bokowski and Vahey, 1987) are used here. The CD span of the transducers in the Microscan Sensor is 10.5 inches. Thus, a narrow moisture or basis weight streak would be averaged over this distance, whereas our configuration would be sensitive to CD variations with higher resolution. The Microscan Sensor makes tangential contact from one side of the web. This causes a deflection of the web from the pass line. This makes it particularly difficult to maintain good contact as web tension decreases near the edges. In our configuration, the pass line is maintained by having wheels on both sides of the web with an independent wheel rotation drive system. The Microscan Sensor measures the CD longitudinal velocity and the CD shear velocity and calculates the MD longitudinal velocity, using the relationship in Eqn. 27,

$$V_{MD} = 2.58\ (V_{SH})^2/V_{CD}. \tag{28}$$

Since the shear velocity, V_{SH}, should be the same whether measured in CD or MD, we measure both the longitudinal velocity and the shear velocity in the MD, and using Eqn. 27 calculate the CD longitudinal velocity,

$$V_{CD} = 2.58\ (V_{SH})^2/V_{MD}. \tag{29}$$

By making both longitudinal and shear velocity measurements in the MD, short-range CD variations should be resolved as the system scans across the web. Figure 34 is an example of data taken with transducer sets aligned in the MD to measure MD shear and MD longitudinal velocities for 4600 feet of a 26-lb liner. The lower left quadrant of Fig. 34 shows the application of Eqn. 29 to calculate the CD longitudinal velocity from the smoothed data recorded in the upper half of the figure. The lower right quadrant shows the calculated MD/CD stiffness ratio using the measured MD longitudinal velocity and the calculated CD longitudinal velocity.

A third configuration would provide on-line determinations of the in-plane polar specific stiffness. This would involve the addition of two wheels to the shaft of one of the wheels or extension of one of the wheels into a cylinder, as mentioned above, with the added transducers oriented at ±45 degrees to the MD (see Fig. 35). A transmitter on the lower wheel would be positioned such that the angle between it and each outer transducer would also be ±45 degrees. These two 45 degree measurements and the MD longitudinal measurement would determine three points to define an ellipse. This would allow nondestructive, on-line determination of polar stiffness values, such as polar angle and area.

Figure 36 shows the wheel design for mounting the transducers. Space is provided for mounting on-board preamplifiers. Electrical communication with the preamplifiers and transducers would be provided through slip rings at the end of the shaft. Figure 37 illustrates how the wheels would be mounted along with servo motors and shaft encoders.

The synchronous "three-wheel" configurations described above continue the use of transducers in sets of three. This provides velocity measurement by determining the transit time difference over different distances. It may be possible to simplify the hardware required; for example, use no transducers in the bottom wheel. The system would then use transducers in sets of two (transmitter and receiver). A technique to calibrate for time delays in the circuitry would be required.

