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. Fiber optic delivery of the generation pulse was demonstrated. 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, and a 280g/m^2 paperboard were tested. For the six paper grades, the on-line laser-ultrasonic measurements of flexural rigidity agreed within experimental error with conventional laboratory contact ultrasonic measurements on stationary samples. The effects of web tension and moisture content on flexural rigidity measurements were quantified. The low frequency signal amplitude from the paperboard was insufficient for accurate measurements.

Introduction

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

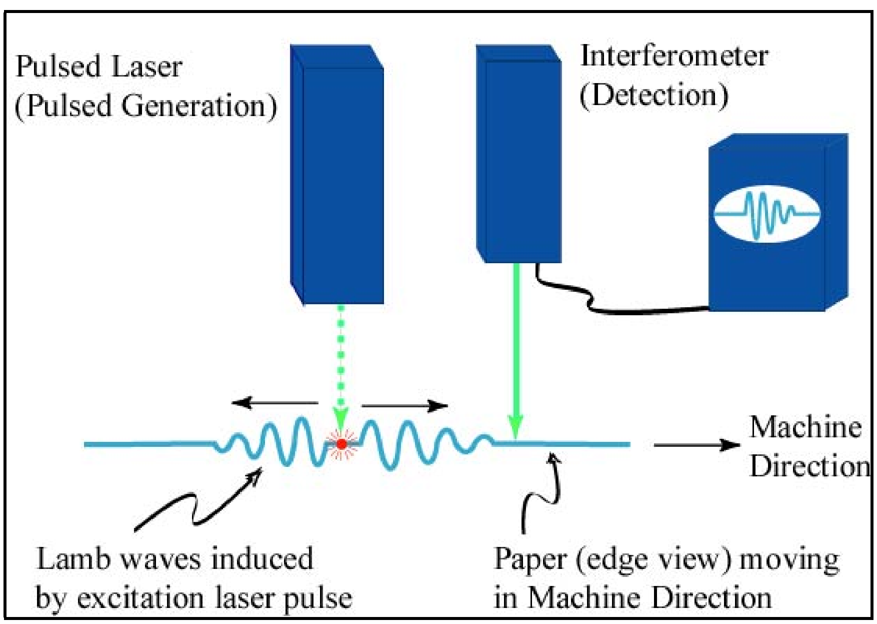

Figure 1. System for LUS analysis of paper.

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 opportunity for routine measurement of these properties during manufacture, and for feedback control of the papermaking process based on these measurements (5,6). 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 (7). 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 (8). In addition to monitoring end-use properties, on-line measurements of D and SR are potentially useful as inputs for feedback process control.

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 (9,10,11,12,13,14). 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.

Experimental

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, low-power (eye-safe) 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 innovation was crucial. Without it, textural noise from the moving, rough paper surface under the detection laser would saturate the LUS signal. 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 and to collect data with a personal computer equipped with an oscilloscope card (Gage Compuscope 1250) operated with LabView-based software.

An alternative fiber optic delivery system for the excitation beam was incorporated, as shown in Figure 2. Fiber optic delivery demonstrates the potential to position excitation laser at an arbitrary distance from the primary apparatus, thus reducing the size of the sensor-head and number of components mounted near the paper surface.

