ON-MACHINE ULTRASONIC SENSORS FOR PAPER STIFFNESS

Final Report

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INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

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to the

U.S. DEPARTMENT OF ENERGY

AND THE

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

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- to contribute to the economic and technical well-being of the nation through innovative educational, informational, and technical services.

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ABSTRACT

This final report presents the results of a 5-year effort by the Institute of Paper Science and Technology (IPST) and its participating partners. The objective of this work was to develop and demonstrate sensors capable of measuring the velocity of ultrasound in the out-of-plane (ZD) and in-plane directions of paper as it is being produced on a commercial paper machine. On-machine ultrasonic measurements can be used to determine various mechanical properties of paper and to monitor process status and product quality. This report first presents a review of the background and potential benefits of on-machine ultrasonic measurements, then summarizes the results of previous work. The ZD measurement system involving the use of ultrasonic transducers in fluid-filled wheels is described in detail, including the method of measurement, the wheel mounting hardware, the on-machine operation, and an overview of the system software. Mill-trial results from two bump tests when producing 69# and 55# linerboard are presented. For the 69# trial the correlation of ZD transit time with plybond and with ZDT (Z-direction tensile or internal bond strength) was greater than 0.8 (R squared). Also observed were ZD stiffness responses to refining and to calendering. ABB Industrial Systems Inc. was responsible for the in-plane sensor. A paper describing ABB's sensor and mill experience is appended.

INTRODUCTION

This final report summarizes work supported by Cooperative Agreement DE-FC02-95CE41156 from the U.S. Department of Energy (DOE) and by the member companies of the Institute of Paper Science and Technology (IPST). Additional in-kind support was provided by the participating partners: ABB Industrial Systems Inc., The Herty Foundation, and the Georgia-Pacific Cedar Springs Mill.

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

A 4-year development and testing program was proposed. The proposed program involved a cooperative effort between the Institute of Paper Science and Technology (IPST) and ABB Industrial Systems Inc. (ABB), a vendor of measurement and control instrumentation to the paper industry. Additional participants were to be the Herty Foundation Research and Development Center with sensor and system testing on its pilot paper machine and a paper manufacturing company selected to provide a Host Mill with a paper machine and support for "Beta Site" evaluation of the developed sensors and instrumentation. Funds were requested from DOE for the 4-year program with cost-sharing by IPST, ABB, Herty, and the Host Mill, such that DOE's share would not exceed 50%.

Pilot-scale prototype and full-scale proof-of-principle units, for both in-plane ultrasonic velocity measurements and out-of-plane (ZD) ultrasonic velocity measurements, were to be built and tested. ABB would be responsible for the in-plane sensor system and IPST would be principally responsible for the ZD sensor system. The pilot-scale prototype units were to be tested at IPST and at Herty. The full-scale proof-of-principle units were to be verified at IPST and Herty and demonstrated on a paper machine in an actual commercial production environment in a Host Mill.

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

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

This final report emphasizes the ZD sensor system including reviews of the background, previous work, and a chronicle of project events. Then an overview of the ZD fluid-filled wheel system and the electronics and software developed for it is given. The report concludes with a description of the mill trials and results obtained followed by some discussion and the principal conclusions.

BACKGROUND

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

The degree of fiber-to-fiber bonding and the extent of ZD fiber orientation are the most important factors influencing the ZD stiffness of paper. Since nearly all of the fibers in a sheet of paper are preferentially oriented in the MD-CD plane, the ZD stiffness is roughly two orders of magnitude lower than the in-plane stiffnesses. Compared to the in-plane stiffnesses, the ZD stiffness exhibits greater dependence on manufacturing-process variations. It has been observed that the ZD stiffness increases with increased refining and wet pressing (Fleischman et al., 1982; Berger and Baum, 1985) and decreases 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 stiffness. It has also been demonstrated that ZD stiffness can be useful as a nondestructive predictor of strength properties.

These studies have demonstrated that the ZD elastic stiffness is a particularly sensitive indicator of changes in furnish, yield, refining, wet-pressing pressure, wet straining (draws), calendering, and drying restraints. This background provided the incentive to develop instrumentation that could make on-machine ZD ultrasonic measurements along with in-plane ultrasonic measurements that would provide a means to continuously monitor product quality and to actually control the paper manufacturing process. The sensors to measure the velocity of ultrasound would be mounted at the dry end of the paper machine just ahead of the reel. These sensors would be mounted along with the basis weight, moisture, and caliper gauges now used on most paper machines and would also scan across the cross direction (CD) of the web. The basis weight, temperature, and moisture measurements would be used to adjust the elastic stiffness measurements to constant temperature and moisture-content conditions for comparison with laboratory measurement and for appropriate use in control algorithms.

BENEFITS

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

Sensors capable of monitoring mechanical properties continuously on the machine during production could immediately identify substandard material, and process settings could be adjusted to correct the problem. Additional energy benefits would result from optimum utilization of energy-intensive processes, such as refining, and from efficiency improvement in subsequent converting processes as a result of improved product uniformity.

For products requiring specific mechanical "strength" properties for end use, a nondestructive measurement of elastic stiffnesses would permit the manufacturing process to be controlled to stiffness targets rather than basis weight targets. Several process conditions (calendering, wet straining, wet pressing, refining, furnish, fiber orientation) are "transparent" to basis weight but are intimately associated with the elastic stiffnesses. Although elastic stiffnesses are not precise predictors of strength, they do vary more directly and more strongly with strength than does basis weight. Since the specified "strength" might be achieved with a reduced basis weight, stiffness measurements could reduce the amount of pulp required.

The instrumentation has the potential of providing:

- 1) Improved First Quality
 - a) Quicker Grade Changes
 - b) Fewer Culls due to CD Product-Performance Variations
 - c) Less Downgraded Tonnage during the Run
- 2) Fiber Savings
 - a) Reduce Fiber Usage while Maintaining Product-Performance Targets
 - b) Use Cheaper Fiber Sources while Maintaining Product-Performance Targets
 - c) Reduce Ring-Crush Variability Creating Opportunity to Operate at Lower Ring-Crush Targets
- 3) Energy Savings
 - a) Minimize Refiner Loads while Maintaining Product-Performance Targets
 - b) Reduce Total Steam Requirements Through Better Drainage and Less Fiber to Dry
- 4) Increased Production
 - a) Increase Machine Speed while Maintaining Product-Performance Targets

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

Energy Benefits: Energy savings result from optimum utilization of energy-intensive processes, such as refining; and from efficiency improvement in subsequent converting processes as a result of product uniformity. Energy waste is avoided by minimizing substandard production that must be repulped and remanufactured.

A 1000-ton/day machine producing 350,000 tons/year uses approximately 4.725 trillion Btu/year. For each 1% of production that is substandard and reprocessed at 13.5 million Btu/ton, the 1000-ton/day machine wastes 47.25 billion Btu/year. Assuming that this technology may limit substandard production to 2%, the energy saving would be 94.5 billion Btu/year or \$378,000 (@ \$4/million Btu) annually for the 1000-ton/day machine.

Further energy savings should result from optimum utilization of refining and drying (Lantz and Chase, 1988). Refining requires approximately 200 kWh/ton or 2.1 million Btu/ton (1 kWh = 10,500 Btu). For a 1000-ton/day machine, the annual energy usage for refining is approximately 70.0 million kWh or 735 billion Btu. Assuming the optimization of refining could reduce the energy required by 10%, this would be equivalent to savings of 73.5 billion Btu or \$294,000 annually.

By decreasing refining, drainage is improved, requiring less steam for drying the web. The steam required for drying is equivalent to approximately 8 million Btu/ton, or 2.8 trillion Btu/year for a 1000-ton/day machine. If the moisture of the paper entering the dryer were reduced by 1.0%, the dryer steam

required would be reduced by about 3%. This would save an additional 84 billion Btu/year or \$336,000 annually.

Summary for a 1000-ton/day paper machine:

Annual Energy Use = 4.725 trillion Btu = \$18,900,000 @ \$4/million Btu

Reprocessing savings:

*	Electricity	38.5 billion Btu	
*	Steam	56.0 billion Btu	
	Total reprocessing savings	94.5 billion Btu	= \$378,000

Refining savings:

*	Electricity	73.5 billion Btu	= \$294,000
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Drying savings:

*	Steam	84.0 billion Btu	= \$336,000
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Total potential savings for 1000-ton/day machine:

*	Electricity	112.0 billion Btu	= \$448,000
*	Steam	140.0 billion Btu	= \$560,000
		@ \$4/million Btu	= \$1,008,000
	Total potential savings/year	252 billion Btu/year	= 5.3%

Environmental Benefits: Minimizing the need for repulping and remanufacture reduces water utilization and provides consequential environmental benefits. The ability to control the production process to stiffness targets would not only provide the potential 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.

REVIEW OF PREVIOUS WORK

IPST has developed instruments to measure the in-plane and out-of-plane (ZD) ultrasonic velocities through paper samples in the laboratory. These nondestructive measurements have been used in the laboratory by IPST for many years to characterize the mechanical properties of paper. IPST initiated work on in-plane ultrasonic velocity measurement in moving webs in the early 1980s (Baum and Habeger, 1980; Baum and Habeger, U.S. Patent 4,291,577; Habeger and Baum, 1986). 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 technology associated with the in-plane measurements was licensed to a number of instrument manufacturers.

The above developments represented a major step forward in terms of on-machine monitoring of product quality. However, in order to differentiate the separate effects of refining, jet-to-wire-speed ratios, wet-pressing pressure, draws, calendering, and drying restraints on paper properties, the elastic stiffnesses in both the in-plane and thickness directions should be measured. This would provide the maximum sensitivity to the effects of the various paper-machine variables and provide the ability to partially resolve their influence for machine control. Therefore, the project emphasis at IPST became the development of a sensor to make measurements of the ultrasonic velocity in the thickness direction (ZD) of a moving paper web. Then an appropriate in-plane sensor would be used in combination with the ZD sensor to provide a complete system to measure paper mechanical properties on the paper machine.

The IPST member companies and the Office of Industrial Technologies of the U.S. Department of Energy supported a research project at IPST titled, "On-Machine Sensors to Measure Paper Mechanical Properties," through Contract DE-AC05-86CE40777, from October 1, 1986, through May 31, 1993. The details of this work are recorded in a final report dated October 1993. The primary objective of this project was to develop sensors and techniques to make ZD ultrasonic measurements in the laboratory and improved in-plane ultrasonic measurements on moving webs.

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 of up to 2500 feet per minute, running in either an endless loop or a reel-to-reel mode. A dancer arm provides adjustable tension in the loop mode, and tension is automatically controlled in the reel-to-reel mode. The system is able to handle webs up to 14 inches in width with tension controllable from 0.5 to 4 pounds per linear inch. This system has been used to perform tests on 42-foot endless loops and reels wound onto 3-inch cores with roll diameters of up to 34 inches.

Laboratory In-Plane Ultrasonic System for Moving Webs: 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. The cylinder is mounted in the web handling system. The transducers are oriented outward so that each active element protrudes slightly outside the circumference of the cylinder. Part of the housing is square in cross section and slides freely in a square hole in the carrier. The square shape maintains the rotational alignment of the bender transducer. The web is wrapped part way around the cylinder. Relatively weak spring loading is used in the carrier to imitate the light contact force used in the IPST laboratory instrument for in-plane ultrasonic measurements.

The transducers are used in sets of three. One transducer serves as a transmitter and the other two transducers are used as receivers. The transducers may be oriented and aligned to operate in the longitudinal or shear mode in the MD or CD. For example, a transmitter positioned to excite longitudinal waves in the MD of the web also excites shear waves in the CD. 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.

ZD Measurements with Ultrasonic Transducers in Fluid-Filled Wheels: Fluid-filled wheels containing ultrasonic transducers, similar to those used commercially in testing railroad rails for flaws, were found to provide a promising sensor configuration for making measurements of ZD ultrasound velocity through moving paper webs. Each wheel is constructed with an ultrasonic transducer mounted to a fixed axle inside the wheel. Bearings are used to mount a hollow elastomer tire on the axle. Fluid is

pumped into the tire and all air bubbles are carefully removed. In our application, the paper runs in the nip between two such wheels and acoustic energy is transmitted from the transducer in one wheel through the paper to the transducer in the other wheel.

A test stand for mounting the fluid-filled wheels was designed and constructed to operate with the unwind/rewind web handling system. This test stand has cross-web positioning in 1-inch increments. The wheel mounts are extended and retracted along the Z direction 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.

