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ABSTRACT

A dry-contact ultrasonic technique using two fluid-filled rubber wheels is used to probe the thickness and Z-direction sound traveling time of paper materials. The Z-direction longitudinal velocity and specific stiffness are determined from these raw measurements. In addition to time domain measurements, frequency domain analysis of ultrasonic pulses is used to evaluate the dispersion and attenuation of sound in the Z-direction. Since these phenomena depend upon the dimensions of sound scattered sites inside a material, they can be used to further probe down the fibrous and porous structure of paper. The fluid-filled wheels technique can also be used to investigate the reflection of sound on both sides of paper, and establish a relationship to surface roughness. Results are presented for fine papers, mediums, linerboards and heavy boards. The potential of the technique for off-line and on-line monitoring of various paper physical properties is discussed.

INTRODUCTION

Standard liquid coupling immersion techniques, which are routinely used for nondestructive ultrasonic testing of plastics and metals, are inappropriate for paper materials. Although there is a growing interest in the development of noncontacting methods using gas-coupled transducers or laser-ultrasonics principles (1), demonstrated use of these techniques for papers has not yet been reported. Thus, it is necessary to rely on dry-contact coupling methods using conformable rubber platens to optimize energy transmission through paper (2-3). Among applications of out-of-plane ultrasonic testing of paper, one notes the measurement of elastic stiffness constants (4), prediction of internal bond strength (5), tissue softness characterization (6), and control of delamination (7-8).

Using the concept of dry-contact coupling, we present a new technique using ultrasonic sensors immersed in fluid-filled rubber wheels mounted on opposite sides of paper. The technique can be used for laboratory testing of paper specimens (9-11), and on-line monitoring of a moving paper web (12). It is primarily used to measure thickness and traveling time through paper, from which the out-of-plane velocity and specific stiffness (square of the velocity) are obtained. Additional information regarding sound dispersion, attenuation and reflection can be gathered from the frequency domain analysis of ultrasonic pulses. Measurement principles are first presented. The fluid-filled rubber wheels instrument is next described. Then, selected results are exposed and discussed.

PRINCIPLES OF MEASUREMENT

Consider the cross-sectional view shown in Figure 1. Two immersion-type piezoelectric ceramic transducers, an emitter and a receiver, are used to transmit and receive ultrasonic pulses, respectively. They are permanently mounted on the axles of rubber tires filled with a fluid. In this manner, continuous acoustic coupling is ensured between the stationary transducers and the rotating wheels. Since the tires are under constant mechanical pressure, the total fluid sound path is reduced by an amount equivalent to paper thickness when paper is present in the nip.

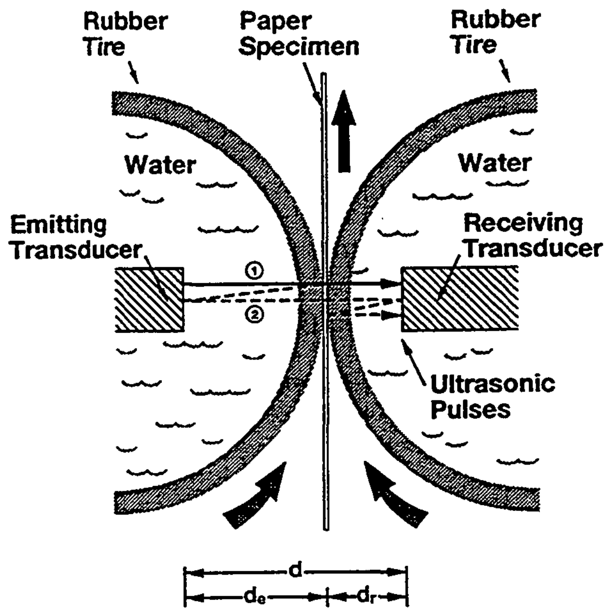

Figure 1. Cross-sectional view of the fluid-filled rubber wheels (FFW) measurement technique for out-of-plane ultrasonic inspection of paper.