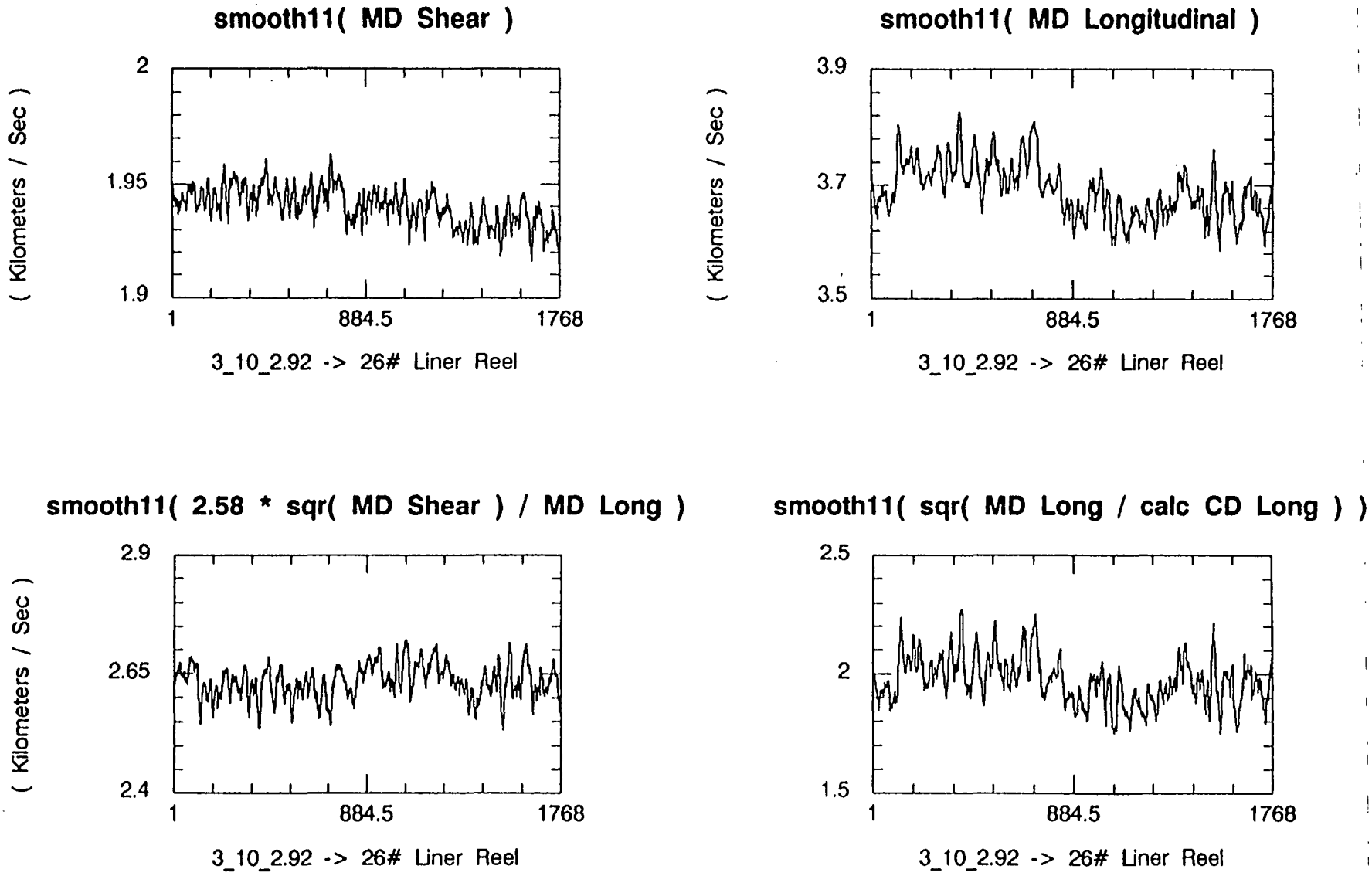


Figure 34. Example of in-plane data measured with transducer sets aligned in the MD to measure MD shear and MD longitudinal velocities for 4600 feet of a 26-lb liner. The lower left quadrant shows the calculated CD longitudinal velocity, and the lower right quadrant shows the calculated MD/CD stiffness ratio.

