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An elastic-wave ellipsometer for measurement of material property variations

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Electromagnetic-acoustic transducers (EMAT's) can excite and detect elastic shear waves with electronically controlled elliptical polarizations. These can be used to construct an ellipsometer for precise measurement of mechanical properties of solids, in analogy to devices presently used in optical studies. The elastic-wave case differs from the optical case in two important ways. Longitudinal as well as transverse waves will, in general, exist, and the propagation medium, as well as the surfaces, play an important role in determining the system response. A device is described which is designed to avoid the former mode conversion effects on thin plates. The results of two simple experiments to demonstrate its performance are then reported. In one, measurement of the texture of a metal plate demonstrates the ability to sense bulk property changes which alter the relative velocities of the two-wave components. In the second, measurements of the effect of a fluid on one side of the plate demonstrates the ability to sense surface changes which alter the relative attenuation of the two-wave components. The technique appears likely to find future application in the high-precision measurement of a number of elastic properties, particularly in view of the fact that it requires no couplant and hence can perform well under various adverse conditions.

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Small changes in physical properties of a medium can be precisely measured by sensing the relative shift in the phase or amplitude of two orthogonally polarized waves as they interact with the medium. In an optical ellipsometer,[1] a series of polarizers and quarter-wave plates are used to determine the change in the elliptical polarization of an optical beam which occurs during reflection from a metal surface. The components polarized parallel or perpendicular to the plane of incidence have identical propagation properties in air but are affected differently when reflected by the surface. Foreign layers on the metal as thin as one atomic thickness, $10^{-3}\lambda$ or less, can be readily detected by monitoring these changes.

In an isotropic solid, shear elastic waves might be used in an analogous way to sense material properties since two polarizations exist which propagate with equal velocities. However, three major differences exist. First, longitudinal, as well as transverse, waves can propagate in the medium. Second, in contrast to the optical isotropy of air, anisotropies in a solid can cause the two waves to have different velocities. For example, measurements of shear-wave birefringence is used to detect body stresses in materials.[2] Thus, bulk as well as surface properties are sensed in the elastic-wave case. Third, elastic-wave devices analogous to optical polarizer–quarter-wave plate combinations are not readily available. Piezoelectric transducers can be used to excite or detect waves of a fixed polarization, but the plane of the polarization cannot be changed without physically rotating the transducer and then reestablishing the mechanical bond.[3] This paper discusses a new device which overcomes the third problem by using a new type of transducer which excites and detects waves whose polarizations can be changed electronically. The properties of guided wave propagation are used to design a particular transducer for operation on thin plates which does not couple to longitudinal waves and thus avoids complications due to the first difference. The results of simple experiments to demonstrate the device's sensitivity to both bulk and surface conditions are reported.

The device is based upon the periodic permanent magnet EMAT (electromagnetic-acoustic transducer).[4] Such a transducer is sketched in Fig. 1. When the axial coil is driven by a dynamic current of frequency f, the horizontally polarized shear (SH) waves are launched into an adjacent metal body at an angle

$$\theta=\sin^{-1}(V_s/fD) \qquad (1)$$

with respect to the surface normal. Here, V_s is the shear-wave velocity and D is the coil period. When the circumferential coil is driven, a vertically polarized shear (SV) wave is launched at the same angle. Based on the principle of super-

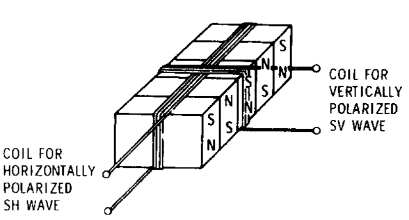

FIG. 1. Schematic of a periodic magnet EMAT for simultaneously exciting SH and SV elastic waves.

position, a wave of arbitrary elliptical polarization can be launched by simultaneously driving the two coils with apropriately phased signals.