Testing and evaluation in the laboratory using the web handling system identified challenging requirements for achieving accurate ZD transit time and velocity measurements through moving paper webs. Since the paper webs are typically less than one millimeter in thickness, the ZD measurement system must be capable of measuring ZD pulse flight times through paper with near nanosecond accuracy. Techniques were developed to compensate for the effects due to temperature changes and to physical limitations of the measurement apparatus itself.

The ZD measurements proved to be very sensitive to temperature changes in the fluid filling the wheels and in the tires that contain the fluid, both of which lie along the ultrasonic propagation path. It was found that the time of flight in a delay line attached to the active surface of the transmitting transducer provided an accurate and precise measure of temperature. The current transit times were compared with "reference" values that were measured at the current system temperature. The reference values were determined off-sheet when the temperature of the apparatus was at equilibrium on-sheet. The temperature-dependent "reference" values were determined as a function of the temperature-dependent, delay-line transit times. These relationships were then used to correct the "reference" values to the current system temperature.

A pulser/receiver was 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 electronics in combination with the delay line also provided an appropriate set of pulses to permit time-difference measurements. The pulse trains were digitized at a rate of 10 MHz (100 nanoseconds/point) to allow fast averaging (approximately 500 pulse trains averaged per second). By using cross correlation and then using second-order interpolation around the peaks of the cross-correlation integrals, time differences within averaged pulse trains could be determined with near nanosecond accuracy.

Since velocity is a function of both distance and time, a caliper measurement is required along with the transit time through the sample in order to calculate the ZD velocity of ultrasound. The caliper of the sheet can also be determined from the acoustic pulses transmitted between these wheels. With a fixed distance between transducers, the time of arrival for a transmitted pulse is independent of any variation in the precise location of the pass line between the two wheels. When a paper sample is inserted in the nip, the path-length change in the fluid is precisely equal to the paper thickness. Using the time difference with and without a sample in the nip, the caliper (paper thickness) can be calculated. Either ultrasonic pulses in the fluid-filled wheels or an independent caliper gauge may be used to determine the web caliper. The principal advantage of the use of the ultrasonic pulses for web caliper is that the data are collected at precisely the same instantaneous sample locations and with the same sample compression at which the transit-time data were collected.

For on-line process and quality control, there may be ways to get around the need to determine caliper. Acoustic impedance is the mass per unit area traversed in unit time. If the basis weight of the

sample is known, the acoustic impedance, $Z = \rho v_p$, (where ρ represents the density of the sample) can be calculated from the time-of-flight of ultrasound 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. From the standpoint of providing a nondestructive test indicative of paper mechanical integrity, there is no apparent reason to prefer v_p over ρv_p when evaluating a single grade. Since basis weight is determined routinely on-line, it may be preferable, in the design of an on-machine out-of-plane ultrasonic sensor, to avoid the difficulties of caliper determination by using the more convenient impedance measurement.

The details of the work supported through Contract DE-AC05-86CE40777 are recorded in the final report dated October 1993. Briefly, both ZD and in-plane ultrasound velocity data were collected in the laboratory on a variety of commercial paper grades. The ZD fluid-filled wheel sensor system was believed to be ready for engineering development into a prototype system on the path toward commercialization. Continued development of the ZD sensor should include working with a vendor interested in providing in-plane and ZD sensors to the paper industry. The in-plane cylinder-mounted system in the laboratory provided reliable measurements on moving webs that closely corresponded with the laboratory instrument measurements on cut samples. This, together with the web handling system, provided an excellent system to test and evaluate performance of in-plane measurement prototypes.

Toward Commercialization: In view of the status of this technology and its potential benefits, work continued with support by Cooperative Agreement No. DE-FC05-93CE40006, U.S. Department of Energy (DOE), and by the member companies of the Institute of Paper Science and Technology (IPST). The central purpose of this grant, effective from October 1, 1993, through June 30, 1994, was to establish a plan: to develop a commercially viable system for on-machine, out-of-plane and in-plane measurements of ultrasonic velocities; to install a working system on a paper machine in a host paper mill; to demonstrate the system's capabilities and benefits to the paper manufacturing industry; and to have a vendor committed to providing and supporting the system. A report titled "Commercialization of On-Machine Sensors to Measure Paper Mechanical Properties" and dated September 1994 summarizes this work.

An essential step on the path toward commercialization of on-machine ultrasonic velocity measurement was the establishment of a working relationship with a vendor of instrumentation and control systems for paper machines. The various vendors were contacted. ABB Industrial Systems Inc. (ABB) of Columbus, Ohio, was the only vendor that expressed a willingness to participate.

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

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

The Department of Energy (DOE) Office of Industrial Technologies (OIT) sponsored a solicitation for Cooperative Agreements as part of its Industrial Waste Reduction Program in September 1993. This solicitation was focused on the metals industry and the pulp and paper industry. The program targeted key

waste-reduction opportunities that offered significant savings in material, energy and cost, as well as environmental benefits. The solicitation required industry participation and 50% cost sharing. Working with ABB and with the concurrence of the Herty Foundation Center in Savannah, Georgia, a plan to pursue commercialization aggressively was prepared, and IPST submitted a cost-share proposal to DOE by the solicitation due date, December 2, 1993.

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

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

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

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

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

CHRONICLE OF PROJECT EVENTS

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

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

October 24-25, 1994: A report on the past and anticipated project work was presented at the DOE/Industry Advanced Sensors Technical Conference in Gaithersburg, Maryland.

December 1994: ABB completed fabrication of a system, including Operator Station, System Electronics, "Smart Platform" Scanner, with integrated basis weight, moisture, caliper, and temperature sensors for installation on the web handler in the IPST laboratory.

May 8, 1995: Negotiation of the IPST-ABB Subcontract was completed and signed. Mac Hall visited ABB for project discussion and to view the ABB hardware before shipment. The ABB hardware was later shipped to the ABB facility in Norcross, Georgia.

May 9-11, 1995: A brief overview of the project was presented at the Office of Industrial Technologies (OIT) 1995 Industrial Pollution Prevention Program Review in Oak Brook, Illinois.

June 8, 1995: Negotiation of the IPST-Herty Subcontract was completed and signed.

June 20, 1995: The Smart Platform 1200 scanner was delivered to IPST. A crane was used to move the scanner into the building through a window on the third floor. The scanner was positioned on the mounting pedestals and aligned with the web handler.

July 19, 1995: Conduit runs and wiring were completed and ready for the ABB AccuRay® 1190™ System and Smart Platform 1200 system startup procedures. The system software was loaded and the basis weight, moisture, and caliper sensors were made operational by ABB.

July 25, 1995: Installation of an in-plane ultrasonic velocity sensor in the sensor carriage at IPST was initiated by Brad Pankonin (ABB, Columbus). Brad completed installation and check-out in mid-August.

July 27, 1995: Mac Hall visited Herty along with 5 people from ABB. The purpose of the trip was to review the plans and specifications for installation of an ABB 1190/1200 system on Herty's Number One pilot paper machine.

October 23, 1995: The ABB AccuRay® 1190™ System and the Smart Platform 1200 scanner were delivered to Herty.

October 23, 1995: The project was reviewed at the DOE/Industry Advanced Sensors Group Meeting in Eastlake, Ohio.

November 15, 1995: A "Host Mill" information meeting was held at IPST. A letter was sent to the 15 member companies of IPST who produce linerboard. The companies were invited to send representatives to IPST on November 15, 1995, for a detailed information meeting regarding the "opportunity to provide a Host Mill for demonstration of on-machine ultrasonic sensors." Twelve of the companies responded and five sent representatives to the meeting.

December, 1995: Champion informed us that they were interested in being chosen as the Host Mill with their PM no. 4 at their mill in Roanoke Rapids, North Carolina. Georgia-Pacific decided they would like to participate with their PM no. 1 at their mill in Cedar Springs, Georgia.

February 8, 1996: Representatives of ABB and IPST visited the Champion mill in Roanoke Rapids, North Carolina. Their PM no. 4 is a Beloit Fourdrinier with wire width of 248" and trim of 228". The machine has a Beloit secondary hydraulic headbox and an Extended Nip Press (ENP). The basis weight for the natural grades produced ranges from 31 to 69-lb/1000 ft² and 31 to 42-lb/1000 ft² for white top grades.

February 19, 1996: ABB completed installation and startup of the AccuRay® 1190™ System and the Smart Platform 1200 scanner on Herty's Pilot Machine No. 1

February 22, 1996: Representatives of ABB and IPST visited the Georgia-Pacific mill in Cedar Springs, Georgia. Their PM no. 1 is a Beloit Fourdrinier with wire width of 280" and trim of 257". The machine has a Beloit concept 2 secondary headbox. They produce 38 to 90-lb/1000 ft² at an average production of 1438 tpd.

March 4-6, 1996: Plots of MD Shear velocity data and CD Longitudinal velocity data were prepared by ABB for presentation in their exhibit at TAPPI '96 in New Orleans. The plots showed that the response of the ABB in-plane engineering prototype sensor correlated very well with the IPST drum-mounted transducers over the range of paper properties that would be encountered in web-wide samples.

March 18, 1996: The ABB in-plane ultrasonic velocity sensor was added to the Herty scanner.

March 28-29, 1996: Linerboard samples, 26, 32, and 42-lb/1000 ft² with variations in wet pressing and calendering, were produced during initial pilot machine trials at Herty. The various test combinations were recorded. Four rolls, twelve inches in width, were slit from these samples by Howard Zuker and Assoc. in Savannah and sent to IPST for measurements on the web handling system. An example of results is plotted below.

The above plot shows the changes in the ZD, CD, MD, and Shear specific stiffnesses for the 42# samples as a result of wet pressing and calendering. The values are plotted relative to the values for the 42# sample with Low wet pressing (value 1.0). The plot shows that the effects of wet pressing and calendering on the ZD values are significantly greater than on the three in-plane values or even density in terms of percent change in response to the change in process conditions. As expected, calendering decreases ZD stiffness, whereas wet pressing increases it.

September 4-5, 1996: Bob Pfeifer and Kevin DePoy from ABB visited IPST. A revised schedule for completion of the Phase III tasks and a schedule for the major tasks of Phase IV were prepared. On September 5th, Joe Bryson, Program Manager from the Office of Industrial Technologies of DOE, and Joe Mavec, Project Officer from the Chicago Operations Office of DOE visited IPST. The status, revised schedule, and plans were reviewed with them and the project equipment was demonstrated in the laboratory.

September 20, 1996: The Georgia-Pacific mill in Cedar Springs, Georgia, was selected to participate as the Host Mill. Negotiations were completed and the Subagreement between Georgia-Pacific and IPST was signed by the Vice President of Cedar Springs Operations.

December, 1996: ABB procured a "Dynamic Test Machine" that can handle rolls or belts of paper up to 36 inches in width. This system includes an ABB scanner and sensor carriage identical to those installed at IPST and at the Herty.

December 9, 1996: The scanner and 1190 system for the Host Mill were shipped to ABB's Atlanta office (now in Duluth, Georgia) and then shipped to arrive at the Cedar Springs mill before the end of 1996.

February 27, 1997: Mac Hall and Bob Pfeifer presented a review of this project at the Agenda 2020 Sensors & Controls Operating Task Group meeting at the American Forest & Paper Association (AF&PA) headquarters in Washington, DC.

April, 1997: Installation of the ABB scanner and 1190 system at the Georgia-Pacific Cedar Springs mill was completed in April.

April 1-4, 1997: A second pilot-machine run at Herty was completed. The furnish for this run was supplied by linerboard shipped from the G-P Cedar Springs mill.

Sensitivity of Specific Stiffnesses
to Refining - CSF 497 and CSF 450 vs CSF 650

The above plot shows the ZD, CD, MD, and Shear specific stiffness for Canadian Standard Freeness (CSF) of 497 and 450 relative to CSF = 650. As expected, the measured stiffnesses increase with increased refining. The plot shows that the changes in the ZD values with increased refining are significantly greater than the changes in the in-plane values.

April 1-4, 1997: Two modules, each containing a ZD wheel, a motor to drive the wheel, and a mechanism to extend and retract the wheel, were completed at the end of March and taken to Herty for the pilot-machine trials. The modules were fitted into the sensor carriage on the ABB scanner. External wiring and hand-operated air valves were used. When the sensor carriage was scanned with the wheels in contact with the paper, the web would wrinkle, demonstrating the need to steer the wheels when scanning.

June 4-5, 1997: A paper entitled "Small-Scale Variations in CD Strips Observed Using Ultrasonic Velocity Measurements" by Mac Hall and Ted Jackson was presented by Mac Hall at the International CD Symposium in Tampere, Finland.

June 17, 1997: Ted Jackson and Mac Hall (IPST) and Brad Pankonin and Ted Kemp (ABB) met with David Malphurs, Rusty Wilson, and Chip Hammons of G-P, and Mike Granger and Scott Olsen, ABB resident engineers at the mill. The in-plane and ZD sensors were described with available pictures. The space available for working on the sensor carriage was reviewed, and installation requirements and probable timing were discussed.