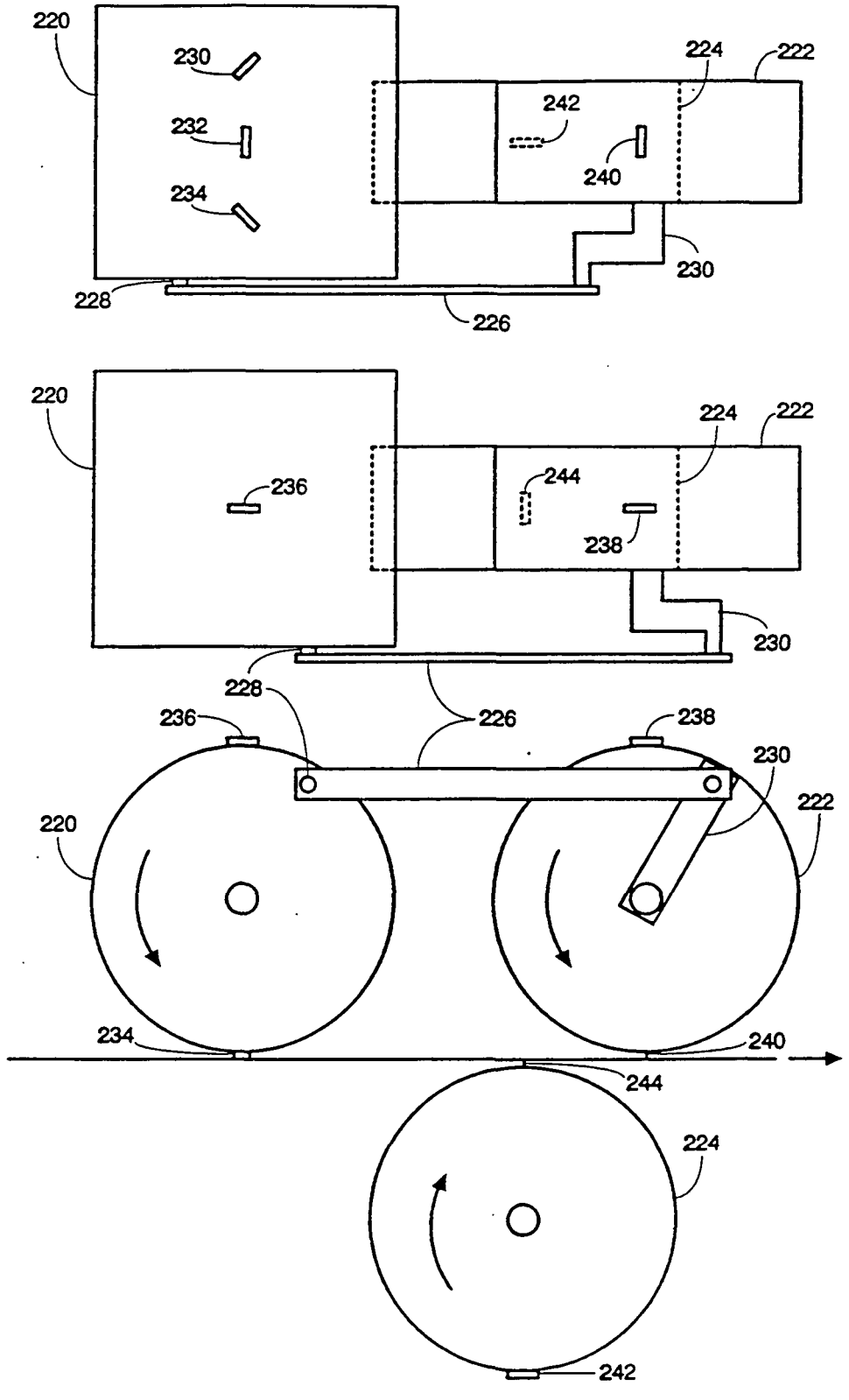


Figure 35. System design that would provide on-line determinations of the in-plane ultrasonic velocity ellipse and "polar angle." This configuration would be suitable for scanning across a wide web.