For these first tests, this approach was modified by slight transducer design changes and by placing two separate transducers side by side and making measurements in the far field where the beams overlapped. One transducer produced SH waves and the other SV waves, thereby reducing electromagnetic cross-talk problems. The transducers had a period of 0.25 in. (0.635 cm) and an aperture of 0.5 in. (1.27 cm). A tone burst of 0.69 MHz was impressed on each of the two transmitting transducers with equal phase so that $\theta = 45°$ in aluminum. A similar pair of transducers individually received the two polarizations. Their outputs were then combined after suitable amplification. In the most general case, the phase and amplitude of both the transmitting and receiving channels would be controlled. In these experiments, a simpler null output format was chosen. The phase and amplitude of the transmitted signals was fixed, and the phase and amplitude of the received signals was adjusted to produce a null output. Changes in physical properties were then indicated by a destruction of this null. Separate outputs for the SH signal, the SV signal, and the null were provided for monitoring.

Such a device can operate on a thick plate by exciting a tone burst which propagates through the plate, reflects from the back surface, and is detected by the receiver. However, it is often desirable to make measurements on thin plates for which the tone burst would be too long to allow resolution of the individual reflections. For this case, the guided wave representation of the elastic fields, as illustrated in Fig. 2, is more convenient to use. Here, the dispersion curves for both SH and Lamb modes in an isotropic plates are shown.[5] In general, two modes do not coexist with equal phase and group velocity as required for ellipsometric operation. However, one exception occurs at the point of tangency of the $n = 1$ SH mode and the $n = 0$ symmetric Lamb mode. At this point, each mode can be decomposed into plane shear waves bouncing at 45° between the faces of the plate. Hence, the two modes travel with equal phase and group velocities. It should be noted that this occurs because, at 45°, the SV wave is fully reflected with no mode conversion to evanescent longitudinal waves. The transducer described above acts in this mode on a 0.125-in. (0.318-cm) plate since $H = 2D$ at that point.

The theory of the device is symbolically summarized in Eq. (2):

$$S = \{A_1 \exp[-j(k_1 + \alpha_1)x] - A_2 \exp[-j(k_2 + \alpha_2 x)]\} \exp(j\omega t), \qquad (2)$$

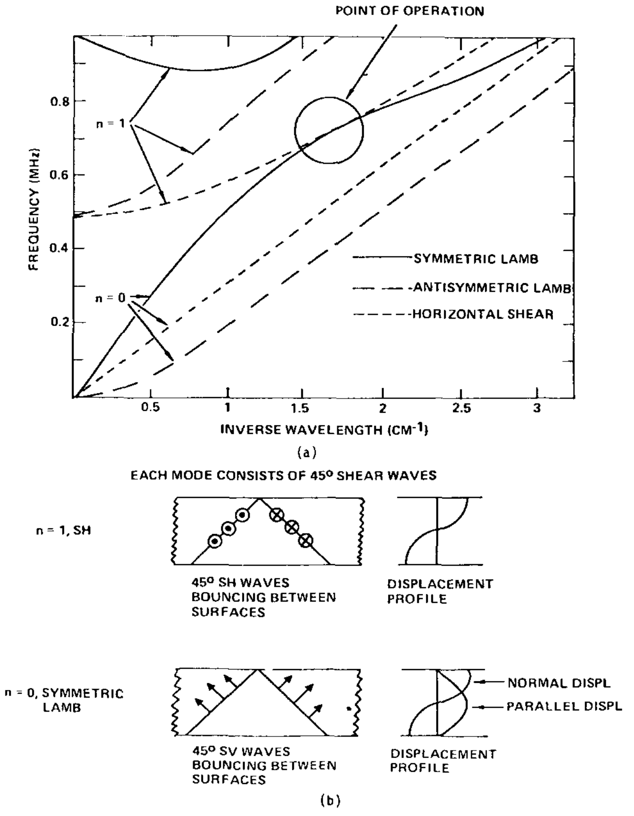

FIG. 2. Ellipsometric operation on a 0.125-in. (0.318 cm) aluminum plate. At the point shown in the dispersion curve (top), two orthogonally polarized guided shear waves exist. Each of these may be decomposed into plane shear waves traveling at ±45° with respect to the surfaces and hence travel with the same phase and group velocities.