September 28 - October 3, 1997: A paper entitled "New On-Line Out-of-Plane Ultrasonic Elastic Stiffness Measurement Technology" by Ted Jackson and Mac Hall was presented by Ted Jackson at the 1997 TAPPI Process and Product Quality Conference and Trade Fair in Jacksonville, Florida.

September 30, 1997: IPST received notification from the DOE Chicago Operations Office that the proposed statement of work and budget for Phase IV was approved with the project period extended through September 30, 1999.

October 1, 1997: The installation of the in-plane "Product Prototype" Sensor was completed at IPST.

October 2, 1997: The Agenda 2020 Sensors & Controls Operating Task Group met at IPST. Mac Hall and Bob Pfeifer presented the status of this project.

November 20, 1997: Andy Brown and Mac Hall (IPST) visited the Cedar Springs Mill to discuss work plans for installation of the "Stand Alone" ZD System during the planned extended shutdown of PM no. 1 in December.

December 1-5, 7-10, 1997: The In-Plane Ultrasonic Sensor provided by ABB was installed on PM no. 1 at the Georgia-Pacific Cedar Springs Mill. Cabling for the ZD sensor and a rail potentiometer (resolver) for determining CD position were added to the Host Mill scanner by ABB when the scanner and sensor carriage was modified for installation of the in-plane sensor.

December 4-5, 1997: Andy Brown, Ted Jackson, and Mac Hall (IPST) took partially assembled modules to the Cedar Springs Mill during the PM no. 1 extended shutdown to check how the modules fit in the scanner.

December 15, 1997: The ABB in-plane "Product Prototype" Sensor was installed on Pilot Machine no. 1 at Herty.

February 13, 1998: Brad Pankonin (ABB) and Mac Hall (IPST) visited the Cedar Springs Mill and met with Doug Jimmerson and Herman Wade (G-P), and Mike Granger and Scott Stacks (ABB support at the Mill). The status of the installation, measurement operation, and procedures for validation of the in-plane on-machine sensor were discussed.

June 25, 1998: Ted Jackson, Andy Brown, and Mac Hall visited the mill to attend presentations by representatives from Pavilion Technologies and Pacific Simulation. A copy of FactNet 4.5 software was later purchased for use at IPST.

July 6-9, 1998: The ZD system was taken to ABB's lab in Columbus, Ohio, for an installation trial and test run on their web handler. On July 9th, the web handler was left running at 725 ft/min. with the ZD system scanning overnight and everything was operating the next day after about 15 hours.

July 28-30, 1998: The Georgia-Pacific Mill in Cedar Springs, Georgia, had a scheduled outage for PM no. 1 on July 28th. Ted Jackson, Andy Brown, and Mac Hall installed the ZD modules in the scanner while the machine was down. The Resolver was replaced with an Encoder and mounting taken from the scanner at IPST. Scanning with wheels closed was first tried after noon on July 30th. This initially caused some ripples when the scanner reversed at the edges of the web, but with software changes in the timing of the change of steering direction, ripples at reversal were eliminated. With the timing properly adjusted we were able to scan with wheels in continuous contact with the web without a problem for about one hour. The speed of the motor driving the top wheel became erratic and we stopped, packed up the ZD system, and returned to IPST. When the wheel was opened back in the lab the next day, the transducer had come loose and dropped against the tire, wearing a deep groove. We remounted the transducer and replaced the tire that had been damaged by the loose transducer and were ready to reinstall the ZD system on PM no. 1 during the next outage scheduled for August 26, 1998.

August 26-28, 1998: Ted Jackson, Andy Brown, and Mac Hall took the ZD system with an air conditioner added to the electronics enclosure to the mill and installed the ZD modules in the scanner during the scheduled machine outage. During this "outage", Georgia-Pacific electricians provided a connection to the tachometer on the motor driving the reel drum (pope reel) to provide a web-speed signal for our system. The reflected signals in the transmitter wheel were good, but the signals in the receiver wheel were very weak. After collecting reflected-energy data while scanning on August 27th and 28th, the modules were removed and returned to IPST.

August 31, 1998: When the modules were removed from the PM no. 1 scanner on August 28th the receiver wheel had low pressure and had leaked some fluid through the bearing bleed holes in the hub. We shipped the two fluid-filled wheels to Mike Pagano at DAPCO Industries for inspection. They found dirt in the seals of the bearings. They cleaned and reassembled the wheels and returned them promptly.

September 8-11, 1998: Andy Brown returned to the mill and installed the ZD modules in the scanner while the machine was down on the morning of September 8th. He was able to collect data for a total of 30 hours and approximately 480 miles by the end of the week. The signals in the receiver wheel continued to be weak.

September 16, 1998: Ted Jackson and Andy Brown worked on the system at the mill during the scheduled outage. After startup the receiver still had low signal-to-noise.

September 22-23, 1998: Additional data was recorded. The pressure in the tires was increased in an effort to improve the signal. The receiver tire cracked, and the modules were removed for return to IPST. Blisters were observed in the caps of the transducers. The transducers were sent to DAPCO for repair. A modification was made in the modules to provide air cooling to the wheels.

October 2, 1998: A project status meeting was held at the G-P Cedar Springs Mill. Joe Mavec visited the mill and participated in this review.

October 13, 1998: The Agenda 2020 Sensors & Control Committee met at the Weyerhaeuser Technical Center in Tacoma, Washington. A review of the project was presented by Bob Pfeifer and Mac Hall.

November 23-24, 1998: Ted Jackson, Andy Brown, and Mac Hall met with Bob Pfeifer, Brad Pankonin and others at ABB in Columbus, Ohio, to outline the configuration for integrating the ZD system with the ABB scanner, 1190, and Advant display.

December 14, 1998: PM no. 1 was shut down for an extended maintenance. During this shutdown ABB installed two co-ax cables each and two air hoses each in the top and bottom auxiliary flex tracks of the scanner. Two air regulators were also installed for use in supplying air to the ZD modules separate from the air-supply system for the other sensors in the carriage. The positions of the in-plane and the ZD sensors in the carriage were interchanged (ZD modules downstream, in-plane sensor upstream) in order to place the center of gravity closer to the center of support in the scanner frame. A further change in sensor positions for weight distribution was later made with the ZD modules remaining in the downstream position.

March 15-19, 1999: *ZD System Ran Around the Clock* -- During the week, the ZD system ran on the machine for 46 hours. It was run overnight on the 17th and 18th with ZD transit-time data collected continuously for 24 hours from approximately 6 AM on March 18th to 6 AM on March 19th.

April 6, 1999: A presentation on the project was given at a meeting of the Agenda 2020 Sensors & Control Committee at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Bob Pfeifer (ABB) and Gary Baum (IPST) participated in this presentation.

May 17, 1999: Step-test trials were conducted at the G-P Cedar Springs Mill with PM no. 1 running 69# (69 lb/1000 ft²) linerboard. The ZD system operated successfully for an eighteen-hour period that included the trial.

June 8, 1999: Eric Lightner, Program Manager from the Office of Industrial Technologies of DOE, visited the G-P Cedar Springs Mill to see the on-machine ultrasonic sensor systems.

June 9, 1999: Step-test trials were conducted at the G-P Cedar Springs Mill with PM no. 1 running 55# (55 lb/1000 ft²) linerboard. The ZD system operated successfully for an eighteen-hour period that included the trial.

September 12-16, 1999: A paper entitled "Mill Experienced with On-Line Ultrasound Based Stiffness Measurements" by Bradley Pankonin and Doug Jimmerson was presented at the TAPPI Engineering/Process and Product Quality Conference held in Anaheim, California.

ZD MEASUREMENT SYSTEM (Ultrasonic Transducers in Fluid-Filled Wheels)

Method for Measurement of ZD Transit Time of Ultrasound:

A new method and measurement system has been developed using ultrasound for determining ZD characteristics of a moving web. The new system is free-running in that any given transit-time measurement may be made instantaneously at any point in time as the wheels rotate with the passage of the specimen through the nip. The previous system required an electronic rotational synchronization circuit such that each measurement represented an average of measurements through one or more rotations of the wheels. The new measurement method is insensitive to variations in tire thickness around the circumference, because the components of ultrasonic transit time through the tires and fluid (T_{fe} , T_{we} , T_{wt} and T_{ft} - see sketch on following page) are now continuously resolvable from the ultrasonic transit time (T_s) through the specimen. The new method accurately retains point-to-point specimen transit-time variation information, whereas the old method could not. Thus, each measurement represents the ultrasonic transit time through a portion of the specimen the area of which is equal to the cross-sectional area of the propagating ultrasonic wave front at the point of nip contact between the tires without the need for averaging successive measurements to improve accuracy.

The new system is able to measure ultrasonic transit time through the moving web without requiring any measurement of separation distance between the two ultrasonic transducers located within the two fluid-filled wheels. This makes the new system appropriate for inclusion into a split-head sensor carriage on a scanning platform where a precise relative separation between the head components above and below the web are nearly impossible to maintain while scanning. The new system is also immune to changes in the temperature of the fluid and the tire media along the ultrasonic propagation path.

Every measurement begins with the emission of a short duration highly damped ultrasonic pulse from the transmitting ultrasonic transducer. A pulse-echo circuit is electronically reconfigured an instant after the emission to receive ultrasonic echoes arising from the original emission. Ultrasonic energy propagates away from the transducer surface through the fluid within which the transducer is immersed until the ultrasonic wave front reaches the boundary between the fluid and the inside of the corresponding tire. At this boundary, a portion of the energy is reflected back from the boundary and the rest of the energy propagates through the tire thickness. Every boundary between pairs of adjacent media produces a through-transmitted and a reflected pulse in this way, ultimately producing a train of pulses distributed over time and arriving at the transmitting transducer (now an echo receiver) and the receiving transducer. Several pulses within the pulse train arising from the original emission are useful for the measurement of ultrasonic transit time through the specimen. Referring to the sketch on the following page, the pulses of interest are labeled (P_{e1} , P_{e3} , P_{t1} and P_{t2}). These measurement pulses must be separated in time from the many other pulses in the pulse train arriving at either transducer surface. The path lengths through each medium are chosen such that the measurement pulses are clearly resolved in time from each other and from the nonmeasurement pulses. By measuring the relative time offset between pairs of measurement pulses via a cross-correlation integral, represented as $CR(P_a, P_b)$, the calculation of transit time through the specimen (T_s) proceeds as follows:

Sketch: Transducers in Fluid-Filled Wheels

Calculations Corresponding to Pulse Set in Sketch of Transducers in Fluid-Filled Wheels:

$$\begin{aligned} \text{CR}(P_{e1}, P_{e3}) &= (4 * T_{fe} + 4 * T_{we}) - (2 * T_{fe} + 2 * T_{we}) \\ &= 2 * T_{fe} + 2 * T_{we} \end{aligned}$$

$$\begin{aligned} \text{CR}(P_{t1}, P_{t2}) &= (T_{fe} + T_{we} + T_s + 3 * T_{wt} + 3 * T_{ft}) - (T_{fe} + T_{we} + T_s + T_{wt} + T_{ft}) \\ &= 2 * T_{ft} + 2 * T_{wt} \end{aligned}$$

$$\begin{aligned} \text{CR}(P_{e1}, P_{t1}) &= (T_{fe} + T_{we} + T_s + T_{wt} + T_{ft}) - (2 * T_{fe} + 2 * T_{we}) \\ &= T_s + T_{wt} + T_{ft} - T_{fe} - T_{we} \\ &= T_s + \text{CR}(P_{t1}, P_{t2}) / 2 - \text{CR}(P_{e1}, P_{e3}) / 2 \end{aligned}$$

So:

$$T_s = \text{CR}(P_{e1}, P_{t1}) + \text{CR}(P_{e1}, P_{e3}) / 2 - \text{CR}(P_{t1}, P_{t2}) / 2$$

The calculated value for T_s is very close to the actual transit time of ultrasound through the specimen at the point of nip contact with the tires. However, in practice, the two transducers themselves and the electronics that amplify the electrical signals generated by the transducers have slightly different phase-response characteristics. These characteristics add a slight constant inaccuracy to the measurement of T_s and must be taken into account. With the specimen absent from the nip, the actual transit time through the nip is exactly zero. However, some small nonzero transit time will generally be produced from the calculation of T_s . This residual T_s (T_{s0}) is directly attributable to the nonidentical transducer and electronics phase characteristics mentioned above. If an average value for t_{s0} is subtracted from every value for T_s calculated while the specimen is present in the nip, then the resulting measurements of T_s will be quite accurate and free of the transducer and electronics unique phase-response characteristics.