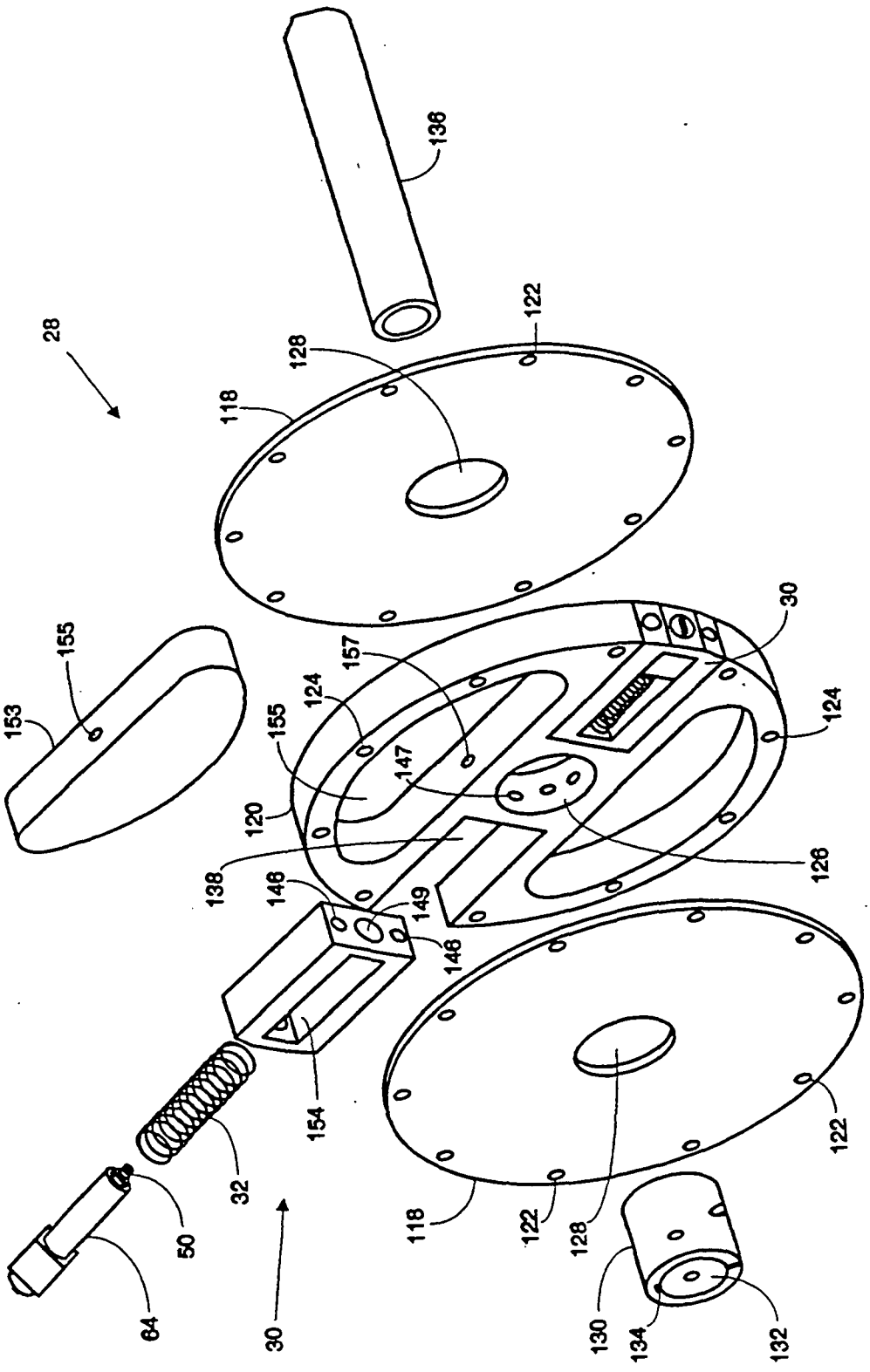


Figure 36. The wheel design for mounting the in-plane transducers.

