EXAMINATION OF OBJECTS MADE OF WOOD USING AIR-COUPLED ULTRASOUND

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ABSTRACT

The speed of ultrasound is approximately 330 m/s in air and 1500 m/s in water. Many materials exhibit surface-acoustic-wave velocities in the 300-1500 m/s range. For this reason, air appears to be the ideal coupling fluid for exciting and detecting flexural waves, which are generally slower than surface acoustic waves, and shear waves. Air coupling may also be ideal for launching and detecting the quasi-longitudinal plate wave in materials which can exhibit very low longitudinal phase velocities, such as balsa wood (800 m/s). In this paper, we describe an experimental, air-coupled, ultrasonic measurement system that can be used to study the propagation of MHz signals in wooden plates ranging in thickness from 3 to 25 mm. Also, we report experimental measurements of the amplitude of transmitted, narrow-band, 0.5 MHz signals as a function of the angle of incidence for different grain orientations. We compare the experimental results for balsa and poplar with results obtained on plates made of poly-methyl-methacrylate (PMMA). Finally, we interpret our results using a slowness-surface approach.

INTRODUCTION

The propagation of guided elastic waves in isotropic and anisotropic plates has been the subject of numerous theoretical investigations [1,2,3,4] and experimental investigations, particularly in connection with fiber-reinforced composite materials.[5] Also, serious attempts have been made to invert the experimental data so that material-parameter values could be obtained.[6]

Although theoretical investigations generally address the dispersion over the entire frequency range, accurate measurements of guided-wave phase velocities appear limited to the range $1<fh/v_s<\infty$, where f is the frequency, h is the plate thickness, and v_s is the shear-wave velocity. Possibly, this limitation is imposed by the 1500 m/sec speed of sound in water, which appears to be the immersion liquid of choice. In many cases, and particularly in the case of thin plates of materials exhibiting slow longitudinal and shear wave phase velocities, the speed of 1500 m/sec exceeds the phase velocity of the two lowest-order guided waves and, hence, coupling cannot occur.

We believe that, by replacing water with air or another gas as the acoustic coupling medium, useful guided-wave phase velocity determinations can be made in the range $0<fh/v_s<1$ on plates made of many technologically-important materials. In particular, measurements could be made on many ligneous materials, foams, and fiber-reinforced composites that exhibit low sound propagation speeds. The use of air as a couplant has another important advantage, recognized previously.[7] Air does not saturate the material. Thus, permanent damage of the material and decontamination problems can be avoided.

EXPERIMENTAL MEASUREMENT APPROACHES

Figure 1 illustrates the two experimental configurations that we have used to study the propagation of ultrasonic waves in flat, wooden plates. The configuration in Fig. 1a is essentially a confocal configuration using two coaxially-aligned, spherically-focused piezoelectric transducers. The second configuration in Fig. 1b uses one focused piezoelectric transducer and one flat piezoelectric transducer. The axes of symmetry for the two transducers are parallel.

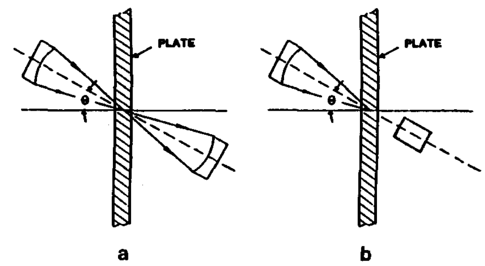

Fig. 1 Experimental Configurations

In a typical experiment employing the Fig. 1a configuration, the wooden plate would be placed between the two transducers so that the central plane of the plate would contain the foci of both transducers, shown in Fig. 1a. When using the Fig. 1b configuration, the focal point of the spherically-focused transducer would be located at the surface of the wooden plate, and the front face of the flat transducer would be located near the opposite surface of the plate.

In both configurations of Fig. 1, the angle of incidence (θ) is variable. The design of our transducer-holding fixtures insures that the location of the focal points would remain stationary as θ varies. Typically, we record the amplitude of the transmitted signal as a function of the angle of incidence.

