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Laser ultrasonics on moving paper

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Abstract

The propagation velocities of laser-generated ultrasonic plate waves were measured on paper moving at $10\ \mathrm{m\ s^{-1}}$ using a Mach–Zender interferometer and scanning mirror. Fast- and slow-propagating plate wave vibrational modes were detected. Velocity measurements were made on four types of paper, perpendicular to and in the direction of paper motion. Laser-ultrasonic measurements of phase velocities for the fast-propagating vibrational mode were compared with contact transducer-based measurements. The effect on signal amplitude of (1) distance from the detection point to the ultrasound generation point and (2) the pulse energy of the ultrasound generation laser was studied using stationary paper.

Keywords: Lamb waves; Laser ultrasonics; Non-destructive testing; Paper

1. Introduction

Ultrasound can be used to probe fiber orientation, tensile breaking strength, compressive (buckling) strength, and other mechanical properties in paper. These mechanical properties empirically correlate with the elasticity of the paper, which in turn correlates with the propagation velocity of ultrasonic plate waves through and along the paper sheet [1,2]. A measurement of the time-of-flight of an ultrasonic wave over the known distance between a generation point and a detection point (or between two detection points) permits determination of the propagation velocity.

To date, in order to measure strength, fiber orientation etc. using ultrasonic techniques, industry analysts have relied on measurements on samples cut from the ends of large paper rolls because measurements cannot be made on the moving sheet in the papermaking machine. As a result, delays in making necessary adjustments to the machine cost manufacturers significant time and money. A roll of paper weighing several tons may be recycled or sold as an inferior grade if it does not meet strength specifications. A monitor of paper strength installed on the papermaking machine would allow real-time feedback control of the papermaking process, resulting in valuable savings in feedstock and energy. Such a strength sensor must make non-destructive measurements on paper moving at production speeds, up to $30\ \mathrm{m\ s^{-1}}$.

Contact transducer-based methods for non-destructive on-line measurements have been in development for over 25 years [3–5]. Systems based on contact transducers have progressed to the stage of extensive mill trials; a commercially viable instrument remains elusive. Problems that plague this approach include excessive noise due to mechanical vibrations and paper damage where transducers contact lighter grades of paper. No practical method is yet available for measuring paper strength on-line during manufacturing.

Laser ultrasonics (LUS) is a non-contact, potentially non-destructive, method that has recently been applied to analysis of paper mechanical properties [6,7]. A short (less than a microsecond) pulse of laser light is used to generate ultrasonic waves by either a thermal expansion and/or an ablation shockwave. The wave propagates along the sheet and is detected at a precisely known distance (several millimeters) away using a non-contact interferometric technique [8]. The time of flight of the wave over the known distance gives the propagation velocity of the wave. The wave velocity is theoretically related to elastic properties, which in turn are empirically related to strength properties as described in Section 2.

This work is an initial application of LUS to achieve

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non-contact, real-time measurement of paper properties during the papermaking process. We report the first non-contact detection and measurement of propagation velocity of ultrasonic waves in moving paper. Measurements were made on paper moving at 10–12 m s^{-1}, a typical operating speed for many papermaking machines. Until now LUS has been applied only to stationary paper.

2. Lamb wave theory

Ultrasonic waves are mechanical waves that cause periodic displacements of matter at frequencies greater than 20 kHz. In bulk materials, ultrasonic waves appear as bulk waves and on surfaces as surface or Rayleigh waves. When the thickness of a solid plate or sheet becomes much less than the length of the wave, the properties of the waves that propagate along the sheet differ from those of either bulk or surface waves. In this case they are called plate waves or Lamb waves after Prof. Horace Lamb, who described them mathematically in 1916 [9]. Lamb waves appear in two fundamental modes, anti-symmetric (A, out-of-plane motion of the surfaces of the sheet are both in the same direction) and symmetric (S, out-of-plane motion of the surfaces of the sheet are opposite to each other). These modes can appear in several vibrational orders with higher orders containing higher frequencies. For the purpose of quality control in paper only the lowest order of each of these two modes (S_0 and A_0) is normally measured.

The velocities of both modes vary with frequency as shown in the qualitative dispersion curve sketched in Fig. 1. As the frequency drops the propagation velocity of the zero-order symmetric (S_0) wave rises to a constant value V_{S0}. At high frequencies the zero-order anti-symmetric (A_0) wave propagation velocity rises to a constant value V_{A0}. Fortuitously, V_{S0} and V_{A0} represent the highest velocity components of the A_0 and S_0 modes, and thus they define wave fronts. As wave fronts, their arrival times at the detection point are relatively easy to detect, making it possible to determine the velocities V_{S0} and V_{A0} without sophisticated signal analysis. Since V_{S0} and V_{A0} do not vary with frequency, the frequency components of the wave front need not be measured. It is also felicitous that the speeds of the two modes are so different that they do not interfere with each other at the detection point, as can be seen in the LUS signal shown in Fig. 2.

