Noncontact Laser Generation and Detection of Lamb Waves in Paper

P.H. BRODEUR, M.A. JOHNSON, Y.H. BERTHELOT
and J.P. GERHARDSTEIN

A laser ultrasonics method has been used to investigate the propagation of Lamb waves in paper, and thus determine paper stiffness in a noncontact manner. Ultrasonic pulses were generated on nonmoving paper using a Nd:YAG pulsed laser. An Ar:ion CW laser was used in combination with two optical heterodyne interferometric systems to probe out-of-plane and in-plane surface motions of Lamb waves. Two simultaneous propagation modes were observed with substantially different velocities and frequency contents. They were identified as the fundamental dilatational and bending modes for Lamb waves, respectively. Velocity measurements obtained for the dilatational mode were found to be in very good agreement with velocities obtained using contact bimorph transducers. Results collected along machine and cross-machine directions for selected fine papers and paperboards are reported.

INTRODUCTION

The development of instrumentation for on-machine monitoring of paper mechanical properties has been an ongoing process for more than 20 years [1–15] because these properties are critical to the papermaking process, converting operations and end-use performance. Among expected benefits for on-machine sensors would be pulp usage optimization (less fibre usage and/or better use of virgin/reclaimed fibres to achieve targeted strength), reduction of energy consumption (less refining and/or less repulping/remanufacturing), product quality optimization, and basis for the development of manufacturing strategies prioritizing mechanical properties and de-emphasizing grammage and/or thickness.

Since it is known that empirical relationships exist between paper strength and stiffness properties [10,16], it is generally agreed that on-machine monitoring of paper strength is best achieved by testing elastic stiffness properties. In that regard, three different contact approaches have been considered. The first one involves the use of a mechanical sensor in contact with the moving web and aimed at measuring the force required to distort paper in a controlled manner [11]. The second method relies on the use of contact ultrasonic transducers to infer specific stiffnesses from the propagation of Lamb waves in the moving web. Various prototype implementations using rotating wheels [6–9] and sliding transducers [15] have been tested. The third approach uses a friction-induced noise generator for excitation and a contactless microphone for detection [5].

While contact methods offer robustness, full consideration must also be given to the development of contactless technologies because they are, in principle, far more desirable to the papermaker. For instance, latent physical damage to the web would be eliminated. Also, in addition to paperboards, monitoring of fine papers and coated grades would be possible. One distinguishes two different contactless methods: air-coupled transduction and laser ultrasonics.

Significant progress has been made in recent years toward the development of efficient air-coupled capacitive transducers, which are more sensitive and have a larger bandwidth than air-coupled piezoelectric transducers [17]. These transducers are relatively inexpensive. However, their utilization remains limited by the air medium itself: sound absorption in air increases with frequency, sound velocity in air is temperature dependent, and path lengths are sensitive to turbulence [18]. A resonance technique to induce and detect Lamb waves using air-coupled transducers was tested successfully on stationary paper [19–20]; an on-line implementation is hardly possible because the transmitter–receiver assembly must be rotated to get the maximum transfer of energy into the paper. Also, the sheet must be fairly thick to excite Lamb waves (>400 μm) [20].

Laser ultrasonics considers the use of lasers to induce and detect Lamb waves in paper. The discipline is now well established [21]. Merits include point source excitation (ideal configuration for detection of stiffness orientation distribution), absence of measurement artifacts due to the coupling medium (insensitivity to air temperature and moisture, turbulence), uniqueness of information, large bandwidth, and the availability of extensive R&D support. Referring to Fig. 1, when a normally incident pulse of light from a focused laser beam is absorbed by paper, it produces localized heating and, thus, thermal expansion in the network of fibres. Thermoelasticity leads to the formation of Lamb waves propagating in the plane of paper from the point of illumination. As discussed further below, bending and dilatational Lamb wave modes can be excited.

Bending waves propagating in paper were investigated recently using a ruby laser for excitation and an holographic technique for detection [22]. Holograms were recorded on a photographic film. A Michelson interferometer was used to reconstruct out-of-plane surface displacements, and a CCD

JPPS
P.H. Brodeur and
J.P. Gerhardstein
IPST
500 10th St. N.W.
Atlanta, GA, USA
30318-5794
M.A. Johnson and Y.H. Berthelot
School of Mechan. Engin.
Georgia Inst. of Technol.
Atlanta, GA, USA
30332

camera was used for visualization of defects such as thickness, stiffness, or density variations. Three patents related to the use of lasers for elastic wave generation in paper have been issued [23–25]. In the patent by Leugers [23], a Nd:YAG laser is used for ultrasound generation; elastic waves are detected by means of a piezoelectric transducer in contact with paper. Recordings of received pulses are reported for high-density polyethylene, and numerical results are presented for various paper grades in the machine direction. These results are shown to correlate with measurements obtained using piezoelectric transducer induction. The second patent, by Pace and Salama [24], concerns the use of a nitrogen laser directed onto one planar surface of a sheet of paper and aimed at generating elastic waves propagating in the thickness direction; a piezoelectric transducer placed in contact with the opposite surface is used for detection. Laser- and contact transducer-induced numerical results are shown to agree for selected paper grades. The third patent, by Keyes and Thompson [25], considers the use of a CO_2 laser for in-plane excitation and the use of a deflectometer technique employing a HeNe laser for detection; there is no indication of measurements. The above patents do not provide details about wave propagation modes. Moreover, contactless detection using laser heterodyne interferometry was not considered.

