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ON-MACHINE SENSORS TO MEASURE PAPER MECHANICAL PROPERTIES

Report One

**By
Maclin S. Hall
Charles C. Habeger, Jr.**

October 1988

Work Performed Under Contract No. AC05-86CE40777

**For
U. S. Department of Energy
Office of Industrial Programs
Washington, D.C.**

**By
The Institute of Paper Chemistry
Appleton, Wisconsin**

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Project No. 3613

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Office of Industrial Programs
U.S. Department of Energy
Conservation and Renewable Energy

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ON-MACHINE SENSORS TO MEASURE PAPER MECHANICAL PROPERTIES

SUMMARY

Nearly all paper grades must meet some type of mechanical property specification. However, mechanical tests 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.

Sensors 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 and a more uniform product could be manufactured. The latter, in turn, would result in more efficient operation of associated converting operations.

With a recognized potential for significant savings in energy and improved product uniformity by on-machine measurement and control of certain paper mechanical properties, the Department of Energy is supporting this research project at The Institute of Paper Chemistry.

Previous research at The Institute of Paper Chemistry has demonstrated that ultrasound velocity techniques may be used to make nondestructive measurements of the three dimensional elastic stiffnesses of paper. These mechanical properties are indicators of product quality and also can be correlated with the end-use strength specifications used in the paper industry.

Ultrasonic sensor instrumentation capable of on-machine measurements of elastic stiffnesses in the plane of the paper was developed at The Institute

of Paper Chemistry (Baum, 1980; U.S. Patent 4,291,577; Habeger, Baum, 1986). However, this instrumentation was incapable of measuring out-of-plane elastic properties. It is important to be able to measure elastic stiffnesses in both the plane and thickness directions, because this will enable us to separate the effects of different paper machine variables.

Therefore, the initial thrust of this four-year program, which began October 1, 1986, is to develop an ultrasonic sensor capable of on-machine measurement of elastic stiffness in the thickness direction of paper. This sensor would then be integrated with an appropriate in-plane sensor to provide a complete system to measure paper mechanical properties on the paper machine. This report presents the progress to date toward these objectives.

Two approaches for making on-line ZD sensors have been developed: the IPC, neoprene-faced wheel transducers; and the fluid-filled wheel transducers. Our work to date has demonstrated that each of these has the potential of on-machine determination of caliper and longitudinal ultrasonic velocity in the thickness direction of paper. Work with both transducer approaches is continuing.

For in-plane measurements, we are experimenting with surface-hardened, bimorph or bender transducers. These offer potential advantages over transducers used in previous on-line, in-plane work in that they are broadbanded and have a much smaller area of contact with the web.

OVERVIEW AND OBJECTIVES

Substantially all paper grades must meet some type of mechanical property specification. However, mechanical tests 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 perhaps 25 minutes, or more, have elapsed after reel turnup. Therefore, perhaps one hour's production of substandard material would have to be repulped and reprocessed to meet specifications.

An hour of substandard production per day would represent about 4% of a paper machine's production. Repulping and remanufacture requires about 13.8 million BTU per ton (Hersh, 1981). If 4% of the annual 70 million tons of paper and board produced by the industry requires reprocessing, the energy wasted by substandard production may be as much as 0.04 Quads (40,000,000,000,000 BTU) annually, an approximate value of \$160,000,000/year at \$4.00/million BTU.

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 and a more uniform product could be manufactured. The latter, in turn, would result in more efficient operation of associated converting operations.

With the recognized potential for significant savings in energy and improved product uniformity by on-machine measurement and control of certain

paper mechanical properties, the Department of Energy is supporting this research project at The Institute of Paper Chemistry.

This project is a four-year program which began October 1, 1986. The work may be separated into two distinct parts and four phases. Part I (Phases 1 and 2) is being emphasized to date, and Part II (Phases 3 and 4) will be initiated upon successful completion of Part I.

Part I: The development of suitable sensors to measure the desired sheet properties.

Phase 1. Design and construction of a sensor to make on-machine measurements of elastic stiffnesses in the thickness direction of the paper.

Phase 2. Integration of the thickness-direction sensor with an improved in-plane sensor.

Part II: The application of these ultrasonic sensors to the automatic control of the paper manufacturing process.

Phase 3. Machine-direction control of the papermaking process.

Phase 4. Cross-machine-direction control of the papermaking process.

Part I of this project is specifically concerned with the development of a sensor to make on-machine measurements of elastic stiffnesses in the thickness direction of the paper and the integration of this sensor with an appropriate in-plane sensor. Upon completion of Part I (Phases 1 and 2), we expect to be able to independently monitor the effects of refining, jet-to-wire speed ratios, and draws (and the related drying restraints) on paper properties. This means that we should be able to control these three machine variables continuously and independently during the manufacturing process. Part II of the project will then be concerned with the development of algorithms, hardware, and software necessary to control these variables on the paper machine in the

machine direction (Phase 3) and the cross-machine direction (Phase 4). Project objectives call for a successful demonstration of the sensor and control scheme on a laboratory scale paper machine. Success would lead to further work on a pilot scale and eventual scale-up to a full size paper machine.

BACKGROUND

Research at The Institute of Paper Chemistry (Mann, 1979) has demonstrated that it is possible to use ultrasound velocity techniques to make nondestructive measurements of certain paper sheet properties that are indicators of product quality and also can be correlated with the end-use strength specifications used in the paper industry.

Paper is normally treated as an orthotropic elastic material requiring nine elastic parameters to describe its mechanical behavior (Habeger, 1979). The three principal orthogonal directions are taken as the machine direction (MD), the cross machine direction (CD), and the 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, 1979; Mann, 1979; Mann, 1980; Habeger, Wink, 1986). The effects of machine and process variables on these seven parameters has been the subject of extensive staff and student research at The Institute of Paper Chemistry. The sensitivity

of elastic parameters to yield, refining, fiber orientation, wet pressing pressure, wet straining, and drying restraints have been studied in recent years (Baum, 1981; Fleischman, 1982; Baum, 1983; Berger, 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, 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 (normally measured off-machine) suggest that these tests may be replaced by a set of non-destructive 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 their sensitivity to paper machine variables, and the desire to use the measurements to actually control the paper manufacturing

process, sensors that measure elastic stiffnesses would be mounted on the dry end of the paper machine just ahead of the reel. We envision that these sensors would be mounted along side the basis weight gage and moisture gage 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 as inputs to our sensors, 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 The Institute of Paper Chemistry (Baum, 1980; U.S. Patent 4,291,577; Habeger, Baum, 1986). This equipment was tested in a linerboard mill in 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 (Project 2692-4, 1985). The research successfully served to demonstrate the mill worthiness of the sensor, demonstrated that the correlations between elastic properties and strength properties observed in the laboratory also hold in the mill setting, and showed the sensitivity of the measured values to changes in machine operating variables. 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 elastic properties. As discussed above, it is important to be able to measure elastic stiffnesses in both the plane and thickness directions, because

this will enable us to separate the effects of different paper machine variables. When this is done, it should be possible to monitor and control these variables independently in the papermaking process.

Therefore, the initial thrust of this project is to develop an ultrasonic sensor capable of on-machine measurement of elastic stiffness in the thickness direction of paper. This sensor would then be integrated with an appropriate in-plane sensor to provide a complete system to measure paper mechanical properties on the paper machine. This report presents the progress toward these objectives.

ZD ELASTIC STIFFNESSES AND THEIR MEASUREMENT

There are three different elastic stiffnesses of paper which involve the out-of-plane direction (or ZD). They are the ZD longitudinal stiffness (C_{33}), the shear stiffness (C_{55}) in the plane determined by the machine direction (or MD) and the ZD, and the shear stiffness (C_{44}) in the plane of the cross-machine direction (or 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 wave 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 one second duration) test at standard conditions.

The degree of fiber-to-fiber bonding and the amount of ZD fiber orientation are the most important factors influencing the ZD stiffnesses. Since the preponderance 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 sample moisture and temperature at the time of the test. It has been observed that the ZD stiffnesses increase upon refining and wet pressing (Fleischman, 1982; Berger, 1985) and fall when wet straining (Fleischman, 1982), calendering (Berger Thesis, 1985), or supercalendering (Charles, 1988) are performed. In addition, furnish (Habeger, 1983) and yield (Berger, 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 stiffnesses of single ply sheets correlate with ZD tensile strength (Fleischman, 1982); ZD stiffnesses are important in modeling the in-plane compressive strength (Habeger, 1983) of paperboard; and ZD longitudinal stiffness correlates with the retention of medium compressive strength during corrugation (Whitsitt, 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}).