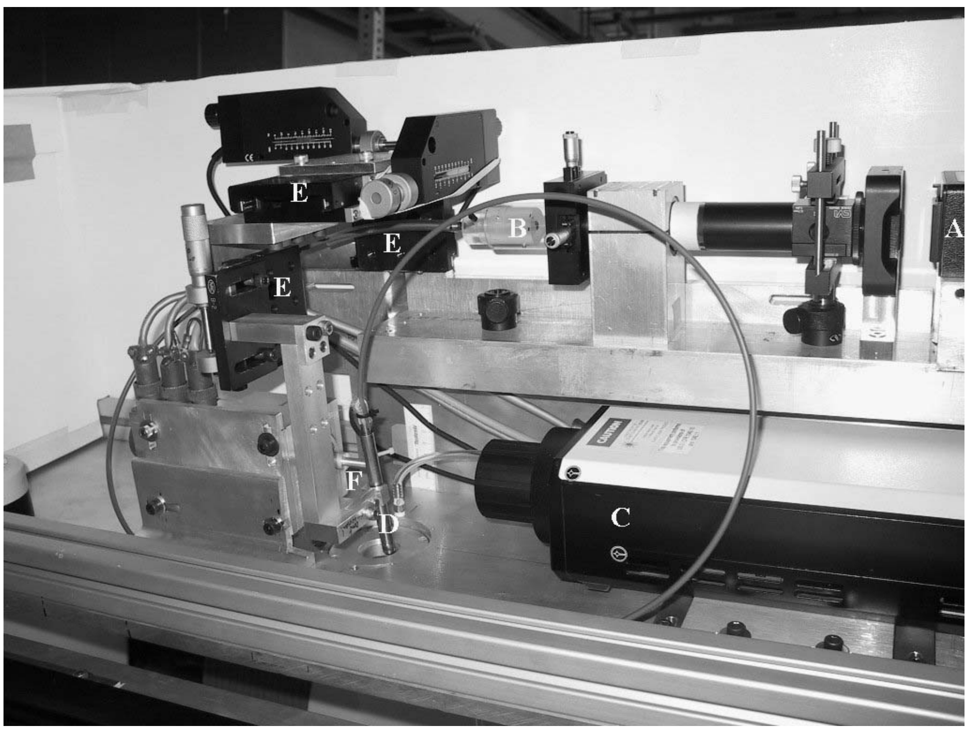

Figure 2. Optical fiber delivery system for excitation pulse. A: excitation laser; B: fiber optic insertion; C: Mach-Zehnder interferometer (detector); D: tube aligning optical fiber output and focusing lens; E: translation stages and motorized actuators for positioning the excitation spot in the MD and CD; F: spinning shaft holding the detector’s scanning mirror (hidden)

The LUS system was installed on a pilot coating machine at the Mead (now MeadWestvaco) research facility in Chillicothe, Ohio (Figure 3). This machine drives a 76 cm (30”) wide paper web at up to 25.4 m/s (5,000 ft/min) from a supply reel to a take-up reel. 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.

Figure 3. LUS system installed on pilot coating machine.

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 were used in the tests. They included three uncoated white papers with basis weights of 39, 67, and 72 g/m^2, two coated white paper samples with basis weights of 93 and 99 g/m^2, and two uncoated papers with basis weights of 93 and 94 g/m^2 that were coated "upstream" from the LUS test stand. Data were also collected on an uncoated brown paperboard of basis weight 280 g/m^2. All the paper samples tested at MeadWestvaco Research were later analyzed by contact ultrasonics to obtain independent estimates of D and SR (15).

Test sheets were subjected, off-line, to laser shots at multiple locations under the same conditions used to generate the on-line ultrasound data. These paper samples were then printed with solid blocks of color in order to evaluate the damage from the laser shots. Laser marking of the sheets was very slight. MeadWestvaco print quality inspectors were able to locate some of the laser shots, but they considered the level of 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-$\Delta\varphi$,

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

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,

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

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 (2,14). 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. 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).

A partially automated Lab View program was used for data acquisition, signal averaging and curve fitting. 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. For a single data collection run on a given paper sample, multiple measurements are reported as an average value with a standard deviation.

Results

Effect of Web Speed

LUS measurements were made on three uncoated papers as the web speed was increased incrementally to the upper limit of the machine. Tables 1 and 2 document the results. The data show that the measured D and SR are not affected by web speed, within experimental error.

Web Speed/ Basis Wt.	5.1 m/s (1kfpm)	10.2 m/s (2kfpm)	20.3 m/s (4kfpm)	25.4 m/s (5kfpm)
72 (g/m^2)		3.9 ± 0.7	4.1 ± 0.3	3.9 ± 0.2
67 (g/m^2)		4.7 ± 0.5		5.3 ± 0.2
39 (g/m^2)	1.8 ± 0.2	1.8 ± 0.2		

Table 1. Effect of web speed on LUS measurement of flexural rigidity ($*10^{-4}$ N*m)

Web Speed/ Basis Wt.	5.1 m/s (1kfpm)	10.2 m/s (2kfpm)	20.3 m/s (4kfpm)	25.4 m/s (5kfpm)
72 (g/m^2)		3.0 ± 0.2	2.88 ± 0.02	3.1 ± 0.2
67 (g/m^2)		2.3 ± 0.6		2.1 ± 0.2
39 (g/m^2)	0.63 ± 0.09	0.590± 0.001		

Table 2. Effect of web speed on LUS measurement of shear rigidity ($*10^4$ N/m)

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 (17). Specifically, for contact ultrasonics the flexural rigidity (D) is computed as

$$D = V_{S0}^{2} BW t^{2}/12$$

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. The wave properties monitored in the LUS technique provide a more direct and therefore more reliable measure of flexural rigidity, because no assumptions are made about sheet thickness. Nevertheless, D calculated from the contact ultrasonic measurement should be within 20-40% of the true value of the flexural rigidity, and a comparison provides a sanity check.

