LASER ULTRASONIC SYSTEM FOR ONLINE MEASUREMENT OF ELASTIC PROPERTIES OF PAPER

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Abstract

A laser-based ultrasonic system for non-contact measurement of the elastic properties of paper was evaluated on a pilot paper coating machine operating at paper web speeds of up to 25.4 m/s (5,000 ft /min). Flexural rigidity and out-of-plane shear rigidity were calculated from the frequency dependence of the phase velocity of Ao mode Lamb waves. These ultrasonic waves were generated in the paper with a pulsed Nd:YAG laser. Lamb waves were detected with a Mach-Zehnder interferometer coupled with a scanning mirror/timing system to compensate for paper motion. Six paper grades ranging in basis weight from 39 to 100g/m^2 were tested. The on-line laser-ultrasonic measurements of flexural rigidity agreed within experimental error with laboratory contact ultrasonic measurements on stationary samples. The effects of web tension and moisture content were quantified.

Introduction

Laser ultrasonics has been applied in recent years to measurement of mechanical properties of paper in the laboratory (1,2). Further laboratory demonstrations of LUS on moving paper demonstrated the opportunity for routine measurement of these properties during manufacture, and for feedback control of the papermaking process based on these measurements (3). Further developments in signal processing and the results of the first (to our knowledge) demonstration of LUS on moving paper in an industrial setting are discussed in this paper.

LUS signal energy in paper goes predominantly into the zero order anti-symmetric (Ao) mode plate wave (3). The Ao 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 Ao wave signals (4). The properties are flexural rigidity (D) and out-of-plane shear rigidity, SR (for a homogeneous material shear rigidity is equal to shear modulus times caliper). Flexural rigidity differs slightly (it is about 9% larger) from bending stiffness (BS) through a term the 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 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 conventional papers.

Bending stiffness is routinely measured in paper 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, 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 (5). 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 online (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 MM/yr 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, and additional savings of $0.4MM/yr is expected (6).

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 (7), in-plane shear horizontal plate waves, and out-of-plane bulk waves (8,9,10,11,12,13). 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 advantage of LUS is that it does not require physical contact with the sheet, eliminating that potential cause of paper damage.

Methods

The experimental system consisted of a pulsed Nd:YAG laser (New Wave Minilase III) which delivers a 5 nanosecond pulse at 1.06 µm for ultrasound generation, a Mach-Zehnder interferometer (Polytec-PI OFV303/OVD02) which includes a continuous 2 mw helium-neon laser source for detection, 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. The scanning mirror optics prevents textural noise from the moving, rough paper surface from saturating the LUS signal. Details of the apparatus have been described previously (3). The system has since been modified to rotate the scanning mirror with a feedback-controlled DC servomotor and to collect data with a personal computer equipped with an oscilloscope card (Gage Compuscope 1250) operated with LabView-based software.

The LUS system was installed on a pilot coating machine at the Mead (now MeadWestvaco) research facility in Chillicothe, Ohio (Figure 3).

Figure 1. LUS system installed on pilot coating machine.

The LUS system was used to measure D and SR in the machine (MD) and cross (CD) directions at paper speeds up to 25.4 m/s (5,000 ft/min). Moisture, MD web tension, basis weight and paper speed were independently varied to explore their effects on the measurements.

To generate the ultrasonic signal, the generation laser beam was focused on the sheet with a 150 mm focal length spherical lens. When the laser beam was delivered by the optical fiber, it was focused with a 10mm focal length aspheric lens. The laser pulse energies were as high as possible without causing visible damage to the paper, and ranged from 2 to 8 mJ. The detection interferometer beam was focused onto the paper at a position separated by either 5 or 10 mm from the position where the generation beam was focused.

Paper samples in 76 cm (30 inch) wide rolls 0.6 to 1.5 m (2 to 5 feet) in diameter with basis weights ranging from 39 to 99 g/m^2 were used in the tests. The samples were later analyzed by at IPST to obtain independent contact ultrasonic estimates of D and SR.

