A FULLY FIBERIZED LASER-ULTRASONIC INSTRUMENT FOR MEASURING THE STIFFNESS PROPERTIES OF PAPER

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Abstract

Flexural rigidity and shear rigidity of paper webs can be determined by analysis of the zero order antisymmetric (A_0) Lamb wave. Using Laser Based Ultrasound to excite and detect Lamb waves in paper is advantageous because it is a non-contact technique suitable to both on-line and off-line measurements. The authors have developed a laser interferometer using the two-wave mixing technique in an undoped Gallium Arsenide photorefractive crystal. The interferometer is part of a laboratory instrument in which both the generation and the detection laser beams are carried through fiber optics. The instrument is computer-controlled and automated for routine testing of the paper samples. The results of non-contact laser generation and detection of ultrasound are presented. Different paper grades have been investigated. The paper grades were heavy grades like linerboard (used in the paper industry to produce corrugated boxes), as well as light-weight paper (such as publishing paper).

Introduction

After a long transition Laser Ultrasonic [1] has evolved from the research laboratories to the factories. It has been successfully used for process control on sheets or tubes of steel or aluminum [2]. Laser Ultrasonics has also been used for process control or non-destructive testing of: glass, silicon wafers, optical crystal growth, carbon-epoxy manufactured parts, etc. [3-5].

Experiments with industrial application to paper have recently begun [6-10]. The definition of the word “paper” in this application is very broad. It includes copy paper, as well as paper for drawing, tissue paper, newsprint, and coated paper. Heavier grades of paper such as linerboard (generally brown color), and bleach board (white color) are used for packaging. Mass specific elastic stiffnesses as determined from the velocity of ultrasonic pulses are direct measures of the mechanical state of a material. For monitoring product quality and providing feedback for process control, measuring the stiffness properties of the paper would be a valid method.

Principle of the measurements

The thickness of a paper web produced on a paper machine ranges from .06 to .5 mm depending on the paper grade. Paper is a thin plate and Lamb waves propagate well in it. Because of the orientation of the wood fibers, paper produced on a paper machine is strongly anisotropic. On a paper web, one can identify the MD direction which is the Machine Direction along which the fibers are aligned and the web is moving; the Cross Direction CD, perpendicular to the MD; and ZD which is perpendicular to the plane of the paper web. MD and CD are the in-plane directions of the web and the flexural rigidity of a paper web is always significantly higher in the MD than in the CD.

Because of the fibrous structure of paper [11] and of the scattering nature of paper (typically 10 μm diameter fibers, 10 μm holes, mm long fibers therefore many interfaces), only low frequency ultrasonic waves (< 4 MHz) can propagate without being attenuated after a few mm travel. Hence even if the acoustic source generates some high frequencies, only low frequency waves can be detected.

The power spectral density is very small over 1 MHz and the consequence is that only the first order symmetric Lamb wave named S_0 and the first order antisymmetric Lamb wave named A_0 are observed in a paper sheet [6, 12] with a decent signal to noise ratio. The second order symmetric Lamb wave S_1 is usually at too high frequency to be observed in heavy paperboard.

The A_0 and S_0 waves in paper are different from many points of view. With the laboratory instrument described in this article we only measure A_0. The A_0 wave at low frequencies is mainly an out-of-plane wave, i.e. generates displacements in a direction perpendicular to the surface of the web. The phase velocity of the A_0 mode depends on the frequency, flexural rigidity, shear rigidity and basis weight (weight per unit area). The A_0 wave is dispersive at low frequencies where we typically can observe it. For paper webs, the basis weight is easily and exactly measured.

The calculation of flexural rigidity and shear rigidity is performed as follows:

The instrument digitizes and saves two A_0 waveforms at two different emitter-to-receiver separations. The phase difference between the two waveforms is unwrapped. The phase velocity of A_0 is determined as function of frequency. Then the phase velocity of A_0 divided by the square root of frequency is also determined as a function of frequency. The flexural rigidity and shear rigidity are determined by a least square of two parameters fit of this function. A typical frequency range for those calculations is 20 kHz to 600 kHz. The data acquisition, phase unwrapping, mechanical constants determination are performed by a LabView program developed in-house. A view of the analysis panel of the instrument's software is presented in Figure 1. From top to bottom, one can see: the near signal in the time domain (short emitter to receiver distance); the far signal in the time domain; the spectra of the near and far signals (middle left); the raw curve of the phase velocity divided by the square root of frequency and the fit (middle right, in red) used to determine the Flexural Rigidity (FR) and Shear Rigidity (SR); the parameters for the semi-automated analysis, and the FR and SR output (in blue).