Two ultrasonic pulses are collected: the directly transmitted pulse between the emitter and the receiver (solid line or pulse #1 in Figure 1), and a reflection-delayed pulse (dashed line or pulse #2). Time differences between these pulses obtained without and with paper in the nip between the wheels are used to determine paper thickness and traveling time through paper. The reflection-delayed pulse exists because sound travels through mediums with different acoustic impedances, i.e., fluid-rubber-air/paper-rubber-fluid. Since many other unwanted reflection-delayed pulses occur, special precautions are necessary to ensure that pulses #1 and #2 are free of interference. This is achieved by appropriate adjustments of the transducers' separation distance d, and the ratio d_e/d_r of the transducers' positions with respect to the nip interface. Also, the specified tire rubber thickness must be sufficiently large to avoid interference from internal reflections in the rubber paths. It is assumed that internal reflections do not occur in paper. As a rule of thumb, this is most likely the case for papers thicker than 100 μm. Although internal reflections should not affect thickness measurements, traveling time measurements may be affected (11).

Time Domain Analysis

Defining arrival times associated with transmitted and reflection-delayed pulses #1 and #2 by t_1 and t_2 when no paper is in the nip, and by $t_{1'}$ and $t_{2'}$ when paper is in the nip, it can be shown[9] that the thickness of paper, h, is

$$h = \frac{v_a}{2}\left[\Delta t_{21} - \Delta t_{2'1'}\right] \qquad (1)$$

where v_a is the apparent sound velocity in the fluid (slightly different from the true fluid velocity); $\Delta t_{21} = t_2 - t_1$; $\Delta t_{2'1'} = t_{2'} - t_{1'}$. The apparent fluid velocity can be considered as a calibration factor. Also, taking into account the time difference $\Delta t_{1'1} = t_{1'} - t_1$, the traveling time through paper, t_h, is evaluated as follows (9):

$$t_h = \frac{h}{v_a} + \Delta t_{1'1} \qquad (2)$$

The acoustic impedance of paper, Z, is given by the basis weight divided by the traveling time. From Eqs. 1 and 2, one gets the Z-direction longitudinal velocity, .i.e.,

$$v_z = \frac{h}{t_h} = \left[\frac{1}{v_a} + \frac{\Delta t_{1'1}}{h}\right]^{-1} \qquad (3)$$

The out-of-plane specific stiffness corresponds to v_z^2. The out-of-plane longitudinal elastic stiffness constant C_{33} is

$$C_{33} = \rho\, v_z^2 \qquad (4)$$

where ρ is the apparent density of paper. Thus, assuming that v_a is a known parameter and that the time differences Δt_{21}, $\Delta t_{2'1'}$, and $\Delta t_{1'1}$ are accurately determined, it is possible to evaluate h, t_h, and v_z using the same measuring technique. It is interesting to note that the measurements do not depend upon tire roundness. They are also independent of the tire thickness, providing that it is constant. In practice, the latter assumption is not verified and measurements must either be collected by rotating the tires to preset angular positions (off-line measurements), or by averaging results over full tire rotations (on-line measurements).

Frequency Domain Analysis

In the above treatment, it is assumed that the sound velocity in paper is independent of frequency, i.e., that paper does not exhibit a sound dispersive behavior. This assumption may not always be adequate, especially for thick papers. Thus, a more advanced analysis that considers sound dispersion is necessary. This is of particular interest, because the measurement of sound dispersion can be used to probe down the fibrous and porous structure of paper. Moreover, sound dispersion is associated with a second phenomenon known as sound attenuation and defined as the decrease in amplitude of a pulse as it propagates through a medium. Providing that both effects are evaluated independently, the reflection of sound can be studied in a transmission mode.

Theoretical details about sound dispersion, attenuation, and reflection for the fluid-filled rubber wheels instrument are described in Ref. 11. Essentially, ultrasonic pulses are analyzed in the frequency domain rather than in the time domain. A Fourier transform procedure is used to gather amplitude and phase information as a function of frequency.

The frequency dependent out-of-plane velocity or phase velocity (dispersion effect) is

$$v_p(f) = \left[\frac{1}{v_a} + \frac{\Delta\phi}{2\pi f h}\right]^{-1} \qquad (5)$$

where f is the frequency, and Δϕ is the phase difference between pulses #1 obtained with and without paper in the nip, i.e., $\phi_s(f) - \phi_r(f)$.