The velocities V_{S0} and V_{A0} depend on the elastic properties and density of the medium. Because the displacement of the S_0 wave has a larger compression and a smaller shear component than the A_0 wave, the S_0 wave contains information about tensile elasticity and the A_0 wave information about shear elasticity. Paper has been successfully modeled as an orthotropic material [10]. This model indicates that the elastic properties differ in the machine direction (MD, the axis in the paper sheet which coincides with the direction of sheet motion on the papermaking machine), cross direction (CD, the in-plane axis perpendicular to the MD) and thickness direction (ZD). Lamb wave theory for an orthotropic material predicts that the velocity of the S_0 wave is directly related to the tensile stiffness of the sheet in the direction of wave propagation:

$$C_T \cong \rho V_{S0}^2, \tag{1}$$

where C_T is the tensile elastic constant or tensile 'stiffness' (in units of stress/strain per unit area) in a given direction in the plane of the sheet, V_{S0} is the velocity of the S_0 wave in that direction, and ρ is the apparent density of the sheet [7].

The same theory predicts that the velocity of the A_0 wave is directly related to the shear stiffness of the sheet in the direction of wave propagation by:

$$C_S \cong \rho V_{A0}^2, \tag{2}$$

where C_S is the shear elastic constant or shear 'stiffness' in a given direction in the plane of the sheet, V_{A0} is the velocity of the A_0 wave in that direction in the plane of the sheet. Though they are not exact, Eqs. (1) and (2)

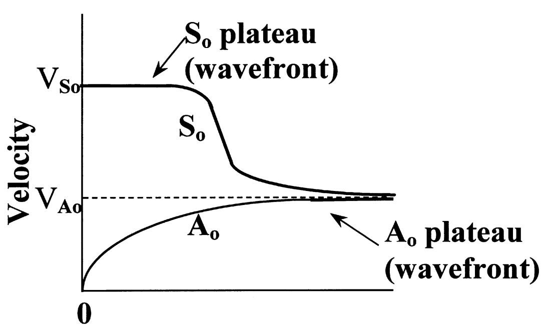

Fig. 1. Lamb wave dispersion curve: a plot of wave propagation velocity versus frequency.

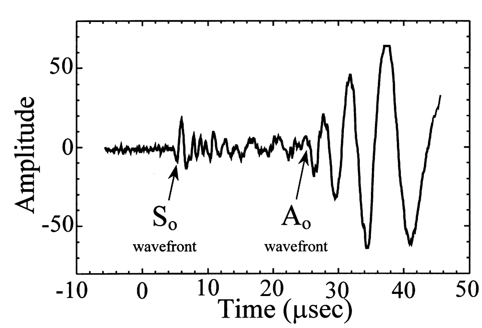

Fig. 2. Typical LUS signal obtained on brown postal wrap moving at 10 m s^{-1} using a Mach–Zender interferometer and rotating mirror. Generation–detection spot separation, 10 mm. Generation pulse wavelength, 1064 nm; energy, 40 mJ; pulse width, 4–6 ns.

are routinely used to relate wave velocities to elastic constants in the paper industry.

Some of the observed characteristics of ultrasonic plate waves that propagate in paper differ strikingly from theoretical predictions [11]. In particular, the fast-propagating mode in paper appears to be anti-symmetric in its distortional properties, in contrast to theoretical predictions for an S_0 wave. Thus it could be argued that this is not a Lamb wave, and that Eqs. (1) and (2), which are the result of plate-wave theory, may not be valid. On the other hand, experimentation has shown that elastic constants obtained from ultrasonic wave velocities and Eqs. (1) and (2) are useful predictors of tensile and compressive strength in paper [2,12]. While ultrasonic wave propagation in paper is not completely understood, ultrasonic analysis has proven value to the paper manufacturing industry as a convenient measure of paper strength properties. Great motivation exists for development of the fundamental theory and of practical, robust laser-based techniques for non-contact, real-time, on-line measurement.

3. Experimental system

The LUS system for moving paper developed at the Lawrence Berkeley National Laboratory (LBNL) is shown schematically in Fig. 3. A laboratory-built device rotated a paper belt 6 in wide and 52 in in circumference at up to 15 m s^{-1}. A laboratory-built synchronization circuit coordinated the LUS detection and generation systems that will be discussed in the following sections. Stray light from the generation laser pulse triggered data collection on a Tektronix Digital Signal Analyzer 602A via a Thor Labs DET200 high speed photo diode.