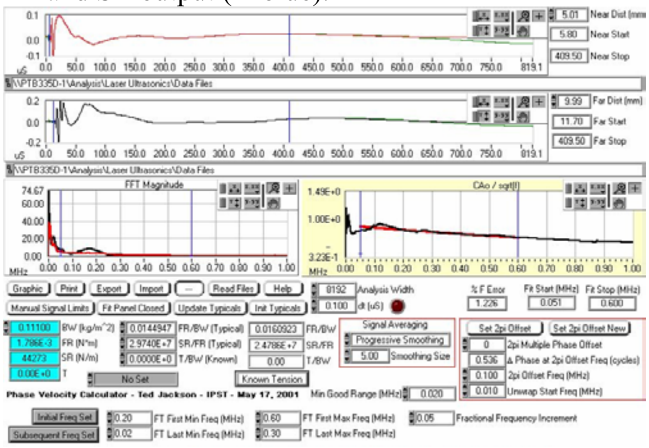

Figure 1: View of the analysis panel of the software

Layout of the instrument

The schematic of the instrument is displayed in Figure 2 and a photo of it is shown on Figure 3. The pulsed generation beam (Nd:YAG) is delivered through a multimode silica fiber optic of 365 µm core diameter having a 0.22 numerical aperture (N.A.). The instrument is fully computer-controlled. The computer controls the movement of the paper sample and the generation and detection probe separations. It also controls the firing of the laser and data acquisition.

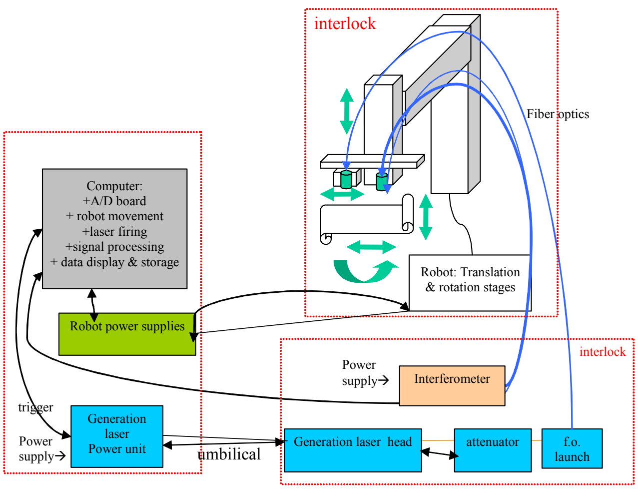

Figure 2: Schematic of the automated laser-ultrasonic laboratory instrument

Figure 3: Photo of the automated laser-ultrasonic laboratory instrument

Finally the computer also processes the data, and extracts the Flexural Rigidity and Shear Rigidity.

Two-wave mixing interferometer

For demodulating the phase shift of the laser light produced by the ultrasonic motion of the paper surface, we used a Two-Wave Mixing (TWM) photorefractive interferometer [13] shown on Figure 4. The beam paths of the incident, pump, and signal laser beams (with a wavelength of 1064 nm) are materialized in red on the figure. The interferometer uses a 8mm x 8mm x 6 mm (in the thickness direction) crystal of Gallium Arsenide (GaAs) to which no voltage is applied. This interferometer was developed in-house and the optical setup is very similar to the one described in detail in reference [14].

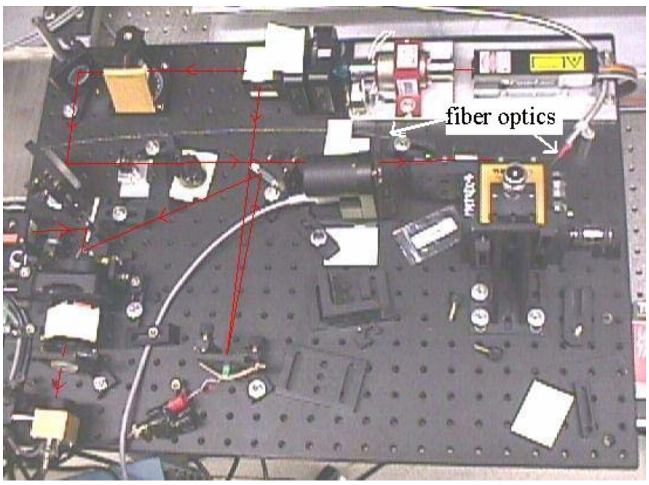

Figure 4: Photo of the interferometer and partial view of the detection fiber optics.

An improvement over the previous setup is that two fiber optics are bringing the incoming beam to an objective above the paper surface and carrying the backscattered light back to the interferometer. The fiber bringing the light to the sample is a monomode fiber with a mode field of 6.6 µm and a 0.13 N.A.. The laser light backscattered by the paper surface is collected by the same aspheric lens that focuses the incoming beam [15]. The collected light is carried by a 200 µm core diameter, 0.22 N.A. silica-silica multimode fiber and then partly collimated before being refocused onto the GaAs crystal. Thus, this TWM interferometer is fully fiberized.

Instrument's results

Recent results obtained with the instrument are presented hereafter.