The attenuation coefficient, α(f), can be obtained directly from the amplitude information,

$$\alpha(f) = \frac{-1}{h}\ln\left[\frac{U_s(f)}{U_r(f)}\frac{1}{\left[1 - R_a^2\right]}\right] \qquad (6)$$

in which $U_r(f)$ and $U_s(f)$ are the amplitude spectra associated to the directly transmitted pulses collected without and with paper in the nip, respectively; R_a is the apparent sound reflection coefficient, which takes into account acoustic coupling conditions on both sides of paper.

α(f) can also be determined indirectly from the phase information by using the so-called Kramers-Kronig relationships, i.e.,

$$\alpha(f) = \frac{-\pi f^2}{2h} \frac{d[\Delta\phi/f]}{df} \qquad (7)$$

Equating Eqs. 6 and 7, and solving for the apparent reflection coefficient, one gets

$$R_a = \left[1 - \frac{U_s(f)}{U_r(f)} \exp^{-1}\left[\frac{\pi f^2}{2} \frac{d[\Delta\phi/f]}{df} \right] \right]^{1/2} \qquad (8)$$

As seen below, this coefficient can be related to the apparent surface roughness of paper which is an average of the wire and felt surface roughnesses.

EXPERIMENTAL SETUP

Two identical, unfocused immersion piezoelectric ceramic transducers are used to launch and receive ultrasonic pulses. They are mounted on the axles of free-to-rotate, water-filled, molded urethane (hard-rubber) tires. The transducers' separation distance is approximately 9.5 cm. The d_e/d_r ratio is approximately 2. Tires have a 16.5 outer diameter, a 6.0 cm width, and a 0.8 cm thickness. The emitting transducer is excited with a 1 MHz, one-cycle sine wave electrical pulse. Received pulses are amplified using a 34 dB preamplifier and digitized using a 2432 Tektronix digital oscilloscope. Full length pulses are transferred to a computer for processing. A cross-correlation technique is used to get Δt_{21}, $\Delta t_{2'1'}$, and $\Delta t_{1'1}$. Measurements are collected at 50% RH and 23 °C.

RESULTS

In order to demonstrate the measurement capabilities of the fluid-filled wheels technique, off-line results obtained for 29 different paper specimens are presented. For the purpose of illustrating trends, specimens are divided into four classes: "fine paper" which include newsprints, and copier, writing, and draft papers; "medium"; "linerboard"; "heavy board" (paperboards and cardboards). The linerboard class is the most uniform of all. The thickness ranges from 40 to 1750 µm. Measurements are repeated three times and then averaged.

Time Domain Measurements

Figure 2 shows the fluid-filled wheels (FFW) thickness (Eq. 1) as a function of the soft-platen (SP) thickness. Conformable rubber platens are used to determine the SP thickness. Apart from slightly underestimated measurements for fine papers, a linear relationship is generally observed. Since each data point is an average of only three measurements (at three different locations), this is quite good. Although additional measurements are required to further assess the FFW technique as an effective thickness gauge over a wide range of paper grades, results obtained so far are promising.

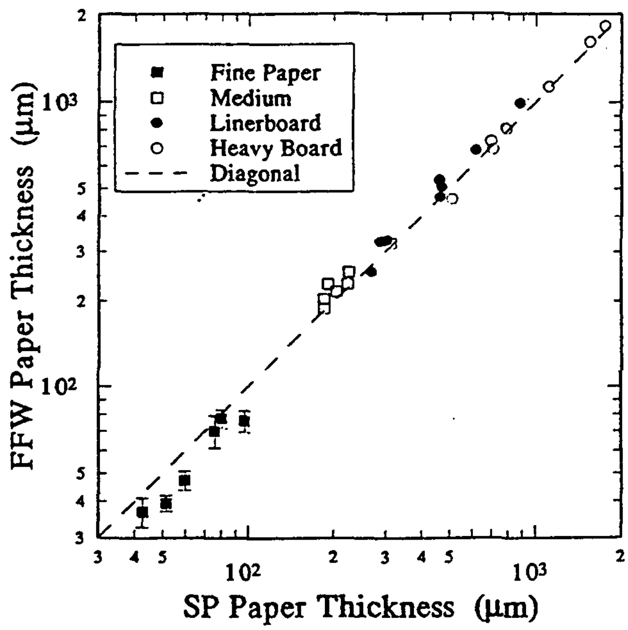

Figure 2. Plot of the fluid-filled wheels thickness versus the soft-platen thickness (reproduced from Ref. 11)