If the materials constituting both tires are identical, then the acoustic impedance of the two tires will also be identical. When a specimen is absent from the nip during the off-sheet calculation of T_{s0} , very little energy may be reflected back from the nip where the two tire surfaces meet due to the very low acoustic impedance mismatch. This is especially true when the tires are static or are moving at a slow rotation rate. Thus, the doubly nip-reflected pulse P_{e3} may be very small and will generally have a very low signal-to-noise ratio under these conditions. However, if the tires are moving at a relatively high rotation rate with no specimen present, a substantial acoustic boundary that leads to larger reflections from the nip is observed. When a specimen is present in the nip, regardless of rotation rate, the acoustic impedance mismatch between tire material and specimen is generally quite large, leading to strong nip-reflected pulses.

The ZD Fluid-Filled Wheels and Mounting Modules:

Below is a picture of two fluid-filled wheels and two modules for mounting them in the sensor carriage of the ABB Smart Platform™ 1200.

When placed in the modules, the wheels are mounted on circular bearings so that they can swivel and be steered in the direction appropriate for the current scan direction and web speed. The modules shown here were replaced by the more recent design pictured on the following page.

The modules were redesigned to make two major changes. The first was to collect most of the on-board electronic components in an air-cooled chamber so that cooling and protection from the harsh environment would be more effective.

The second major change was to design the modules so that they could be inserted or removed from the sensor carriage more conveniently. Quick connectors were used for the electrical and air connections so that one would only need to slide the modules into position and fasten. With the earlier design it was necessary to laboriously remove the side panel from the sensor carriage in order to make the necessary electrical and air connections.

These modules were designed by Mark Szlemko at IPST. The drawings for the top and bottom modules are collected in a manual filed at IPST. The table of contents is presented on the following two pages.

Table of Contents from Manual Containing Design Drawings for Mounting Modules - Page 1

General Assembly

3942-05-00-00 On-Machine Wheel Sensor Ass'y

Bottom Module

3942-05-01-00 Bottom Module	3942-05-01-05 Bot. Module – Rear Bar
3942-05-01-01 Bot. Module – Bottom Plate	3942-05-01-06 Bot. Module – Front Bar
3942-05-01-02 Bot. Module – Front Plate	3942-05-01-07 Crossbeam
3942-05-01-03 Bot. Module – Rear Plate	3942-05-01-08 Wheel Side Rail
3942-05-01-04 Bot. Module – Wheel Side Wall	3942-05-01-09 Welded Nut

Bottom Electronics Bay

3942-05-02-00 Electronics Bay Assembly	3942-05-02-07 Bot. Module – E.B. Conn. Plate
3942-05-02-01 Bot. Elect. Bay Bearing Mount	3942-05-02-08 Elect. Bay Bearing Mnt. Rail
3942-05-02-02 Elect. Bay Wire Hole Plate	3942-05-02-09 Elect. Bay Connector Plate Rail
3942-05-02-03 Elect. Bay Inside Wall	3942-05-02-10 Elect. Bay Side Rail
3942-05-02-04 Bot. Elect. Bay Front Plate	3942-05-02-11 Bot. Elect. Bay Cover
3942-05-02-05 Bot. Elect. Bay Side Wall 1	3942-05-02-12 Bot. Elect. Bay Support Bar 1
3942-05-02-06 Bot. Elect. Bay Side Wall 2	3942-05-02-13 Bot. Elect. Bay Support Bar 2

Bottom Electronic Side Base

3942-05-03-00 Bot. Elect. Side Base Assembly	3942-05-03-02 Bot. Base – Stopper (Elect. Side)
3942-05-03-01 Bot. Base Plate (Elect. Side)	3942-05-03-03 Elect. Quick-Disconnect Mount
3942-05-03-04 Pneumatic Quick-Disconn. Mount	

Bottom Wheel Side Base

3942-05-04-00 Bottom Base (Wheel Side)

Bottom Rotating Plate

3942-05-05-00 Bottom Rotating Plate	3942-05-05-03 Shaft
3942-05-05-01 Bottom Plate	3942-05-05-04 Bot. Align Plate
3942-05-05-02 Shaft Mount	3942-05-05-05 Alignment Insert

Bottom Wheel Assembly

3942-05-06-00 Bot. Wheel – Steering Assembly	3942-05-06-05 Wheel Mount Cap
3942-05-06-01 Rotating Disk	3942-05-06-06 Wheel Pulley
3942-05-06-02 Driving Plate	3942-05-06-07 Drive Pulley
3942-05-06-03 Bot. Motor Mount	3942-05-06-08 Steering Insert
3942-05-06-04 Wheel Mount	

Table of Contents from Manual Containing Design Drawings for Mounting Modules - Page 2

Top Module

3942-05-11-00	Top Module	3942-05-11-04	Top Module – Wheel Side Wall
3942-05-11-01	Top Module – Top Plate	3942-05-11-05	Top Module – Rear Bar
3942-05-11-02	Top Module – Front Plate	3942-05-11-06	Top Module – Front Bar
3942-05-11-03	Top Module – Rear Plate		

Top Electronics Bay

3942-05-12-00	Electronics Bay Assembly	3942-05-12-07	Top Module – E.B. Conn. Plate
3942-05-12-01	Top Elect. Bay Bearing Mount	3942-05-12-11	Top Elect. Bay Cover
3942-05-12-04	Top Elect. Bay Front Plate	3942-05-12-12	Top Elect. Bay Support Bar 1
3942-05-12-05	Top Elect. Bay Side Wall 1		

Top Electronic Side Base

3942-05-13-00	Top Elect. Side Base Assembly	3942-05-13-02	Top Base – Stopper (Elect. Side)
3942-05-13-01	Top Base Plate (Elect. Side)	3942-05-13-03	Top Elect. Quick-Disconn. Mount

Top Wheel Side Base

3942-05-14-00	Top Base (Wheel Side)
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Top Rotating Plate

3942-05-15-00	Top Rotating Plate	3942-05-15-04	Top Alignment Plate
3942-05-15-01	Top Plate		

Top Wheel Assembly

3942-05-16-00	Top Wheel – Steering Assembly	3942-05-16-03	Top Motor Mount
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Purchase Orders

Notes

The above picture shows the bottom module inserted in the bottom half of the sensor carriage on the ABB Smart Platform™ 1200 in the laboratory at IPST. Note that the fluid-filled wheel is in line with the beta gauge, moisture gauge, and caliper gauge. The top module is mounted in a similar position in the top half of the sensor carriage.

Overview of On-Machine Operation of ZD System:

System Start-up

The wheels are rotated up to web speed (off-sheet) according to stored angular velocity vs circumferential velocity (and motor driving voltage vs angular velocity) calibration curves.

$V(\theta)$'s (angular velocities) are known precisely.

The V_c 's (wheel circumferential velocities) are known approximately as a function of $V(\theta)$'s. The V_c 's of the soft fluid-filled tires can change slowly over time due to changes in fluid temperature, inflation, wear, etc.

V_{web} is known approximately via an external tachometer signal.

First On-sheet

The wheels are brought into contact with the web for the first time. The greatest risk of sheet marking occurs at the moment of this first time contact following ZD system start-up.

Thereafter, the two wheel circumferential velocities are precisely equal to the web velocity.

The current corresponding wheel angular velocities are measured to high accuracy and are recorded.

Subsequent Off-sheets

The next time the head package is taken off-sheet (presumably for the next scheduled scanning platform standardize), the off-sheet angular and circumferential wheel velocities will generally shift away from the current web speed at the current wheel motor driving voltages. The stored angular vs circumferential velocity calibration curves are updated with a constant offset to bring the wheel velocities to precisely the most recent in-contact web speed.

Subsequent On-sheets

The wheel circumferential velocities are precisely equal to the current web speed before the wheels contact the sheet, so the potential for sheet marking is minimal. If the web speed changes (even if only slightly) while the wheels are in contact, the change is detected as a change in wheel angular velocity and a constant offset is applied to the angular vs circumferential velocity calibration curves.

Engage enable interlock circuit - sheet presence. Only when the two sheet-presence sensors both do or do not see paper can the wheels possibly engage each other (or the web). The web is thus intrinsically protected during off-to-on-sheet and on-to-off-sheet transitions of the scanning platform's head package.

Engage Enable Interlock Circuit - In addition to the sheet-presence component of the interlock, two additional enable signals must also be enabled before engagement can occur. The internal enable is disabled by the ZD system if it determines that any fault condition has occurred that could compromise its ability to obtain accurate measurements or the ability of the wheels to contact the web at precisely the current web speed (to minimize the potential for sheet marking).

The external enable signal is generally connected to a fail-safe signal whose source is external to the ZD system. The shutter state signal (if available) of a nuclear basis weight sensor is a good choice and is a usual companion instrument within the head package of a typical scanning platform. This signal makes use of the host scanning platform's own ability to detect potential fault conditions. It effectively determines that the head package is ready to measure and that personnel are not performing potentially unsafe maintenance tasks. Personnel are well protected from accidental exposure to radioactive devices.

Also, the web is protected intrinsically against failure due to the loss of air pressure or electrical power, which only together make engagement possible.

Wheel Swivel Control. An inductive sensor is used to verify swiveling of the wheels. Swiveling allows the ZD wheels to follow the best path along the web at the current combination of web speed and CD scanning speed of the scanning platform.

Only if the sensor detects the wheel (to within the distance of a few millimeters and within a brief period of time) after the wheel has been commanded to swivel in the direction of the sensor and then does NOT sense the wheel after the wheel has been commanded to swivel in the opposite direction will a fault condition NOT be detected and the wheels allowed to engage the web or each other.

The ZD system continuously monitors the web speed and the Direction and Velocity components of head-package motion along the CD and across the width of the scanning platform. If the scanning velocity is abnormally slow or fast or the web speed is not within normal production limits, then the preset swivel angles may not be appropriate for the current combination of scan and web velocities and the ZD system will not allow the ZD wheels to engage and contact the web.

ZD Electronics Box - Back Side Connector Layout

ZD Electronics Box - Front Panel Indicators - Attenuation Indicators

Two levels of display feedback are included for the attenuation control circuit. The control indicator displays the current attenuator states as set by the ZD system's control circuit. The solenoid current indicator (placed electrically in series between the attenuator control circuit and the attenuator solenoids) displays whether current is actually flowing through the attenuator within the three 6-bit attenuators. It is therefore easy for an operator to determine if attenuator solenoid failure has occurred, if a solenoid current indicator does not match its corresponding control indicator.

ZD Electronics Box - Front Panel Indicators - Other Indicators

The front panel indicators provide the operator with rapid, hard-wired visual feedback about aspects of the operational state of the ZD system.

The toggle state indicators change state with each signal edge detected and provide rate information. In the case of the wheel rotation inductive switches, the indicators change state with each wheel rotation. In the case of the CD scan encoder, the indicator changes state after approximately 1 mm of CD travel. The web speed tachometer indicator toggles after approximately 1 ft of MD travel. All rate indicators allow the operator to make reasonably good rate estimates of the four described rates (with a little experience).

The swivel state indicators provide verification that both wheels are swiveling properly. The wheels engaged indicator reflects the output of the wheel engagement interlock circuit.

- Top Wheel Rotation Inductive Switch Toggle State
- Bottom Wheel Rotation Inductive Switch Toggle State
- Sheet-Presence A
- Sheet-Presence B
- Internal Engage Enable
- External Engage Enable
- Wheels Engaged
- Top Wheel Swivel State
- Bottom Wheel Swivel State
- CD Scan Encoder Toggle State
- CD Scan Direction
- Web Speed Tachometer Toggle State

Contour Display of ZD Ultrasonic Measurements

The ZD system has a stand-alone E-box separate from the ABB 1190 system. However, a position encoder is used to provide scan position for the ZD system. The distance between scan limits is divided into 600 data boxes similar to the ABB 1190 system. It takes slightly more than one minute to scan across the 256-inch-wide web. A data box has a width slightly less than one-half inch. With a sampling rate of 20 per second, approximately 2 measurements will be averaged in each data box. A computer connected to the E-box can display the ZD Transit Time or Receiver Energy as a gray scale or color contour plot and concurrently as a profile plot and a trend plot. The transit-time profile observed on machine is typically a "frown" – larger transit time in the center than at the edges of the web. Since the caliper is relatively constant across the web, ZD velocity and ZD stiffness profile would be a "smile" – smaller in the center than at the edges of the web.