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) and the caliper (t)(17):

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

However, paper thickness and time-of-flight measurements are both required to determine V_{ZS}. Once again, the LUS measurement of SR is a more direct and reliable measurement than the contact ultrasonic technique because the latter relies on (the cube of) an estimate of sheet thickness (caliper).

Laser-ultrasonic flexural rigidity measurements in the MD and CD on all paper types except 280g/m^2 paperboard were compared to the contact transducer–based results (Figure 4). 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.

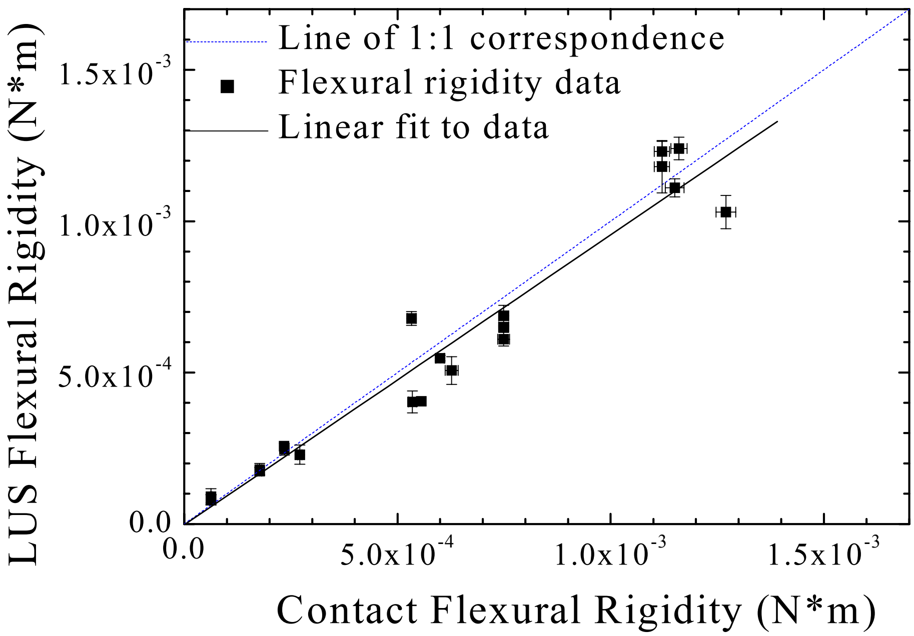

Figure 4. Correlation of flexural rigidity values derived from LUS with contact transducer measurements.

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 5). 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.

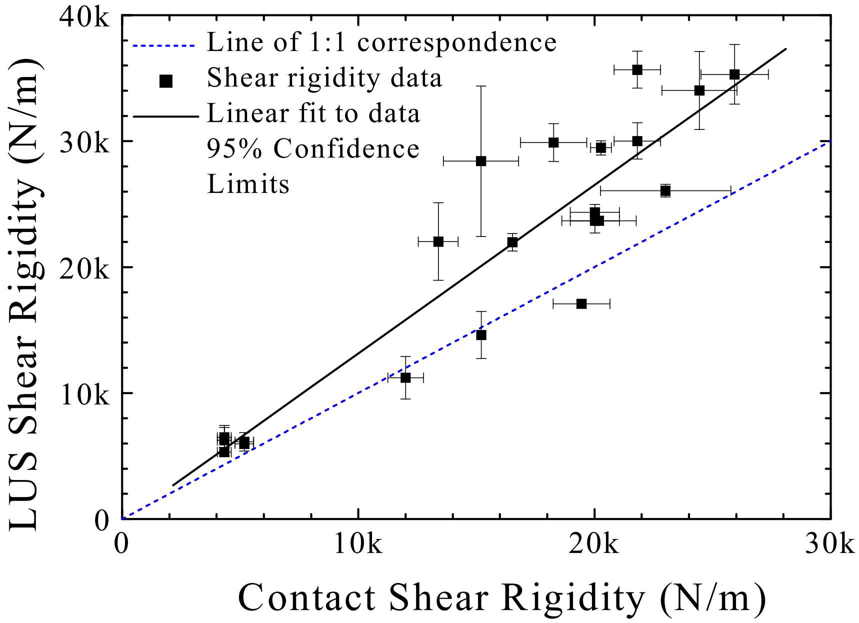

Figure 5. Correlation of shear rigidity values derived from LUS with contact transducer measurements.

