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Publication Date
2004-06-01

A SENSOR FOR LASER ULTRASONIC MEASUREMENT OF ELASTIC PROPERTIES OF MOVING PAPER

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ABSTRACT. An automated, non-contact, non-destructive sensor has been developed for measurement of sheet flexural and shear rigidity in paper manufacturing. It was tested on a pilot web handler at web speeds up to 25.4 m/s. A model equation was fitted to the frequency dependence of the phase velocity of A_o mode Lamb waves. Ultrasound was generated in paper with a pulsed Nd:YAG laser and detected with a Mach-Zehnder interferometer coupled with a scanning mirror/timing system to compensate for paper motion.

INTRODUCTION

In Laser Ultrasonics (LUS), also known as laser-based ultrasonics, acoustic waves are generated in a material with a pulsed laser. These acoustic waves are monitored with a laser-based detector, usually a form of interferometer [1], without physical contact to the sample, to measure one or more of its physical properties. In this work, plate (Lamb) waves [2] are detected several millimeters from the generation point as they move along the sheet. A diagram of this system is shown in Figure 1.

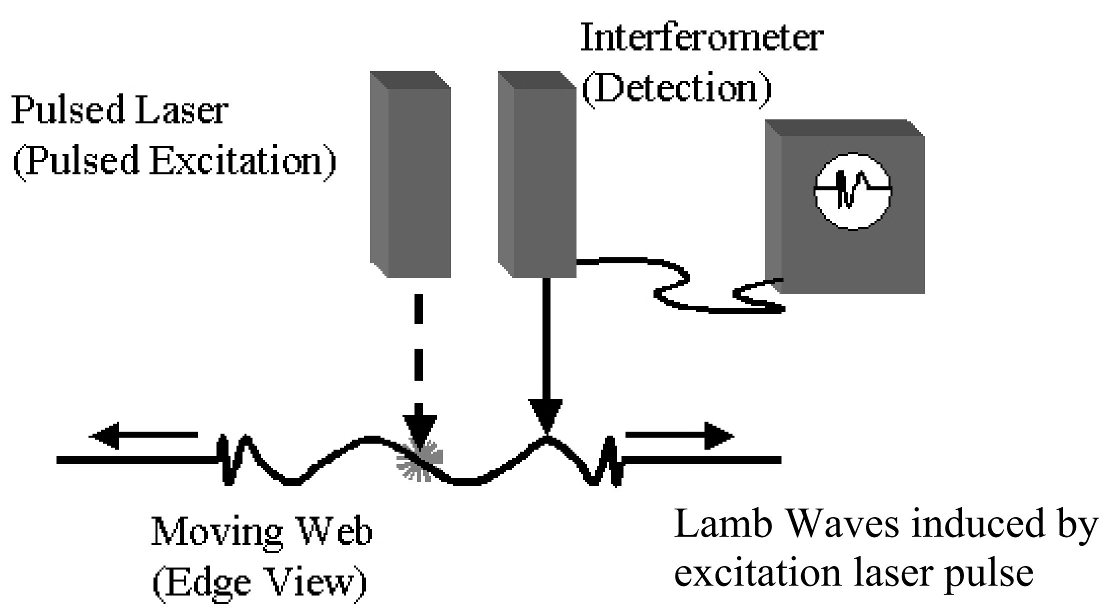

FIGURE 1. System for laser ultrasonic analysis of paper.

Laser ultrasonics has been applied in recent years to measurement of mechanical properties of paper in the laboratory [3,4]. Further laboratory demonstrations of LUS on moving paper demonstrated the possibility for routine measurement of these properties during manufacture, and for feedback control of the papermaking process based on these measurements [5,6,7]. Developments in signal processing and of a miniaturized and industrialized scanning LUS sensor for moving paper are discussed in this paper.