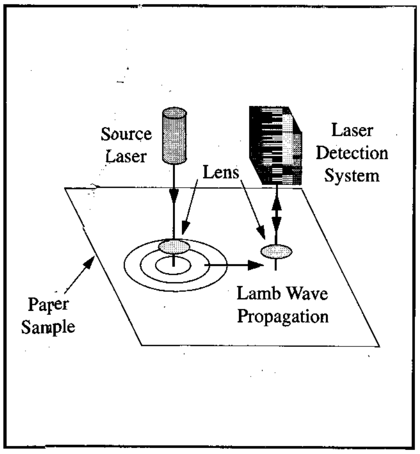


Fig. 1. Schematic diagram of laser ultrasonics generation and detection principles

This paper reports on the demonstration of a fully contactless laser ultrasonics technique to generate and detect Lamb waves in nonmoving paper. Following a brief review of Lamb wave propagation in paper, the experimental procedure is described. Then, results are presented and discussed for various paper grades. A study of Lamb wave propagation in copy paper using laser ultrasonics has been reported elsewhere [26–27].

LAMB WAVE PROPAGATION IN PAPER

As a first approximation, machine-made paper can be considered as an orthotropic material, i.e. a material with three mutually orthogonal symmetry planes. Then, assuming that paper is sufficiently thin to be considered as a plate, i.e. a medium for which surface waves can no longer propagate because their wavelength is much larger than the plate thickness, the propagation of plate waves (Lamb waves) is possible [1,19–20,28–29]. Lamb waves are of two types: dilatational or symmetric wave and bending or asymmetric wave. Figure 2 illustrates symmetric and asymmetric zeroth (fundamental) and first-order modes for Lamb waves; higher order modes also exist, but are not shown.

Typical machine-direction Lamb wave dispersion curves computed using elastic stiffness constants C_{11}, C_{33}, C_{55} and C_{13} for a 42-lb linerboard (see Table I for numerical values) are shown in Fig. 3. It is seen that the fundamental asymmetric mode, A_0, is dispersive at low frequencies. The fundamental symmetric mode, S_0, is nondispersive up to a cut-off frequency. Measurement of the S_0 mode phase velocity in the low-frequency limit can be used to determine the planar longitudinal specific stiffnesses Q_{11}/ρ and Q_{22}/ρ in the machine direction (MD) and cross-machine direction (CD), respectively, i.e. [28]

$$\frac{Q_{11}}{\rho} = v^2_{S_0,\mathrm{MD}} \tag{1}$$

$$\frac{Q_{22}}{\rho} = v^2_{S_0,\mathrm{CD}} \tag{2}$$

TABLE I
TYPICAL MEASURED ELASTIC STIFFNESS CONSTANTS FOR A 42-LB LINERBOARD. C_{13} AND C_{23} ARE ESTIMATES

C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}	C_{12}	C_{13}	C_{23}
GPa	GPa	GPa	GPa	GPa	GPa	GPa	GPa	GPa
10.3	2.94	0.057	0.126	0.174	1.93	0.917	0.1	0.1

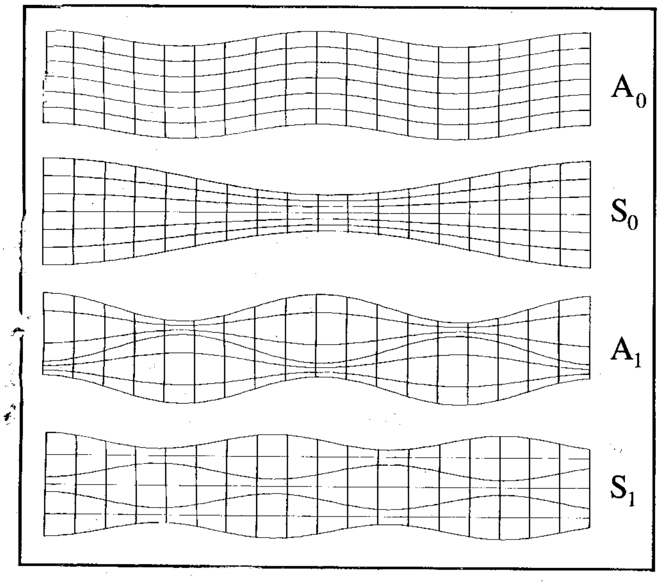


Fig. 2. Symmetric (S_n) and asymmetric (A_n) propagation modes for Lamb waves. From top to bottom: A_0, S_0, A_1, S_1. Note that these plots are only for specific places on each propagation mode curve (See Fig. 3). Moving along the propagation mode curve changes the frequency of the plot and may cause subtle changes to the actual mode shape.