Escanaba Coated Matte Paper

In table 1 we show data obtained on a coated matte grade with a basis weight of 111 g/m^2. For each data point the instrument was averaging 1 to 4 (depending on the waveform quality) near and far ultrasonic signals (waves traveling 5 and 10 mm or 6 and 11 mm). We did statistics over 10 data points representing 10 different locations on an 18 cm x 18 cm sample. The energy deposited on the paper was 1.8 mJ per pulse.

Table 1: Lab instrument results for coated matte paper

Paper grade: Escanaba Coated Matte basis weight: 111 g/m^2	MD Orientation	CD Orientation
Flexural rigidity (N.m)	2.015E-03	8.613E-04
Flexural rigidity coef. of variation (%)	6.82	8.71
Shear Rigidity (N/m)	3.80E+04	3.78E+04
Shear Rigidity coef. of variation (%)	9.6	17.4
MD/CD flexural rigidity ratio	2.339	

The Flexural Rigidity (FR) along MD is significantly higher than the one along CD which is normal. Notice that the coefficients of variation for both the FR and SR are quite small compared to many other paper grades, making this paper very uniform in its stiffness properties. We think this is due to the coating than smoothes out the valleys between fibers and evens out the stiffness variations between the different locations on the web.

Linerboard 33-Lb Paperboard

In Table 2 we show data obtained on a paper called a "Paperboard" because of its high stiffness properties that makes it suitable for packaging.

The separation distances were 5 and 10 mm and a few mJ were deposited on the paper. 7 locations along MD and 8 along CD were sampled, and the waves were averaged 10 times. The color of this paper is light brown and although the reflectivity coefficient at the wavelength of the interferometer (1064 nm) is smaller than white bleached paper, the interferometer can still detect the A_0 waves. On figure 3 we show A_0 waveforms in 33-Lb linerboard. The horizontal axis is the time in µs while the vertical axis is the displacement of the paper surface as measured by the two-wave mixing interferometer.

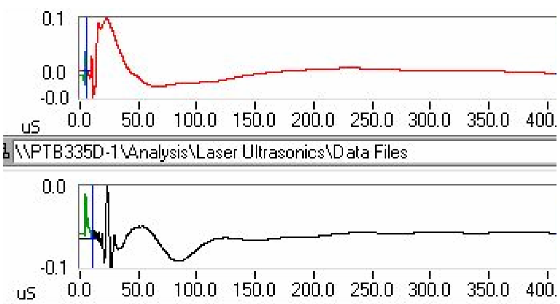

Figure 3: A_0 waveform in 33-Lb linerboard for 5 mm separation (top) and 10 mm separation (bottom)

Table 2: Results for 33-Lb linerboard

Paper grade: 33-Lb Linerboard basis weight: 163 g/m^2	MD Orientation	CD Orientation
Flexural rigidity (N.m)	5.450E-03	1.851E-03
Flexural rigidity coef. of variation (%)	13.9	12.9
Shear Rigidity (N/m)	3.30E4	2.04E4
Shear Rigidity coef. of variation (%)	7.9	26.0
MD/CD flexural rigidity ratio	2.945	

Double-ply Paperboard

In Table 3 we show results obtained from a paperboard made by the assembly of 2 paperboards with different stiffness properties glued together to produce a more rigid material.

Since the typical wavelength of the A_0waveform is of the order of a few millimeters and the thickness of the board is a few hundreds of µm, the ultrasonic wave generated by the laser pulse is still an A_0 wave that is not affected by the interface between the two plies.

Table 3: Results for Double-ply Paperboard

Paper grade: Double-ply Chillicothe Paperboard basis weight: 278 g/m^2	MD Orientation	CD Orientation
Flexural rigidity (N.m)	3.50E-2	1.49E-2
Flexural rigidity coef. of variation (%)	14.9	20.2
Shear Rigidity (N/m)	3.58E4	3.48E4
Shear Rigidity coef. of variation (%)	4.6	2.6
MD/CD flexural rigidity ratio	2.340	

Conclusion

In this publication we have described a laboratory instrument utilizing a pulsed laser and a CW laser interferometer for non-contact and broadband ultrasonic generation and detection on web-like materials. The instrument is used for the determination of flexural rigidity and out of plane shear rigidity of paper and paperboard samples. It is automated. It uses fiber optics for the delivery of generation and detection beams so as to allow more flexibility and versatility in the design and manipulation of the samples. Preliminary results obtained with very different grades of paper showed that the signal to noise ratio is sufficient over a wide range of basis weights. Moreover the spatial variability of the mechanical properties of paper produced on a paper machine were found to be within the expected values over a span of a few mm. More extensive testing of the instrument and software development for instrument controls and end-user interface is proceeding. Future plans include enclosing the areas of the instrument exposed to laser radiation so as to make it a portable class I laser system.

Acknowledgments

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