BACKGROUND

LUS signal energy in paper goes predominantly into the zero order anti-symmetric (A_o) mode plate wave [3]. The A_o mode is characterized by relatively large (hundreds of nanometers) out-of plane displacements, which are easily detected with commercially available laser vibrometers. In this work, a Fourier transform, 'phase unwrapping' computational method was used to calculate two elastic properties from a phase velocity versus frequency dispersion curve that was constructed from two A_o wave signals [7]. The properties are flexural rigidity (D) and out-of-plane Shear Rigidity, SR (for homogeneous material shear rigidity is equal to shear modulus times caliper). Flexural rigidity differs slightly (for paper it is typically about 9% larger) from Bending Stiffness (BS) through a term that depends on the in-plane Poisson's ratios (ν_{xy} and ν_{yx}):

$$D = BS/(1-\nu_{xy}\nu_{yx}).$$

The flexural rigidity measurement comes primarily from the low frequency portions of the dispersion curve, whereas shear rigidity comes from the high frequency components. As basis weight decreases (the basis weight is the weight per unit area of the web), the division between the high and low frequency regimes of the dispersion curve moves to higher frequencies. For low basis weight papers, there is little range for SR determination in our LUS frequency range (about 10 KHz to 600 KHz). In practice, this means that LUS methods provide good estimates of D and SR for paperboard products, but only good D values for light-weight papers.

Bending stiffness is routinely measured in paperboard mill laboratories. Bending stiffness is of interest because it is closely related to flexural rigidity, which is the determining factor in the rigidity of paper sheets and structures. Of all the elastic parameters that could conceivably be measured "on-line" (on the papermaking machine), flexural rigidity is the one most directly related to important end use performance and the one of most practical value. Out of plane shear rigidity is a sensitive indicator of fiber bonding and is an important contributor to in-plane compressive strength [8]. In addition to monitoring end-use properties, on-line measurements of D and SR are potentially useful as inputs for feedback process control.

The ability to monitor bending stiffness during manufacture (and implement the corresponding feedback process control) is expected to reduce production costs by reducing the basis weight needed to reach stiffness targets and reducing the amount of off-standard (low-stiffness) product. For example, a modest 2% reduction in basis weight needed to reach stiffness targets on a 479 ton per day uncoated free sheet machine is estimated to save \$1.1 million/year in reduced fiber, chemicals and energy use.

If a reduction in off-standard product from 6.2 to 5.2% (a 1% increase in first grade product) is achieved, an additional savings of \$0.4 million/yr is expected. Further, a reduction in paper breaks is likely since on-line monitoring will allow a more uniform stiffness in the product, and therefore a more uniform strength of the web. Additional savings from recycling less off-standard product and fewer web breaks have not been included in this savings estimate [9].

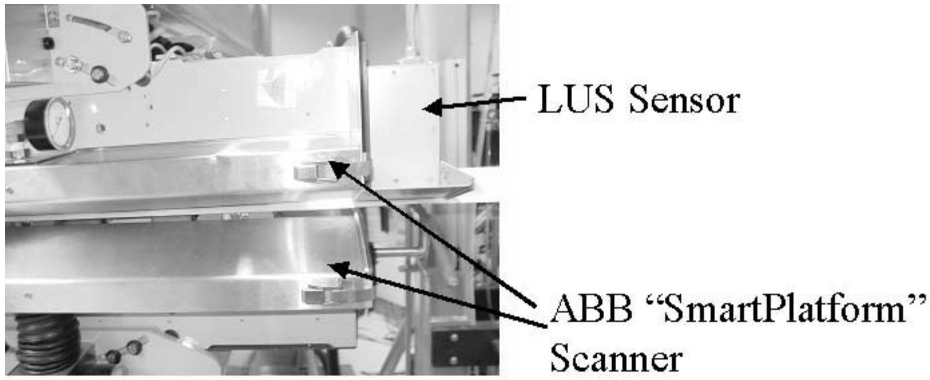

FIGURE 2. The sensor housing installed on the pilot web simulator at IPST at Georgia Tech.

LUS measurements are complementary to contact ultrasonic techniques. Contact methods are applicable to the detection of low frequency zero order symmetric (S_0) plate waves [2], in-plane shear horizontal plate waves, and out-of-plane bulk waves [10-15]. Rather than flexural and shear rigidity, contact methods provide determinations of planar stiffness, in-plane shear rigidity, and effective out-of-plane bulk stiffness. The contact transducer coefficients find application through correlation with strength properties, whereas flexural rigidity is of practical importance in its own right. Another significant advantage of LUS is that it does not require physical contact with the sheet, eliminating that potential cause of paper damage.