MeadWestvaco inspectors considered the level of laser damage to be insignificant and well within product specifications.

LUS 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-Δφ,

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

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(ω) to D/BWand D/SR,

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

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 (7,13). For the Ao mode at low frequencies, wave motion can be modeled with beam equations. The above, simplified dispersion equation 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. Mathematical comparisons between the full and approximate dispersion equation for typical papers in the frequency range of our measurements showed very small differences.

Ten to twenty signals at each separation were averaged. The resulting pair of signals and the web basis weight were used to calculate D and SR. Measurements are reported as an average value with a standard deviation (standard deviation of the mean).

Results

Correlation with Contact Measurements

The online LUS values at the running moisture content were compared to contact ultrasonics measurements made in a laboratory at 50% relative humidity. If one assumes that paper is homogeneous and of known thickness, contact ultrasonic analyses of So waves can be used to estimate D (14). Specifically, for contact ultrasonics the flexural rigidity (D) is computed as

$$D = V_{S0}^2 BWt^2/12$$

from the velocity of the low-frequency (70 kHz) portion of the S_0 Lamb wave (V_{S0}), the basis weight (BW), and the caliper (t). The validity of this computation rests on the dubious assumption that paper is a homogeneous plate of well-defined and uniform thickness. However, paper stiffness values vary through the thickness, its surface is very irregular, and thickness determinations are notoriously dependent on the surface conformability of the caliper platens and on the mechanical load under which thickness is measured. Nevertheless, D calculated from the contact ultrasonic measurement should be within 20-40% of the true value of the flexural rigidity, and a comparison is useful.

The out-of-plane shear rigidity (shear modulus times caliper, SR) can be calculated from the contact out-of-plane shear velocity (V_{ZS}), the basis weight (BW):

$$SR = V_{ZS}^2 BW$$

However, paper thickness and time-of-flight measurements are both required to determine V_{ZS}.

Laser-ultrasonic flexural rigidity measurements in the MD and CD on all paper types were compared to the contact transducer–based results (Figure 2). A linear fit to the data and a line representing 1:1 correspondence between contact and LUS measurements show the overall close correspondence between the two techniques.

The vertical error bars on the data points in Figure 4 indicate a variance of approximately 10% for LUS determined flexural rigidity. From laboratory experience, this reflects the real variability in paper properties rather than uncertainties in measurement. Over the short span (5mm) of the LUS measurements, variations of this magnitude are expected in paper. Due to these local variations in D, timely, meaningful measurements of average paper mechanical properties can be realized only by averaging a large number of on-line measurements.

Laser-ultrasonic measurements of SR, in the MD and CD, were compared to contact transducer–based results (Figure 3). As indicated by the large error bars, this measurement is much less reliable than the measurement of D, whether by laser or contact ultrasonics. Also, the correlation between contact and LUS measurements of SR is much weaker. This discrepancy may be due to the lack of sufficient high frequency content in the LUS signals. The high frequency components of the signal strongly affect the SR measurement; and high frequency components of the acoustic wave tend to damp out more rapidly in paper.

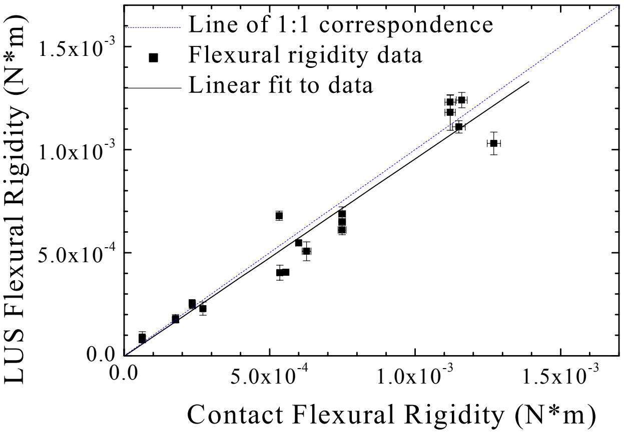

Figure 2. Correlation of flexural rigidity derived from LUS with contact transducer measurements.