INSTRUMENTATION

Figure 2 shows a side view of our experimental measurement system. This system mechanizes the experimental configurations of Figs. 1a and 1b. Typically, we use 25 mm diameter focused piezoelectric transducers and 12 mm diameter flat piezoelectric transducers. The focal lengths of our focused transducers are approximately 50 mm. The angle of incidence (θ) can be continuously adjusted from nearly -90° to nearly +90°. Currently, our transducers operate at 0.5 and 1.0 MHz. However, with commercially available transducers, the frequency of operation can be increased to approximately 2.5 MHz.

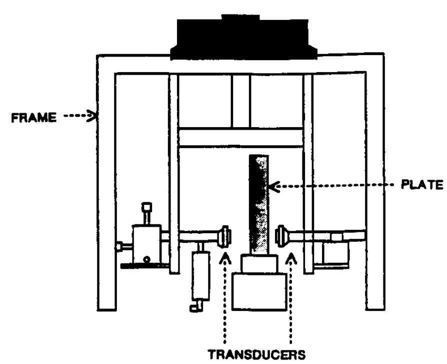

Fig. 2 End View of Measurement Fixture

Figure 3 shows the block diagram of our experimental measurement system. The transmitting transducer is driven by a high-power, unipolar pulse generator, which can supply a burst of up to 9 square-shaped pulses. The pulse generator has a maximum output voltage of 450 V and an output impedance of approximately 3 Ω. To convert the unipolar output of the pulser to the bipolar, sinusoidally-shaped signal needed to drive the transducer, we use a lumped-element, high-pass inverter. The inverter also acts as a step-up impedance transformer with a turns ratio of 6:1. The output of the inverter is applied directly to the transmitting transducer. At the present time, the peak-to-peak voltage applied to the transducer is in the neighborhood of 2000 V.

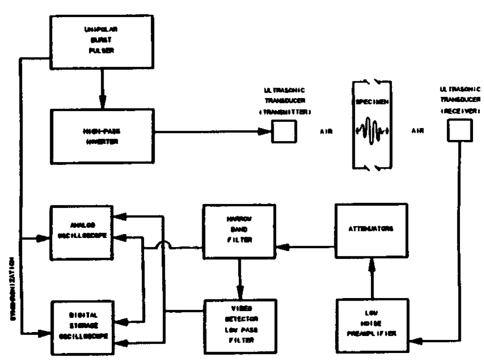

Fig. 3 Block Diagram of Apparatus

To minimize the noise factor (NF) on reception, we utilize a custom-designed, low-noise preamplifier (less than 1 nV/√Hz), which is followed by precision attenuators (total range of 132 dB) and an active, manually-tunable band-pass filter with a bandwidth of approximately 50 kHz. After filtering, the radio-frequency (RF) and "detected" signals are first displayed on analog and digital-storage (9-bit) oscilloscopes, then stored on the hard disk of a personal computer (PC) not shown in the figure.

PHENOMENOLOGY

To interpret the experimental results obtained with air-coupled measurement systems, it is helpful to use the graphical slowness-surface approach. Figure 4 shows the dispersion curves of elastic guided waves in a homogeneous, isotropic plate.[8] (In this case, PMMA is used as an example.) However, in contrast to the usual case, where the phase velocity of a guided wave is plotted as a function of frequency, we plot the <u>reciprocal</u> (1/v) of the phase velocity. In Fig. 4, normalized frequency units, $2fh/v_S$, are used. To the left of the "dispersion" diagram for PMMA, we show the slowness surface for air. In our experimental convention, the 3-direction is normal to the plate and the 1-direction corresponds to the direction of propagation along the plate. The axes of the slowness surface for air are aligned such that the angle of incidence is contained in the 1-3 plane.

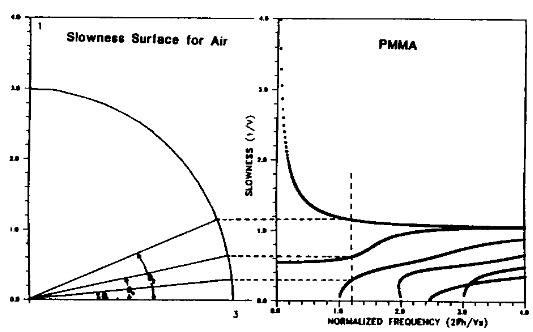

Fig. 4 Calculation of Critical Angle for a Plate

The diagrams in Fig. 4 can be used directly to determine the critical angles for coupling to plate waves. First, the operating point is established along the frequency axis of the dispersion diagram for PMMA. Then, the critical angles in air are determined by projecting the operating points of the propagating modes onto the slowness surface for air. (The dispersion curves of the higher-order, non-propagating modes of the plate are located to the right of the operating point along the frequency axis.)