SENSOR HARDWARE

The sensor is shown in Figure 2. The sensor's aluminum enclosure was designed to be mounted on the upstream end of the "head package" of a commercially available scanning system (Smart Platform by ABB, Inc.) designed for papermaking machines. The head package contains various sensors and scans the width of the web, perpendicular to the direction of web motion

The sensor is shown in Figure 3 with its front cover removed. The cables are enclosed in a 2" diameter plastic conduit that is external to the scanning system and connects to an ancillary instrument platform up to 5 meters away. The ultrasound generation system consists of a pulsed Nd:YAG laser (New Wave Tempest 10) that delivers a 15 nanosecond pulse at 1.06 μm into an optical fiber, which transmits the laser pulse over a distance of approximately 8 m to the sensor where it is focused onto the web with a 10mm focal length aspheric lens. The laser pulse energies ranged from 3 to 8 mJ. The detection interferometer beam was focused onto the paper at a position separated by from 5 to 15 mm from the position where the generation beam was focused. The generation spot was positioned in the Machine Direction (MD: direction in which the web is moving) or Cross Direction (CD: direction in the plane of the web perpendicular to MD) by X-Y position servos.

The sensor is continuously purged with instrument air to protect its components from particulates and moisture. An air pressure-driven refrigeration device (Vortex tube by Exair, Inc), thermostat and thermocouple are used to regulate the sensor temperature in industrial papermaking conditions. The sensor monitors the web surface temperature with a non-contact "IR-Thermocouple" (Omega Inc.) to allow correction for the effect of web temperature on the flexural rigidity.

The ultrasound detector is a Mach-Zehnder interferometer (Polytec-PI CLV1000/OVD02) which includes a continuous, low-power (eye-safe) helium-neon laser source, coupled with a scanning mirror to move the detection laser beam and track paper motion, and a timing system to fire the generation laser when the detection beam is in the proper position on the paper surface.