FIRST TRANSDUCER DEVELOPED FOR ON-LINE ZD MEASUREMENT

The ZD elastic stiffness of interest can be calculated from measurements of the velocity of a bulk longitudinal wave traveling in the thickness direction. The square of the ultrasound bulk velocity is equal to the elastic stiffness divided by the apparent density, i.e., the "mass specific elastic stiffness". Z-direction (ZD) ultrasound velocity in paper is calculated by measuring the caliper and dividing by the transit time or time-of-flight of an ultrasonic pulse through the sample. There are published reports of the basic approach (Habeger, 1979; Mann, 1979; Mann, 1980; Habeger, 1986) for making ZD measurements in paper.

The first step in developing an instrument to make ZD measurements on a moving web is to devise a method of transmitting a pulse of ultrasonic energy through a sheet and detecting it on the opposite side, while the paper is moving at high web speed. Figure 1 is a drawing of the receiver wheel which was built for our first on-line ZD trial. The wheel, which was machined from a solid piece of aluminum, is 5.0 inches in diameter. Its functions are to provide a rolling contact to the web, to house some electronics and acoustic transducers, and to electrically shield the sensor. The transducer-to-web coupling is done with 1/32 inch thick sheet of soft neoprene epoxied to the face of the transducer. This is the same neoprene used in the IPC thickness gage and in our laboratory longitudinal ZD instrument (Wink, 1983).

Figure 1. First ZD receiver wheel.

The active element itself is made from two piezoelectric ceramic disks (1/10 inch thick P.Z.T. 5A). They are oriented with opposite polarity and epoxied together. The outer surfaces are held at ground potential, while the connected surfaces form the active electrode. One piezoelectric element is epoxied to a thin aluminum button which is machined to the same radius as the wheel. The button also has a threaded flange for mounting the active element. The neoprene sheet is epoxied to the aluminum button, which is clamped to the wheel. The active element is mounted in a threaded, hollow cylinder made of Delrin. The Delrin piece is clamped by two screws to the wheel housing. Two pieces of 1/8" Coroprene (a sheet material made with cork and neoprene particles) are used to acoustically isolate the active element from the wheel.

The in-wheel preamplifier is built around a high-speed operational amplifier (Burr Brown 3554 SM). It has a full power band width of 20 MHz and is suitable for the higher frequencies employed in the ZD measurements to stabilize the high-speed circuitry, the electronic components were mounted and interconnected on a double-sided printed circuit board. This combination of the Burr Brown operational amplifier and printed circuit board construction produced a very stable, low noise, high speed preamplifier. The transmitter wheel differs from the receiver only in that no preamplifier is necessary.

The system was mounted on the IPC web strainer and tested at high speed. The transmitter wheel was placed on a shaft and mounted below the paper web which was threaded around the IPC web strainer. The receiver was positioned above the web. The wheels were synchronized by means of gears attached to each shaft off the side of the belt. The time of contact of the transducer to the web was detected with a photoelectric sensor. When transducer contact occurred,

an rf pulse was applied to the transmitter and the oscilloscope triggered. The resulting signal at the receiver was viewed on the oscilloscope.

Tests were conducted on 42-lb linerboard and on a low basis weight bond paper. The signal quality was excellent even at the highest speeds available on the web strainer (2000 ft/min). The signal-to-noise ratio was about 100 to 1. The resonant frequency of the transducers, however, was not as high as desired. They operated well between 100 and 300 kHz, but not at the desired higher frequencies. The frequency response was limited by the transducer, not the preamplifier. The frequency might be raised by eliminating one of the ceramic disks or by decreasing the diameter of the disks. However, further development of this design was abandoned in favor of a new design described below. This new design was modeled after the low-impedance, broadband, flat disk transducers which were built for laboratory ZD testing.

REVIEW OF TRANSDUCER DESIGN CONSIDERATIONS

The transducers are the critical components of a ZD velocity instrument. For optimum transfer of mechanical energy into paper, they should conform perfectly to the paper surface and have the same mechanical impedance as the ZD wave in the sample. The impedance is equal to the density of the material times the sound velocity, or, since the velocity is the square root of stiffness divided by density, the impedance can be expressed as the square root of the stiffness times the density. For smooth, perfectly bonded surfaces, the ratio of transmitted to incident energy is:

$$TE = 4Z_1Z_2/(Z_1+Z_2)^2, \quad (1)$$

where Z_1 and Z_2 are the impedances of the two materials. The value of TE is maximum if $Z_1 = Z_2$. Paper has very low ZD stiffnesses and ZD impedances, and it

is not feasible to build broadband transducers that have impedances as low as those found in paper. Therefore, the transducers should be designed to have the smallest possible impedances. In the limit that one material has the much larger impedance, TE from Equation 1 becomes proportional to the impedance ratio, and the coupling efficiency varies as the inverse of the impedance of the higher impedance material.

Equation 1 gives the optimum energy transfer for perfectly bonded materials. Poorly coupled surfaces can result in greatly degraded transmission. Good acoustic bonding is normally achieved through epoxy or viscous fluid interfaces. These procedures, however, are unacceptable for paper applications since they grossly alter the mechanical properties of paper and since they render a potentially nondestructive measurement destructive. Ultrasonic transducers for ZD testing in paper should have the lowest feasible impedance and should couple to rough paper surfaces without altering the sample properties.

Another important consideration in transducer design is the duration of the ultrasonic pulse. In time-of-flight velocity determinations, the measured transit time of a pulse is used to calculate the velocity. The time resolution of the pulse improves as it narrows. Ideally, the pulse width would be much shorter than the transit time through the sample. However, the fibrous structure of paper places a lower limit on the pulse width. In a heterogeneous material, scattering severely attenuates and disperses the signal when the pulse width approaches the transit time through the structural elements. This means that the effective wave length of the pulse in paper must be greater than the scale of heterogeneity (roughly the fiber width). The ratio of transit time to pulse width therefore must be considerably less than the caliper divided by fiber width. In addition, the pulse width is limited on the high end by the

transit time through the sample. If the pulse width is greater than twice the transit time, a secondary pulse, resulting from reflections at the transducer-sample interfaces, will interfere with the main pulse. This will make it difficult to resolve the main pulse, and it will result in an arbitrarily low calculated velocity. So, there are conflicting requirements on the pulse width; it must fall between the transit times through the fiber width and through the sample. Another way of reaching the same conclusion is to realize that ultrasonic stiffness determinations assume a homogeneous material and, if the approach is to be valid, there must be some wavelength, intermediate between the fiber width and sample caliper, at which the material appears homogeneous. This, of course, means that there are fundamental reasons that measurements become suspect on thin papers, and care must be taken in interpreting the results.

For most paper samples, scattering of ZD ultrasonic energy becomes prohibitive at frequencies above 2 MHz. Therefore, we have chosen to make our measurements with a pulse width of about 1.0 μ sec as a compromise between good resolution and good signal-to-noise ratio. In order to produce and receive discrete pulses of this duration, the transducers should be broadband as well as sensitive in the megahertz frequency regime. Broadband transducers have flat frequency responses, and they can faithfully convert between mechanical and electrical energies without signal distortion. They do not have resonances which lead to oscillations that increase the pulse width. In summary, the objectives in designing ultrasonic transducers for ZD operation with paper is that they are low impedance, are broadband and sensitive in the megahertz frequency range, and can couple ultrasonic energy efficiently without altering the properties of the paper. As will be demonstrated below, we accomplished this

by: (1) using a high loss, low impedance plastic piezoelectric rather than a standard ceramic piezoelectric; (2) carefully designing the transducers to avoid any resonances near 1 MHz; and (3) coupling longitudinal waves into the paper through soft neoprene.

FLAT, LONGITUDINAL TRANSDUCERS

The construction of the flat longitudinal transducers is diagrammed in Figure 2. The active piezoelectric elements are $110\text{ }\mu\text{m}$ thick, polarized polyvinylidene fluoride (PVDF or Kynar) films. They are bonded together in stacks either two or four films deep. The active electrode of the transducer is connected to the stack center, while the outer surfaces are grounded. Films on either side of the center electrode are stacked with opposite polarity so that all films act in unison. The stack is bonded to a cylinder of unpolarized Kynar. This aids in the production of broadband transducers by providing a good impedance match, which reduces reflections off the back-side of the stack. The Kynar is also a good absorber of ultrasonic energy and helps to mechanically isolate the films from the transducer housing. The other side of the stack is bonded to a layer of polystyrene. Polystyrene is a plastic with low ultrasonic attenuation and of intermediate impedance between the Kynar and the neoprene frontface, which is attached to the top face of the polystyrene. Lateral expansion of the neoprene disk is restrained by a tightly fitting brass ring that is acoustically isolated from the transducer body by a thin layer of cork. A comprehensive description of the transducer construction is provided elsewhere (Habeger, 1988).