An examination of Fig. 4 reveals that, at sufficiently low operating frequencies, only the flexural wave and the quasi-longitudinal wave in the plate will be excited. As the frequency of operation is increased, coupling to the higher-order plate waves will occur. However, because the bulk shear and longitudinal-wave velocities in PMMA are large (1100 and 2700 m/s, respectively) in comparison to the speed of sound in air (330 m/s), the critical angles will be small and may be difficult to resolve. This can verified experimentally, as shown in Figs. 5 and 6.

Figures 5 and 6 show the peak amplitude of a transmitted signal as a function of the angle of incidence for two plate thicknesses, 2.8 mm and 5.4 mm. In this case, the experimental configuration of Fig. 1a is employed. At the operating point with the plate thickness of 2.8 mm and the center frequency of the ultrasonic signal at 480 kHz, five modes may be expected to propagate. On the other hand, at least eight modes may be expected to propagate in the thicker (5.4 mm) plate.

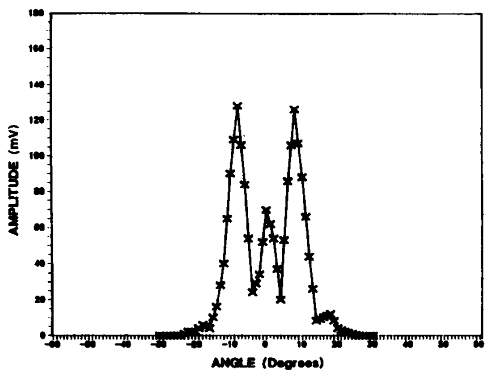

Fig. 5 - Polar Scan of 2.8mm PMMA Plate

An examination of Fig. 5 reveals two sets of symmetrically-located maxima in the transmission coefficient. These maxima are observed at approximately 17° and 7°, with respect to the surface normal, and correspond to the combination of the first anti-symmetric (F1) and symmetric (L1) plate waves and the second anti-symmetric (F2) and symmetric (L2) plate waves, respectively. In addition, another maximum is observed at normal incidence. This signal is attributed to the presence of the third symmetric plate wave (L3), which is close to its cut-off frequency.

In contrast to the results shown in Fig. 5, only one strong maximum is observed at normal incidence in the thicker (5.4 mm) plate. In addition, evidence of smaller, symmetrically-positioned maxima is present at

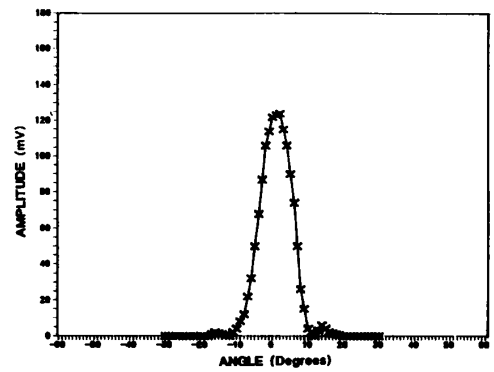

Fig. 6 - Polar Scan of 5.4mm PMMA Plate

approximately 14°. The experimental results shown in Fig. 6 can be interpreted as follows. The transmission is dominated by the higher order modes. Near normal incidence, these modes are approaching their cut-off frequencies. Physically, this corresponds to plane longitudinal waves reverberating in the plate along the plate-normal direction. In PMMA, coupling to longitudinal waves cannot occur above 7°. (This effect is confirmed experimentally in Fig. 6.) The small maxima, at approximately 14°, are probably caused by coupling to the combination of the second anti-symmetric and symmetric modes, F2 and L2. The two lowest-order modes are not observed. (This is probably due to dynamic-range limitations of our experimental system.)