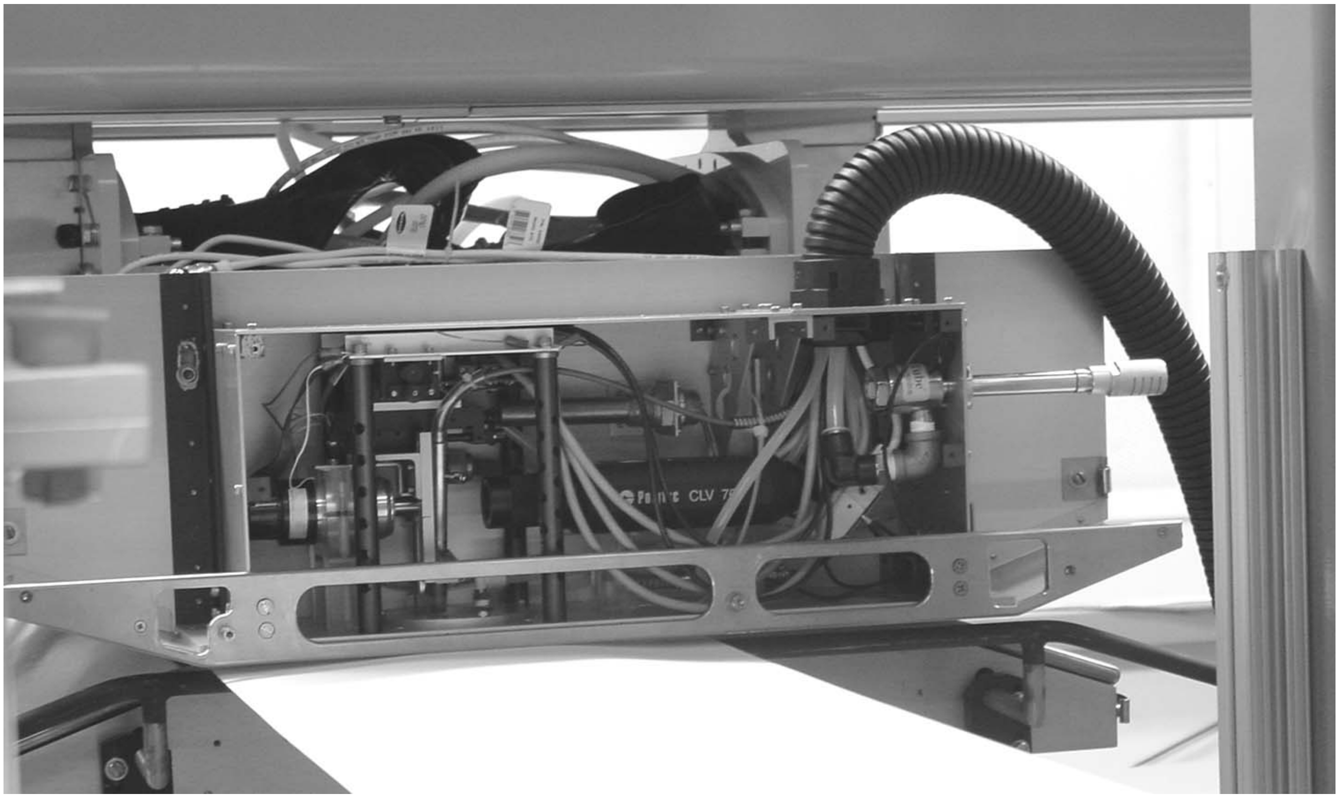

FIGURE 3. Sensor front view with cover removed.

The scanning mirror optics innovation was crucial. Without it, textural noise from the moving, rough paper surface under the detection laser would overwhelm the LUS signal, which has a much smaller amplitude. Details of the apparatus have been described previously [5]. The system has since been modified to rotate the scanning mirror with a feedback-controlled DC servomotor.

SENSOR SOFTWARE

Data collection

Ultrasound-induced interferometer signals are recorded with a personal computer equipped with an oscilloscope card (Gage Compuscope 1250). LabVIEW-based software collects data from the ABB scanning system such as basis weight, web water content and temperature, web tension along MD and web speed. These data are used to correct measurements of D for the effects of variations in these properties. Typically, 5 to 15 signals collected within a CD position range are averaged for better signal to noise ratio

Signal Analysis

The Fourier transforms of two ultrasonic signals, recorded at different excitation-to-reception separations (d) (usually 5 or 10 mm), were used to calculate the phase velocity C as a function of angular frequency, ω. At each frequency, the phase velocity was calculated from the difference in separation, Δd, and difference in Fourier phase-$\Delta\varphi$,

$$C(\omega) = -\omega\Delta d/\Delta\varphi.$$

A plot of the phase velocity versus frequency is known as a dispersion curve. In order to calculate values of D/(basis weight, BW) and SR/BW, an approximate relationship of $C(\omega)$ to D/BW and D/SR,

$$C^4+(D/SR)\omega^2C^2-(D/BW)\omega^2 = 0,$$

was fitted to a selected region of the curve by an iterated, least square method. A proper determination of the dispersion equation requires the solution of a complex transcendental equation involving in-plane and out-of-plane elastic properties [2,15]. For the A_o mode at low frequencies, wave motion can be modeled with beam equations. The simplified dispersion equation shown earlier is easily derived if deformation is taken as the sum of shear and bending deformations, plane sections of the beam are assumed to remain planar during wave motion, and rotational inertia is ignored. We made mathematical comparisons between the full and approximate dispersion equation for typical papers in the frequency range of our measurements and found very small differences [16].

An artifact created by moving the detection beam with the paper is the changing optical path length, which induces a large amplitude distortion of the ultrasound signal at frequencies below about 5 KHz. This distortion is in the form of linear ramp that is useful in tuning the excitation laser trigger timing system, and can be filtered out when collecting ultrasound signals. The change in optical path length (~100μm) is very large compared to the displacement due to ultrasound (~100nm) we detect. This requires a very large dynamic range in the displacement measurement. The range of the Polytec vibrometer is large enough so that there is no saturation of the signal due to this changing optical path. This is partly because the vibrometer system measures out-of-plane velocity, rather than displacement.