The print above is a copy of the computer display used to present the data collected by the ZD "stand alone" ultrasonic sensor system. The data shown are the transit times for ultrasound to pass through the web in the thickness direction (ZD). In real time the data from the current scan is added across the bottom of the rectangle. The data are collected across the 260-inch-wide web into 600 data boxes. At the end of each scan the display moves up one row, adding the most recent scan at the bottom and dropping the oldest scan at the top. The time stamps for the scans are shown on the left.

If one were standing at the headbox looking down the machine toward the dry end, the display from bottom to top shows the paper as it is wound onto the reel. Each scan takes slightly more than one minute, and 100 scans or approximately 100 minutes of production may be shown in the display. Thus, the display can present data from the most recently produced 3 to 4 reels and approximately 30 miles of paper. The number of scans displayed can be changed from 100 to 10 in steps of 10, if one wishes to display more detail.

NOTICE

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The transit-time (or receiver-energy) values may be displayed in gray scale or in false color. The color scale may be adjusted by inserting the desired minimum and maximum scale values. The minimum value selected for transit time in the above example is one microsecond and the selected maximum is three microseconds.

The black line profile across the bottom of the display and just below the multiscan plot shows the CD profile for the scan corresponding to the black horizontal line drawn within the multiscan plot. The black horizontal arrowhead controls the position of the horizontal line. This line can be moved up or down to select a different scan profile. A red line profile across the bottom shows the average profile for all scans falling between the two white horizontal lines corresponding to the two white arrowheads on the right. The white arrowheads can be moved to select any group of scans.

Similarly, black and red lines are shown vertically on the right and provide machine direction or "trend" profiles. The black line shows the MD trend for the data box (CD position) selected by the black arrowhead at the top. The red line shows the average of the profiles for the data boxes falling between the vertical white lines. The arrowheads can be moved to select other CD positions or CD ranges for display.

The vertical and horizontal white lines together define a rectangular area of the display. The mean and standard deviation for the data corresponding to this selected area is calculated and displayed.

Overview of Software for ZD Ultrasonic System

First some definitions:

M44 - This is the DSP (Digital Signal Processor) motherboard which runs independently of the host PC (computer), handling some of the system tasks and the timing and amplitude measurements of the ultrasonic pulses. During normal operation, the host program (written using LabView programming language) running within the PC periodically downloads calculated values from the M44.

Apps - App1 is the software program that runs within the M44 DSP board. App2 is the LabView host program running within the PC.

PCI bus - This is a high-speed bus (a series of digital data paths) that is built into the motherboard architecture of many newer PCs. This bus is capable of transferring data at high speeds between peripherals plugged into a PCI slot within the PC and the PC memory banks with minimal interference to the PC's processor.

ISR - Interrupt Service Routine - Virtually all computers respond to interrupts (an event initiated either by hardware or software) very quickly. When the interrupt occurs, the processor immediately executes a piece of code that performs some arbitrary function in response. This code is the ISR.

RAM - Random Access Memory - This is the storage hardware that computers use to temporarily store data while the computer is powered up (as opposed to hard disk storage which is for long term storage of data files which remain even when the computer is turned off).

SRAM - A type of RAM that maintains the information stored within it until that information is written over by new data or the computer is turned off. DRAM is another type of RAM that must be continuously refreshed so that the data stored within it is not lost. DRAM is less expensive than SRAM but requires more data maintenance than SRAM.

The ZD software is divided into 3 main sections of code:

- The Target Program (App1) (written in C, downloaded to the M44) runs the sensor.
- The Host Program (App2) provides a user interface as well as displays and stores the results.
- DSP.DLL (Dynamic Link Library written in C) provides communication between the 2 apps.

The Target Code is responsible for running the sensor. In fact, it can completely control and run the sensor without any communication with the user through the Host. The Host configures the Target Code and also provides a means to display/store results.

The Target Code must perform all of the tasks needed to run the ultrasonic measurement calculations. It performs each of these tasks once per loop and repeats the loop continuously and independently until the sensor is stopped or reconfigured by the Host. The general flow of code in the Target can be seen in the following chart:

Communication

Communication between the Target code and the Host occurs in three distinct ways. All communication is done through DSP.DLL. Also all three ways utilize the features of the PCI bus. The PCI bus provides several mailboxes that let devices on the bus communicate with one another. The M44 can use one PCI mailbox for M44-to-PC communication and another PCI mailbox for PC-to-M44 communication. It is set up such that the PC's outbox is the M44's inbox and the M44's outbox is the PC's inbox. Each mailbox can hold one 32-bit piece of information. The mailboxes are used to pass configuration and status information between Host and Target (but not the large volume of measured data). The PC side of the communication process is as follows:

On the M44 side, no looping occurs

The DSP runs a function to read or write a mailbox and does not return from that function until the read or write is successful. Therefore, it becomes crucial that both the PC and the M44 know what data to transfer and when to transfer it.

Synchronization occurs using the second type of PC-to-M44 communication -- mailbox interrupts. A mailbox interrupt is a special form of PC-to-M44 interrupt where, in addition to tripping an interrupt on the M44's DSP (and hence causing it to run the PCI Interrupt ISR), it also writes a value to a PCI mailbox. This mailbox is different from those used above so there is no chance of overwriting any other data. When the ISR runs on the DSP, its primary task is to take the value from the mailbox and assign it to a variable. This variable can be checked at a later point in the code (outside of the ISR) to determine which actions need to be performed. ISRs should be as small as possible because when they are run, global interrupts are masked, which might cause encoder or wheel-rotation pulses to be missed while the ISR is being serviced.

The final type of communication between the M44 and the PC is through the use of PCI bus mastering. With bus mastering a device (not necessarily the PC) can take control of the PCI bus and transfer data to memory locations mapped to the PCI bus. Both the PC RAM and the M44's SRAM are mapped to the PCI bus. This allows the PC to write directly to the M44's global SRAM without intervention from the M44's DSP and also allows the M44's PCI controller to write to PC RAM without intervention by the PC.

In the ZD system, the only bus master transferring that occurs is from the M44 to the PC and is used to transfer calculated ultrasonic measurements. For this process to occur, the data to be bus mastered must first be transferred from the M44's local SRAM to its global SRAM. The reason for this is that bus master transfers are performed by the M44's on-board PCI Controller chip. This chip can "see" data in the global SRAM but not in the local SRAM. The DSP performs a fast memory copy from local-to-global

SRAM, then configures the PCI Controller. This configuration sets up the location in the M44's global SRAM to copy data from, the location in PC RAM to copy data to, and the number of bytes to transfer. When this transfer is complete, the M44's PCI Controller can be configured to interrupt the M44's DSP. From the time the M44's PCI Controller is configured to the time the PCI Controller interrupts the M44's DSP, the DSP is free to perform any other tasks and is free from any other responsibilities during this transfer.

The PC has no knowledge that the M44 has bus mastered new data into its RAM. Different techniques (discussed later) are used to inform the PC that a new transfer is complete.

Data Format

Data in the system is stored in structures within the Host program. These structures are divided into sections corresponding to the different systems of the ZD sensor. The systems, section names, and variable names are:

System Name	Section Name	Variable Name
Paper Machine	machine	pm01
Scanner	scanner	abb
ZD Wheels	wheels	zd
Measurements	measurements	ultra

With these systems there is a group of data whose values are controlled by the Host and a group of data whose values are controlled by the M44. The name describes whether or not the data is read-only to the Host or whether the Host can write to these structures. Host read-only structures are named with the ?????_read nomenclature, while Host write-able structures are named with the ?????_write nomenclature. In both cases, the "?????" represents the section name. Global variables are created from these structure type definitions. The naming convention for the variables is identical to the structures except for replacing the section name with the variable name.

Both the Host and the M44 keep a copy of this data (the Host in clusters and the M44 in structures). Due to the way these structures are passed back and forth between the M44 and the PC, any Host writes to its ?????_read clusters will be overwritten at the next transfer. Also, any M44 writes to the ?????_write structures will be overwritten during the next transfer.

Data Transfer

Data transfer utilizes the techniques discussed in the Communication section to pass the structures between the M44 and the PC. As stated earlier, interrupt service routines must be very short so that encoder pulses and wheel rotations are not missed. Therefore, it is impossible to transfer structures inside these ISRs. The structure transfer routines are run as part of the normal M44 operating loop to pass status information. As described earlier, the M44 performs all the tasks required to run the measurement algorithms (including passing structures) once per loop and continues this loop until the sensor is stopped.

If the M44 had to pass every structure every loop, it would greatly reduce the number of measurements that it could perform per unit time. Almost all of the data only needs to be transferred when the user wants to monitor/change the status of a particular system. In general operation, the software is not monitored, and most of the structures do not need to be transferred. A few system variables need to be

transferred on a regular basis. These variables report key information like engagement status and current errors on the system.

The Host controls which structures are transferred and when. For the system data, the Host automatically requests that the M44 download stored measurement data once every 50 milliseconds. For all other structures, the Host only requests a download from the M44 when the user is requesting that information (when the user is viewing the front panel associated with a particular system).

When the Host requests that the M44 transfer a particular type of data, it does so by calling a DLL (Dynamic Link Library) function to perform a mailbox interrupt. As mentioned before, a mailbox interrupt not only interrupts the DSP, but also passes a value to a PCI mailbox that is read by the DSP inside its ISR. The message passed to the mailbox is the type of data that is being requested by the Host. When this interrupt arrives, the M44 can be in any position in its loop; however, it only checks to see if the Host has requested a transfer (by checking the value of the variable updated in the ISR) at the end of each loop. When the end of the loop and therefore the transfer routine is reached, the M44 will branch to the appropriate transfer code.

Immediately after the interrupt is sent, the Host starts writing values to the mailbox. However, as mentioned earlier, the Host cannot write over unread data. The Host will write the first piece of data into its outbox and then try repeatedly to write the second piece of data to the outbox until either one of two things has happened:

1. The M44 reads (clears) its inbox (which is the same as the Host's outbox). This allows the Host to write a new piece of data to its outbox.
2. The M44 doesn't read (clear) its inbox (which is the same as the Host's outbox) within 5 seconds. It is assumed then that the M44 is locked and the sensor is stopped and disengaged from the web.

One structure is passed a little differently. The `measurement_read` structure contains 5 large arrays (2 channel arrays and 3 convolution integrals). The ultrasonic signals themselves are contained in these arrays for use in evaluating the signal strengths and performance of the sensor. These large arrays would take too much time to pass through the mailboxes. To fix this, these 5 arrays are passed using the bus master transferring technique discussed earlier. The M44 side of the transfer goes like this:

1. The M44 does a quick copy of the 5 arrays from local to global SRAM.
2. The M44 configures and starts the on-board PCI Controller chip.
3. The M44 reads all the data for the `measurement_write` structure from the Host.
4. The M44 writes all the data, minus the arrays and the last variable, of the `measurement_read` structure to the mailbox.
5. The M44 polls and waits for the bus master transfer to complete.
6. The M44 writes the last variable of the `measurement_read` structure to the mailbox.

As mentioned before, the Host has no way of knowing when a bus master transfer has occurred. By using this technique the Host can be sure that when the last variable has been transferred, not only has a bus master transfer occurred, but also that it is complete. At this point the Host can retrieve that data.

Transferring Results

Measurement results are the only data types that the M44 controls when they are transferred. The M44 must pass the data up to the Host whenever its data arrays are full. The Host has no knowledge of measurement rate or when the arrays fill up.

At the end of a measurement the M44 checks to see if it has filled its measurement arrays. If it has, it bus master transfers the data to the Host's RAM using the technique described earlier. While the transfer is taking place, the M44 is free to continue normal operations that include making and storing additional measurements. Care has to be taken to be sure that bus master transferred data is not overwritten before it is processed. As soon as a transfer starts, a variable on the M44 (`data_transferring`) is set to 1. While this value is set to 1, no other bus master transfers can occur. This variable prevents the arrays inside `measurement_read` from being transferred (trouble occurs when both the Host and the M44 attempt to access the same memory space in RAM). Another variable (`pc_uploading`) is also set to 1 after the bus master transfer is complete. This variable prevents the M44 from performing another bus master transfer of results data until the Host has had a chance to retrieve it. Both variables are set back to 0 after the Host has retrieved the data.

When the bus master transfer is complete, the PCI Controller trips an interrupt on the DSP. This interrupt's ISR updates a variable (`data_points`), which is downloaded every time system data is downloaded. When, while downloading system data, the Host sees that the `data_point` variable is nonzero, it realizes that new result data has been bus master transferred to its RAM. At this time it calls a DLL function to get the data and signal the Host after it as been retrieved (generate an occurrence). This occurrence causes the Host to run a DLL function to pass the data into the Host. The Host then calls a DLL function to send a mailbox interrupt to the M44. The command sent along with the interrupt clears the `data_transferring` and `pc_uploading` variables, which informs the M44 that it is OK to bus master transfer more data.