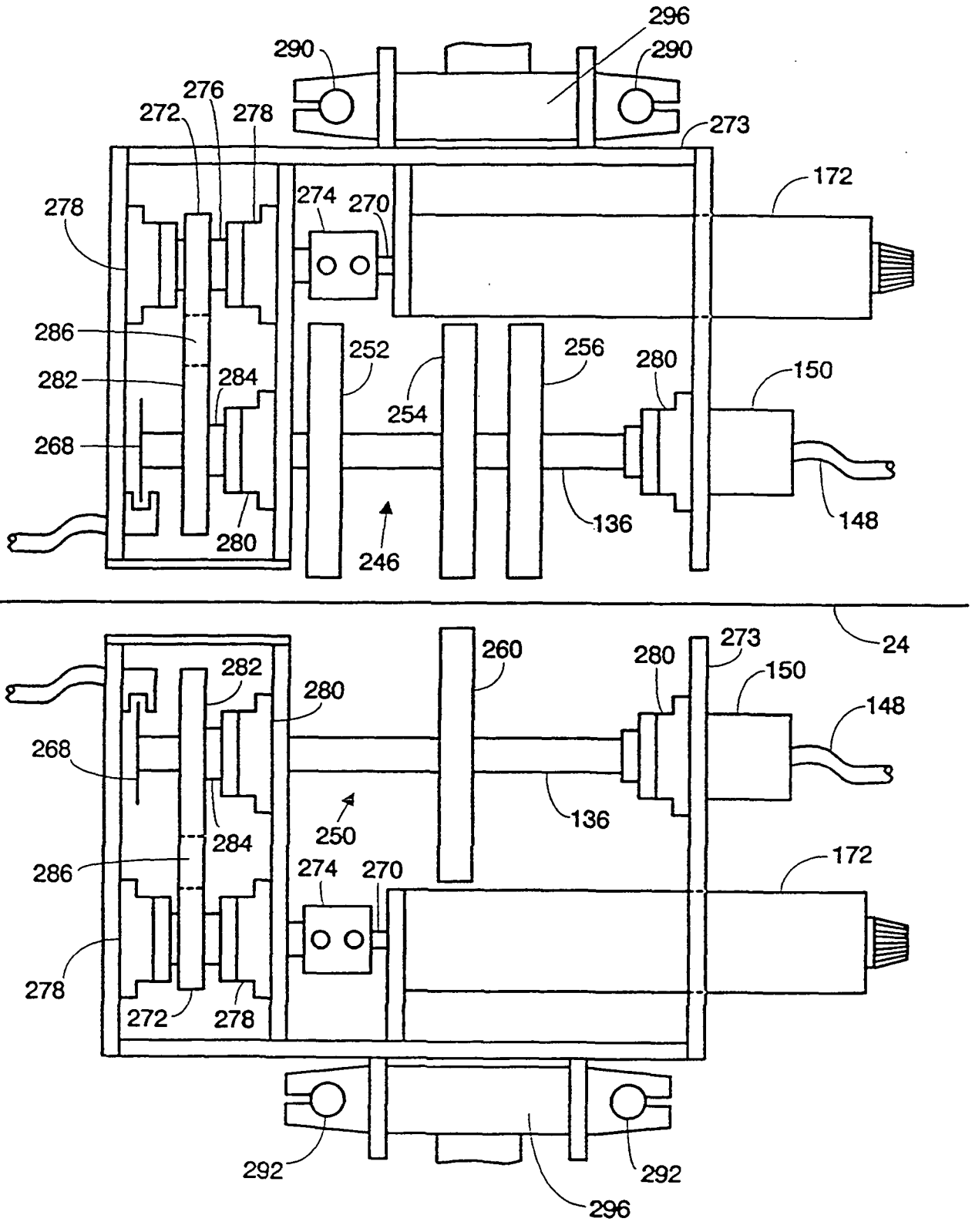


Figure 37. Drawing showing how the wheels would be mounted along with servomotors and shaft encoders in a synchronously driven wheel system.

CONCLUSIONS

This project has succeeded in identifying the fluid-filled wheel configuration as a promising sensor for making ZD ultrasound velocity measurements on the paper machine. Testing and evaluation in the laboratory on a web handling system have identified and solved unique requirements for achieving accurate ZD velocity measurements through moving paper webs.

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 ZD measurements are sensitive to temperature changes in the fluid-filled wheels. 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.

A caliper measurement is required along with the transit time through the sample in order to calculate the ZD velocity of ultrasound. Either multireflected ultrasonic pulses in the fluid-filled wheels or an independent caliper gauge may be used to determine the web caliper. The main advantage of an independent gauge is that it is less sensitive to temperature changes. 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.