The transit time of ultrasound waves through the polystyrene and neoprene layers is considerably greater than $1\text{ }\mu\text{sec}$. This ensures that multiple reflections through these materials do not interfere with the main pulse. The

Figure 2. A mechanical drawing of the flat longitudinal transducers.

impedances of the Kynar film, polystyrene, and neoprene are, respectively, about 3.8, 2.5, and 1.6 kg/m²s. The ZD impedances of paper are about an order of magnitude lower than these values; however, these PVDF transducers provide a significantly better impedance match than do standard ceramic piezoelectric elements which have impedances of about 25 kg/m²s. The purpose of the soft neoprene is to conform to the rough paper surfaces so that reasonable caliper values (Wink, 1983) and good ultrasonic coupling are obtained. The benefits and limitations of neoprene coupling and the effects of loading pressure are discussed extensively in the previous publication (Habeger, 1988). At a loading pressure of 50 kPa, energy is efficiently coupled into paper, and the errors in velocity calculations resulting from imperfect coupling are very small.

The performance of the transducers can be judged by examining the CRT traces depicted in Figure 3. These represent signals from receiver transducers that are coupled at 50 kPa loading pressure through a thin aluminum foil sample to identical transmitters that are pulsed with a 1.5 MHz single-cycle sine wave. In order to get an expanded view of the main pulses, the oscilloscope is operated in a delayed mode with the traces starting about 12 μ sec after the transmitters are pulsed. The time base of the expanded traces is 182 nanoseconds per division. The two traces are generated by using two different transducer pairs. The bottom trace was obtained from transducers built with four layer stacks of 110 μ m thick standard PVDF piezoelectric film from Pennwalt Corporation, while two layer stacks of an experimental PVDF copolymer film (also from Pennwalt) were used for the top trace. The oscilloscope gain is twice as great for the bottom trace. Notice that in both cases narrow, well-defined pulses of about a microsecond duration were achieved. The copolymer stack gives significantly improved performance in that a higher amplitude, shorter duration signal is realized.

Figure 3. Oscilloscope traces of the signals resulting from direct coupling between the copolymer PVDF and the standard PVDF longitudinal transducers.

IPC, NEOPRENE FRONT-FACE, PVDF WHEEL TRANSDUCERS

The wheel transducers are intended to replicate in a rotary instrument, the performance of the flat, longitudinal transducers. The rotary instrument is designed to profile caliper and ZD velocity by driving the sample through the nip between two wheel transducers and testing at discrete intervals. Fabrication of these wheels introduced some new challenges and required several experimental trials in order to identify and overcome construction difficulties. For proper ultrasonic coupling, it is mandatory that all transducer interfaces are uniformly bonded with thin layers of epoxy or fluid couplants. We found this difficult to accomplish at the film interfaces and at the Kynar-neoprene

boundary in the cylindrical geometry needed for the wheels. As one might expect, we were unsuccessful in developing a straightforward technique of uniformly bonding PVDF film strips between plastic cores and rings to produce transducer wheels. We were successful, however, at coupling the films with small amounts of silicone grease and fitting an undersized plastic ring over a plastic core wrapped with the film layers. Adhering a neoprene belt uniformly to the circumference of a wheel presented another set of special difficulties. We overcame these by constructing a fixture that, by the application of negative or positive gage air pressure, could expand or contract the diameter of the neoprene belt. During assembly, adhesive is applied to the rim of the wheel; the neoprene belt is expanded and placed around the rim; the belt is contracted; and the adhesive is allowed to set.

Fabrication of a transducer wheel begins with the construction of the plastic core and ring between which the PVDF films will be secured. The core, which provides the transducer back-face, is a 2.54 cm thick, 7.145 cm diameter Kynar disk. In order to accomplish later steps in the assembly, a mandrel is pressed into a hole in the center of the core. The 2.54 cm thick ring has a 7.188 cm inside diameter and a roughly 8.25 cm outside diameter. It is also made of Kynar. Better sensitivity would be realized with a polystyrene ring. However, since polystyrene is brittle and its thermal expansion coefficient is well below that of Kynar, transducers made of Kynar and polystyrene had an annoying tendency to fracture. A Kynar ring does not provide as good an impedance match to the neoprene, and it dissipates some ultrasonic energy. Nonetheless, the assembled structure is tough and tight, and it is not destroyed when thermally cycled.

The 110 μm thick PVDF films must be carefully cut to ensure that when each film is wrapped on the core its ends will touch but not overlap. The first of the four films is cut so that its ends are butted when wrapped inside the Kynar ring. The second film is slightly shorter; its ends meet when wrapped inside the ring and the first film. The third and fourth films are likewise each slightly shorter. Electrical contact to the film interfaces is accomplished with number 36 copper wires. The ends of these wires are flattened to a thickness of 12 μm by placing them between smooth, hardened steel surfaces under load in a press and striking the loaded assembly once with a heavy hammer.

Assembly begins by metering a thin, uniform layer of silicone grease to one side of each PVDF film. The first and second films are greased on the positive polarity side, while the third and fourth films are greased on the negative side. A small amount of silicone grease is also applied to the core at three locations, 120 degrees apart on the periphery. At each location, a flat end of a copper wire is fixed. The fourth strip is wrapped around the core with the greased side facing inward, and the third strip is wrapped around the fourth, greased side also in. The flat ends of three copper wires are placed on deposits of grease applied at 120 degree intervals around the third film. The second and first films are then wrapped around the core with greased side facing inward. The film butt joints and the electrode wires present small defects in the structure. During assembly, care is taken to maintain even spacing between these imperfections. A specially designed "compression fixture" is used to expel excess grease from the interfaces. The core and compression fixture are placed in a sealed polyethylene bag and stored in a freezer for twelve hours. The Kynar ring is greased uniformly, and the flat ends of copper wires are applied at 120 degree separations. The ring with wires is heated in an 80°C

oven for two hours. The cold core must be inserted inside the hot ring as rapidly as possible. First, the ring is placed on a flat surface. The core is removed from the compression fixture and placed over the ring. A Teflon plate is set upon the core, and the core is pressed into the ring. A 20 pound weight is rested on the plate and left for 24 hours.

The wheel is then mounted in a lathe and machined to an outer diameter of 8.09 cm. The front-face is a 25.09 cm taper-cut strip from a 0.318 cm thick, 4.13 cm wide section of 5-10 durometer soft neoprene, manufactured by Crane Packing Co. The ends of the strip are cleaned with a Freon TA solvent and bonded together with a thin layer of Armstrong 520 adhesive that has been diluted with xylene. The outer edges of the neoprene belt are glued to the fixture which was designed to uniformly apply the belt to the core. The fixture is centered and held by a plate mounted in the tail stock of the lathe. Vacuum is applied to the fixture, and the diameter of the belt expands. The transducer assembly is turned in the lathe, and a doctor blade meters a 0.02 cm layer of Loctite Black Max adhesive to its circumference. The doctor blade is quickly removed, and the rotation of the transducer assembly is halted. The wheel on the tail stock is turned, and the neoprene belt is centered over the transducer assembly. Vacuum is released from the fixture. Pressure is applied and held for three hours. The edges of the neoprene are cut to remove the wheel from the fixture. A surgical blade is cemented to a blank lathe cutting tool supported by the tool holder of the lathe. With the wheel rotating, the blade is slowly turned into the neoprene, and a 2.54 cm wide neoprene front-face with smooth, right angle cuts is produced. The three wires from the stack center are soldered to a single lead wire, as are the six exterior ground wires. Construction of the wheel is completed by replacing the mandrel with a shaft and

by attaching aluminum sidewalls that house the wheel and restrain the lateral expansion of the neoprene. The two lead wires are threaded through a hole in the shaft and connected to terminals on a mercury slip ring attached to the end of the shaft. Precision deep-groove radial ball bearings are press fit on each side of the shaft so that the wheel can be securely supported in stationary yokes. Due to the irregularity of the neoprene, the diameters of these wheels vary about 40 μm around their circumferences. When coupled together and rotated, there is less than a 10% variation in signal strength.