3.1. Ultrasound generation system

A pulsed Nd–YAG laser (New Wave Minilase III) which produced a light pulse with a wavelength of 1064 nm, energy of 100 mJ, and a pulse width of 4–6 ns was used to generate the ultrasonic waves. Laser pulse energy was attenuated with a selection of beam splitters. The generation laser pulse energy that generated a sufficient detection signal ranged from 16 to 80 mJ depending on the paper type being analyzed and the generation–detection spot separation. The generation pulse was concentrated with an 80 mm cylindrical lens placed at the focal distance from the paper surface to provide a focused line about 3 mm in length. The line focus was found to generate much larger signals (in a direction perpendicular to the line) than a circular spot. The distance between the generation and detection spot was varied from 5 to 25 mm by moving the generation system optics and beam with micrometer-driven translation stages.

3.2. Ultrasound detection system

The difficulty in detecting acoustic vibrations in paper moving at production speeds (10–30 m s^{-1}) [13] comes from the roughness of the surface which becomes, as the surface moves under a stationary interferometer probe beam, out-of-plane displacements on the order of 10 μm for copy paper. Ultrasonic waves in copy paper have out-of-plane displacements of up to 0.01 μm for

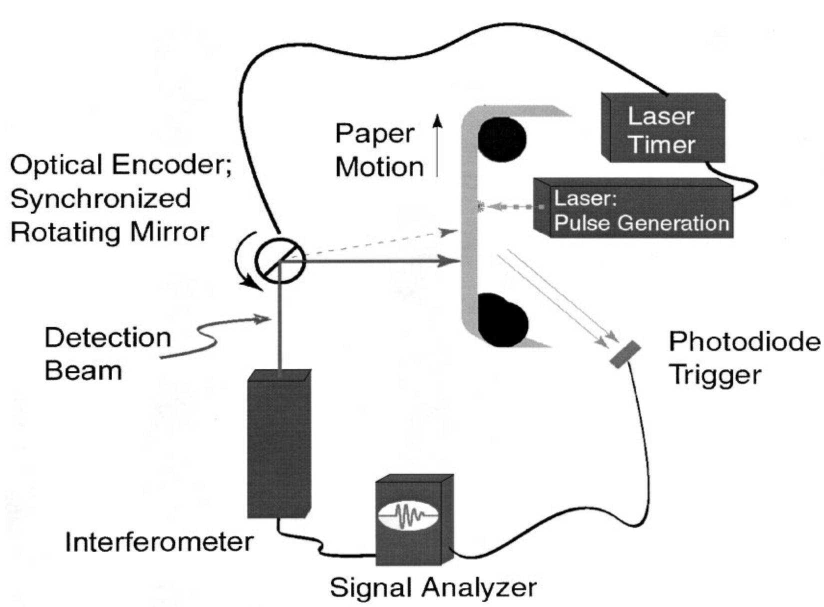

Fig. 3. Schematic diagram of LBNL experimental system for LUS analysis of moving paper.

one mode and up to 0.08 μm for the other [6]. Thus the ultrasound signal is masked by noise generated by the roughness of paper when it is moved under a stationary detection beam, except in the case of the confocal Fabry–Perot interferometer, which was one of three detection systems evaluated in this work. The solution to this problem which provided the best performance was to move the detection beam with the paper using a scanning mirror and to detect the signal with a Mach–Zender interferometer, as described in Section 3.2.2.

3.2.1. *Comparison of interferometers*

Three types of interferometer were tested as ultrasonic wave detectors. All of them require the use of a continuous wave laser to illuminate the desired detection point on the paper surface, and are based on optical interference principles. These instruments were compared with respect to frequency range, laser power and sensitivity to laser-generated ultrasonic waves in paper: a confocal Fabry–Perot (*Ultra*Optec LISOR-RT), a 'photo-induced EMF' (PI-EMF) detector-based system (Lasson Technology PI-830) and a Mach–Zender (Polytec-PI OV303/OVD-02). The performance of each interferometer was tested on stationary paper and on moving paper both with and without the use of a rotating mirror as discussed in Section 2.2.2. The results are shown in Table 1.