In this setup, the only way that the measurements are slowed because of transfer happens if the Host is unable to realize and move the bus mastered data before the M44 has filled its data array again. The data array is the space within the M44's memory for distinct ultrasonic measurements. The data array size (120) is chosen to ensure the Host has ample time to process the data while not using too much memory on the M44. The Host must regularly download measurements from the M44. If the number of measurements exceeds 120 before the Host grabs the next set of measurements from the M44, then some measurements will be lost.

The detailed documentation of the software for the ZD ultrasonic system is contained in a manual prepared by Andy Brown. This "ZD Ultrasonic Software Manual" is on file at IPST. This manual discusses the software used to run the sensor, provide remote user displays, simulate the sensor hardware, manipulate the output files, and perform Fourier analysis on the results. The table of contents for the manual is presented on the following page.

The software falls into 3 main areas based on type of code. These areas are Host code, Windows DLL code, and Target code written for the M44 board. An additional area deals with miscellaneous documentation. The following list shows the organization of this manual.

I. Host Code

- A Main Program**
 - 1 Initialization
 - 2 Upload Data from DLL
 - 3 Process Data
 - 4 Service M44
 - 5 Scanner
 - 6 Wheels
 - 7 Measurements
 - 8 Paper Machine
 - 9 Display Main
 - 10 Debug
 - 11 Other Routines
- B Simulator**
 - 1 Run Main Program
 - 2 Simulation Main
- C File Manipulation**
 - 1 Create Text File from ZD Data
 - 2 Create Sequential Text File
- D Remote Display**
- E Pulse Viewer**
- F Fourier Series**

II. Windows DLLs

- G DSP.DLL**
- H SIMULATOR.DLL**

III. M44 Code

- I Target Code**
 - 1 zd.c
 - 2 zd.h
 - 3 initialize.c
 - 4 transfer.c
 - 5 web.c
 - 6 wheel.c
 - 7 scanner.c
 - 8 pulses.c
 - 9 calculation.c
 - 10 utilities.c & utilities.h
 - 11 structs.h

IV. Miscellaneous

- J Save File Formats**

MILL TRIALS

Detailed plans were prepared for both step tests and end-of-reel testing to determine relationships between in-plane stiffness measurements, sheet properties, and process variables for PM no. 1. The following step tests were conducted: 69 lb/1000 ft² linerboard, May 17, 1999; and 55 lb/1000 ft² (USP 120) linerboard, June 9, 1999. The process variables manipulated during the trials are listed below, followed by the turn-up time, reel number, and notes for first the 69# trial and then the 55# trial.

Process Variables Manipulated:

1. Machine Speed
2. Rush/Drag
3. Number of Calender Stack Nips
4. % Top Stock Coverage
5. Basis Weight
6. % Moisture
7. Base Refiner Load
8. Broke Flow
9. DLK Flow

Date	69# Reel	Process Variable Step Notes
05/17/99 - 16:39	24z	Initial Conditions
05/17/99 - 17:04	25	Same as Reel 24
05/17/99 - 17:26		
05/17/99 - 17:53	27	Decrease Speed 50 fpm
05/17/99 - 18:18	28zp	Same as Reel 27
05/17/99 - 18:43		
05/17/99 - 19:08	30p	Increase Speed 50 fpm
05/17/99 - 19:31	31zp	Same as Reel 30
05/17/99 - 19:55	32zp	Change Rush/Drag from -10 to -30 fpm
05/17/99 - 20:19	33p	Lost Mullen, Reel 32: Changed R/D from -30 to -20 fpm
05/17/99 - 20:42	34p	Calender Nips changed from 3+4 to 2+3
05/17/99 - 21:06	35zp	Same as Reel 34
05/17/99 - 21:29	36p	Increase top coverage from 15%: when increased top coverage, lost some plybond back end
05/17/99 - 21:53	37zp	Same as Reel 36 having to back out on refining on base and top
05/17/99 - 22:17	38p	Transition from top coverage change to Conditioned Wt change
05/17/99 - 22:40	39zp	Change CW from 69# to 70#
05/17/99 - 23:04	40p	Same as Reel 39
05/17/99 - 23:28	41p	Decrease CW from 69# to 68#
05/17/99 - 23:52	42zp	Same as Reel 41
05/18/99 - 00:16	43zp	Change % Moisture Target from 7.2 to 7.8%
05/18/99 - 00:40	44p	Same as Reel 43
05/18/99 - 01:04	45zp	Increase Base Refiner Loads: #1&2 - 64 to 67; #3 - 63 to 65: #4 - 37 to 39: Couch Vac inc 0.25 in Hg
05/18/99 - 01:28	46p	Same as Reel 45
05/18/99 - 01:52		Had to change refining back and change Broke flow: both changed Couch Vac and waited to settle
05/18/99 - 02:15	48p	Change in Broke flow from 1000gpm to 600 gpm
05/18/99 - 02:39	49z	Same as Reel 48
05/18/99 - 03:03		Increase DLK: up to 100 gpm @2:35; up to 300 @ 2:50; up to 400 @ 3:05; up to 500 gpm in Reel 51
05/18/99 - 03:27	51p	Change DLK Flow from 0 to 500 gpm
05/18/99 - 03:50	52z	Same as Reel 51

Time	55# Reel #	
6/9/99 - 7:46	2	Initial Conditions (Back RC low; 142,141,121)
6/9/99 - 8:15	3	Same as R2 with RC good; 135,146,134
6/9/99 - 8:44	4	Decrease Speed 1690 to 1650 fpm - RC 135,133,133
6/9/99 - 9:13	5	Same as R4 - RC 133,129,131
6/9/99 - 9:42	6	Increase Speed 1650 to 1750 fpm - RC 140,134,136
6/9/99 - 10:12	7	Same as R6 - RC 136,140,133
6/9/99 - 10:40	8	Speed @ 1750 rest of trial. Change Rush/Drag from 25 to 40 fpm - RC 140,138,130:Mullen 138,132,130
6/9/99 - 11:08	9	Same as R8 - RC 134,141,128
6/9/99 - 11:36	10	Change Calender from 2+2 to 1+1 - RC 136,151,133
6/9/99 - 12:03	11	Same as R10
6/9/99 - 12:31	Skip 12	Skipped 12 for top % Transition
6/9/99 - 12:59	13	Top % change from 17 to 15.5% (1065 to 960 gpm, top stock)
6/9/99 - 13:27	14	Same as Reel 13
6/9/99 - 13:54	15	Increase Conditioned Wt from 55.0 to 56.0#
6/9/99 - 14:22	16	Same as R15
6/9/99 - 14:50	17	Decrease Conditioned Wt from 56.0 to 54.0#
6/9/99 - 15:20	18	Same as R17
6/9/99 - 15:49	19	Increase Moisture Target from 6.5 to 7.2%
6/9/99 - 16:18	20	Same as R19
6/9/99 - 16:46	21	Transition: Inc. Base Refiner Loads: #1&2-75/81,#3-75/79,#4-42/46. Couch Vac -19.5.19.6 to 19.8/19.9
6/9/99 - 17:15	22	Conditons set up in R21 (Steam at max in 3rd section; Moisture up to 8.4% before back to control)
6/9/99 - 17:44	23	Same as R22: Freeness 689 to 667
6/9/99 - 18:13	24	Decrease Broke Flow - 900 to 450 gpm
6/9/99 - 18:41	25	Same as R24
6/9/99 - 19:09	26	Decrease Rush/Drag from 40 to Zero fpm
6/9/99 - 19:37	27	Same as R26

Data were collected from the sources listed below:

Sources of Data

1. Recorded Notes
2. ABB 1190 Profiles (600 or 60 data boxes):
Basis Weight/Conditioned Weight; % Moisture; Caliper; Temperature;
Longitudinal Velocity Squared; & Shear Velocity Squared
3. ZD Sensor Profiles (600 or 60 data boxes):
ZD Transit Time; Energy of ZD Pulse at Receiver
4. Mill PI System Time-based Process Data
5. Mill PI System Profile data (60 data boxes)
6. Mill RMS (Roll Management System) Data
7. GP QC test data (30 point profiles on CD strips)
8. IPST Lab test data (60 point profiles on CD strips)

Twenty-five reels were sampled for each trial. At least 3 CD strips were collected from the end of each reel. G-P kept one strip and two were taken to IPST.

Tests Performed on Collected CD Strip Samples at GP:

1. CD Ring Crush
2. Plybond (69#)
3. Mullen, felt side & wire side
4. CD STFI
5. Basis Weight
6. % Moisture
7. Caliper

Tests Performed on Collected CD Strip Samples at IPST:

1. In-plane CD, MD, and SHEAR ultrasonic velocity (and stiffness) using IPST Robot instrument.
2. Caliper and ZD transit time (ultrasonic velocity and stiffness) using IPST laboratory instrument.
3. CD Ring Crush
4. CD STFI
5. Burst (Mullen)
6. ZD Tensile (69#)
7. Basis Weight
8. % Moisture

Sample ID	Weight grams	Sheet Dimension inches	T410 Basis Weight gm ²	T410 Basis Weight lbs/1000ft ²	T411 Caliper mil	IPST Caliper microns	IPST Travel Time microsecs	IPST Velocity m/sec	IPST Specific Stiffness kn/m ²	IPST Elastic Stiffness Mpa	T807 Burst psi	T822 Ring Qus CD lb	T826 STFI CD lb/in	T541 ZDT psi	Coeff Var Burst FC STFI
Reel 35 34	33.332	9x17	337.6778	69.22365	20.82	465.0	1.97	237	0.055	40.5	110.42	105.4	27.89	28.4	
					20.27	460.0	2.20	209	0.044	32.1	146.92	108.4	27.00		
					20.86	481.0	2.21	218	0.047	33.3	126.42	108.3	27.22	29.2	
					20.70	460.0	2.05	224	0.050	37.0	139.03	110.6	32.24		
					20.77	477.0	2.13	224	0.050	35.5	114.70	123.4	35.89	29.0	
					20.82	468.0	2.09	224	0.050	36.2	136.78	110	24.04		
					20.46	473.0	2.19	216	0.047	33.3	114.25	109.7	26.05		
					20.79	477.0	2.20	217	0.047	33.3	105.13	128.3	30.55		
					21.03	464.0	2.05	226	0.051	37.3	140.39	118.4	24.93		
					20.42	474.0	2.23	213	0.045	32.2	155.16	117.2	34.11		13.28
					20.69	470.0	2.13	221	0.049	35	129.12	113.97	28.99	28.9	6.58
Average					0.23	7.5	0.09	8	0.004	2.722	17.15	7.50	4.01	0.4	13.83
Std Dev.															
Reel 35 56	33.954	9x17	344.0804	70.536487	20.69	475.0	2.30	207	0.043	30.9	153.01	104.2	28.98	24.2	
					20.65	469.0	2.13	220	0.048	36.6	116.05	119.7	35.17		
					20.55	478.0	2.20	217	0.047	34.0	129.80	120.7	32.88	28.2	
					20.80	475.0	2.04	233	0.054	39.3	125.51	109	31.65		
					20.68	466.0	2.23	218	0.047	33.6	120.55	113.9	23.31	28.8	
					20.46	470.0	2.36	199	0.040	29.0	139.03	124.7	27.41		
					20.77	478.0	2.12	225	0.051	36.6	119.66	108.6	27.36		
					20.40	473.0	2.00	237	0.055	40.7	130.47	103.2	22.55		
					20.68	472.0	2.28	207	0.043	31.2	130.92	125.7	24.26		
					20.94	475.0	2.11	225	0.051	36.7	131.82	115.3	23.59		8.23
					20.66	475.1	2.18	219	0.048	35	129.68	114.50	27.72	27.1	7.10
Average					0.16	4.9	0.12	12	0.005	3.731	10.67	8.13	4.40	2.5	15.89
Std Dev.															

The table above is an example of data recorded by the IPST Paper Testing Laboratory. The CD strips were conditioned and then cut into 9-inch segments. With a CD strip divided into 60 data boxes, each data box would be 4.5 inches. The data shown is for Reel no. 35 (69#) for a 9-inch segment containing data boxes 3 and 4, and another 9-inch segment containing data boxes 5 and 6. The first 5 readings in each column are for data box 3 and the last 5 are for data box 4, etc. The columns headed with the word IPST are measurements from the laboratory ZD ultrasonic instrument. The averages and standard deviations are calculated for the measurements within each 9-inch segment, and the coefficients of variation are presented for Burst, CD Ring Crush, and CD STFI. No measurements were made for the web edge data boxes 1 and 2 or 59 and 60. Thus, 14 sets of data like the example shown above were collected for each reel sampled. Twenty-five reels were sampled for each of the two mill trials.