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. The mean flexural rigidity in the MD was 16 ±3% lower and in the CD was 9 ±4% lower for the moistened paper. 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%).

Measurement Axis	MD		CD	
Moisture Content (wt-% water)	2.96 ± 0.04 (Dry)	6.8 ± 0.6 (Wet)	2.96 ± 0.04 (Dry)	6.8 ± 0.6 (Wet)
D ± std. dev. of mean (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± std. dev. of mean (x10^{4}N/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

Laboratory experiments on "copy paper" (approximately 80 g/m^2) over a different moisture content range (5-10%), resulted in a three percent decrease in MD flexural rigidity *per* percentage increase in moisture content (18). The experimental methods, the conditions and the paper sample in the laboratory study were different. However, the results of those studies agree, and both studies show that flexural rigidity is sensitive to increasing moisture. Moisture content must be taken into account when evaluating flexural rigidity measurements.

Effect of Tension

From a theoretical point-of-view (17), web tension on very lightweight papers should cause a detectable increase in phase velocity at the low frequency end of the A_0 dispersion curve. If (as was the case) tension is not taken in account in the elastic constant determination, tension should lead to an apparent increase in flexural rigidity (which is predominantly calculated from the low frequency portion of the dispersion curve) and to no change in shear rigidity (which comes from the high frequency portion). An experiment was conducted on the lowest basis weight grade to see if the flexural rigidity effect manifests itself in the on-line testing measurement. Machine direction tension was set at 2.6 and 4.4 N/cm (1.5 and 2.5 lb/in) during measurements on a 39 g/m^2 uncoated white paper. The average MD flexural rigidity rose about 6% from 1.75 10^{-4} Nm to 1.86 10^{-4} Nm as tension was increased (Table 4). At the 2.6 N/cm (1.5 lb/in) setting, seven on-line measurements were made, and the standard deviation was 0.11 10^{-4} Nm. Thus, the standard deviation in the mean was 0.04 10^{-4} Nm. Four measurements were made at 4.4 N/cm (2.5 lb/in), the standard deviation was 0.08 10^{-4} Nm and the standard deviation in the mean was 0.04 10^{-4} Nm. Consistent with theoretical expectations tension experiments in the laboratory produced an apparent 10% change in MD flexural rigidity on this paper grade over this tension range (17). This value compares well with the on-line measurement. The on-line tension effect on lightweight papers was statistically significant and of the expected magnitude.

Measurement Axis	MD		CD	
MD Tension N/cm (lb$_f$/in)	2.6 (1.5)	4.4 (2.5)	2.6 (1.5)	4.4 (2.5)
D ± std. dev. of mean (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± std. dev. of mean (x10^4N/m)	0.60 ± 0.02 (3x avg)	0.585 ± 0.006 (3x avg)	0.53 ± 0.02 (3x avg)	0.65 ± 0.03 (3x avg)

Table 4. Effect of tension on LUS measurements on uncoated white 39g/m^2 paper

Paperboard Results

Laser ultrasonic analysis of the brown paperboard (basis weight of 280 g/m^2) was much less reproducible and had a poor correspondence with contact measurements. These results reflect those obtained with the Mach-Zehnder interferometer in the laboratory, where accurate flexural rigidity can be extracted from data collected from paper samples of basis weights up to 165 g/m^2. LUS and contact transducer-based measurements on this sample are given in Table 5. Flexural rigidity measured by LUS was much lower than that obtained by contact ultrasonics, especially in the cross direction.

Measurement Axis		MD		CD	
Measurement Type		LUS	Contact	LUS	Contact
D ± std. dev. of mean ($x10^{-2}$N*m)	Trial 1	1.14 ± 0.04 (4x avg)	3.67 ± .02 (8x avg)	0.31 ± 0.08 (7x avg)	1.79 ± 0.01 (8x avg)
	Trial 2	2.8 ± 0.3 (10x avg)		0.47 ± 0.07 (5x avg)	
SR ± std. dev. of mean ($x10^{4}$N/m)	Trial 1	4.7 ± 0.2 (4x avg)	5.1 ± 0.2 (10x avg)	3.3 ± 0.2 (7x avg)	4.8 ± 0.1 (10x avg)
	Trial 2	4.0 ± 0.2 (10x avg)		4.2 ± 0.7 (5x avg)	

Table 5. Comparison of LUS and contact measurements of flexural rigidity and shear rigidity on 280g/m^2 paperboard

Generally, as basis weight increases, there is a decrease in the upper limit of the frequency range over which Ao phase velocity depends almost exclusively on D. The inaccurate results on the 280 g/m^2 paperboard indicate a necessity to monitor lower frequencies than could be detected with the sensor as configured.