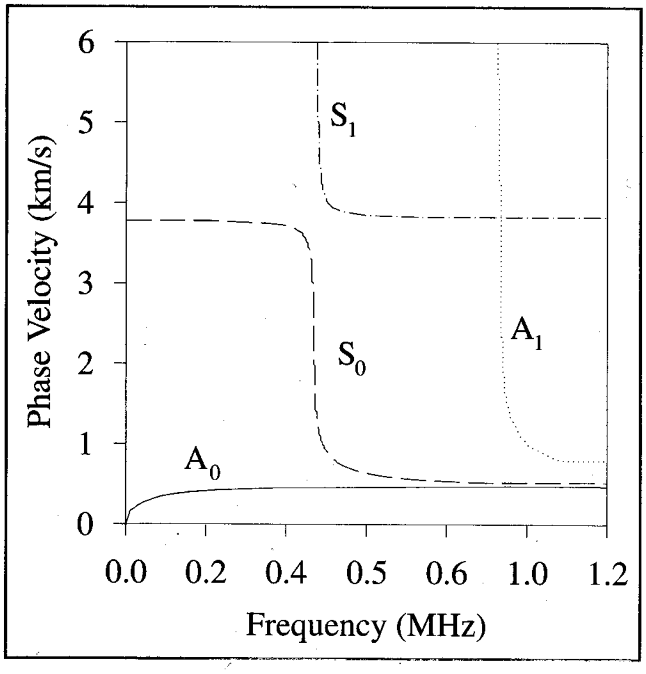


Fig. 3. Machine-direction dispersion curves for Lamb waves propagating in a 42-lb linerboard.

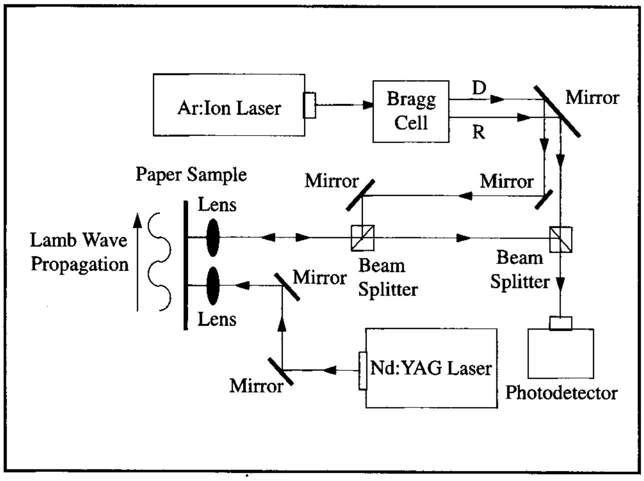


Fig. 4. Schematic of the out-of-plane motion detection system. Exiting the Bragg Cell, "R" refers to the reference beam, and "D" refers to the detection beam.

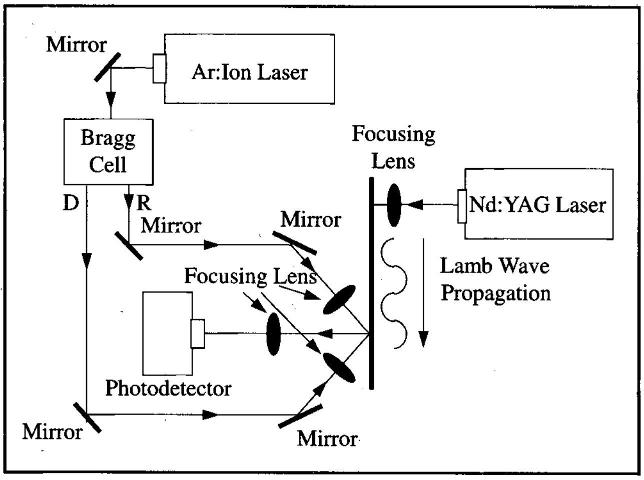


Fig. 5. Schematic of the in-plane motion detection system. Exiting the Bragg Cell, "R" refers to the reference beam, and "D" refers to the detection beam.

where $v_{S_0,MD}$ and $v_{S_0,CD}$ are the MD and CD S_0 mode velocities in the low-frequency limit and ρ is the apparent density of paper. Planar stiffnesses are approximated values to bulk stiffnesses C_{11}/ρ and C_{22}/ρ [30]. Dispersion analysis of the A_0 mode can be used to determine shear specific stiffnesses C_{55} and C_{44} in the MD-ZD and CD-ZD planes, respectively [26].

EXPERIMENTAL PROCEDURE

Experimental Set-Up

Observation of Lamb wave propagation in paper was accomplished by using laser ultrasonics equipment available at the Georgia Institute of Technology. A single-source configuration and two configurations for out-of-plane and in-plane surface displacement detection were used. The source laser was a pulsed Nd:YAG laser operating at 1064 nm with an energy output of 5.7 mJ, a pulse width of 10 ns, and a repetition rate of 10 Hz; the pulse width was not adjustable. The laser was focused down to a spot size of 70 µm on the target using a focusing lens. A 2 W CW Ar:ion laser operating at 514.5 nm was used for detection. Schematic diagrams for out-of-plane and in-plane detection systems are shown in Figs. 4 and 5, respectively. These systems, based upon optical heterodyne interferometry [31], are used typically for testing various materials other than paper or wood products. While slightly adapted for the purpose of this study, they were by no means optimized for paper testing. They are now briefly reviewed.