A disadvantage of out-of-plane velocity measurement is that the low-frequency sensitivity is much lower than in the case of interferometers which measure displacement, such as the Two-Wave Mixing (TWM) photo-refractive interferometer developed at IPST at Georgia Tech for use on stationary paper and paperboard [17-18]. The TWM-based instrument is, however, too sensitive to a fast and continuous motion of the object along the direction of the detection beam. This prevents its use in our sensor for moving paper. On the other hand, TWM signals cover a wider frequency range, and can be more readily compared with theory to extract elastic properties. Thus the TWM interferometer is preferred for the development of automated algorithms for calculation of elastic properties from laser ultrasound signals on both stationary and moving paper.

The software described above is used for data acquisition, signal averaging and curve fitting. Signals at each separation are averaged. The resulting pair of signals and the web basis weight are used to calculate D and SR. The software panel that analyzes the waves, calculates and displays D and SR is shown in Figure 4. One can see a 5 mm (top window, in red) and a 10 mm (2nd window from top, in black) separation LUS-generated Lamb wave and the magnitude of their spectra (center left window).

RESULTS

The results presented hereafter are some preliminary data collected immediately after installing the sensor described above for testing on IPST at Georgia Tech's pilot facility, prior to installation in the mill. Results of more extensive measurements made with an earlier version of this sensor on several paper grades at web speeds up to 25 m/s were published previously [19].