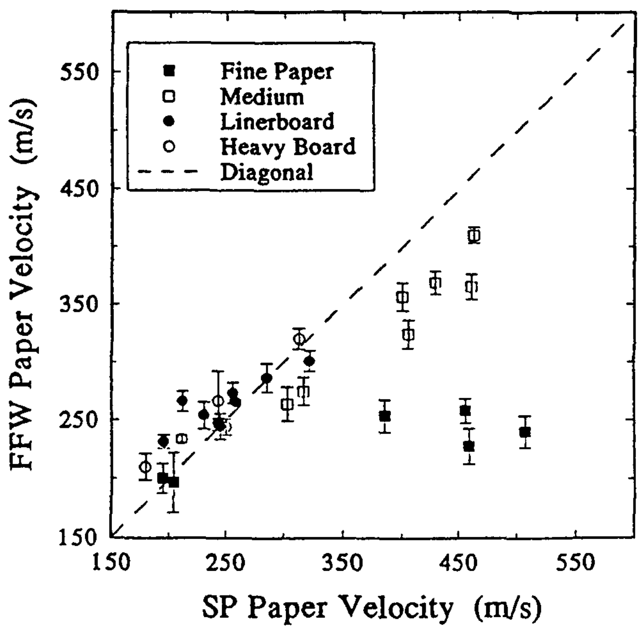

Figure 3. Graphics depicting the fluid-filled wheels velocity as a function of the soft-platen velocity obtained

using the IPST ultrasonic out-of-plane longitudinal velocity tester (reproduced from Ref. 11).

The fluid-filled wheels (FFW) velocity (Eq. 3) is depicted in Figure 3 as a function of the soft-platen (SP) velocity obtained using the IPST ultrasonic out-of-plane longitudinal velocity tester (3). This instrument uses a pair of neoprene-faced transducers to optimize acoustic coupling. Although velocity data are more scattered than thickness data, satisfactory agreement is obtained for linerboards and heavy boards, and to a lesser extent for mediums. FFW and SP velocities generally disagree for fine papers. Since reference velocity measurements are not as yet available for paper materials, one can say that FFW velocities are just as good as SP velocities.

Observed discrepancies for fine papers (less than 100 μm) are partially explained by slight differences in the frequency content of the reference pulse for each testing method. For thicker papers, measurement sensitivity to pulse frequency content is not a problem. Regardless of technical limitations, it is not recommended to determine "absolute" out-of-plane velocity measurements for fine papers, because they may be affected by the presence of internal reflections. However, "relative" velocities collected for the sole purpose of indicating trends may be acceptable.

Frequency Domain Measurements

Using Eq. 5 and the frequency domain phase information, one gets the Z-direction phase velocity. Results at 1 MHz are shown in Figure 4 as a function of the SP velocity. A comparative analysis of Figures 3 and 4 shows that the phase velocity and the time domain velocity (FFW velocity) are essentially the same for linerboards and heavy boards. This is an indication that the dispersion effect is generally weak below 1 MHz for these materials. It also means that the time domain velocity measurements, as obtained using a cross-correlation technique, are a good approximation to the more involved frequency domain velocity measurements.

As already mentioned, sound dispersion implies sound attenuation, and vice-versa. Hence, it is possible to evaluate α(f) directly using the amplitude information (Eq. 6), and indirectly using the phase information (Eq. 7). Selected results are presented in Figure 5 for four specimens. If one neglects unsatisfactory results for the medium specimen (top left corner), there is a very good agreement between solid lines (dispersion-determined coefficient) and short-dashed lines (amplitude-determined coefficient when the apparent reflection coefficient, R_a, is used as fitting parameter) for thicker specimens. Poor results for the medium specimen are due to the inability of the fluid-filled wheels technique to cope with very weak dispersion (or attenuation) at sub-MHz frequencies. One observes that the cut-off frequency (no sound transmission) decreases as the thickness increases. It is near 0.8 MHz for the thick solid board (bottom right corner).