Description of the out-of-plane system is as follows. Referring to Fig. 4, the linear polarized Ar:ion laser enters a 40 MHz Bragg cell that splits the laser into a detection beam (D) that is frequency shifted by 40 MHz, and a reference beam (R). The detection beam is steered perpendicular to the surface of the sample and focused onto a 5–10 µm spot size with a microscope objective lens. A portion of the beam is scattered back off the sample and is recombined with the reference beam, thus producing an interference pattern that is then collected by an avalanche photodetector. The recombined beam contains a 40 MHz beat frequency due to the Bragg cell frequency shift of the detection beam. The signal from the photodetector is processed by an FM discriminator that is set to zero output at 40 MHz. Any further frequency shifting of the detection beam due to motion of the sample under the detection spot (i.e. from Lamb waves passing by) then appears as slight changes in the 40 MHz beat. These changes are registered as such by the FM discriminator. These changes are proportional to the instantaneous surface velocity of the sample, and are integrated to determine the position of the sample as a function of time. The out-of-plane detection system is sensitive to motions perpendicular to the sample surface [31].

The in-plane motion detection system is shown in Fig 5. Upon exiting the Bragg cell, the reference beam (R) and frequency-shifted detection beam (D) are steered around and focused at the same spot on the sample so that they illuminate the paper at a 45° angle to the surface and 180° apart longitudinally (where the z axis is perpendicular to the sample surface). The spot size is approximately 50 µm. These beams scatter off the sample surface and are collected by a microscope objective lens directly above and perpendicular to the impact spot. The interference pattern is collected by an avalanche photodetector. A beat frequency similar to that described above for the out-of-plane detection system is in the collected beam and is processed similar to the out-of-plane signal. The detection geometry is sensitive to motions parallel to the surface [31].

Sample Preparation and Characterization

Samples with an area of 12.5 × 12.5 cm^2 were prepared from seven different commercial grades of paper (Table II). Characterization was performed in a controlled environment at 23°C and 50% RH, except for laser ultrasonics tests, which could not be made at controlled temperature and relative humidity (typical test conditions were around 20–25°C and 20–50% RH). Grammage and soft-platen thickness measurements are shown in Table II. No attempt was made to gather information about furnishes, fibre dimensions, or additives. Using a test procedure involving a pair of polarized contact bimorph transducers operated at 80 kHz [32], in-plane longitudinal velocity measurements (S_0 mode) were obtained in the machine and cross-machine directions of the samples. These measurements served as a basis for comparison.

TABLE II
SELECTED PAPER GRADES AND BASIC PROPERTIES

Sample	Grammage (g/m²)	Soft-platen Thickness (µm)
Printing Paper	40.2	54
Newsprint	47.8	74
Copy Paper	77.0	96
Sack Paper	81.4	113
Medium	157.4	231
42-lb Linerboard	211.1	299
69-lb Linerboard	314.7	410

Laser Ultrasonics Testing

During a test, a sample was mounted in an aluminum frame. The source and detection systems were aligned and set at a known separation distance. Alignment was either along machine direction or cross-machine direction. The Nd:YAG laser was fired and the detection system (either out-of-plane or in-plane) recorded the ultrasonic pulses produced. The source beam power density and diameter were adjusted in such a way as to attempt to maximize signal

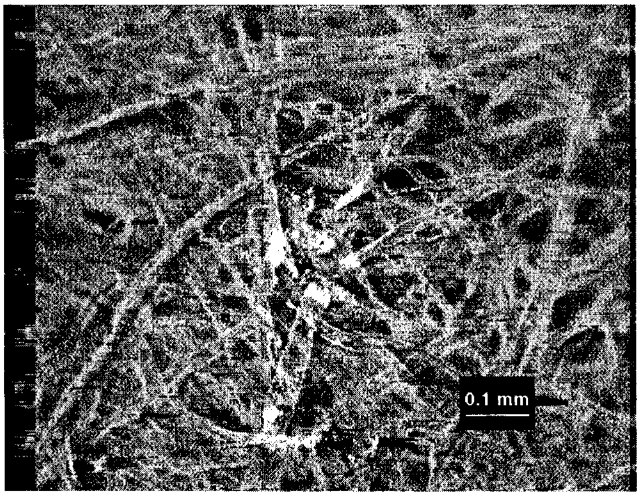


Fig. 6. Microscopic view of a single laser shot on brown paper.