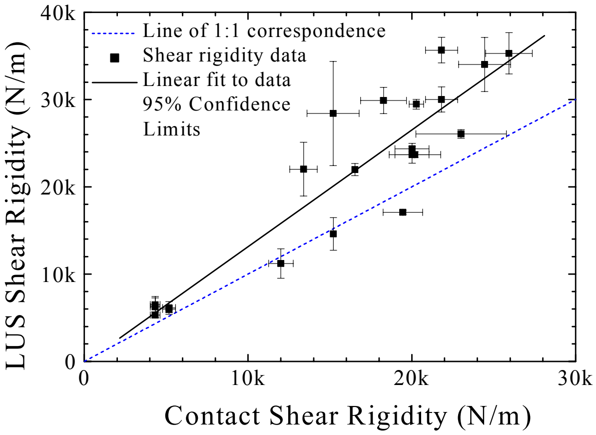

Figure 3. Correlation of shear rigidity values derived from LUS with contact transducer measurements.

Effect of moisture

A 95 g/m^2 pre-coated, white paper was first tested “dry” (moisture content: 3.0 wt-%), and then re-measured with moisture applied at one of the coater stations to allow a “wet” (moisture content: 6.8 wt-%) test. A Comparison (Table 3) of the results of these two runs provides an on-line demonstration of the influence of moisture on D and SR. For each weight-percent increase in moisture, the MD flexural rigidity decreased 4.2% and the CD flexural rigidity decreased 2.4%. The moisture effect on SR was less than the experimental variability (6%).

Measure-ment Axis	MD		CD	
Water Content (wt-%)	2.96± 0.04 (Dry)	6.8±0.6 (Wet)	2.96±0.04 (Dry)	6.8±0.6 (Wet)
D(x10^{-4} N*m)	11.8±0.05 (3x avg)	9.9±0.3 (4x avg)	6.50±0.03 (3x avg)	5.9±0.2 (3x avg)
SR (x10^4N/m)	3.36±0.09 (3x avg)	3.0±0.07 (4x avg)	2.4± 0.1 (3x avg)	2.43±0.04 (3x avg)

Table 3. Effect of Moisture on LUS measurements on pre-coated white 95 g/m^2 paper. Uncertainties are standard deviations of the mean.

Effect of Tension

Machine direction tension was raised from 2.6 to 4.4 N/cm during measurements on a 39 g/m^2 uncoated white paper. The average MD flexural rigidity rose about 6% from as tension was increased (Table 4). The on-line tension effect on lightweight papers was statistically significant.

Measure- Axis	MD		CD	
Tension(N/cm)	2.6	4.4	2.6	4.4
D (x10^{-4}N*m)	1.75±0.04 (3x avg)	1.86 ± 0.04 (3x avg)	0.9 ± 0.1 (3x avg)	0.8 ±0.05 (3x avg)
SR (x10^4N/m)	0.60±0.02 (3x avg)	0.585±.006 (3x avg)	0.53±0.02 (3x avg)	0.65±0.03 (3x avg)

Table 4. Effect of MD tension on LUS measurements on uncoated white 39g/m^2 paper. Uncertainties are standard deviations of the mean.

Summary

Laser ultrasonic measurement of paper flexural rigidity has been demonstrated in an industrial environment on paper webs moving at speeds up to 25.4 m/s. measurements have been reported at such The flexural rigidity measurements for papers with basis weights up to 100 g/m^2 agree well with contact transducer-based measurements in the lab.

The data confirm that flexural rigidity is strongly affected by moisture. To allow comparison of flexural rigidity and shear rigidity properties of different paper samples, and to permit specifications for flexural rigidity and shear rigidity to be established, specifications must include a moisture content, and the measurements must be corrected to the value at that moisture content.

The influence of MD tension on the online flexural rigidity measurements compares well with theoretical predictions and laboratory experience.

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