MECHANICAL MOUNTING APPARATUS FOR IPC WHEELS

The mechanical mounting apparatus, electronic instrumentation, and measurement procedures are similar to that for the flat transducer laboratory instrument. However, the rotary instrument is necessarily more complicated. Therefore, we will describe its operation in detail and point out differences in the other system when appropriate.

A drawing of the mechanics of the rotary instrument is presented in Figure 4. The mounting for the wheels is similar to the paper caliper instrument developed by Hardacker, 1984. The yoke for one wheel transducer is attached to the anvil of the caliper gage, while the other is bolted to the pressure foot. A Daedal (model 4801) linear motion ball-slide allows the pressure foot low-friction vertical motion, while at the same time providing rigid horizontal restraint. In the original caliper gage (Hardacker, 1984) and in the flat transducer instrument, the same functions are achieved with graphite pistons that slide in a precision-bore glass tube. The ball-slide was used in the rotary device since we felt it could better deal with the extra stresses encountered in rotation. The core of a linear variable differential transformer (LVDT), attached to the slide, moves vertically in a fixed LVDT coil as the

Figure 4. A mechanical drawing of the rotary ZD ultrasound instrument.

pressure foot rises and falls. This provides an electrical signal that is proportional to the displacement of the upper wheel. The shaft of the bottom wheel is driven by a computer-controlled stepping motor. There is a mechanism that, when manually engaged, rotates the wheels until the splices in the neoprene front-faces are aligned. The flat transducer gage does not have a stepping motor or an alignment mechanism, but it instead is equipped with a computer-controlled motor that raises and lowers the pressure foot.

ELECTRONIC INSTRUMENTATION

Figure 5 is a representation of the electronics used in the rotary instrument. A Superior Electric model M063 stepping motor drives the lower wheel. It is regulated by a Superior Electric 230 PT0 motor controller, which receives instructions over digital I/O lines from the PC class AT computer. The LVDT and amplifier are identical to the one described by Hardacker, 1984. The signal from the LVDT amplifier goes to an H.P. 3487A Multimeter. This is used as a high speed (up to 50 samples/second) digital voltmeter. It communicates the elevation of the upper wheel to the computer over a GPIB bus.

The upper wheel performs the function of ultrasonic transmitter. The drive signal (a 1.5 MHz, single-cycle, sine wave) originates from a Wavetek model 143 function generator. This signal is amplified to 100 volts by a E.N.I. model 2401 R.F. power amplifier and applied to the wheel through mercury slip rings. An ultrasonic wave then propagates through the specimen, and an electric signal is created in the lower wheel. This signal passes through mercury slip rings to a Panametrics 5050AE ultrasonic preamplifier, which is set to a gain of 60 dB. The output of the preamplifier goes to a LeCroy 6103 variable gain amplifier which is the front end of the LeCroy 8013A transient recorder. The gain of the 6103 amplifier is adjusted by the computer in order to take full

Figure 5. An operational schematic of the rotary ZD ultrasound instrument.

advantage of the 8 bit resolution of the transient recorder. Under computer direction, the transient recorder performs 8192 eight bit analog-to-digital conversions at a 100 MHz sampling rate. Upon request, it transmits the results over a GPIB bus to the computer.

Capture of an ultrasonic signal begins when the computer instructs the transient recorder to digitize a receiver signal. As the acquisition starts, a trigger output from the transient recorder activates the emission of a pulse by the function generator. The transmitter is then fired and the resulting ultrasonic signal is received, amplified, and digitized. The signal is then transferred to the computer over the GPIB bus. This process is repeated an adjustable number of times with the computer digitally averaging the results. The other system uses a different digitizer (an H.P. 1980A digital oscilloscope) and does not signal average, but the data gathering strategy is the same.

Figure 6 is a photograph of the rotary instrument and a CRT display of an averaged signal produced when the wheels are directly coupled. Notice that there is a longer positive overshoot at the end of signal than observed in the Figure 3 traces with flat transducers. As a result, the pulse width is about 50% greater. There are two reasons for this: (1) the pressure is not uniform in the nip between the wheels, and there is a range of transit times; and (2) the wheels have a large capacitance (about 5000 pf) making it difficult for the power amplifier to supply the high frequency components of the pulse. The pulse is sufficiently short to produce a discrete pulse through most paperboard samples, but the rotary system cannot be used on some lower caliper samples that are acceptable in the other instruments.

Figure 6. A photograph of the rotary ZD ultrasound instrument with a CRT display of a direct coupled signal.

TESTING PROCEDURE

Before samples can be tested a calibration is performed. After positioning the wheel with the alignment mechanism, the calibration procedure is initiated by placing an 8 μm strip of aluminum foil in the nip and notify the computer. The computer feeds the foil through the nip in steps. The number of steps (usually about 10) and separation between steps (usually about 1 cm) are selected by the operator. Upon completion of each step, the computer allows the neoprene to settle for an operator chosen length of time (usually about 1 second) and then reads the digital multimeter. Next, it fires the appropriate number of ultrasonic pulses and stores the average signal in memory. If the

signal level is outside the optimum range for the transient recorder, the gain to the 6103 amplifier is adjusted, the wheels back off, and the test is repeated. The computer reads the multimeter again and stores the average of this value and the first reading. After the multimeter readings and ultrasonic signals are stored for all steps, the computer returns the wheels to the aligned position, backing the foil out of the nip in the process. Now, a thicker calibration sheet is presented to the wheels. It has a known caliper, somewhat greater than the thickest sample to be tested. This is stepped between the wheels and analyzed as before, but only the multimeter readings are recorded. The wheels again return to the aligned position and the calibration shim is retrieved.

Paper samples can now be profiled. A specimen is placed in the nip and analyzed in the same manner as the aluminum foil. The caliper at each position is determined by linear interpolation of the multimeter readings on the calibration standards at the same location. Using an optimization routine, the computer then determines the time which gives a maximum in the cross correlation function of the sample ultrasonic signal and the aluminum foil signal at the same position. The time-of-flight is this time minus a 10 nsec correction for the transit through the aluminum foil. The time-of-flight velocity is the caliper divided by the time-of-flight. The calipers, times-of-flight, and velocities, along with their averages and standard deviations, are reported. A typical printout for a linerboard sample is presented in Figure 7.

For operation of the flat transducer instrument, the computer controls a motor that raises and lowers a pressure foot (rather than a stepping motor that turns the wheels). Calibration is simplified since it is required only at one position. In order to conduct a measurement, the computer lowers the

THE INSTITUTE OF PAPER CHEMISTRY
ROTARY ZD VELOCITY MEASUREMENT

OPERATOR: CCH
DATE: JUNE 28, 1988
TIME: 13:30:4

PROJECT: 3467
SAMPLE: liner board

TEST NUMBER	CALIPER (microns)	DELAY (micro sec)	VELOCITY (km/sec)	V SQR (km ² /sec ²)
1	309.1	1.2559	0.246	0.061
2	307.0	1.2965	0.237	0.056
3	305.3	1.2696	0.240	0.058
4	313.3	1.3180	0.238	0.056
5	311.2	1.3403	0.232	0.054
6	307.8	1.2925	0.238	0.057
7	307.1	1.3032	0.236	0.056
8	307.1	1.3224	0.232	0.054
9	304.7	1.3060	0.233	0.054
10	309.0	1.3132	0.235	0.055

AVERAGE	308.1	1.3018	0.237	0.056
STD DEV	2.6	0.0249	0.004	0.002

GRAMMAGE (g/m²) = 209.00
DENSITY (g/cm³) = 0.678
C33 (GPa) = 0.038

V*RHO (E+6 kg/(sec*m²)) = 0.161

STABILIZATION DELAY (secs) = 1
THIN SHIM THICKNESS (microns) = 8.0
THICK SHIM THICKNESS (microns) = 793.0

REFERENCE CALIPER (microns) = 8.00
INTEGRATION WINDOW = 507
TEST INTERVAL = 0.39
TEST INTERVALS CALIBRATED = 10

TRANSMITTER - IPC#1; RECEIVER - IPC#2

Figure 7. A report generated by the rotary ZD ultrasound instrument for a linerboard sample.

pressure foot and, after the prescribed time, takes multimeter readings and an ultrasonic signal. The jaws part; the operator moves the sample; and the next position is tested. Velocities are calculated in the same way, and a report, similar to Figure 7, is generated.