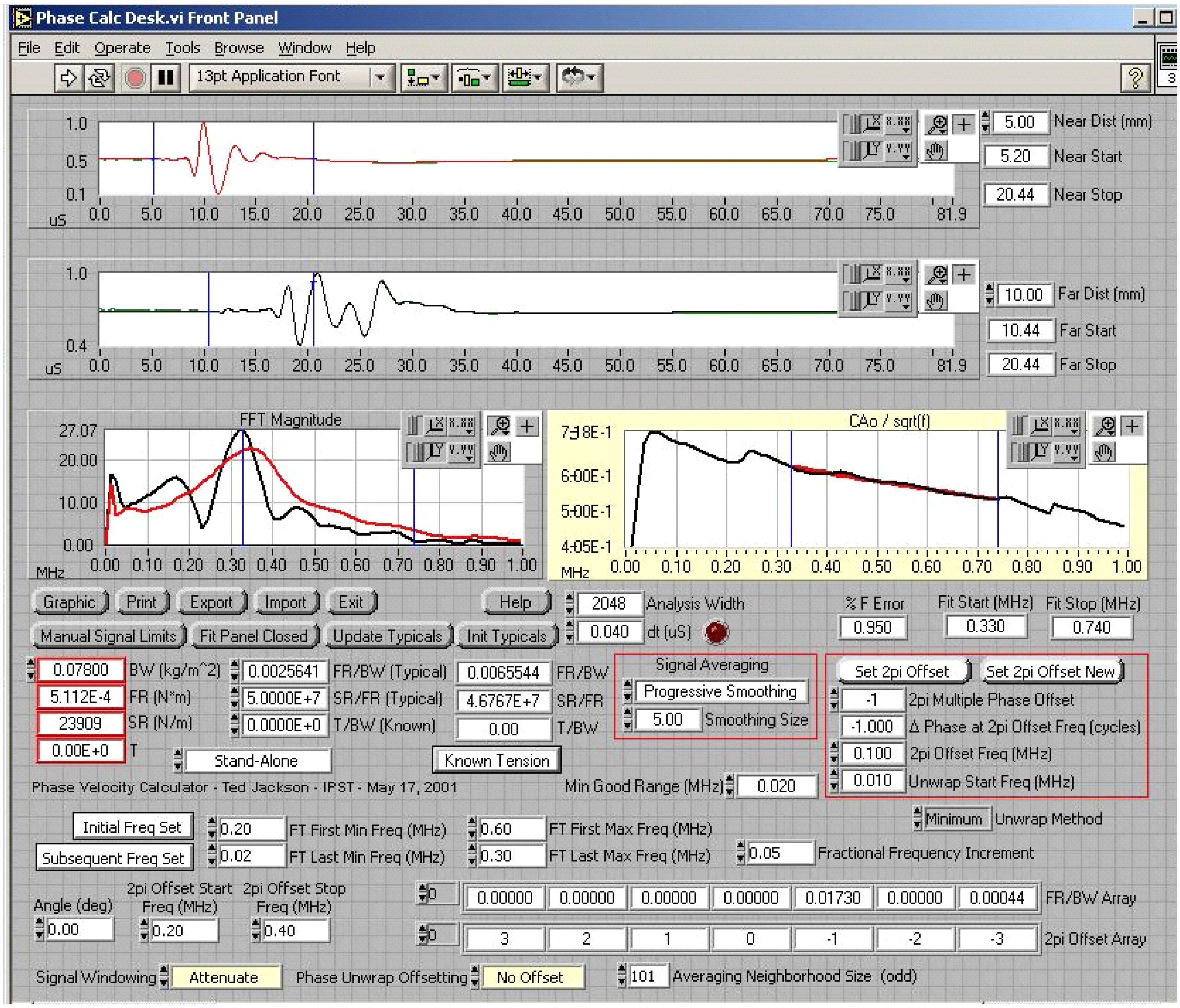

FIGURE 4. Software panel for display of automated D and SR measurements in real time. D is labelled FR.

Laser Ultrasonic Measurements on Moving Paper

In the data presented in Table 1, the signals obtained with the LUS online sensor were not averaged, and the measurements have not been corrected for web moisture content, temperature, variations in basis weight, or MD tension as those parameters were not varied.

Table 1 shows the flexural rigidity along the MD and CD obtained by the laser ultrasonic on-line sensor, at varying web speeds, on a belt of "IP offset" paper (paper used for copy machines; basis weight 77 g/m^2), 1 foot wide and about 40 feet in circumference. The standard deviations in the measurements indicate the large local variability in elastic properties that is characteristic of paper.

TABLE 1. Laboratory and online sensor measurements on "IP Offset" paper

Sensor		TWM Laboratory	Online sensor
Web speed (m/s)		0	1-9
D (N.m) (avg)	MD	5.03E-04	5±1 E-04
	CD	3.33E-04	3.7±0.8 E-04

Correlation with Measurements from the TWM Laboratory Instrument

The LUS values measured on the moving web were compared to offline LUS measurements made with the TWM laboratory instrument. In the later case, dozens of TWM ultrasonic signals obtained at separation distances from 5 to 35 mm were combined into a single averaged measurement of the flexural rigidity of the sample. Therefore we cannot report a standard deviation of the measurement for comparison with the variation in the averaged measurements on moving paper. However, a variation of approximately 6% from location to location is expected from past work with the TWM instrument on samples of similar basis weights and dimensions. The area tested was only a few inches long, instead of the 40-foot length needed for measurements on moving paper. The ±20% standard deviation in the online measurement is attributed to the local variations in the paper over the 40-foot span. The TWM results are well within the range of the results on moving paper, as shown in Table 1.

Further work will include tests on paper samples with basis weights ranging from 50-160 g/m^2, and comparison of the on-line laser ultrasonic flexural rigidity results with off-line measurements.

SUMMARY

A compact, automated laser ultrasonic sensor has been developed for non-contact measurement of flexural rigidity of moving paper during manufacture. Prototype sensor hardware and software designed for demonstration on a full-scale paper machine in commercial operation, and data collected in the initial stages of system tests at a pilot facility are described. The continuous monitoring of flexural rigidity on moving paper during manufacture that this sensor provides will allow control of the papermaking process to reduce stiffness variability and maximize stiffness while minimizing basis weight when desired, and reduce waste reprocessing costs. It is another step toward a paper manufacturing process that is more efficient and cost-effective in use of energy and natural resources.

ACKNOWLEDGEMENT

We thank Ake Hellstrom of ABB Corp. for consultation and design advice. We thank David White, technology transfer director of IPST for the economic analysis [9]. This research is supported by the Department Of Energy/ Industrial Technology Programs, under Contracts No. DE-AC03-76SF00098, DE-FC07-97ID13578 and DE-FC07-02ID14344, and by internal funding from IPST at Georgia Tech.

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