The confocal Fabry–Perot interferometer was able to detect both S_0 and A_0 waves on paper moving at the maximum test speed of 15 m s^{-1}. It performed equally well (no change in signal to noise ratio) with and without the rotating mirror. However, this interferometer has a significant loss in sensitivity to signals with frequency components below 1 MHz. This is a disadvantage when trying to measure V_{S0}, which requires detection of waves with frequency components as at least as low as 500 kHz. The PI-EMF detector was eliminated because it was unable to detect an S_0 signal on moving paper, even with the use of the scanning mirror.

The Mach–Zender interferometer required the rotating mirror for detection on moving paper. A signal-to-noise ratio of 10 was attained with this system. This sensitivity was greater than three times better than that observed using the confocal Fabry–Perot interferometer. Also, the Mach–Zender has no sensitivity loss at frequencies within the range of interest. The Mach–Zender interferometer was the easiest to set up because the probe laser is part of the sensing head and needs no separate alignment. A third advantage of this instrument is that the probe beam power of 1 mW is far below what might cause any paper damage. In contrast, the other two systems required a probe beam power greater than 150 mW, which is close to the damage threshold for colored papers when the focal spot size is 50–100 μm. For these reasons, the Mach–Zender interferometer was chosen for this work.

3.2.2. *Detection system for LUS on moving paper*

The key components of the detection system were a Mach–Zender interferometer (Polytec-PI OV303/OVD-02) and a rotating mirror. The interferometer probe beam was moved with the paper, effectively stopping the paper motion with respect to the detection spot. This was accomplished by moving the probe beam with a flat mirror oriented 45° to the incoming beam, deflecting the beam by an angle of 90°. The mirror was rotated about the axis of the incoming beam, moving it in the direction of paper motion. The mirror was rotated via geared coupling to the paper drive motor at a speed which caused the beam to illuminate a fixed spot (the detection spot) on the moving paper surface as the beam became perpendicular to the paper surface.

When the interferometer beam was near or exactly perpendicular to the paper surface, the velocity of the detection spot relative to the paper surface was low (or zero) so that frequency components of the interferometer signal due to paper roughness were well below the range of interest of 0.05–2 MHz. The paper surface was at the

Table 1
Comparison of interferometers

	Interferometer type		
	Mach–Zender	Confocal Fabry–Perot	Photo-induced EMF
Manufacturer/model	Polytec-PI OFV303/OVD-02	*Ultra*Optec LISOR-RT	Lasson Technology PIE-830
Laser type	HeNe	CW Nd–YAG	Argon ion
Beam power (mW)	1	150	150+
Frequency range	0–1.5 MHz	0.5–140 MHz	0.1–24 MHz
S/N[a]	10	3	0 (No S_0)
Pros	Best S/N. Low power beam. Good frequency range. Inexpensive laser.	Stationary beam. Fiber optic beam delivery is standard	Rapidly improving technology. Potential for in-plane detection
Cons	Beam must track paper motion. Fiber optic version does not work with diffusely reflecting surfaces.	Low sensitivity below 1 MHz. High power beam may damage paper. Costly narrow line-width laser required.	Beam must track paper motion. No S_0 signal on moving paper. High power beam may damage paper.

[a] Peak-to-peak amplitude of S_0 wave at 10 mm distance (butcher paper moving at >10 m s^{-1}, 80 mJ generation pulse).

focus point of the interferometer probe beam when the beam was oriented normal to the paper surface. An optical encoder was used to track the mirror rotational position. An adjustable delay circuit was used to trigger the firing of the generation laser pulse so that the ultrasonic wave was detected when the interferometer beam was normal to the paper surface.

4. Results

One of the challenges in LUS on paper is to obtain adequate signal amplitude while keeping generation laser pulse power density below the ablation threshold. To obtain information relevant to that task the effect of two variables, generation pulse energy and generation–detection spot separation, on LUS signal amplitude was studied on stationary paper. These results are described in Sections 4.1.and 4.2. Ultrasonic wave velocities V_{S0} and V_{A0} were experimentally determined for the first time by LUS on moving paper. These data are described in Section 4.3. In Section 4.4 the LUS measurements of V_{S0} and V_{A0} are compared with contact transducer measurements on stationary paper.

4.1. Effect of energy on amplitude: identification of ablation threshold

Identification of and operation below the 'ablation threshold' in power density of the laser generation pulse is probably necessary to avoid paper damage[1]. Ultrasonic signal amplitude was measured at varying pulse energies to see whether an 'ablation threshold' could be observed as a sudden increase in the slope of a plot of detection signal amplitude versus generation laser pulse energy. These experiments were done on stationary paper (brown postal wrap, 48 g m^{-2}) at a generation–detection spot separation of 10 mm. The Nd–YAG laser and the Mach–Zender interferometer described above were used for signal generation and detection. The data are shown in Fig. 4. Pulse energies from 12 to 37 mJ were used. The minimum pulse energy for which a detection signal could be obtained was 16 mJ. The maximum pulse energy of 37 mJ showed slight damage, indicative of ablation. As no discontinuity in the slope of the plot was observed, we suspect that the ablation threshold occurs at or below 16 mJ, though the surface-destructive effects of ablation become apparent to the unaided eye only when pulse energies reach 37 mJ and above.