There is a lower limit to the frequencies that can be detected with the online sensor (at a given web speed) due to the changing optical path length associated with the detection system's spinning mirror. The low-frequency sensitivity of the Mach-Zehnder detector is well matched to the rest of the sensor system in that the aforementioned changing optical path length does not saturate the detector. Methods for increasing the amplitude of the low-frequency components of signals on heavy grades are under investigation, with the goal of enhanced detection of lower frequencies in the online sensor.

In the meantime, for laboratory laser ultrasonic measurements on stationary paper, we use a Two Wave Mixing (TWM) interferometer which is much more sensitive to lower frequencies, resulting in accurate flexural rigidity measurements on grades with basis weights up to 210g/m^2 (19).
Figures 6 and 7 are re-plots of the data in Figures 4 and 5 with the paperboard data added to show that the paperboard is significantly stiffer than the other paper grades, and to show that there is much less agreement between the contact and laser ultrasonic measurements for the paperboard than for the other samples.

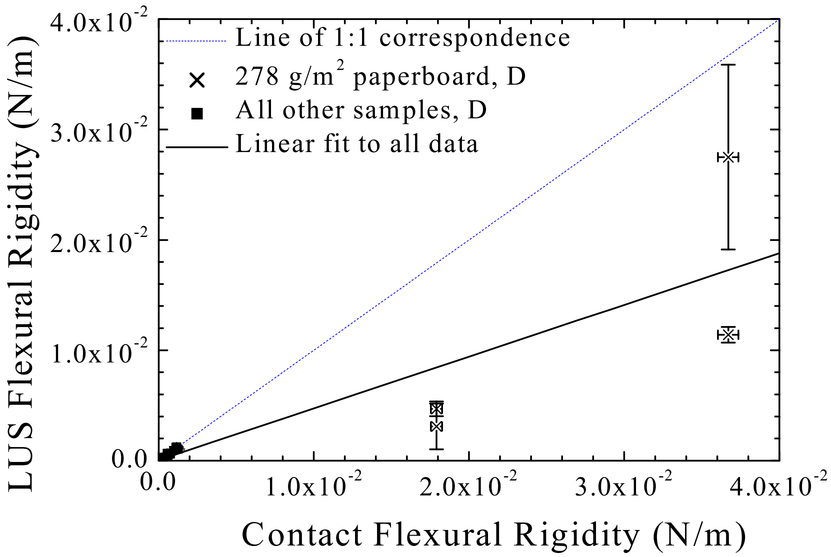

Figure 6. Correlation of flexural rigidity values derived from LUS versus contact transducer measurements, including paperboard data.

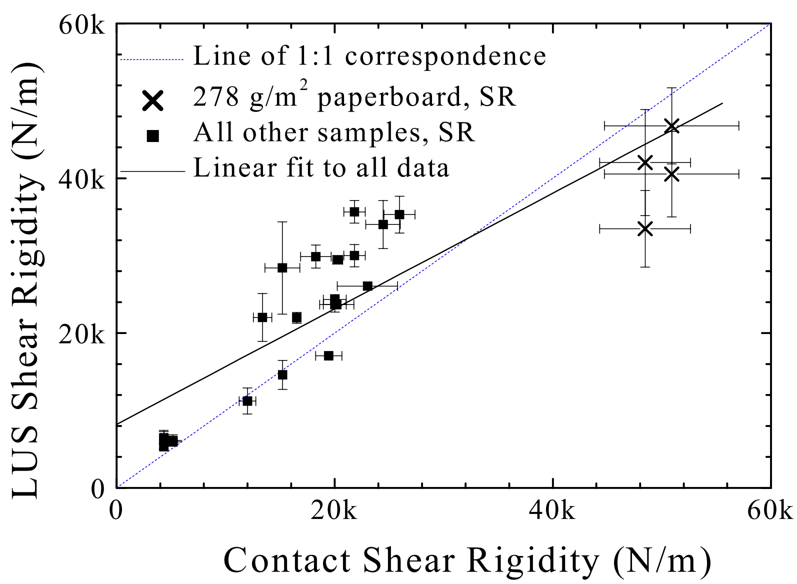

Figure 7. Correlation of shear rigidity values derived from LUS versus contact transducer measurements, including paperboard data.

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 (5,000 ft/min). To our knowledge, this is the first time that elastic parameters measurements have been reported at such high web speeds on paper. 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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