For in-plane measurements on moving paper webs in the laboratory, small bimorph, bender transducers are mounted in the surface of a 10-inch diameter aluminum cylinder. A special transducer housing and carrier were designed for mounting the transducers in the cylinder. The housing is square to maintain rotational alignment of the bender transducer. Relatively weak spring loading is used in the carrier to minimize variation in the contact force between the transducers and the web.

In addition to various MD and CD longitudinal and shear measurement configurations, provision is also included in the cylinder to mount transducer sets at ±45 degrees to the machine direction. These two measurements can be used to indicate the in-plane stiffness alignment relative to the machine direction, i.e., the "polar angle." Data recorded for the MD and the ±45 degrees can be used to define an ellipse which provides a good approximation to the standard polar test for polar angle and polar plot area.

The cylinder system requires a partial wrap, which is appropriate for use with narrow webs. However, this system would not be useable in a scanning system for wider webs. A system has been designed, which provides the required interface of the transducers to a moving web in a configuration suitable for scanning across a wide web. This system includes three synchronously driven wheels positioned to contact the web tangentially, with two wheels placed above or on one side of the web and the third wheel placed below or on the other side of the web. The contact point of the third wheel is in line and preferable between the contact points of the two wheels above the web. This configuration could be scanned and would maintain the pass line with minimum sensitivity to web tension variation. The design could be extended to include the capability to determine polar stiffness values on-line.

In summary, both ZD and in-plane ultrasound velocity data have been collected in the laboratory on a variety of commercial paper grades. The ZD fluid-filled wheel sensor system is believed to be ready for engineering development into a prototype system on the path toward commercialization. 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 synchronously driven "three-wheel" system designed for making in-plane measurement with a configuration that can be scanned appears to have merit. However, detailed design, construction, and testing remain before the concept can be confirmed to be worthy of prototype development.

Two patent applications, covering the significant elements of this project, were filed with the U.S. Patent Office on November 3, 1992. One is titled, "Out-of-Plane Ultrasonic Velocity Measurement." The other is titled, "In-Plane Ultrasonic Velocity Measurement."

RECOMMENDATIONS

In view of the potential benefits and status of this technology, it is recommended that future activities be directed along the path toward commercialization of on-machine ultrasound velocity measurement.

An early essential step is the establishment of a working relationship with a vendor of instrumentation and control systems for paper machines. This vendor must be committed to developing ultrasonic velocity sensors and then supplying and supporting the systems for the paper industry.

The IPST web handling system with its current in-plane and ZD measurement instrumentation should be used to evaluate prototypes in preparation for testing on a pilot paper machine or at a host mill test site. Continued development of the ZD sensor by IPST should include incorporating the data collection and data processing hardware and software of the vendor.

Following development of engineering and production prototype systems, extensive on-machine testing and performance demonstration will be required to gain acceptance by the paper industry. A multiyear development and testing program will be needed along with significant investment to ensure success.

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CONTRACT NO. DE-ACO5-86CE40777 - REPORTS

The project status, progress, and plans were presented periodically at DOE/Industry Sensor Technical Conferences. The reports are published in the following proceedings for these conferences:

"Proceedings of the DOE/Industry Advanced Research and Development Sensor Working

Group Members Meeting," Chicago, Illinois, CONF-8704186 (DE87013939), April 30, 1987.

"Proceedings of the DOE/Industry Advanced Research and Development Sensor Working Group Meeting," Phoenix, Arizona, CONF-8711169 (DE88007713), November 13, 1987.

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"DOE/Industry Advanced Sensors Technical Conference," Atlanta, Georgia, November 12-13, 1990.

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Hall, M.S., and Habeger, C.C. "On-Machine Sensors to Measure Paper Mechanical Properties," Report One DOE/CE/40777-T1 (DE89005579) (October 1988).