MEASUREMENTS ON BALSA WOOD AND POPLAR

Figure 7 shows the experimental results for a 6.35 mm balsa wood plate whose grain direction is aligned normal to the direction of incidence. As in Figs. 5 and 6, the value of the transmitted amplitude is plotted against the angle of incidence. It is of interest to observe that, in addition to the central maximum, symmetrically-spaced minor maxima are

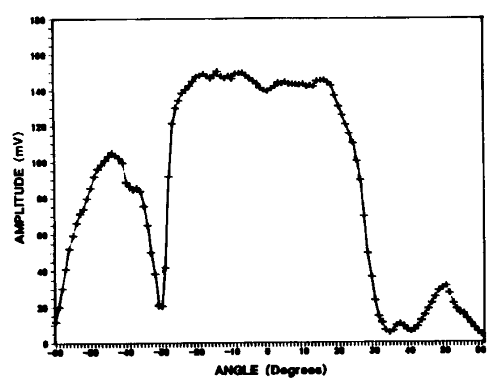

Fig. 7 Polar Scan of 6.35mm Balsa Wood Plate

observed at approximately 50° with respect to surface normal. At the 480 kHz operating frequency, many higher-order modes would be expected to propagate. The experimental evidence appears to confirm this supposition. The magnitude of the central maximum is essentially constant for angles of incidence up to 24° and then decreases rapidly. The 24° angle corresponds to the longitudinal-wave critical angle, assuming a longitudinal-wave velocity of 800 m/s.[9] The 50° maxima correspond to a plate-wave phase velocity of 430 m/s.

Figure 8 shows the experimental results for 3.22 mm and 3.20 mm balsa-wood plates. (The other experimental parameters correspond to those of Fig. 7.) It is interesting to note that the broad central maximum in the transmission coefficient extends to at least 40°. (In this case, we were unable to obtain experimental data for larger angles of incidence.) At 480 kHz, at least 14 modes can be expected to be above cut off. However, we are unable to separate the phase velocities of specific guided waves.

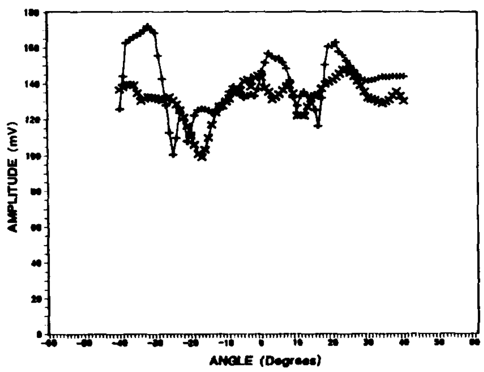

Fig. 8 Polar Scan of 3.2mm Balsa Wood Plate

For completeness, we include some results for a different wood species, poplar. Figure 9 shows the transmitted amplitudes for a 4.78 mm thick plate. The measurements were made with the direction of incidence both normal and parallel to the grain. The central maxima are significantly narrower than for balsa wood. This is the result of higher longitudinal-wave velocities (between 5000 and 2000 m/s) than in balsa. Also, symmetrical subsidiary maxima can be seen when the direction of incidence is normal to the grain. These maxima disappear as the plate is rotated 90° around the plate-normal (3) direction. The observed results appear to agree qualitatively with previous results for longitudinal waves.[10]

We attribute our inability to isolate specific modes in wooden and plastic plates to the limited angular resolution (approximately 6°) of our present experimental apparatus, which utilizes the confocal transducer arrangement of Fig. 1a as the primary measurement configuration. In principle, the

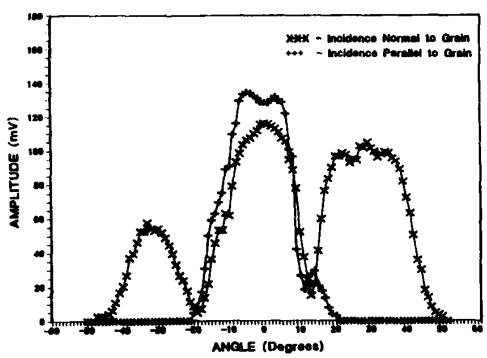

Fig. 9 Polar Scan of 4.78mm Poplar Plate (Two Orientations)

configuration of Fig. 1b should provide greater selectivity. However, at the present time, this configuration suffers from inadequate signal-to-noise performance, due to diffraction effects.