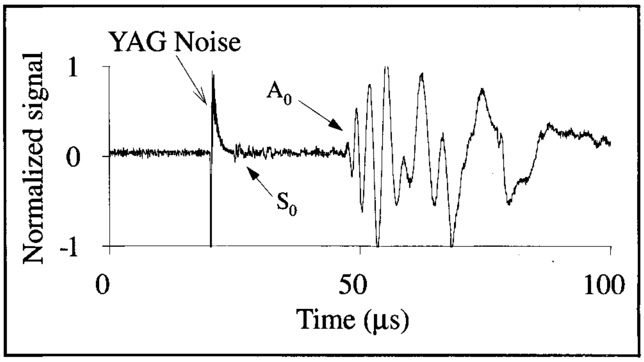
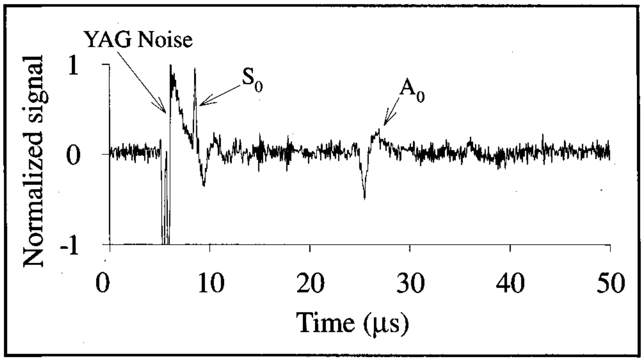


Fig. 7. Lamb waves detected in copy paper using the out-of-plane motion detection system.

Fig. 8. Recording of Lamb waves in copy paper as obtained using the in-plane motion detection system. →



amplitude while avoiding damage to the sample. This was not done in a systematic manner due to equipment limitations. Figure 6 depicts a microscopic view of a single laser shot on a linerboard sample. There is a slight "bleaching" effect not visible to the naked eye. Further source optimization including varying wavelength, pulse width and beam intensity may reduce or completely eliminate this effect.

Typical data collection runs involved averaging shots at the same source/detector locations, then changing the separation distance between the source and detection spots and running again. The number of repetitions (shots) was not the same for all samples or separation distances: with a typical average of 10, it was increased or decreased depending upon signal strength for a particular paper grade. For the out-of-plane detection system, the source and detection spots were separated initially by 3.50 cm, and then decreased by 0.30 cm using a micrometer actuator translational stage for each successive run. Similarly, for the in-plane system, the source and detection spots were initially 1.50 cm apart, and then decreased by 0.20 cm for each successive run. Physical restrictions did not allow observations when the separation distance was less than 0.20 cm. All samples were tested with both the out-of-plane and in-plane detection systems.

Recorded signals were filtered using a software bandpass filter (50 kHz to 5 MHz) to help remove noise. A cross-correlation technique was used to determine the time delay, Δt, between two signals obtained for two different separation distances. In order to enhance time resolution, a second-order polynomial fitting procedure was applied to the maximum peak of the correlation function [12]. The cross-correlation/fitting procedure combination yielded results with a time resolution of approximately ±5 ns. Using the change in separation distance, Δd, between the two waveforms, it was straigthforward to compute the velocity of Lamb waves, i.e. $v = \Delta d/\Delta t$.

RESULTS AND DISCUSSION

Figures 7 and 8 show typical normalized recordings as obtained for copy paper using the out-of-plane and in-plane detection systems, respectively; the source-detector separation distance is 2.00 cm. A closer look at these figures indicates that three features can be identified. The first one is a noise pulse originating from electromagnetic interference generated during the firing of the Nd:YAG laser. This pulse is not real ultrasonic data and should be ignored. On the trailing edge of this pulse is a fast wave signal. Further away in time is a slow wave signal. Amplitudes of the fast and slow signals are somewhat inverted when in-plane detection is considered. It was not possible in this work to eliminate the Nd:YAG noise pulse, which unfortunately interfered with the fast signal for some of the observations. Also, the presence of the noise signal ruled out the possible detection of elastic waves propagating in the thickness direction of paper. In the results displayed in Figs. 7 and 8, the frequencies for the slow and fast signals are approximately 350 kHz and 2 MHz, respectively. When the source-detection separation distance was changed, the frequency content for the fast signal did not change; however, it changed for the slow signal. These observations, combined with observations for other paper grades, indicated that the slow signal was dispersive and that the fast signal was nondispersive.

There was sufficient experimental evidence to associate the slow signal to the fundamental bending mode (A_0) for Lamb waves; the fast signal was identified as the fundamental dilatational mode (low frequency limit of S_0). Further evidence for the S_0 mode was obtained by correlating the velocity for this mode with the velocity gathered using contact transducers (see below). Since the A_0 and S_0 modes were detected using both detection systems, it appeared that neither mode was pure.