Presentations and papers reviewing work supported in part by this contract:

Habeger, C.C., Wink, W.A., and Van Zummeren, M.L., "Automated Measurements of Out-of-Plane Ultrasonic Elastic Stiffnesses in Paper," IPST Tech. Paper Series 301 (August 1988).

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Dr. Charles C. Habeger provided scientific leadership in the research and application of ultrasound velocity techniques at The Institute of Paper Chemistry (now IPST) in Appleton, Wisconsin, until his departure in March 1989. His significant contributions to the background and early work of this project are gratefully acknowledged.

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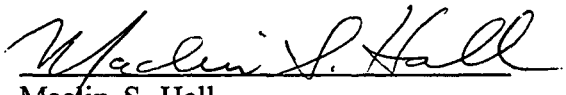

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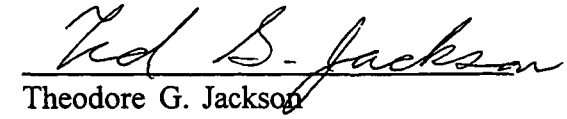

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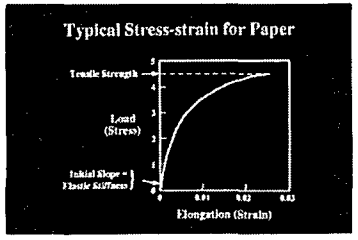
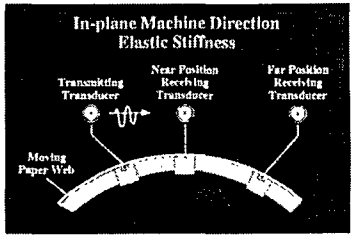
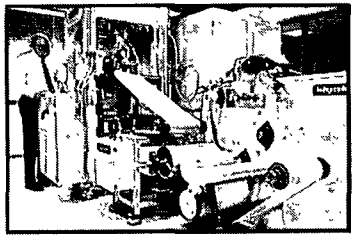
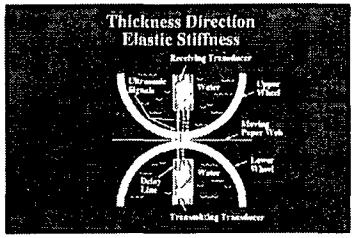
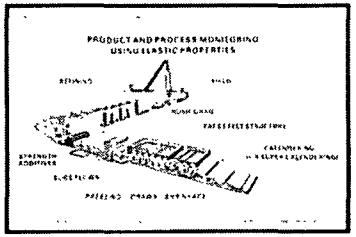
Productivity through Technology





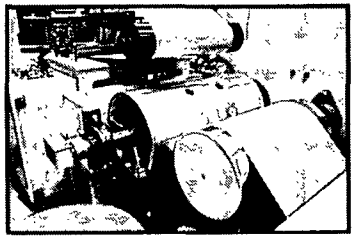


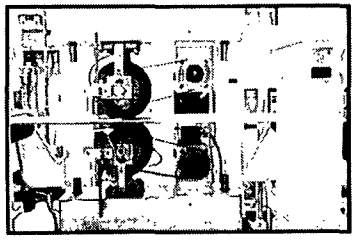




Ultrasound provides nondestructive measure of elastic stiffness:

$$\left[\frac{\text{Ultrasound}}{\text{Velocity}}\right]^2 = \frac{\text{Elastic Stiffness}}{\text{Sheet Density}}$$





Benefits:

- data for process control
- improved product uniformity
- increases energy efficiency
- increases use of recycled fiber
- reduces reprocessing
- increases productivity
- technology transfer

In-plane (MD & CD) and thickness direction (ZD) stiffnesses:

- are sensitive indicators of paper machine performance
- are measures of product quality
- can predict end-use performance

Elastic stiffnesses affected by papermaking process parameters:

Furnish
Recycle Content
Refining
Strength Additives
Rush/Drag
Slice Flows
Pressing
Draws
Shrinkage