In summary, non-destructive ablation appears to be necessary to generate ultrasonic waves of sufficient

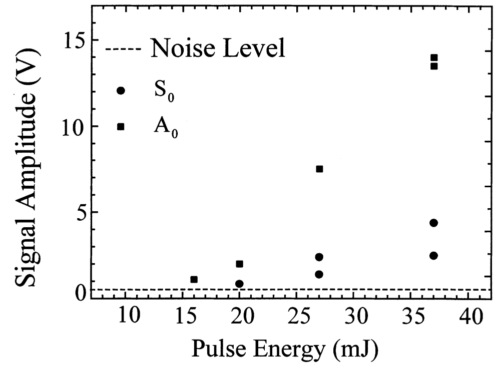

Fig. 4. Signal amplitude versus pulse energy; brown postal wrap; generation–detection spot separation, 10 mm.

amplitude to be detected by our system. Optimization of laser generation conditions or improvements in detection sensitivity may allow LUS generation in the thermoelastic regime to be sufficient in the future. On the other hand, mild ablation may be acceptable to the paper industry if no signs of damage to the paper surface are visible and printing properties are not degraded.

4.2. Effect of distance on amplitude

The distance between the generation and detection spots (GDD) strongly affects signal amplitude. Normalized signal amplitude is plotted versus GDD in Fig. 5. The amplitudes of A_0 and S_0 signals on various papers at GDDs from 5 to 25 mm were measured. The A_0 and S_0 mode signal amplitudes were normalized to the highest amplitude measured for each mode on a given paper type. Then the data for all paper types were averaged to give a single value at each GDD. The resulting plot indicates that the generalized behavior of ultrasonic signal amplitude is to increase exponentially

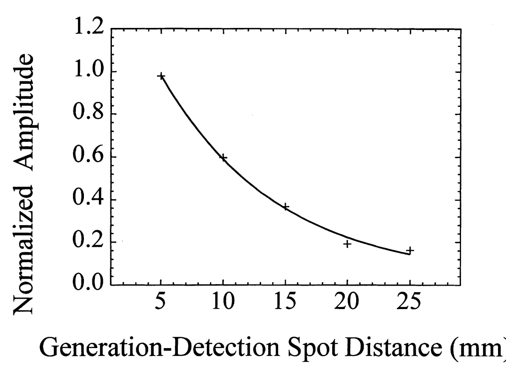

Fig. 5. Normalized signal amplitude versus distance from generation spot: each point represents the average of six data sets of signal amplitudes from the publishing grade paper, newsprint and postal wrap CD S_0 and A_0 wave signals measured at GDDs from 5 to 25 mm. Amplitudes within a data set were normalized with respect to the maximum amplitude in the set. The plot indicates that the generalized effect of increasing GDD on signal amplitude follows an exponential decay.

[1] Finite ablation resulting in microscopic damage may be acceptable in that such damage can be extremely minimal, not effecting print quality or paper strength and being invisible to the naked eye.

as GDD decreases. Thus reducing the GDD in LUS measurements may be an effective way to increase signal to noise ratio and/or reduce required generation laser pulse energy.

4.3. LUS data on moving paper: determination of V_{S0} and V_{A0} via time-of-flight measurements

To determine the velocity of the fast and slow-moving vibrational modes (V_{S0} and V_{A0}), time-of-flight measurements were made at a GDD of 5–20 mm in 5 mm increments on paper moving at 10–12 m s^{-1}. The slope of the best-fit linear regression line through plots of GDD versus time-of-flight gave V_{S0} and V_{A0} in the machine and cross directions (MD and CD) in four types of paper. These measurements are required for calculation of tensile and compressive strength properties that are important manufacturing parameters, as discussed earlier. The four paper types were butcher paper, newsprint, brown postal wrap, and a coated, white publishing grade paper. Table 2 lists the basis weights of these papers.