As mentioned above, the source beam had a spot size of 70 μm, i.e. approximately twice as large as the typical average fibre diameter for wood pulp fibres. This means that thermal coupling overlapped more than one fibre but could still be susceptible to small-scale formation fluctuations. Indeed, signal strength was seen to vary by simply translating the sample with respect to the source beam position. However, and most importantly, there was no evidence that the velocity measurements were sensitive to the coupling efficiency. This would support the idea that averaging takes place in the fibre network during propagation from the

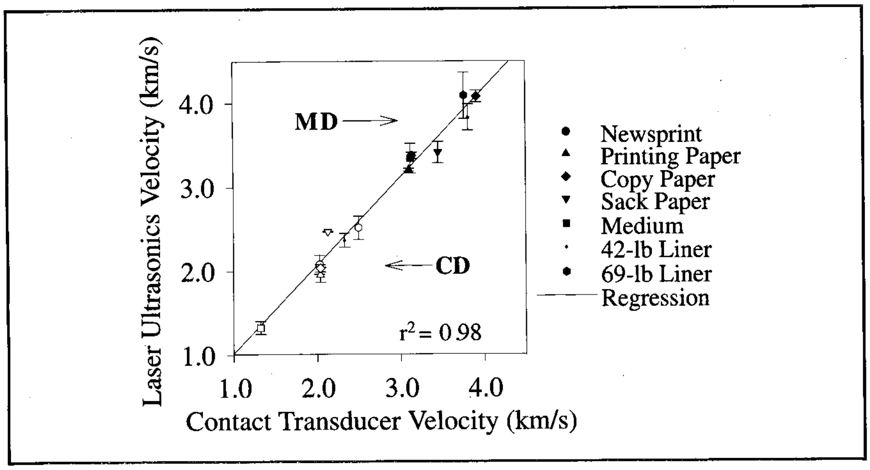


Fig. 9. S_0 mode laser ultrasonics velocity vs contact transducer velocity. MD and CD data points are located on the upper right and lower left corners of the plot, respectively.

source to detection positions.

Since the A_0 mode cannot be observed using contact bimorph transducers, the attention focussed on the verification of the S_0 mode velocity using contact measurements. Machine and cross-machine direction results are shown in a graphical form in Fig. 9 for all samples. The solid line represents a linear regression with a regression coefficient of 0.98, indicating an excellent correlation between the two data sets. The slope is not exactly one, a consequence of several experimental uncertainties: each laser ultrasonics data point is an average of only three to five measurements obtained for as many different source-detection separation distances, poor signal-to-noise ratio for some of the measurements, different test locations, uncontrolled moisture/temperature conditions, and unoptimized laser generation and detection conditions. It should be noted that the average measuring length using laser ultrasonics was approximately 2 cm, i.e. less than the 7 cm measuring length using contact transducers. Planar specific stiffnesses Q_{11}/ρ and Q_{22}/ρ are easily obtained by using Eqs. (1) and (2); they were not computed.

CONCLUSIONS

The use of a contactless laser ultrasonics technique to investigate Lamb wave propagation in paper has been demonstrated. A source laser and two heterodyne interferometric detection systems were used to observe the A_0 and S_0 modes for various paper grades. It was shown that the dilatational mode velocity as obtained using laser ultrasonics and contact transduction methods were in very good agreement.

The study was in essence exploratory. As such, additional work is required to optimize the mechanisms of laser generation and detection, perform controlled measurements, and better understand the propagation of laser-induced Lamb waves in paper. Also, in the context of on-machine monitoring of paper mechanical behaviour, the laser ultrasonics approach must be demonstrated on moving paper.

ACKNOWLEDGMENTS

We would like to acknowledge the Member Companies of the Institute of Paper Science and Technology for their kind support through a seed-grant project, as well as the Georgia Institute of Technology, which contributed partial support of the project.

REFERENCES

1. PAPADAKIS, E.P., "Ultrasonic Methods for Modulus Measurement in Paper", *Tappi J.* 56(2):74–77 (1973).
2. LU, M.T., "On-Line Measurement of Strength Characteristics of a Moving Sheet", *Tappi J.* 58(6):80–81 (1975).
3. BAUM, G.A. and HABEGER, C.C., "On-Line Measurements of Paper Mechanical Properties", *Tappi J.* 63(7):63–66 (1980).
4. BAUM, G.A. and HABEGER, C.C., "On-Line Ultrasonic Velocity Gauge", U.S. Patent No. 4,291,577 (1981).
5. KAZYS, K.R., "Ultrasonic Methods for Non-Destructive Testing of Paper", Proc. XXth Intl. Conf. on Acoustics and Ultrasound, Prahq 192–193 (1981).
6. SENKO, E. and THORPE, J., "On-Line Ultrasonic Measurement of Sheet Modulus", *Tappi J.* 68(2):95–99 (1985).
7. HABEGER, C.C. and BAUM, G.A., "On-Line Measurement of Paper Mechanical Properties", *Tappi J.* 69(6):106–111 (1986).
8. VAHEY, D.W., "An Ultrasonic-Based Strength Sensor for On-Line Measurements", *Tappi J.* 70(3):79–82 (1987).
9. ORKOSALO, J.J., "System and Process for Measuring Ultrasonic Velocity", U.S. Patent No. 4,688,423 (1987).
10. VAHEY, D.W., "Correlating the On-Line Measurement of Ultrasonic Velocity with Strength Properties", *Tappi J.* 71(4):149–152 (1988).
11. CHASE, L., GOSS, J. and ANDERSON, L., "On-Line Sensor for Measuring Strength Properties", *Tappi J.* 72(12):89–97 (1989).
12. BRODEUR, P.H., HALL, M.S. and ESWORTHY, C., "Sound Dispersion and Attenuation in the Thickness Direction of Paper Materials", *J. Acoust. Soc. Am.* 94(4): 2215–2225 (1993).
13. BRODEUR, P.H., "Out-of-Plane Ultrasonic Testing of Paper Materials Using Fluid-Filled Rubber Wheels", *Tappi J.* 77(3):213–218