COMPARISON OF ROTARY AND FLAT LONGITUDINAL INSTRUMENTS

The caliper and ZD ultrasound velocity of paper depend on the loading pressure. Therefore, a standard measurement pressure must be chosen in order to make valid comparisons between samples. We selected 50 kPa as the normal pressure for the flat transducers, partly because it is the TAPPI standard value for hard-platen caliper. The wheels, however, apply a distribution of loading pressures across the nip, and results from the two instruments are not completely equivalent. Therefore, we tested a variety of paper samples at 50 kPa in the flat longitudinal instrument and at different loads in the rotary instrument. The load at which the comparison was best was taken as the standard for the rotary instrument.

The results of this comparison are presented for neoprene-platen caliper in Table 1 and for longitudinal ZD velocity in Table 2. In both cases, the measurements were again determined at 800 gms a week later in order to give an indication of the repeatability of the rotary instrument. Also, two different samples of type A and E were tested to demonstrate the typical variations between samples of a common manufacturer. A brief description of the samples is contained in Table 3. The reported values are the average of ten measurements made one inch apart along a strip.

Disregarding sample (J) for the moment, notice that the comparisons for both caliper and velocity are optimum at about 600 to 800 grams. At 600 grams, the ratio of rotary-to-flat caliper is 0.999 ± 0.010 , and the ratio of

Table 1. A comparison between the calipers in microns of paper samples as measured with the flat transducer at 50 kPa and at different loads in the rotary instrument.

Sample	50 kPa	400 g	600 g	800 g	1000 g	1200 g	800 g
A	260.0	271.0	266.0	264.7	264.0	263.5	267.2
B	461.6	463.7	458.5	457.9	458.2	457.2	458.6
C	624.6	638.0	627.9	624.2	622.9	622.3	623.6
D	188.6	188.8	185.6	183.0	183.9	184.9	185.4
E	315.1	319.6	313.5	311.8	311.0	310.3	314.0
F	513.3	512.0	510.7	508.8	509.5	508.8	509.5
G	710.8	716.7	711.7	710.4	711.1	709.9	711.7
H	1109.6	1115.6	1113.2	1112.2	1114.7	1112.6	1111.1
I	679.8	680.1	678.2	677.1	678.7	678.1	677.9
J	97.4	94.2	91.9	91.5	92.4	92.3	93.4
A2	266.3	270.1	264.2	261.7	262.5	260.9	265.5
E2	309.0	317.1	311.7	309.5	309.4	308.4	312.9

Table 2. A comparison between the ZD longitudinal velocities in km/s of paper samples measured with the flat transducers at 50 kPa and at different loads in the rotary instrument.

Sample	50 kPa	400 g	600 g	800 g	1000 g	1200 g	800 g
A	0.315	0.308	0.317	0.325	0.330	0.338	0.326
B	0.243	0.233	0.235	0.239	0.241	0.242	0.238
C	0.194	0.188	0.191	0.194	0.196	0.198	0.193
D	0.449	0.437	0.448	0.457	0.459	0.473	0.458
E	0.465	0.453	0.453	0.460	0.462	0.470	0.458
F	0.258	0.249	0.255	0.259	0.262	0.264	0.260
G	0.189	0.181	0.184	0.187	0.189	0.191	0.188
H	0.221	0.217	0.219	0.221	0.222	0.222	0.220
I	0.278	0.267	0.272	0.275	0.278	0.280	0.275
J	0.404	0.375	0.382	0.382	0.377	0.375	0.388
A2	0.310	0.304	0.310	0.316	0.321	0.327	0.319
E2	0.442	0.464	0.463	0.470	0.472	0.478	0.470

Table 3. Description of paper samples tested for Table 1 and Table 2.

Sample	Description
A	42 lb/1000 ft ² linerboard
B	60 lb/1000 ft ² linerboard
C	90 lb/1000 ft ² linerboard
D	26 lb/1000 ft ² corrugating medium
E	40 lb/1000 ft ² corrugating medium
F	60 lb/1000 ft ² bleached posterboard
G	two ply coated chipboard
H	heavy wax-coated chipboard
I	90 lb/1000 ft ² chipboard
J	74 gm/m ² bleached writing paper

rotary-to-flat velocity is 0.992 ± 0.022 . The values at 800 grams are 0.995 ± 0.012 and 1.008 ± 0.024 . The two loads give equally good comparisons; however, 800 grams was chosen as the standard since it provided a stronger ultrasonic signal.

As mentioned earlier, in order to make valid time-of-flight measurements, the pulse width must be short enough that a discrete signal, which has no interference from multiple reflections, is generated. This means that the pulse width must be less than twice the caliper divided by the velocity. Since the pulse width in the rotary instrument is larger, there are samples that can be tested with the flat transducer, but not with the rotary ones. Sample J is such a paper. It is barely in the valid regime for the flat transducers. Notice that the rotary velocities are significantly lower for this sample. This is because the interference from the first multiple reflection makes the pulse appear to arrive later and causes the peak in the cross correlation function to occur at a larger time.

In summary, the computer-controlled instruments described above provide a repeatable measurement of paper caliper and, on sufficiently thick sheets

(>100 microns), of ZD ultrasound velocity. When operated at the appropriate load, the flat and rotary instruments agree well on caliper and longitudinal velocity. Because of improved instrumentation and the elimination of the need for operator scanning, the rotary instrument samples about twice as fast as the flat transducer model. Out-of-plane elastic properties, which are important indicators of mechanical integrity, can be rapidly measured in the laboratory without damaging the sample.

DYNAMIC TESTING OF IPC WHEEL TRANSDUCERS

In addition to being a valuable laboratory instrument, the ZD rotary unit was constructed to provide a system to investigate, in a controlled manner, the influence of dynamic phenomena on measurements of soft-platen caliper and ZD velocity. The instrument was modified so that continuous belts can be run through the nip between the transducer wheels at speeds of up to 190 m/min. A description of the results of velocity and caliper measurements as a function of speed for three different board samples follows.

As discussed earlier, calibration of the wheel transducers is normally done by stepping, under computer control, one thick and one thin (8 μ m aluminum foil) shim through the nip. The readings of the LVDT at each step for both shims is recorded. Ultrasonic pulses at the receiver wheel are digitized and stored for each position on the thin shim. When a sample is stepped through the nip, its caliper at each step is determined by interpolation of the LVDT readings for the calibration shims at that step. The time-of-flight through the sample is defined as the time of the peak in the cross correlation function of the foil ultrasonic signal, at that step, and the ultrasonic signal through the sample.

Individual calibration at discrete positions of the wheels is not feasible for continuous operation, and the calibration procedure was altered for on-line operation. As before, two shims are stepped through the nip. Measurements are made at 30 locations uniformly spaced around the circumferences of the wheels. This time, the LVDT readings for the thick and thin shims are averaged, as are the digital ultrasonic signals through the foil. In order to test a belt sample, the wheels are operated at constant speed (not under computer control); a number (20 for the tests below) of LVDT and ultrasonic signals are stored and averaged; caliper and velocity are calculated using calibration averages and sample averages; the results are printed; and the cycle repeats until the operator interrupts. Since the calibration is done at zero speed while the sample readings are taken during rotation, the influence of dynamic factors can be quantized by analyzing the results as a function of speed.

Three different commercial board samples were tested: a 42-lb/1000 ft² linerboard; a 26 lb/1000 ft² corrugating medium; and a 600 μ m thick coated board. The samples were cut into strips; a section at the ends of each strip was surface ground half way through; and a belt was formed by bonding the two ground ends together. A belt of aluminum foil about 50 μ m thick was also formed. A series of measurements were made at speeds up to 190 m/min for all four belts and a special series of runs was made on bare neoprene without a belt. Preliminary testing revealed that the system was vibration prone. There were large variations in the caliper measurements, especially at speeds where resonant vibrations were excited in the instrument. This problem was addressed by adding a dashpot, made from a plunger immersed in a viscous fluid. With the dashpot in place, variance in the average caliper readings, printed by computer, were less than 1.0 μ m at all speeds.

The raw caliper readings as a function of belt speed are plotted in Figure 8 for the five runs. As one would expect, the wheel separation increased with speed in each case. Possible reasons for this are: centrifugal forces act on the neoprene; there is less time for the neoprene to conform; the wheels are expanding due to an increase in temperature; and/or air is entrained between the wheels. Notice that a jump in caliper is experienced at the lowest speed, followed by a gradual increase with speed. The total rise in reported caliper is about 70 μm in each case.