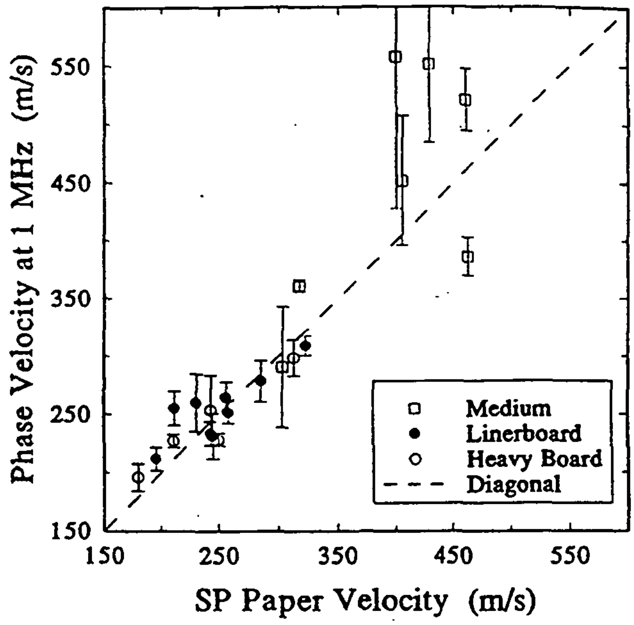

Figure 4. Plot of the frequency domain phase velocity versus the soft-platen velocity. Unreliable results for fine papers are omitted (reproduced from Ref. 11).

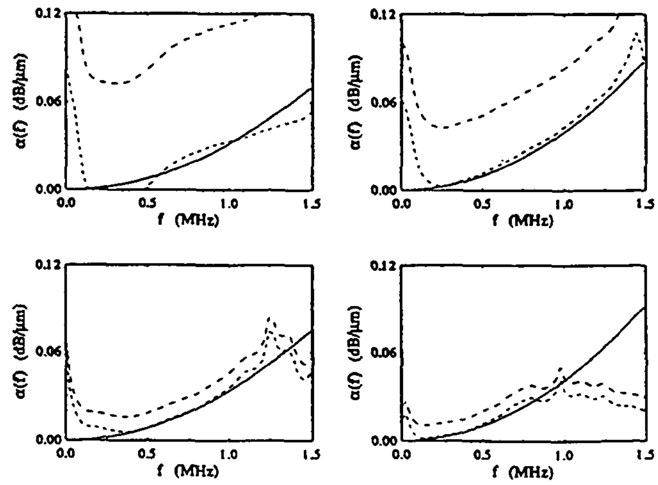

Figure 5. Selected results for the sound attenuation coefficient as a function of frequency. Clockwise from top left corner are the following specimens: 26# medium (185 μm); 42# linerboard (267 μm); tablet board (696 μm); thick solid board (1553 μm). Solid lines refer to the phase-determined attenuation coefficient; large-dashed and short-dashed lines identify the amplitude-determined attenuation coefficient when R_a is zero and used as a fitting parameter, respectively (reproduced from Ref. 11).

In order to appreciate the physical meaning of the attenuation coefficient, this coefficient at 1 MHz is plotted in Figure 6 against the elastic stiffness at 1 MHz for linerboards specimens. Eq. 4 and the phase velocity at 1 MHz are used to compute the frequency dependent elastic stiffness. Results show that the attenuation coefficient is inversely related to the elastic stiffness. Since a stiffer paper is probably less porous and more homogeneous, one should expect less attenuation. Observations seem to support the hypothesis that sound scattering rather than sound absorption is the main mechanism for sound attenuation in paper.