LIMITATIONS OF PRESENT TECHNOLOGY

Our current air-coupled measurement systems use piezoelectric transducers and can operate in the 0.5-1.0 MHz frequency region. This frequency region appears to fulfill the inspection requirements of many organic and inorganic materials. At the present time, the sensitivity of air-coupled systems in this frequency range appears to be limited by a lack of adequate materials for matching the acoustic impedance of typical transducer materials (34 Mrayl) to that of air (0.0004 Mrayl).[11] For example, balsa wood exhibits the correct acoustic impedance (0.1 Mrayl), but suffers from very high attenuation.

In some cases, it may be advantageous to operate air-coupled measurement systems at frequencies lower than 500 kHz.[12] This may be difficult to do using piezoelectric transducers. For frequencies up to 500 kHz, capacitive transducers may be more appropriate than piezoelectric transducers.[13]

It should be noted, that air-coupled systems exhibit higher sensitivity to surface roughness. This is caused by the low velocity of sound in air (330 m/s).

CONCLUSIONS

Air coupling can be used to study the propagation of elastic waves in wooden plates. Because the speed of sound in air is five times slower than in water, air coupling can be used to excite and detect shear waves in balsa wood and similar species, which exhibit very slow longitudinal and shear-wave velocities. At sufficiently low frequencies, the lowest-order flexural wave can also be excited and detected.

In our experiments, we used mainly spherically-focused transducers operating at 480 kHz. The main shortcoming of spherically-focused transducers is poor angular resolution. Therefore, the potential of other transducer types should be investigated. The frequencies of operation should be lowered to mitigate the effects of surface roughness and reduce the number of propagating guided waves in thin (2.5-5 mm) plates.

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REFERENCES

1. L.P. Solie and B.A. Auld, "Elastic Waves in Free Anisotropic Plates," in J. Acoust. Soc. Am., 54(1), Jan. 1973, pp. 50-64

2. A.H. Nayfeh and D.E. Chimenti, "Free Wave Propagation in Plates of General Anisotropic Media," in J. Appl. Mech., Dec. 1989, Vol. 56, pp. 881-889

3. Y. Li and R.B. Thompson, "Influence of Anisotropy on the Dispersion Characteristics of Guided Ultrasonic Plate Modes," in J. Acoust. Soc. Am., 87(5), May 1990, pp. 1911-1931

4. S.A. Markus, M.D. Kaplan, and S.V. Veremeenko, "Propagation of Natural Waves in Orthotropic Plates," in Sov. J. of Nondestr. Test. (English transl.), Vol. 21, 1986, pp. 739-744

5. A.H. Nayfeh and D.E. Chimenti, "Propagation of Guided Waves in Fluid-Coupled Plates of Fiber-Reinforced Composite," in J. Acoust. Soc. Am., 83(5), May 1988, pp. 1736-1743

6. M.R. Karim, A.K. Mal, "Inversion of Leaky Lamb Wave Data by Simplex Algorithm," in J. Acoust. Soc. Am., 88(1), July 1990, pp. 482-491

7. M. Luukkala, P. Heikilla, and Y. Surakka, "Plate-Wave Resonance - A Contactless Test Method," in Ultrasonics (9), 1971, pp. 201-208

8. S.K. Datta, A.H. Shah, R.L. Bratton, and T. Chakraborty, "Wave Propagation in Laminated Composite Plates," in J. Acoust. Soc. Am., 83, 1988, pp. 2020-2026

9. B.T. Khuri-Yakub, Stanford University, CA, private communication.

10. V. Bucur, "Relationships between Grain Angle of Wood Specimens and Ultrasonic Velocity," in J. Catgut Acoust. Soc., No. 41, May 1984, pp. 30-35

11. S. Schiller, C-K. Hsieh, C-H. Chou, and B.T. Khuri-Yakub,"Novel High-Frequency Air Transducers," in Proc. Rev. Prog. in Quant. NDE, D.O. Thompson and D.E. Chimenti (Plenum, New York, 1990), pp. 795-798.

12. C.C. Haberger, R.W. Mann, and G.A. Baum, "Ultrasonic Plate Waves in Paper," Ultrasonics (17), March 1979, pp. 57-62.

13. M. Luukkala and P. Merilainen, "Metal Plate Testing Using Airborne Ultrasound," Ultrasonics (11), Sept. 1973, pp. 218-221.