As is clear from Figure 8, the observed changes in paper caliper can be partially compensated using the reported foil calipers. This is demonstrated in Figure 9, where the change in caliper of the foil is subtracted from the reported paper calipers. In a real on-line situation, it would be impractical to make corrections with a foil belt; however, the wheels could be transported past the edge of the web and the neoprene-to-neoprene displacements could be recorded as a function of speed. Caliper compensation, using neoprene separations, is presented in Figure 10. Notice that the compensated calipers are stable, and that, for the two thinner boards, the neoprene correction is actually better than the foil correction. At the higher speeds, both corrected calipers are independent of speed, and we have every indication that these corrections would be valid at speeds higher than those tested to date.

The factors that caused the caliper to appear to increase with speed have a similar effect on the time-of-flight delays. The raw time-of-flight delays for the four belts and for the neoprene-to-neoprene contact are plotted in Figure 11. The time delays experience a step increase followed by a gradual rise. The raw velocity is simply the reported caliper divided by the raw delay

Fig. 8. IPC wheel raw caliper for readings versus belt speed.

Fig. 9. IPC wheel caliper corrected for changes in foil caliper versus belt speed.

Figure 10. IPC wheel caliper corrected for changes in neoprene-neoprene separation versus belt speed.

time (Figure 8 values divided by Figure 11 values). These are presented in Figure 12 for the three paper belts. The neoprene (or for that matter the aluminum) delays can be used to correct the paper time-of-flights in velocity calculations. This is done in Figure 13, where corrected velocity (defined as caliper minus change in neoprene caliper divided by delay minus change in neoprene delay) is graphed versus belt speed. Since delay and reported caliper both increase with speed, the increases cancel to some extent, in the velocity calculations, and raw velocities are more stable than the delays or calipers. In fact, it is difficult to argue that the corrected velocities in Figure 13 are a better indicator of the static values than are the raw numbers in Figure 12.

Fig. 11. IPC wheel raw time-of-flights versus belt speed.

Fig. 12. IPC wheel raw ZD velocities versus belt speed.

Figure 13. IPC wheel ZD velocities corrected for neoprene-neoprene separation and time-of-flight changes versus belt speed.

We consider the preliminary results, presented above, to be encouraging. We were able to roughly reproduce soft platen calipers at speed, when we used the apparent neoprene-to-neoprene separations for compensation. The dynamic velocity measurements looked good with and without correction.

We don't consider the wheels in the rotary ZD instrument to be suitable for on-line operation, and we are presently constructing a new version. The major concern is, of course, wear to the soft neoprene front-faces. The new wheels will be coated with a harder neoprene, which we hope can withstand the rigors of on-machine operation. If these wheels are rotated at web speed before they are put into contact with the web, we think they have a chance of lasting.

Another significant change will be the use of Pennwalt's improved, high-temperature, high-sensitivity, PVDF film. This product is still in the experiment stage, and samples are hard to come by. However, we have obtained a sufficient amount of the film to produce two wheels. Construction is under way, and we expect to have wheels that can operate on the web strainer within a couple months.

There is one other innovation that we are incorporating into the construction of the new wheels. This is the molding of a neoprene front-face to the Kynar rim. Previously, we used a special fixture to bond a spliced, neoprene belt to the Kynar. We now are experimenting with molding our own neoprene. Early results show that, with proper pretreatment of the Kynar, we can establish excellent bonds between the neoprene and the Kynar. These bonds appear to be more uniform than the epoxied interfaces. It is no longer necessary to load the neoprene (and thereby leave the finished front-face in a nonuniform stress state) while epoxy is setting. In addition, the splice is eliminated. By varying the recipe, we can produce neoprenes over a wide durometer range, including the durometer used in the soft platen caliper measurement.

FLUID-FILLED WHEEL TRANSDUCERS

We are also experimenting with commercially available fluid-filled ultrasonic wheel transducers for on-line out-of-plane velocity measurements. These wheels have a rubber-rim "tire", filled with liquid and mounted, through bearings, to a stationary shaft. An immersion-style ultrasonic transducer is fixed to the shaft. For ZD measurements on paper, a sample is passed in the nip between two such wheels, and ultrasonic signals are communicated between the wheels.

The potential advantages of this approach are: (1) wheels can be obtained without extensive development at IPC; (2) the transducers are not rotating, and therefore, mercury slip rings are unnecessary; and (3) the same transducer surfaces are used for all signals and there is no need to build transducer wheels that are uniform about the circumference. Potential disadvantages are: (1) the distance between the transducers and the rubber tire is not fixed, making it impractical to determine caliper from the relative separation of the axles; (2) the time delay in the fluid path depends on the sample caliper; and (3) the fluid temperature and the temperature dependent velocity of sound in the fluid are needed to determine the time-of-flight.

We purchased two of these wheels along with two ceramic transducers and one PVDF transducer. We rigidly mounted the axles of the wheels so that the separation between transducers remains constant. The time-of-flight between the transmitter and receiver is measured with and without a sample in the nip. The difference in these two times, Dt_1 , is equal to the caliper of the sheet, cal , times the inverse of the velocity of sound in the sample, V_S , less the inverse of the velocity of sound in the fluid, V_F , or

$$Dt_1 = cal(1/V_S - 1/V_F) \quad (1)$$

Therefore, a measurement of caliper is needed just to find the time-of-flight, cal/V_S , through the paper, which from Eqn. 1 is

$$cal/V_S = Dt_1 + cal/V_F. \quad (2)$$

The velocity of sound in the fluid is of the order of five times greater than V_S , and the value of cal/V_F is about 20% of Dt_1 .

It, at first, seems that an independent measurement of caliper is necessary in order to obtain useful information from this approach. However, there may be ways to get around this difficulty. To begin with, if the basis weight of the sample is known, the acoustic impedance,

$$Z_S = \rho V_S, \quad (3)$$

(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_S 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 properties, there is no apparent reason to prefer V_S over ρV_S . In fact, as basis weight is the better-defined, more fundamental property of paper, it may be argued that the use of acoustic impedance is the better parameter, since the determination of the caliper is avoided. These considerations apply as well to all of our ZD velocity determinations. The overriding question is: for a 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 wise, in the design of an on-line out-of-plane acoustic sensor, to evade the difficulties of caliper definition and determination by making an impedance measurement.

Even if we accept mechanical impedance as the proper acoustic measurement, we are still not out of the woods with the fluid-filled wheels technique.

This is because, 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 an approximate caliper determination could be sufficient. As it happens, there may be a way to roughly determine the caliper of the sheet from the acoustic pulses generated between these wheels. After the first straight through pulse is detected in the receiver, a second pulse, which has an additional multiple reflection between a fluid-rubber interface and a fluid-transducer interface, is observed. If transmitter and receiver transducers are the same distance from the fluid-rubber interface, this second pulse is actually an interference of signals from two paths. One path has a multiple reflection in the transmitter wheel, while the other has one in the receiver. Since the separation between axles is fixed, the length of the fluid path in the reflected signals is affected by the caliper of the paper. Taking this into consideration and assuming that the two reflected paths are of equal length, the difference in time, Dt_2 , between the arrival of the second pulse with and without the paper inserted is:

$$Dt_2 = cal/V_S - 2cal/V_F. \quad (4)$$

Subtracting Eqn. 1 from Eqn. 4, and solving for cal, gives the following expression for caliper in terms of time measurements and the velocity of sound in the fluid

$$cal = V_F(Dt_1 - Dt_2). \quad (5)$$

We did some preliminary experimentation with this acoustic caliper measurement technique with identical ceramic transducers mounted in both wheels. Using independently determined calipers and calculating velocity from Eqn. 2, we obtained reasonable velocity values. However, the shape of the second pulse was very dependent on wheel position and was very unrepeatable. Often the

appearance of the second pulses with and without the paper were so different that we could not unambiguously relate the two pulses. We reasoned that this was due to the interference between the two reflected paths. The fluid distance in the two wheels varied causing the resulting pulse to be unstable. We decided to get around this by replacing one of the transducers with a considerably longer PVDF transducer. This separated the two reflections and avoided the interference problem.