REFERENCE: BRODEUR, P.H., JOHNSON, M.A., BERTHELOT, Y.H. and GERHARDSTEIN, J.P., Noncontact Laser Generation and Detection of Lamb Waves in Paper. Journal of Pulp and Paper Science, Vol. 23(5) J238–243 May 1997. Paper offered as a contribution to the Journal of Pulp and Paper Science. Not to be reproduced without permission from the Technical Section, CPPA. Manuscript received May 15, 1996; revised manuscript approved for publication by the Review Panel January 23, 1997.

ABSTRACT: A laser ultrasonics method has been used to investigate the propagation of Lamb waves in paper, and thus determine paper stiffness in a noncontact manner. Ultrasonic pulses were generated on nonmoving paper using a Nd:YAG pulsed laser. An Ar:ion CW laser was used in combination with two optical heterodyne interferometric systems to probe out-of-plane and in-plane surface motions of Lamb waves. Two simultaneous propagation modes were observed with substantially different velocities and frequency contents. They were identified as the fundamental dilatational and bending modes for Lamb waves, respectively. Velocity measurements obtained for the dilatational mode were found to be in very good agreement with velocities obtained using contact bimorph transducers. Results collected along machine and cross-machine directions for selected fine papers and paperboards are reported.

RÉSUMÉ: Nous avons utilisé un système laser-ultrason pour étudier les ondes de Lamb dans le papier, afin de déterminer la rigidité de celui-ci au moyen d'une méthode sans contact. Des impulsions ultrasonores furent émises sur du papier à l'état stationnaire à l'aide d'un laser en régime pulsé ND:YAG. Nous avons employé par ailleurs un laser en régime continu (CW laser) AR:ion de pair avec deux interféromètres optiques de type hétérodyne pour capter les mouvements des ondes de Lamb au même plan et hors plan. Nous avons observé deux modes de propagation simultanée dotés de vitesses et fréquences grandement différentes. Nous avons identifié ceux-ci comme étant respectivement les modes de dilatation et de courbure des ondes de Lamb. Nous avons noté que les mesures de vitesse obtenues pour le mode de dilatation étaient en très bon accord avec les mesures de vitesse obtenues avec des transducteurs bimorphes à contact. Enfin, nous faisons état ici des données recueillies dans les sens machine et travers avec des papiers fins et des cartons sélectionnés.

KEYWORDS: LASERS, MECHANICAL TESTS, NONDESTRUCTIVE TESTS, PAPER TESTS, STIFFNESS TESTS, ULTRASONIC FREQUENCIES.

(1994).

