ABSTRACT

Acoustoelasticity is a promising method for the in situ analysis of both applied and residual stresses. The object of this investigation is to establish a technique for scanned shear wave measurements so as to determine the individual components of an inhomogeneous stress state and their directions. A computer-controlled scanning system with a dry contact rubber backed transducer has been developed which provides complete automation of scanning and data reduction.

The theory of acoustoelasticity for anisotropic material has been developed using perturbation techniques. The experimental results on rolled aluminum plates confirm that, to a reasonable approximation, the effects of material anisotropy and stresses can be uncoupled and the needed stress information thus derived.

INTRODUCTION

Acoustoelasticity determines the change in velocity of a small amplitude acoustic wave due to the presence of a static stress field. It is analogous to the photoelastic effect, but has the advantage that it is directly applicable to metals.

Determining an inhomogeneous stress profile over a given region requires scanning a transducer over the surface of the material being examined. For some time we have used a transducer in water to make scanned longitudinal wave measurements.\textsuperscript{1,2} The lack of suitable contacting transducers has been a problem in scanning with shear waves. Another problem has been that of texture in metal which induces shear wave birefringence similar to that caused by a stress
field. The coupling between these two effects is not well understood.

The objective of this research has been to remove these obstacles by developing a satisfactory dry contact shear transducer and a theory for separating the effect of stress and material anisotropy.

DRY CONTACT TRANSDUCERS

We have spent considerable effort trying to make a scanned shear wave measurement system. For a computer-controlled scan, we cannot bond the transducer to the sample or use a heavy grease to provide coupling because the contact varies as the transducer is moved along the surface of the sample. We have therefore developed a PZT ceramic shear wave transducer with a flexible rubber backing for easy alignment and a dry contact to the sample. The front of the transducer is coated with a metal film and the sample is used as a contact to this film. The transducer itself can be lifted up and down, moved from point to point, and rotated under computer control. Approximately 40 N of force is applied to maintain contact to the 4 mm diameter transducer.

The results obtained are highly reproducible. Measurements carried out on a glass sample covered with a metal film showed very little variation from point to point or with rotation of the transducer.

TEXTURE EFFECTS

The purpose of using shear waves is to be able to measure the direction and magnitude of the individual stress components. One of the difficulties which occurs in longitudinal wave measurements, but is more extreme with shear waves, is that material texture changes the results radically. We have therefore worked out a simple theory to account for this effect.

The effect of texture is like that of a single crystal material whose principal axis is at a certain angle \( \psi \) to the polarization of the incident shear wave, as illustrated in Fig. 1. When stress is applied at an angle \( \theta \) to the principal axis of the crystal, we can regard its effects as rotating the principal axis of the crystal and changing \( \psi \). The relation between stress \( \sigma \) and angle \( \psi \) is determined by regarding the third order elastic constants as being those of the equivalent isotropic material, but perturb the second order constants by an anisotropic term associated with the texture.

We treat the effect of stress and anisotropy by decomposing the second order anisotropic elasticity tensor \( C_{ijkl} \) into an isotropic tensor and a perturbation tensor, and writing it in the form
where \( \varepsilon_{ijkl} \) is a fourth order perturbation tensor. There will, in fact, be a similar deviation from isotropy of the third order elastic constants. If the perturbations are small, however, we can account for the observable anisotropy effects in the simple manner given here.

There are two distinct shear wave velocities in an unstressed solid, with shear polarizations parallel and perpendicular to the axis. We call these

\[
\begin{align*}
V_{10} &= \sqrt{\mu/\rho} \ (1 - \varepsilon), \\
V_{20} &= \sqrt{\mu/\rho} \ (1 + \varepsilon)
\end{align*}
\]

respectively. If the applied principal stresses are \( \sigma_1 \) and \( \sigma_2 \), respectively, and the principal axes of polarization are as illustrated in Fig. 1, then it can be shown that, in the presence of
stress, the plane of polarization is rotated so that shear wave velocities along the principal axes become $V_1$ and $V_2$, respectively, where

$$\sin 2\psi = \sin \frac{2\theta}{\Gamma},$$

$$\frac{V_1 - V_0}{V_0} = S(\sigma_1 + \sigma_2) + D(\sigma_1 - \sigma_2)\Gamma,$$

$$\frac{V_2 - V_0}{V_0} = S(\sigma_1 + \sigma_2) - D(\sigma_1 - \sigma_2)\Gamma,$$

$$\Gamma = \sqrt{1 - \frac{2 \cos (2\varepsilon\theta)}{D(\sigma_1 - \sigma_2)} + \left(\frac{\varepsilon}{D(\sigma_1 - \sigma_2)}\right)^2},$$

and $S$ and $D$ are constants which depend on both the second and third order elastic constants.

We note that one measurement of $V_1$, $V_2$, $V_{10}$ and $V_{20}$ and $\Gamma$ yields $S$ and $D$ so that $\Gamma$ or $V_1$, $V_2$ as a function of $\sigma_1$ and $\sigma_2$ can then be predicted.

EXPERIMENTAL RESULTS

Figure 2 shows a variation of velocity (null frequency) on a rolled aluminum plate made of Al 6061-T6. The curve indicated by stars corresponds to the unstressed state while the curve indicated by crosses corresponds to a uniform tensile stress of 58 MPa applied along the rolling direction. It is seen that the effect of stress is similar and cumulative in the sense that net birefringence has increased after the application of stress.

Figure 3 shows a similar set of results for the stress applied perpendicular to the rolling direction. Now the principal axis of polarization rotates with the applied stress, as we might expect.

Figure 4 shows a tensile specimen made in such a way that the bar axis is at 40° to the rolling direction. The graph shows the direction of principal polarization versus magnitude of the stress. The solid line is calculated from the theory, while dots are experimentally measured data.

Figure 5 shows results of experiments in which a circular disc made out of a rolled aluminum plate is compressed diametrically along several different orientations with respect to the rolling
Fig. 2. Experimentally measured value of $V - V_0$ as a function of angle from the applied stress for zero applied stress and 58.9 MPa applied stress.

Fig. 3. Shear wave orientation in degrees from direction of stress with no applied stress and an applied stress of 53.7 MPa.
The rotation of the principal polarization direction, represented by $\psi$, is plotted versus $\theta$, which shows the location of the principal stress axis with respect to the rolling direction. Again, the solid line is theoretically calculated while the dots are experimentally determined.

To understand this result, consider two extreme cases. If the load is close to zero, the loading position $\theta$ has little influence and the direction of principal polarization remains parallel to the rolling direction. The corresponding curve will be a horizontal line passing through the origin ($\psi=0$). In the other extreme, if the load is so high that the stress effect dominates, then the principal polarization direction will coincide with the principal stress axis $\theta$ and the corresponding curve will be a straight line passing through the origin.

These techniques have also been used to measure the inhomogeneous stress field in a stressed plate with a hole cut in it. The
results obtained for $\sigma_1 - \sigma_2$ are compared to theory in Fig. 6. It will be seen that there is good agreement between theory and experiment.

CONCLUSION

We have shown that it is possible to obtain reliable computer-controlled scanned shear wave measurements. A start has been made on accounting for texture effects and the results obtained are reliable when texture effects are small.

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Fig. 6. Shear wave measurements of stress near a circular hole in a plate.

REFERENCES