As depicted in Figure 14, when the spacings between the transducers and the wheel rim are unequal, there are three distinct pulses resulting in one wheel when a single pulse is induced in the other wheel. The first signal, coming at t_1 , goes directly from the transmitter (through fluid, rubber, sample, rubber, and fluid) to the receiver. At t_2 , a second signal, which results from a multiple reflection between the transducer, closer to the rim, and the rim, arrives. The final signal of interest, coming at t_3 , contains a multiple reflection between the rim and the other transducer. The differences in t_1 , t_2 , and t_3 with and without sample (Dt_1 , Dt_2 , and Dt_3 , respectively) are related to the velocity of ultrasound in the sample, V_S , the velocity of ultrasound in the fluid, V_F , and the caliper of the sample, cal , as shown in Equations 6, 7, and 8.

$$Dt_1 = cal(1/V_S - 1/V_F) \quad (6)$$

$$Dt_2 = Dt_1 - 2d_1/V_F \quad (7)$$

$$Dt_3 = Dt_1 - 2d_2/V_F \quad (8)$$

In the above Equations, d_1 and d_2 represent the change in fluid length in the two wheels resulting from sample insertion. Their sum must equal the caliper. Therefore, these equations can be solved for V_S and the caliper, cal , as in Equations 9 and 10.

Figure 14. Schematic diagram of the definition of T_1 , T_2 , and T_3 .

$$\text{cal} = 0.5(2Dt_1 - Dt_2 - Dt_3)V_F \quad (9)$$

$$V_S = V_F/(1 + Dt_1V_F/\text{cal}) \quad (10)$$

So, by analyzing all three pulses, the caliper as well as the ZD longitudinal velocity of ultrasound can be calculated.

As can be seen from Equations 9 and 10, in order to calculate caliper and ZD velocity, it is important to know the velocity of ultrasound in the fluid. We have developed a method to determine V_F . The time of arrival of t_1 is plotted as a function of the spacing between the shafts of the wheels. The Velocity of ultrasound in the fluid is merely the inverse of the slope of this line. The result, at room temperature, is $V_F = 1644$ m/sec.

The results with wheels of different fluid path length were very encouraging. Table 5 presents a comparison of the acoustic caliper and velocity (using the standard and acoustic caliper) results with the readings from the standard laboratory out-of-plane instrument for the samples having the same description listed in Table 3.

Table 5. A comparison of the caliper and velocity as determined from the fluid-filled wheels and the standard out-of-plane instrument for samples described in Table 3.

Sample	Caliper std. μm	Caliper FF wheels μm	Velocity std. km/s	Velocity FF std. cal km/s	Velocity FF FF cal km/s
A	262	235	0.308	0.296	0.270
B	461	444	0.240	0.218	0.212
C	623	638	0.194	0.193	0.197
D	188	190	0.437	0.393	0.397
E	315	305	0.437	0.427	0.417
F	513	448	0.257	0.249	0.221
G	711	670	0.189	0.190	0.180
H	1.109	1.088	0.223	0.209	0.205
I	678	702	0.283	0.256	0.263
J	98	86	0.405	0.303	0.272

Remember that we were able to alter the caliper and velocity values by adding dead weight load to our neoprene-surfaced wheels. Therefore, it seemed that a similar adjustment could be achieved 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. So, we simply selected a convenient setting and reported the readings only at that separation.

First inspect the caliper readings in Table 5. The fluid-filled wheel values are consistently lower than those of the standard ZD instrument at 50 kPa. Excluding sample J, the average value of the ratio of the two is 0.97 with a standard deviation of 0.06. Considering that the surface of the fluid-filled wheel is less compliant than the neoprene in the standard instrument, that we cannot effectively adjust the loading pressure of the fluid-filled wheels, and that the approach is indirect for determining caliper, this is a better than expected comparison. The 6% variation in the ratio is large; however, the 3% offset could be the result of a higher loading pressure in the fluid-filled wheels, which might be reduced by decreasing the fluid pressure in the wheels.

Now consider the velocity data in Table 5. First, notice that the fluid-filled wheel velocity values for sample J (the thin sample) are even lower than with the neoprene wheels. This is because, with the present transducer combination, the fluid-filled wheel transducers produce a less broadband signal than the neoprene wheels. Therefore, the signal is more contaminated by multiple reflections on thin samples, and the cutoff caliper divided by velocity is higher still. Sample J results are thereby not included in the following comparisons. The ratio of the fluid-filled wheel velocity using standard caliper to the standard velocity is 0.95 with a standard deviation of 0.04; the

velocity ratio using the acoustic caliper for the fluid-filled wheel velocity is 0.92 ± 0.05 . This is not as good a comparison as we achieved with the neoprene wheels; however, it is not that bad either. The lower velocity with the fluid-filled wheels arises because the measured time-of-flight is greater. Contrary to the conclusion from the caliper comparison, this indicates that the effective loading pressure is less than 50 kPa. We had reason to hope that the consistent difference in caliper would compensate for the consistent difference in time-of-flight in the velocity calculation; however, this is not the case. There are some unresolved issues here, but the fluid-filled wheel technique has promise.

In measuring the time-of-flight of pulses, it is important to produce narrow pulses. This reduces the possibility of pulse overlap, and improves the resolution. Originally ceramic piezoelectric transducers were used. We purchased two additional PVDF transducers for the fluid-filled wheels. These are focused transducers. One has a two-inch focal length, and the other has a one-inch focal length. An extending section, which can be used to position the one inch focal length transducer closer to the tire surface, was also purchased. With a change to these commercial PVDF transducers, we have thereby achieved a significant improvement in bandwidth.

However, minimum pulse widths are still about twice those realized in our PVDF wheel transducers. We see no reason for this, and believe that we are capable of making PVDF immersion transducers more appropriate for our purposes. In the near future, we plan to construct our own versions. These will simply be Kynar backings with PVDF films directly applied to one end. The front-face will be sealed, and the PVDF films will come in direct contact with the fluid.

After completing the above static test of the fluid-filled wheels, we initiated simulated on-line testing, using the IPC web strainer. It was

immediately obvious that to get stable and reproducible results, it was necessary to use the signal averaging and cross correlation software designed for the IPC rotary wheel transducers. The software was modified to handle the signals encountered in the fluid-filled wheels, and the transducer leads from the rotary ZD instrument were connected to the fluid-filled wheels (instead of the IPC wheels).

A preliminary on-line test of the fluid-filled wheels was conducted as follows. The wheels are rigidly mounted on the web strainer, so that the distance between axles is fixed. The paper belt, to be tested, is threaded through the nip. The belt is run at speed (for at least 15 minutes) until the temperature of the wheels stabilizes. The rotary instrument is set to function in the calibration mode, with the signal preset delay adjusted to capture one of the three fluid-filled wheel signals. The web is stopped and quickly removed from the nip of the wheels. While gently turning the wheels by hand, the computer takes and averages thirty references. The web is inserted back into the nip, and the web strainer is returned to its original speed. The rotary instrumentation is set to operate in the on-line mode (as used with the rotary belt tests described previously). The computer averages thirty receiver wheel signals and calculates the time of the peak in the cross-correlation function between the reference and the sample signal. The results are printed out, and the process repeats until the operator interrupts. The printed results are averaged to get one of the Dt's. This process is repeated two more times with different preset delays, and the other two Dt's are recorded. Results of the calipers and velocities of a 33 lb/1000 ft² corrugated medium obtained in this way are presented in Figures 15 and 16. The "static cal." line in Figure 15 and the "static vel." line in Figure 16 represent the values measured with our standard laboratory ZD instrument. To get the "static cal." line in Figure 16, the

laboratory caliper was inserted into Eqn. 10 to calculate the ZD velocity in the sample.

Fig. 15 Fluid-filled wheel calipers versus belt speed.

Fig. 16 Fluid-filled wheel ZD velocities versus belt speed.

The reason that we brought the wheels up to speed right before taking the reference signal was that we noticed significant shifts in the Dt 's with web speed. We attributed this to temperature increases. Since there is a relatively long path in the fluid between the transducers, changes in the ultrasound velocity in the fluid can cause large changes in transit times. The proper way to handle this difficulty is to: (1) measure the velocity of ultrasound in the fluid as a function of temperature; (2) measure the effects of temperature on t_1 , t_2 , and t_3 ; (3) implant a thermocouple, which is interfaced to the computer, in one of the wheels; (4) use the results of steps 1 and 2 to calculate Dt_1 ,

Dt_2 , and Dt_3 ; and (5) input the value of V_f from step 1 into Equations 9 and 10 to get sample ZD caliper and velocity. We have, on order, a digital thermometer which will monitor a thermocouple, mounted in a wheel, and report the results to the computer. With this in place, we intend to perform steps 1 and 2 and to make further tests of the fluid-filled wheel system.