Five representative plots are shown in Figs. 6–10. Table 2 lists V_{S0} and V_{A0} in the MD and CD on the four types of paper. Note that time-of-flight data for the CD S_0 wave on Butcher paper obtained with the LISOR interferometer (Fig. 6) gives a considerably lower wave velocity (1.7 km s^{-1}) than does the same data collected with the Mach–Zender interferometer (2.4 km s^{-1}) as shown in Fig. 7. This discrepancy is attributed to the loss in sensitivity of the LISOR interferometer to ultrasonic waves with frequencies below 1 MHz. Apparently, the low frequency, highest velocity components of the S_0 wave that define V_{S0} could not be detected by the LISOR. The Mach–Zender interferometer has no such low-frequency limit and is apparently more sensitive to the fastest-moving components of the S_0 wave.

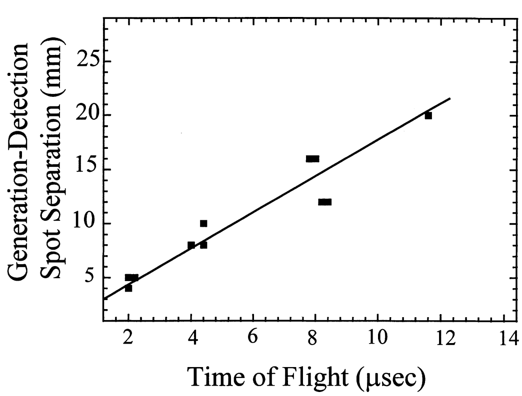

Fig. 6. Plot of generation–detection spot separation (GDD) versus time-of-flight measurements using the LISOR confocal Fabry–Perot interferometer. Butcher paper CD S_0 wave; slope, 1.7 ± 0.2 km s^{-1}.

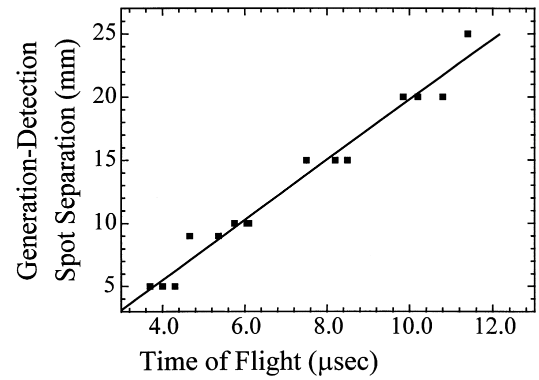

Fig. 7. Plot of GDD versus time-of-flight measurements on paper moving at 10–12 m s^{-1} using the LBNL LUS system. Butcher paper CD S_0 wave; slope, 2.4 ± 0.1 km s^{-1}.

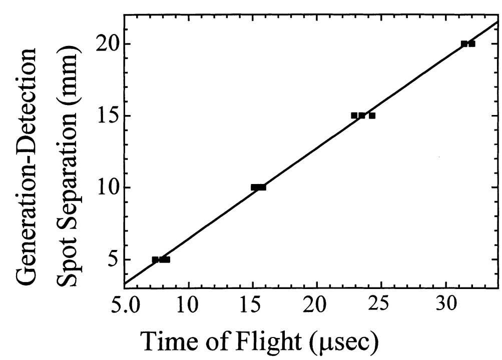

Fig. 8. Plot of GDD versus time-of-flight measurements on paper moving at 10–12 m s^{-1} using the LBNL LUS system. Butcher paper MD S_0 wave; slope, 3.7 ± 0.2 km s^{-1}.

Table 2
Table of S_0 and A_0 wave velocities measured by LUS on paper moving at 10–12 m s^{-1}

Paper type	Wave velocities (km s^{-1})				Basis weight (g m^{-2})
	CD		MD		
	S_0	A_0	S_0	A_0	
Butcher	2.4 ± 0.1	0.367 ± 0.008	3.7 ± 0.2	0.45 ± 0.01	79.2
Newsprint	1.61 ± 0.03	0.31 ± 0.004	3.1 ± 0.3	0.45 ± 0.04	49.0
Publishing grade	2.6 ± 0.1	0.63 ± 0.01	2.7 ± 0.1	0.64 ± 0.04	91.6
Postal wrap	2.11 ± 0.07	0.36 ± 0.01	3.8 ± 0.2	0.48 ± 0.05	48.0

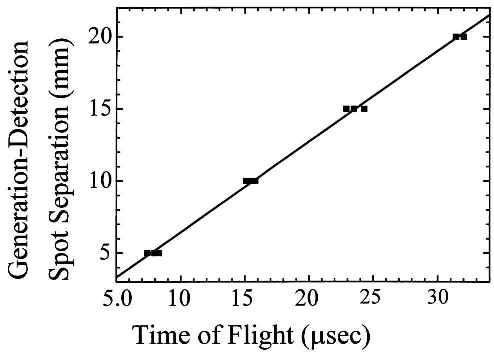

Fig. 9. Plot of GDD versus time-of-flight measurements on paper moving at 10–12 m s^{-1} using the LBNL LUS system. Publishing grade paper, CD A_0 wave; slope, 0.63 ± 0.01 km s^{-1}.