14. CRESSON, T.M., GOSS J.D. and WALLACE, B.W., "Sensor, System and Method for Determining Z-Directional Properties of a Sheet", U.S. Patent No. 5,297,062 (1994).
15. WILLIAMS, P. and PANKONIN, B.M., "On-Line Measurement of Ultrasonic Velocities in Wet Manufacturing Processes", U.S. Patent No. 5,398,538 (1995).
16. BAUM, G.A., "Elastic Properties, Paper Quality, and Process Control", *Appita* 40(4):288–293 (1987).
17. SCHINDEL, D.W., HUTCHINS, D.A., ZOU, L. and SAYER, M., "The Design and Characterization of Micromachined Air-Coupled Capacitance Transducers", *IEEE Trans. Ultrason. Ferroelec. Freq. Cont.* 42(1): 42–50 (1995).
18. SCHINDEL, D.W. and HUTCHINS, D.A., "Applications of Micromachined Capacitance Transducers in Air-Coupled Ultrasonics and Nondestructive Evaluation", *IEEE Trans. Ultrason. Ferroelec. Freq. Cont.* 42(1):51–58 (1995).
19. LUUKKALA, M., HEIKILA, P. and SURAKKA, J., "Plate Wave Resonance, A Contactless Test Method", *Ultrasonics* 9:201–208 (1971).
20. HABEGER, C.C., MANN, R.W. and BAUM, G.A., "Ultrasonic Plate Waves in Paper," *Ultrasonics* 17:57–62 (1979).
21. SCRUBY, C.B. and DRAIN, L., Laser Ultrasonics – Techniques and Applications, Adam Hilger-IOP Publishing, Bristol (1990).
22. OLOFSSON, K. and KYOSTI, A., "Stiffness and Stiffness Variation in Paper Measured by Laser-Generated and Laser-Recorded Bending Waves", *J. Pulp Paper Sci.* 20(11): J328–J333 (1994).
23. LEUGERS, M.A., "Laser Induced Acoustic Generation for Sonic Modulus", U.S. Patent No. 4,622,853 (1986).
24. PACE, S.A. and SALAMA, S.S., "Laser Induced Acoustic Generation for Sonic Modulus", U.S. Patent No. 4,674,332 (1987).
25. KEYES, M.A. and THOMPSON, W.L., "Non-Contacting On-Line Paper Strength Measuring System", U.S. Patent No. 5,025, 665 (1991).
26. JOHNSON, M.A., "Investigation of the Mechanical Properties of Copy Paper Using Laser Generated and Detected Lamb Waves", Ph.D. Thesis, Georgia Inst. Technol. (1996).
27. JOHNSON, M.A., BERTHELOT, Y.H. and BRODEUR, P.H., "Investigation of Laser Generation of Lamb Waves in Copy Paper", *Ultrasonics* 34(7):703–710 (1996).
28. MANN, R.W., BAUM, G.A. and HABEGER, C.C., "Determination of all Nine Orthotropic Elastic Constants for Machine-Made Paper", *Tappi J.* 63(2):163–166 (1980).
29. MANN, R.W., BAUM, G.A. and HABEGER, C.C., "Elastic Wave Propagation in Paper", *Tappi J.* 62(8):115–119 (1979).
30. TSAI, S. and HAHN, H., Introduction to Composite Materials, Tecnomic, Lancaster, PA (1980).
31. MONCHALIN, J.P., AUSSEL, J.-D., HEON, R., KEN, C.K., BOUDREAULT, A. and BERNIER, R., "Measurement of In-Plane and Out-of-Plane Ultrasonic Displacements by Optical Heterodyne Interferometry", *J. Nondestr. Eval.* 8(2):121–133 (1989).
32. HABEGER, C.C., VAN ZUMMEREN, M.L., WINK, W.A., PANKONIN, B.M. and GOODLIN, R.S., "Using a Robot-Based Instrument to Measure the In-Plane Ultrasonic Velocities of Paper", *Tappi J.* 72(7):171–175 (1989).

1997 CONFERENCES

Sponsored or co-sponsored by the Technical Section, Canadian Pulp and Paper Association or TAPPI

Intl. CD Symposium
June 4–5
Tampere, Finland
Co-sponsored by PI, TAPPI, JTAPPI, Appita and TS CPPA

TS CPPA Conférence technologique estivale
June 4–6, 1997
Château Frontenac, Quebec, QC

Intl. Mechanical Pulping Conf.
June 9–12, 1997
Stockholm, Sweden
Co-sponsored by SPCI, PTF, PI, TS CPPA and TAPPI

Intl. Symp. Wood and Pulping Chemistry
June 9–12, 1997
Château Champlain Hotel, Montreal, QC
Co-sponsored by TS CPPA, TAPPI, Japan TAPPI, EUCEPA, Appita, CTAPI and Can. Soc. Chemistry

TAPPI Hot Melt Symposium
June 15–18, 1997
Hyatt Regency, Hilton Head, SC

Electronic Partnership '97
Aug. 12–14, 1997
San Diego, CA
Co-sponsored by GCA and TS CPPA

TAPPI Polymers, Laminations & Coatings Conf.
Aug. 24–28, 1997
Sheraton Centre, Toronto, ON

TAPPI Finishing & Converting Conf. & Trade Fair
Sept. 21–24, 1997
Omni Shoreham Hotel,
Washington, DC

11th Fundamental Research Symposium
Sept. 21–26, 1997
Cambridge, UK
Co-sponsored by PITA, TS CPPA and TAPPI

TAPPI Engineering & Papermakers; Forming Bonds for Better Papermaking Conference & Trade Fair
Oct. 6–9, 1997
Opryland Hotel, Nashville, TN

TS CPPA 4th Research Forum on Recycling
Oct. 7–9, 1997
Château Frontenac, Quebec City, QC

TAPPI Pulping Conf.
Oct. 19–23, 1997
San Francisco Marriott, San Francisco, CA

TAPPI Intl. Corrugated Conf. & Trade Fair
Oct. 27–29, 1997
Milwaukee Convention Centre, Milwaukee, WI

TAPPI Process & Product Quality Conf. & Trade Fair
Nov. 3–5, 1997
Omni Hotel, Jacksonville, FL

For further information on the TS CPPA conferences listed above, please contact the Technical Section, CPPA, 1155 Metcalfe Street, Suite 1900, Montreal, Quebec, Canada H3B 4T6; Tel. 514-866-6621; Fax: 514-866-3035; e-mail: tech@cppa.ca

For further information on the TAPPI conferences listed above, please contact TAPPI Meetings, Technology Park/Atlanta, P.O. Box 105113, Atlanta, GA, USA; Tel. 1-800-332-8686 (US), 1-800 446-9431 (Canada); Fax: 404-446-6947; e-mail: info@tappi.org; Internet: http://www.tappi.org.