The data collected from all sources were transferred to Excel spreadsheets and then plotted and/or analyzed using FactNet 4.5 software. Time stamps from the ABB, G-P, and IPST systems were used to spatially match the data from the different sources as closely as possible. Care was taken to obtain spatial alignment between collected data and actual strips to the extent feasible.

Shown above is an example of a FactNet display showing correlation coefficients for various process and product variables from the 69# trial. FactNet assigned different colors to the R-squared ranges of 0 to 0.199, 0.2 to 0.399, 0.4 to 0.599, and 0.6 to 1.0 in the original display copied here in gray scale. The R-squared correlation value between Plybond and Transit Time is a very good -0.84, and the correlation between Mullen and Receiver Energy is 0.686.

In-Plane Ultrasonic Measurements

A description and discussion of the in-plane system may be found in the appended copy of a paper by Bradley Pankonin and Doug Jimmerson entitled "Mill Experiences with On-Line Ultrasound Based Stiffness Measurements." This paper was presented at the TAPPI Engineering / Process & Product Quality Conference in September 1999. Some additional observations from the mill trials are presented here.

The plot above compares the ABB on-machine in-plane data with the data recorded at IPST on end-of-reel strips with the laboratory "robot" instrument. The data from six reels of 69# produced at different process conditions are plotted side by side. The upper two sets are for the CD Longitudinal Stiffness and the lower two sets are a comparison of the Shear Stiffness. One may note that changes across the profile of each sample (primarily due to shrinkage during drying) are greater than any apparent change due to the process changes.

Of particular note is the observation that the "degree of frown" in the on-machine data profile is greater than that found for the laboratory data. This is particularly apparent in the Shear Stiffness data. Similar observations of differences in the "degree of frown" between on-machine and laboratory measurements have been reported (Reed and Brown, 1999). It appears that this is not an instrumental effect but rather a real physical property change that occurs in the CD strip sample taken from the end of the reel and conditioned in the laboratory.

The plot above is similar to the previous plot except that it is for the data from six reels of 55# produced at different process conditions and plotted side by side. The scale is the same as the previous plot so that one can see that the CD Longitudinal Stiffnesses for the 55# are greater than for the 69# samples. The Shear Stiffnesses are also somewhat greater for the 55#. Again the changes across the profile of each sample are greater than any apparent change due to the process changes.

The above plot compares the CD Extensional Stiffness $[(\text{ultrasound velocity})^2 \times \text{Basis Weight}]$ calculated from the ABB on-machine in-plane data, the CD Extensional Stiffness determined at IPST on end-of-reel strips, and the Ring Crush determined at IPST. Again the data from six reels of 55# produced at different process conditions are plotted side by side. In view of the uncertainty in the spatial alignment between the on-machine data and the sampled CD strips and in view of the apparent property changes in the CD samples, the similarity in CD profile of the data is reasonable. One may again note that changes across the profile of each sample are greater than any apparent change due to the process changes for both the CD extensional stiffness and for Ring Crush. Similar results were observed for CD STFI measurements.

ZD (Out-of-Plane) Ultrasonic Measurements

As noted earlier, a computer connected to the stand-alone E-box can display the ZD Transit Time or Receiver Energy as a color contour plot and as a trend plot of scan averages. For determining relationships of the ZD measurements with process parameters or paper properties, scan averages are used. The averages for the scans completed nearest to the minute-by-minute data from the mill's PI system and nearest to the reel turn-up times from the RMS (Roll Management System) are used. Some observations are presented on this and the following pages: the correlation of ZD Transit Time with Plybond and ZDT (Z-direction Tensile or internal bond strength); the correlation of ZD Receiver Energy with Burst; and the sensitivity of ZD ultrasonic measurements to refining and calendering.

Above is a plot of the plybond measurements entered into the mill's RMS (Roll Management System) for 60 successive 69# reels versus the Scan Average ZD Transit Time recorded near the recorded turn-up time.

Average GP Plybond & IPST Lab Data vs On-Machine ZD Translt Time
for 25 Reels (Reels No. 24-52) (69#)

The Georgia-Pacific mill personnel determined plybond by the procedure that tests a circular sample mounted in a Mullen tester. Comparisons with the ZDT (Z-direction Tensile) method have shown that these procedures provide measurements that differ by a factor of approximately three. G-P measured plybond for 20 of the 25 reels from the 69# trial. IPST measured ZDT for 12 of the same 25 reels. The above plot shows the plybond data measured by G-P and 3.11 times the ZDT for the 12 reels measured by IPST. These are plotted versus the Scan Average ZD Transit Time at reel turn-up. The correlation is apparent and has an impressive R squared greater than 0.8.

IPST Lab Burst vs On-Machine ZD Receiver Energy
for 25 Reels (Reels No. 24-52) (69#)

The above shows Burst (or Mullen) measured in the IPST lab for the reels sampled from the 69# trial versus the scan average Receiver Energy at the time of reel turn-up. This suggests that the on-machine determination of ultrasonic energy received through the web may provide an indication of Burst or Mullen.

The ZD ultrasonic measurements are expected to be sensitive to those process variables that affect fiber bonding. These include furnish, refining, wet pressing, wet straining, and calendering. Sensitivity to refining, wet pressing, and calendering were demonstrated with the pilot machine trials at Herty. The mill trials provided the following examples of ZD ultrasonic sensitivity to calendering and refining. First, the sensitivity of ZD ultrasonic measurements to calendering is present in the following plots. Then an example observed during the mill trials is presented showing the sensitivity of ZD ultrasonic measurements to refining.

On-Machine Caliper & ZD Transit Time (55#)
 Calender change from 2+2 to 1+1 @ about 11:25 and back to 2+2 @ about 12:05

The scan average data was smoothed by a moving average of 5. This plot shows the caliper and ZD transit time versus the time of day for the two hours that included the calender change from 2+2 nips to 1+1 and back during the 55# trial. The increase in caliper is apparent, but no associated change is visible in the ZD transit time.

On-Machine Acoustic Impedance & ZD Stiffness (55#)
 Calender change from 2+2 to 1+1 @ about 11:25 and back to 2+2 @ about 12:05

The acoustic impedance is determined by dividing basis weight by ZD transit time. The ZD stiffness is determined by squaring the ZD velocity, i.e., the caliper divided by the ZD transit time. Since the basis weight and ZD transit time did not change with calendering, there is no change in acoustic impedance. However, there is a significance change in the ZD velocity and ZD stiffness.

The two hours that included the calender change from 3+4 nips to 2+3 and back during the 69# trial was also examined. The above plot shows only a slight change in ZD stiffness with calendering. Since the change in total nips from 7 to 5 for the 69# trial is a much smaller change than the 4 to 2 for the 55# trial, a large change would not be expected here. The bump in the acoustic impedance and in the ZD stiffness at 21:40 was noted and examined by reviewing various process parameters recorded by the mill's PI system. Selected refiner motor-load data are plotted below versus time of day.

The two hours (20:00 to 22:00) during which the bump in the acoustic impedance and in the ZD stiffness were observed are marked in the plot above showing refiner motor loads for refiners #1 & #2 and for refiners #3 & TL (Top Liner). A sharp bump in the #3 & TL refiner motor load is noted just before 22:00.

The #3 & TL refiner motor load is added to the previous plot for the two hours (20:00 to 22:00) during which the bump in the acoustic impedance and in the ZD stiffness were observed and shown below. The acoustic impedance and the ZD stiffness show a sensitive response to the bump in the #3 & TL refiner motor load with a delay of approximately 13 minutes.

The above plots show the ability of the on-machine ZD sensor system to respond to process changes that affect fiber bonding, specifically in the mill-trial cases to refining and calendering. Also shown in the earlier plots were examples of ZD ultrasonic measurement correlation with product properties, specifically plybond and burst. Usually examples of correlation of measurements with properties are presented over a range of paper grades. It is noteworthy here that the examples of ZD ultrasonic measurement correlation with product properties are all within a single paper grade.

DISCUSSION

ZD measurements with ultrasonic transducers in fluid-filled wheels were successfully demonstrated on a commercial paper machine. The installation and operation of the wheels in a scanner provided a number of complications that needed to be overcome. Not only was the space limited in the sensor carriage, but the space available for access to the sensor carriage in the mill was also limited by the positioning of the scanner and reel components. Because the basis weight and moisture sensors were needed to control the paper machine, the opportunity to work on the sensors in the scanner was limited to the paper machine outage for maintenance.

The environment for the sensors on the paper machine required special attention to corrosion resistance and cooling, particularly for the on-board electronic components. The fluid-filled wheels also presented problems in the mill that were not encountered during earlier work in the laboratory. Running at high speed for long distances on paper at about 200 degrees Fahrenheit caused problems with tire wear and fluid leakage. The leakage problem was solved by a rebuild of the wheels with improved seals and bearings. The tire and fluid must be reasonably close in acoustic impedance so that strong ultrasonic signals can pass through the boundary between them. The tire and fluid must also tolerate the temperature. Silicone rubber tires filled with a silicone oil-base fluid seemed to be a good choice and were used during the mill trials. However, it was observed that after a few weeks the silicone oil slowly passed through the silicone rubber, forming a sticky film on the tire. The wheels were not run on-machine to determine whether this would affect performance. Other suggested tire-fluid combinations were not tested before the project was terminated.

A sensor mounting system dedicated to the ultrasonic sensors would provide unlimited access and would have been particularly helpful during the early stages of sensor development. One could then have made adjustments or changes to the sensors as needed rather than stopping the scanner during production or waiting for a monthly down period for machine maintenance.

Scanning provides the data for a contour display, which may be useful in revealing some persistent nonuniformities in the cross direction. However, scanning would not be necessary to obtain data for comparison with process data and for display to the operator as a trend plot. If scanning is not required, a simpler single-point system could be used.

The mill PI (Plant Information) system can provide the status of process variables on a minute-by-minute basis. With a scanning sensor, only scan average data or data in a selected CD data box that is updated once per scan can be used for correlation with process variables. The ZD system is capable of providing readings at a rate of approximately 20 per second. With a single-point measurement one would have the flexibility to average and time-stamp the data in the way most appropriate for comparison with process data and for display to the operator as a trend plot. Thus, scanning the ZD sensor may not be necessary to obtain significant benefit from on-machine ZD measurements.

Support of the project was curtailed just before live display of either the contour plot or the trend plot of the ZD data could be made available to the paper machine operator. Display of ZD data to the operator would have provided constant visibility of product status and early warning of process upsets, helping the operator maintain stable operation and efficient process adjustments through grade changes.

The ZD technology should be given the opportunity to demonstrate its benefit by making the real-time data available to the paper machine operators. An efficient way to do this would be

to mount the ZD fluid-filled wheels on a stand-alone C-frame. This could be positioned at a single point over the web and operate independently from the scanner and sensors that are used to control the process. In addition to displaying single-point ZD data as a trend plot to the operators, the data could be forwarded to the mill's PI system to be combined with data from the scanning sensors and other process data.

CONCLUSIONS

- The out-of-plane (ZD) ultrasonic technology based on fluid-filled wheels containing ultrasonic transducers has been successfully demonstrated on a commercial paper machine.
- The sensitivity of on-machine ZD measurements to refining and calendering has been demonstrated
- On-machine ZD measurements correlate well with laboratory measurement of the paper properties; ZD Tensile, Plybond, Burst, and Mullen.
- Display of ZD data to the operator as a time trend and/or a contour map of scan-by-scan cross-web profiles should provide constant visibility of product status and early warning of process upsets. This would help the operator maintain stable operation of the paper machine and make efficient process adjustments through grade changes.

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MILL EXPERIENCES WITH ON-LINE ULTRASOUND BASED STIFFNESS MEASUREMENTS

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ABSTRACT

ABB has developed an on-line Ultrasonic Specific Stiffness Sensor. The sensor has been installed on a paper machine producing Linerboard in the range of 40-90-lbs/1000 sq.-ft. and the measurement has operated reliably for 6 months. This report summarizes the on-line measurement performance and emphasizes field test results.

Many of the relationships expected between paper stiffness, process parameters, and paper 'strength' are confirmed. The impact of process upsets and grade changes on stiffness properties are tracked. For example, increasing the rush-drag ratio is shown to increase both the on-line CD Specific Stiffness and the QC laboratory CD Ring Crush and Ring crush indexes. These and other results provide the basis for improved product quality and reduced production costs.

INTRODUCTION

Traditional on-line measurements are of parameters used by papermakers because they imply the actual properties of interest. For example, few paper users really care about the papers' weight. What is important is its color, its smoothness, its opacity, its strength, stiffness, feel, volume etc.; that is those properties, which determine the performance of the paper in use.