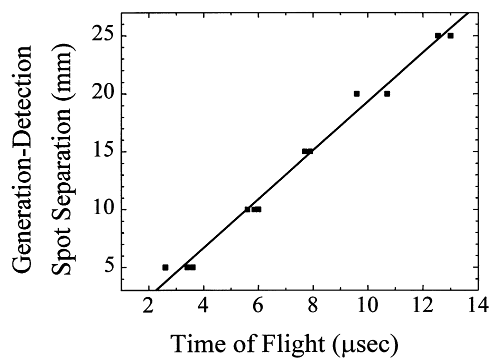

Fig. 10. Plot of GDD versus time-of-flight measurements on paper moving at 10–12 m s^{-1} using the LBNL LUS system. Postal wrap CD S_0 wave; slope, 2.11 ± 0.07 km s^{-1}.

4.4. *Comparison of LUS with contact transducer-based velocity measurements*

Samples of the four paper types used in the LUS velocity measurements were sent to L&W Corporation in Roswell, Georgia, for contact transducer-based measurement of S_0 mode velocities using the L&W TSO Tester. The results were compared with the LUS-based measurements as listed in Table 3. In Figs. 11 and 12, the plot of contact-based velocities versus LUS-based velocity measurements is shown.

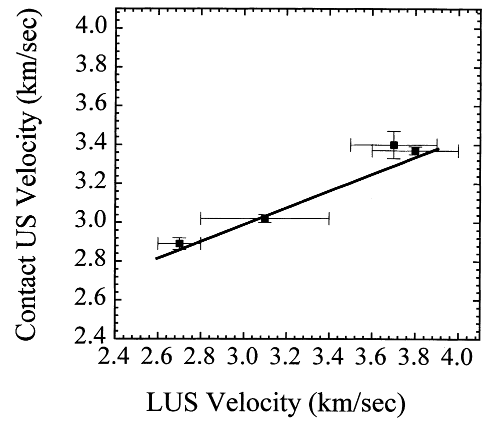

Fig. 11. Comparison of V_{S0} measurements in the MD: LUS on moving paper versus contact transducers (L&W TSO Tester) on stationary paper.

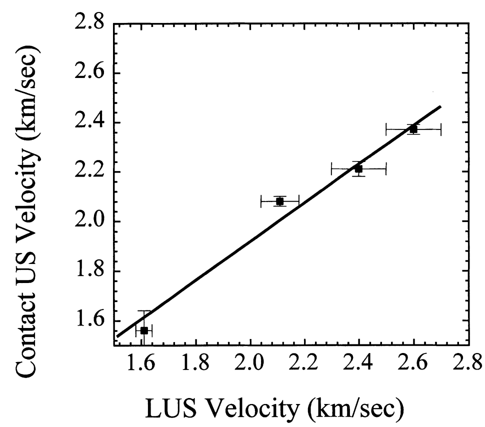

Fig. 12. Comparison of V_{S0} measurements in the CD: LUS on moving paper versus contact transducers (L&W TSO Tester) on stationary paper.

Both the LUS and contact transducer-based measurements show that ultrasonic wave velocities in the machine direction are higher than in the cross direction,

Table 3
Comparison of S_0 wave velocities measured (in Berkeley, CA) on moving paper by LUS with velocities measured by L&W Corp. (in Roswell, GA) on stationary paper using contact transducers (L&W TSO Tester)

Paper type, measurement direction	V_{S0} LUS (km s^{-1})[a]	V_{S0} by contact (km s^{-1})[b]
Butcher, CD	2.4 ± 0.1	2.21 ± 0.03
Publishing grade, CD	2.6 ± 0.1	2.37 ± 0.02
Newsprint, CD	1.61 ± 0.03	1.56 ± 0.08
Postal wrap, CD	2.11 ± 0.07	2.08 ± 0.02
Butcher, MD	3.7 ± 0.2	3.40 ± 0.07
Publishing grade, MD	2.7 ± 0.1	2.89 ± 0.03
Newsprint, MD	3.1 ± 0.3	3.02 ± 0.02
Postal wrap, MD	3.8 ± 0.2	3.37 ± 0.02

[a] Noncontact transducer measurements of V_{S0} made on paper moving at 10–12 m s^{-1}.
[b] Contact transducer measurements of V_{S0} on stationary paper.

for each paper type. This difference in wave velocity in the machine and cross directions reflects the fact that the papermaking process is manipulated to cause fiber alignment in the machine direction to maximize strength in that direction. This fiber orientation causes greater stiffness in the machine direction and thus the higher ultrasonic velocity. Newsprint shows the highest anisotropy in ultrasonic velocity between the machine and cross directions because newsprint is optimized for use on printing presses which require high tensile strength in the machine direction. The publishing grade paper showed the least anisotropy. The fiber orientation in this paper is deliberately made isotropic in the plane of the sheet to optimize the print quality, rather than to achieve a specific stiffness or strength characteristic [14].