IN-PLANE ON-LINE SENSOR DEVELOPMENTS

One objective of this DOE project, is the construction of an in-plane ultrasonic sensor that can be applied with the out-of-plane sensor as part of an integrated on-line measurement system. We could repeat our previous in-plane system that was demonstrated on-line in Valdosta, Georgia (Project 2692-4, 1985). However, we prefer to attempt a new approach, which we believe may yield some significant benefits.

A major drawback of our previous in-plane sensor is that it was very resonant. This meant that the received signal was initially an exponentially increasing sinusoidal wave, the first few cycles of which were below the on-line noise level. Eventually the signal was well above the noise, but the rank of arrival of a particular cycle could not be determined in a straightforward manner. If the cycle rank was not identified correctly a large error occurred in the calculated velocity. This was remedied by putting the transducers close enough together so that a one cycle error produced such a large velocity shift that it could be rejected out-of-hand. That is, the velocity was calculated for multiple cycle assignments, and the one that was most reasonable was selected as correct. This generated the possibility of a large mistake and dictated that the transducers be close together where delay times are short and velocity resolution is poor.

Another problem arises because the contact area of the transducers to the sheet is large (the order of two centimeters). The form and arrival time of a signal is dependent upon the uniformity of the loading of the sheet over the transducer surfaces. Differences in the loading between the two supposedly identical transducers in a three transducer technique can lead to errors, which change as the application of the sensor to the web changes.

A way to avoid these shortcomings is to use broad-banded transducers, which have a limited contact surface. If properly constructed, these would produce narrow receiver signals that could be unambiguously lined up for two different transducer spacings. Recently, we developed broad-banded, in-plane, bender or bimorph transducers for use in our laboratory instruments. The benders are 0.5 mm thick strips of ceramic piezoelectric material. Therefore, it seems that they could solve both problems, and the next step would be to try them on a moving web. One concern is their resistance to abrasion in an on-line operation. Another is whether a sufficient signal-to-noise ratio can be achieved on-line without using resonant transducers.

To investigate abrasion resistance, we devised a simple experiment. A strip of linerboard was attached over the circumference of a wheel. The wheel was rotated by a motor, and a bender transducer was loaded and applied to the paper surface. The transducer showed significant wear after a few hours running. Another transducer, which had a treated surface, was also tested. In this case, Carborundum particles were mixed into an uncured epoxy. A thin layer of this mixture was applied to the bender surface and allowed to cure. This greatly improved the abrasion resistance (without altering electrical or acoustic properties), and we initiated simulated on-line testing.

In order to be viable on-line, the bender transducers must provide a sufficiently strong response and must be insensitive to coupling irregularities between the transducers and the sheet. For the purpose of testing their operation, benders were inserted into an aluminum drum available from previous work. The drum was mounted so that it could be driven by a paper belt on the IPC web strainer. In this way, we are able to make static and dynamic tests at different loading conditions.

In static tests, the velocities measured with a three transducer technique had a variability of less than one percent over a broad range of sheet tensions. This lack of variability in velocity was maintained even when the loading was off-center, creating different tensions for different transducers.

In initial dynamic tests and without signal averaging (i.e., with oscilloscope observation), the signal strength was good enough for the first received pulse to be clearly visible above the noise levels at the highest speed (about 55 m/min) that we could safely run the unbalanced roll. A new drum for mounting and testing the bimorph transducers was designed and constructed. Computer-base, in-plane instrumentation was adapted for dynamic data collection.

As noted above, one of the concerns of the three-transducer techniques is that the results can be sensitive to loading conditions on the transducers. The bimorphs should reduce this problem, as they have very small contact areas. A typical example of the effects of tension, during on-line operation, on an in-plane velocity calculation with the bimorph transducers is shown in Figure 17. Here, a 45 lb/1000 ft² linerboard belt was run at 30 m/min on the web strainer. The belt drove the drum containing three bimorph transducers, which measured CD longitudinal velocity as the transducers contacted the belt. The computer averaged 25 pulses from near and far transducer separations and printed out the

cross-correlation velocities for the averaged signals. Tension was increased by incrementing the position of an idler roll. In Figure 17, the average of 3 reported velocities is plotted versus the location of the idler roll. The range of tensions is extreme; at the lowest level there is barely sufficient sample-transducer contact to produce a signal, while at the highest tension the web soon broke. In the intermediate tension range, a regime of fairly constant reported velocity appears. However, we would like to improve this performance, and we shall experiment with different groove geometries in the drum and with different transducer loadings.

Figure 17. On-line bimorph CD longitudinal velocities versus web tension

We also tested commercial boards and plotted the velocities as a function of web speed. The transducers were spaced in the cross direction, and

by rotating the transducers we could either make CD longitudinal or shear velocity measurements. Four different samples were tested: a 26 lb/1000 ft² corrugating medium; a 33 lb/1000 ft² corrugating medium, a 69 lb/1000 ft² linerboard; and a 45 lb/1000 ft² linerboard. The web tension was set in the intermediate region of Figure 17. The computer did signal averaging on thirty "near" and "far" signals, calculated a cross-correlation velocity, and printed the results. The average of about twenty reported velocities are plotted versus speed in Figures 18 and 19 for the CD longitudinal and shear velocities. The results plotted at zero web speed actually are the average of single sheet measurements made on the IPC robotic in-plane tester. A comparison of the zero speed velocities with the dynamic ones is an indication of how well the on-line system reproduces the robotic in-plane, two-transducer results. The on-line results are a little higher (probably due to transducer mismatchings), but the rankings are maintained and the results are remarkably independent of web speed.

During the above tests, it was observed that the surface hardening used on these bimorph transducers was not sufficient to prevent wear in some of the extreme conditions. We have subsequently altered the recipe for the surface coating, and we are confident that this will provide more durable units.

Figure 18. On-line bimorph CD longitudinal velocities versus web speed.

Figure 19. On-line bimorph shear velocities versus web speed.

FUTURE WORK

We have two approaches for making on-line ZD sensors: the IPC, neoprene-faced wheel transducers; and the fluid-filled wheel transducers. Our work to date has demonstrated that each of these has the potential of on-machine determination of caliper and longitudinal ultrasonic velocity in the thickness direction of paper. We plan to work with both approaches with additional transducer improvements and testing on moving webs.

Work with the IPC, neoprene-faced, wheel transducers will involve building new wheels with improved, high-temperature, higher-sensitivity PVDF films. This Pennwalt product is still in the experimental stage, but we have obtained a sufficient amount to make two wheels. We plan to use a new technique to mold harder, more wear resistant neoprene facing on the wheels. This will eliminate the splice and by varying the recipe, we can produce neoprenes over a wide durometer range.

The fluid-filled wheel transducers will be improved by installing a thermocouple in the wheel and using a digital thermometer interfaced to the computer to correct transit time data for changes in sound velocity in fluid with changes in temperature. We also plan to construct PVDF immersion transducers of our own design for use in the fluid-filled wheels. Our objective is to obtain narrower pulse widths for our application.

We are encouraged by the results to date with the bender or bimorph transducers for in-plane measurements and will continue their development for on-machine use. We will develop and evaluate improved mountings and experiment with different groove geometries in the mounting drum. We will also work on improved wear resistant coatings for the bimorph, in-plane transducers.

To date we have evaluated the sensors on moving webs by adapting electronics and computer software from laboratory instruments. We now need to assemble the electronics and computer software to operate and collect data for a combined ZD and in-plane system on a moving web.

We have designed and plan to construct a ZD test stand. This test stand will initially be used to mount the fluid-filled wheels but can then be adapted for mounting the IPC, neoprene-faced wheels. The test stand will be portable and usable as an O-frame mounting on a narrow web or as a C-frame mounting on a wider web. This stand will have scanning capability, and provision to bring the wheels up to web speed before bringing the wheels into contact with the web.

We have used the IPC web strainer for providing a moving web for testing thus far. We anticipate a need for a web handling system with more flexible capability for this work. We believe an appropriate web handling system would provide greater flexibility and efficiency in developing and evaluating our instrumentation for on-machine performance than would an early trial on a pilot paper machine. Therefore, we plan to design a versatile unwind/rewind system. This system will have web guiding, speed and tension controls, and the capability to run in either an endless loop or a reel-to-reel mode. The maximum reel size would be 30 inches. The maximum proposed speed would be 3000 ft/min.

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