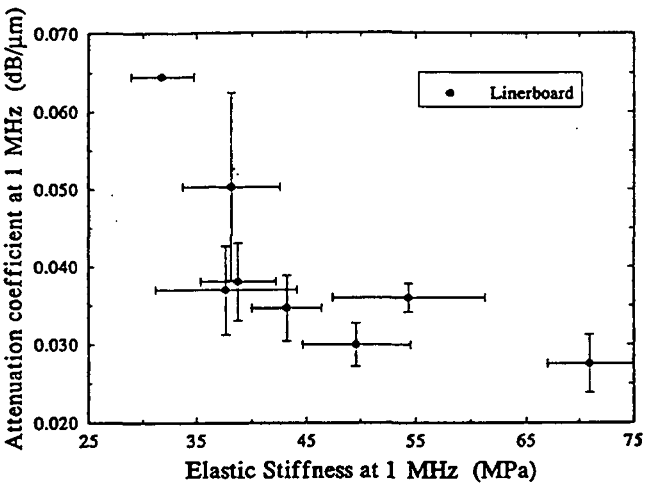

Figure 6. Attenuation coefficient at 1 MHz versus the frequency dependent elastic stiffness at 1 MHz for linerboard specimens (reproduced from Ref. 11).

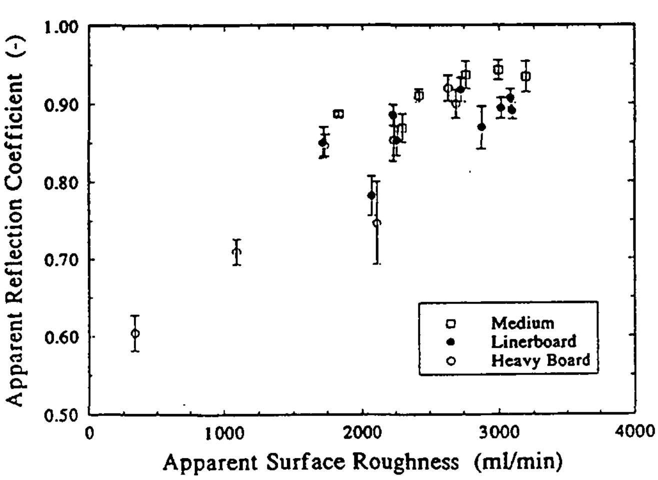

Figure 7. Apparent reflection coefficient as a function of the apparent surface roughness of paper (reproduced from Ref. 11).

Finally, the relationship between the apparent reflection coefficient (Eq. 8) and the apparent surface roughness of paper is examined. The Bendtsen roughness method is used to evaluate wire and felt sides surface roughnesses. Referring to Figure 7, it appears that R_a relates to the apparent surface roughness. This makes sense because the rougher the apparent surface, the poorer are the coupling conditions between the rubber wheels and paper. Poor acoustic coupling implies poor sound transmission through paper. On the scale 0 to 1 (0 corresponds to perfect coupling, i.e., no reflection), the measured apparent reflection coefficient ranges from 0.6 to 0.95. This indicates that whatever the specimen is, coupling is very poor. This is typical of dry-contact coupling conditions.

CONCLUSIONS

A new ultrasonic technique using transducers immersed in fluid-filled rubber wheels was presented. Various off-line results collected in the time and frequency domains were reported to illustrate the versatility of the technique for out-of-plane ultrasonic testing of paper materials.

The fluid-filled wheels instrument can be modified to sustain high temperature and relative humidity, and thus uses to study out-of-plane stiffness properties (including thickness) as a function of temperature and moisture content.

Continuous sensing of mechanical properties such as internal bond strength and compressibility, and defects such as sheet delamination might be achieved by monitoring the sound attenuation coefficient rather than elastic stiffness. It has been hypothesized that the sound attenuation coefficient might be sensitive to the filler content of paper.

While the measurement of the apparent reflection coefficient in a through-transmission mode might be an effective way to evaluate the apparent surface roughness of paper, a more promising approach to surface roughness analysis would be to evaluate the reflection coefficient on either side of the web using soft-rubber tires and a pulse-echo technique. Unpublished results with soft-rubber tires have shown that the reflected pulse on either side of the web is sensible to surface roughness. Since the reflection coefficient is obtained under mechanical pressure conditions, it might be used to predict the printing behavior of linerboards and heavier grades.

As a final word, it has been hypothesized that the simultaneous determination of the attenuation and apparent reflection coefficients might be used to provide independent measurements of bulk and surface tissue softnesses, respectively.

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