Ultrasonic velocity, fiber orientation and paper strength are closely related. Therefore measurements of the directional distribution of the magnitude of ultrasonic velocity in the plane of the sheet are often assumed to indicate directly the distribution of fiber orientation. Instruments based on this assumption are used in the paper industry. However, ultrasonic velocity distribution is an imperfect measure of fiber orientation because ultrasonic velocities are a direct measure only of sheet stiffness. The directional distribution of stiffness in the sheet is affected by both fiber orientation and stresses formed within the sheet during the pressing and drying processes. When such stresses are not collinear with fiber orientation, distribution of the magnitude of ultrasonic wave velocities does not follow the fiber orientation distribution [15]. The distribution and magnitude of strength properties, on the other hand, are directly correlated with the distribution and magnitude of sheet stiffness and ultrasonic velocity as discussed earlier.

The LUS measurements agree fairly well with the contact transducer-based measurements. When the difference between measurements exceeds experimental error they do so only slightly, and in all but one of these cases the LUS-based velocity measurements were higher than the contact transducer-based measurements. Also notable is that the LUS measurements on moving paper have a much larger experimental error. The difference between contact and LUS measurements and part of the variability of the LUS measurements may have been caused by variations in ambient humidity and temperature. Slight variations in the water content and temperature of paper have a large effect on ultrasonic velocity [16]. The generally lower velocities measured with contact transducers would be consistent with higher ambient temperature and/or humidity in the location (Roswell, Georgia, USA) where those measurements were made, compared with these conditions in Berkeley, California, USA where the LUS data were measured. In addition, the relatively large experimental error in the LUS measurements may in part have been caused by local temperature and humidity variations. The measurements were made over several weeks during which weather ranged from clear and sunny to rainy. In this laboratory, humidity and temperature fluctuations are mitigated but not precisely controlled. These measurements will be repeated using both techniques in a single controlled humidity and temperature environment.

Another contribution to experimental error in the LUS data may be related to small separation distances between the generation spot and the detection spot coupled with local variability in paper thickness and internal stresses. Thicker sections are stiffer resulting in higher ultrasonic velocities. During the papermaking process, especially when pressing during the drying process, small islands of internal stress are incorporated into the paper sheet. Ultrasonic velocities increase in areas where stresses have a directional component in parallel with the wave motion.

The contact transducer measurements were made with a transducer separation of 10 cm, whereas LUS measurements were made over much shorter distances (0.5–2 cm). The short distances used in the LUS measurements are required to keep the generation laser pulse energy below the damage threshold of the paper. The short distances used in individual LUS measurements were more likely to mirror effects of local thickness and stress variations in the sheet. Each data point that appears in the plots of LUS data in Figs. 6–10 are an average of many individual measurements, with the intention of reducing the effect of local variations in ultrasonic velocity. However, some of these effects may have contributed to the experimental error in the LUS measurements.

5. Conclusion

Non-contact measurements of ultrasonic-wave velocities have been made on paper moving at production speeds. Both A_0 and S_0 wave propagation velocities were measured. LUS measurements on moving paper were compared with contact measurements on static paper. Three commercially available detection technologies were compared. The Mach–Zender interferometer gave performance superior to confocal Fabry–Perot and photo-induced EMF interferometers. Although there was a consistent correlation between the contact static and LUS non-contact measurements on moving paper, there were slight discrepancies that may have been caused by temperature and humidity variations between the locations where LUS measurements and the contact measurements were made. Ultrasonic velocities obtained by LUS on moving paper will be compared with data obtained with contact transducers on stationary paper in a single controlled humidity and temperature environment.

The measurement of ultrasonic wave velocities on moving paper is an important step in the development of a method for on-line measurement of paper strength properties. Other development tasks are automation of the measurement and measurement of multiple angles between the machine and cross directions to characterize fully the angular distribution of the strength properties within the sheet. Experimental studies in support of these goals are currently under way at this laboratory.

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