The mechanical attributes of the sheet (strength, stiffness, etc.) are very important to the manufactures of heavy paperboard and paper. While '*strength*' can never be measured directly on-line (strength tests are by their nature destructive), elastic stiffnesses can be. Strength can be inferred through correlation relationships. On-line measures of sheet stiffness characteristics are limited, but perceived as valuable. The potential value of an on-line stiffness sensor could easily offset its cost in reducing waste from off-specification product. Other potentials exist by the reduction of weight while maintaining the same load carrying capacity.

Both Honeywell-Measurex (H-Mx.) (1) and Lorentzen & Wettre (L & W) (2) have recently reported solutions to measure the mechanical characteristics of paper at the time of manufacture. The former system physically deforms the sheet by known amount and effectively measures the load to do so. Elastic stiffness coefficients result from the application of Hooks' Law (system in non-acoustic). The system can be mounted on a scanner and hence can generate important profile information. Major error inducing effects are preset as a result caliper and web tension and carefully accounted for. The L & W system is acoustic based, however, at present can only be implemented as a single point measurement. The need for an acoustic based measurement system that is capable of being installed on a scanner has been addressed by ABB in the current work.

MEASUREMENT PRINCIPLE

Physical Acoustics

The sensor is designed to measure the propagation velocity of ultrasound waves in the paper web. These velocities are used to calculate "elastic stiffness" coefficients.

The velocity of ultrasound is related to the elastic stiffness and the density of the material it is traveling in. Extensional stiffness can be derived from the velocity of longitudinal ultrasound waves and shear stiffness can be derived from the velocity of transverse ultrasound waves. For paper, considered as an orthotropic material, the stiffness coefficients for cross machine direction extension, C_{cmd} , and shear, G_{cmd} , are:

$$C_{cmd} = \rho \cdot V_{l,cmd}^2$$

$$G_{md} = G_{cmd} = \rho \cdot V_{s,md}^2 = \rho \cdot V_{s,cmd}^2$$

Mass specific stiffnesses are obtained by dividing the stiffness by the density, ρ .

$$C_{cmd} / \rho = V_{l,cmd}^2$$

$$G_{md} / \rho = G_{cmd} / \rho = V_{s,md}^2 = V_{s,cmd}^2$$

The measurement system described here reports specific stiffnesses, which are compensated for by the process moisture and temperature at the time of the velocity determination.

Conditioned Stiffness

The elastic stiffness coefficients, and hence the ultrasonic velocities, of paper depend on moisture and temperature (4). Paper behaves like a polymer to plastisizers (water) and temperature. Increasing moisture content lowers the elastic stiffness coefficients and hence the ultrasonic propagation velocities. Increasing temperature lowers the elastic stiffness coefficients.

$$C_{cmd} = C_{cmd,0} \cdot [\beta_{M,C} \cdot (M - M_0) + \beta_{T,C} \cdot (T - T_0)] + C_{cmd,T,M}$$

$$G_{cmd} = G_{cmd,0} \cdot [\beta_{M,G} \cdot (M - M_0) + \beta_{T,G} \cdot (T - T_0)] + G_{cmd,T,M}$$

The measurement system reports **conditioned** elastic stiffness coefficients (TAPPI: 50% R.H., 23°C). The moisture content and temperature of the paper are obtained from the other sensors in the measurement platform.

Sensor Description

A digital photograph of the measurement system is shown in Figure 1. The basics of the measurement involve two sets of three ultrasonic transducers (3) mounted in a cylinder, which rolls on the moving paper web. One set is for the shear measurement and the other for the longitudinal measurement. Each sensor set consists of one transmitter and two receivers. In the figure the transmitter is located on the left side of the measurement cylinder and the two receivers are on the right. When the three transducers in a measurement set come into contact with the sheet the transmitter fires a short burst of 60-kHz ultrasound into the sheet. The ultrasound travels in the plane of the sheet and is picked up first by the near receiver (73 mm path length) and then latter by the far (115 mm path length). The time difference between the signal arrival times at the two receivers divided into the path length difference for the two signal paths determines the appropriate ultrasound velocity. The entire measurement takes place inside of a 200 • sec time window. Post processing of the received signals takes place in less than 2 msec., and is performed in a digital signal processor (DSP). The square of the velocity determined is the specific acoustic stiffness for the appropriate mode, shear or longitudinal. Both measurements are cross-machine direction.

Figure 1. Measurement cylinder showing ultrasonic transmitter and two receivers for shear. Longitudinal transducers are located on the opposite side of the cylinder, 180 degrees from the longitudinal transducers. Air driven spin-up assist motor and cylinder steering gumball is also identified.

Sheet control in the measurement system is accomplished with a pair of small backing rollers. The rollers are on the opposite side of the sheet from the measurement cylinder. These *backside* rollers create a small wrap of the sheet over the measurement cylinder, Figure 2. This wrap insures that the transducers are in full contact with the sheet for the duration of the measurement. The rollers and the measurement cylinder do not pinch the sheet.

Figure 2. Sheet control configuration, showing the *backside* rollers creating a 20-degree sheet wrap over the measurement cylinder.

One important feature of the current measurement system is that the cylinder steers across the process as the scanner scans (Figure 3). This has two direct effects. The first is that there is no slippage between the measurement cylinder and the process, minimizing any possible marring of the sheet. The second benefit is that the signal strength during scanning is greatly enhanced. A small amount of slippage between the transducers and the sheet can easily reduce the signal strength by a factor of 100 (kinetic coupling of acoustic energy into the sheet vs. static).

Figure 3. Depiction of sensor path over the process during scanning.

The measurement data rate depends on the process speed. The measurements of shear and longitudinal stiffnesses take place once each per revolution of the cylinder. The measurement cylinder has a circumference of approximately 9 inches. Therefore, at a process speed of 1800 fpm the data rate is about 40Hz.

ON-LINE RESULTS

Moisture and Temperature

Moisture has a profound influence on the stiffness of paper and therefore is addressed first. This interaction is effectively explained as the typical effect of a plasticizer (in this case water) on paper (cellulose).

Stiffness Value	$B_M (\% / \%)^3$	$B_T (\% / C)^3$
Shear(time of flight method)	5.6	0.45
Md (resonance method)	4.7	0.38

Md (resonance method)	4.1	0.33
Cd (resonance method)	5.9	0.49

Table 1. Moisture and Temperature compensation gains used in the current sensor system.

The following operators' trend display page, Figure 4., shows the effect of moisture on the shear and the longitudinal specific stiffness of 55# Linerboard. The trend is for one hour and the data is scan averages of shear and longitudinal specific stiffnesses and percent moisture. The process temperature was approximately constant at 78C. At times before the ruler line indicator β_M was set at 0 (no moisture compensation) and at times after the ruler β_M was set at 5.2 for both shear and longitudinal stiffnesses.

When moisture compensation is off, the specific stiffness is the as measured value on the process including the influence of moisture. It is clear that as moisture increases the shear and longitudinal stiffnesses decrease. Wet paper gets soggy and limp. When β_M is set to 5.2 the influence of process moisture is effectively removed, suggesting that the lab measured stiffnesses of the paper over this time period would show only stiffness changes that were reel and not just the result of variable process moisture.

Figure 4. Trend displays showing scan averages for percent moisture, and shear stiffness, and extensional stiffness. The vertical ruler line indicates when moisture and temperature compensation was turned on. Basis weight, Sheet temperature, and the Basis weight controller set point have been hidden from the display for clarity.

Drying Restraint

Paper dried under restraint (i.e. not allowed to shrink) has a higher stiffness than paper that is allowed to shrink during drying. In addition, paper that is stretched slightly ($<5\% \Delta L/L$) while still wet ($> \sim 20\%M$) will also have a higher stiffness than paper that is not stretched. Typical scanner profiles for shear and longitudinal specific

stiffnesses are presented in Figure 5. Both profiles exhibit a profound frowned shape. These shapes are attributed to the nonlinear shrinkage of the paper web in the cross machine direction during drying.

Figure 5. Profile displays showing shear and longitudinal specific stiffnesses.

On the centerline of the paper machine the web is restrained in both the machine direction and in the cross machine direction. On the edges of the machine it is only restrained in the machine direction and it shrinks in the cross machine direction. The frowned profile shapes are the direct result of the drying restraint conditions that exist on the paper machine. Sheet shrinkage at the edges results in a lower stiffness at the edges.

On-Line vs. Off-Line Profiles

As discussed previously paper machine profiles are frowned. These on-line profile shapes can be verified off-line. Profile verification is presented in Figure 6.

Figure 6. Comparison of off-line measured cross machine direction extensional stiffness with on-line measurement for 55-lb. Linerboard. Offline data was acquired using a L&W TSO tester under standard TAPPI test conditions. On-line data is a composite of 5-minutes of scanner data just prior to reel turn-up.

The 'Lab L&W' data set was collected on samples taken at reel turn-up. Three samples were acquired from the reel at the end of the paper machine, one each from three successive wraps. The samples were 12 inches in the MD by 258 inches in CD. Roughly 60 equally spaced CD TSI measurements were conducted on each sample. The 60 TSI measurements were then mapped back to the 600 data box profile from the Smart Platform. The on-line data was logged in the Smart Platform during five minutes prior to the reel turn-up and mapped to 60 data points.

Good correspondence is observed between the on-line and off-line profiles with the exception of the region above data box 500. The disparity between of the on-line and off-line profiles has not been explained yet and maybe due to the existence of dried in stresses on the machine, which relax by the time the lab tests are conducted.

Jet-to-Wire Ratio

One of the process parameters used to control 'strength' on the paper machine is the rush or drag of the jet relative to the wire. In general, the Mullen grades are manufactured with a rush-drag set point of 'zero' and high performance ring crush grades with positive rush-drag set point. The main effect is to increase the distribution of fibers in the cross-machine direction in the high performance grade.

The following Operators' trend display page, Figure 7, shows Speed Trends (Machine Speed, Reel Speed, Wire Speed, Base sheet rush-drag, and Top sheet rush-drag). The time period is for one day.

During about a four period beginning about 5:00PM on the 15th the paper machine was running out of stock and the machine speed had to be cut back from about 1500 fpm to 1400 fpm. Rush-drag on the top and base sheets were not changed during this period, consequently, the rush-drag ratio or the ratio of rush-drag to wire speed did change, Table 2.

Time period	Rush-drag / wire speed (%)
11:00 to 17:00	2.0
17:00 to 21:00	2.2
21:00 to 11:00	2.0

Table 2. Rush/drag ratio expressed as a percent of wire speed
the three time periods of interest in Figure 7.

The corresponding ultrasonic stiffness trends from the QCS system (Shear Stiffness, CD Longitudinal Stiffness, and Basis weight) follow in Figure 8., along with line plots for the QC lab test data for Ring Crush and Ring Crush Index, Figures 9 and 10. Machine speed can be used as the point of reference into the trends.

It is evident from the CD Longitudinal Stiffness trend that there is a step increase going into the reduced speed time period beginning at 5:00PM on the 15th. The stiffness then decreases at the end of the period, however, not to its original value but some intermediate value and after another five hours to its original value. The Shear Stiffness did just the opposite, it decreased, then increased part way, and finally back to its original value. The QC Lab value for the CD Ring Crush and the Index experienced increases during the slow down period and persisted for about five hours afterwards. Basis weight was constant over the one-day period except for what appear to have been short term upsets. It is not clear at this time what the exact correlation relationships are between Stiffnesses and strength properties like Ring Crush and Ring Crush Index and this is also part of the on-going activity at the mill. Once the relationships are clearly defined it is presumed that fiber could have been reduced during the roughly ten-hour period and the target 'strength' could have been met.

Figure 8. . Operators QCS display page showing Shear Specific Stiffness, Longitudinal Specific Stiffness, and Moisture. Basis weight, Sheet temperature, and the Basis weight controller set point have been hidden from the display for clarity.

Figure 9. Roll Management data for Ring Crush Index for the same time period as shown in Figures 7 and 8.

Figure 10. Roll Management data for Ring Crush Index for the same time period as shown in Figures 7 and 8.

SUMMARY

ABB has developed a new on-line Ultrasonic Specific Stiffness Sensor. The sensor has been successfully installed on a paper machine producing Linerboard in the range of 40-90-lbs/1000 sq.-ft. and the measurement has operated reliably. This report described briefly the sensor and measurement physics and summarized the on-line measurement performance.

Many of the relationships expected between paper stiffness, process parameters, and paper 'strength' are confirmed. The impact of process upsets and grade changes on stiffness properties are tracked. Increasing the rush-drag ratio is

shown to increase both the on-line CD Specific Stiffness and the QC laboratory CD Ring Crush and Ring crush indexes. These and other results can provide the basis for improved product quality and reduced production costs.

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