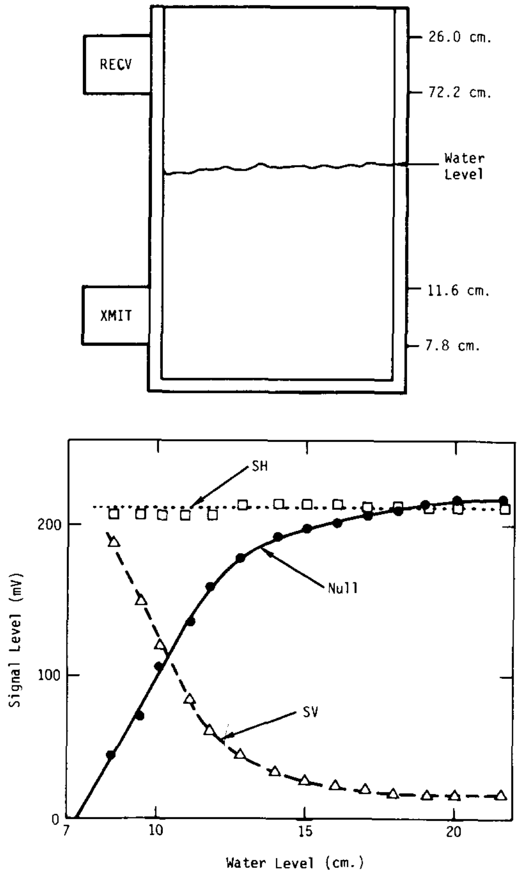

FIG. 3. Demonstration of sensitivity of ellipsometer to surface changes produced by fluid loading.

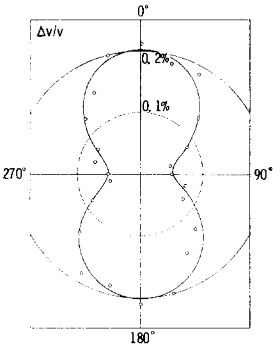

FIG. 4. Demonstration of sensitivity of ellipsometer to bulk changes produced by texturing. Rolling was in the 0° direction.

where S is the output of the null port, ω is the angular frequency, $k_{1,2}$ and $\alpha_{1,2}$ are the propagation constants and attenuations of the two modes, respectively, and $A_{1,2}$ are complex amplitude factors that can be adjusted to null the device, $S = 0$, under particular conditions. Changes in material properties then produce a value of $S \neq 0$ determined by changes in propagation constants and/or attenuation.

Measurements have been made to demonstrate two cases. In the first experiment, the ellipsometer was mounted on the outside of a plate wall of a vessel containing water. This was designed to demonstrate the different sensitivity of the wave types to mechanical changes at the surface of the plate. The SH wave is unaffected by the presence of the water at the plate surface within the vessel. A fluid does not support shear and the components of the elastic boundary conditions are unchanged. However, the SV wave is absorbed since the surface displacement of the $n = 0$ Lamb mode couples to a longitudinal wave radiating into the fluid. Thus, the null output is changed because of an absorption of one wave produced by a change in the surface condition of the plate.

Figure 3 illustrates the experimental configuration and shows the SV, SH, and null signals as a function of fluid level, ranging from a condition in which the fluid is below both transducers to one in which it is above both. The null was established with no water present. The signals exhibit the behavior described above, confirming the sensitivity of the device to changes in surface conditions.

In the second experiment, the device was used to sense the anisotropic elastic properties of a rolled aluminum plate which can be related to the preferential orientation of grains (texture) produced by the rolling process.[6] Changes in output are due to changes in velocity (k_1, k_2) rather than attenuation, and these changes are produced by bulk rather than surface properties of the medium. Figure 4 shows the results where the velocity shift has been derived from the data on the basis of Eq. (2). Assuming that the values of α, k, and A are approximately the same for the two modes, the resulting relation is $|\Delta v/v| = |S/A|/kL$, where L is the propagation distance. Rather small velocity changes were easily measured.

In summary, a new technique for exciting shear waves of arbitrary polarization has been described, an optimum operation point for thin plates has been identified, and results of preliminary experiments have been presented. Applications of the present demonstrations include monitoring the level of fluid in a closed vessel and monitoring the texture of plates during rolling to ensure proper mechanical properties. Future applications appear to be broad because of the potential for high-precision measurement of a number of elastic properties using a device which requires no couplant and hence is suitable for use under many adverse operating conditions.

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