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A STUDY OF LAMB-WAVE PROPAGATION FROM PHOTOACOUSTIC TRANSIENT EXCITATION

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1. INTRODUCTION

This paper describes recent research activities of Lamb-wave propagation in films from laser-induced transient excitation.

Symmetric and anti-symmetric Rayleigh-Lamb waves have been initiated using pulsed lasers for the characterisation of thin (10 - 150μm) films. Detection has also been performed optically, thereby preventing distortion of waves from perturbation by the sensor itself. An optical beam deflection technique has been compared with a Michelson interferometer technique to show that results from the two techniques are self-consistent. These results may be used to evaluate physical parameters of the film. Some modelling of the physical processes will be presented to show that Lamb-wave behaviour is sensitive to a range of parameters.

2. THE OPTICAL APPROACH

Laser-generated ultrasound has become of great interest in non-destructive testing and in general ultrasonic investigations (1). In recent years, an area of investigation has arisen in the study of their behaviour in thin films and plates (2, 3, 4, 5). Thin is defined as a size smaller than the typical wavelength of ultrasound monitored by the sensor. Briefly, if two boundaries in a solid such as a plate are sufficiently close together, the elastic wave motions on each surface will interact to produce Lamb (or plate) waves, whose propagation characteristics are partly a function of the separation between the two boundaries. The two basic types of Lamb-wave mode are known as symmetrical and antisymmetrical, according to whether the displacements on the two surfaces are in antiphase or in phase respectively.

To faithfully monitor the behaviour of such waves, in either metallic-like films, or in polymer films, we have used a range of optical monitoring techniques. Two of these are the optical beam deflection (OBD) technique and the Michelson laser interferometer technique. The two techniques have been shown to be self-consistent, as shown below.

We have used a 10mW He-Ne laser beam reflected from the surface of a sample to monitor beam deflection arising from an ultrasonic wave propagating along the surface of the sample. Assuming a spatially uniform reflected beam with area S_0 at the knife edge, any variation of beam area ΔS

projected beyond the knife edge produces voltage signals on a square-law photodetector system such that (6)

$$V_S\ (t)/V_0 = \Delta S(t)/S_0, \qquad (1)$$

where V_s is the voltage signal corresponding to the acoustic signal changing with time t, and V_0 is the dc voltage of the photodetector when the full laser beam is allowed to fall on the photodiode. Figure 1 illustrates the change in area ΔS of the laser beam which passes beyond the knife edge when an elastic wave is present at the monitoring point. If $\Theta(t)$ is the surface slope of the wave at time t, then it may be shown geometrically that for small angles of Θ,

$$\Theta\ (t) = (\pi\ /4f)\ [V_S(t)/V_0], \qquad (2)$$

where r is the radius of the uniform reflected laser spot at the plane of the knife edge and f represents the distance between the sensing position on the sample and the knife edge plane. Equation (2) shows that quantitative calibration of the beam deflection technique is possible, provided that V_0 is measured, together with a determination of the spot radius at the knife edge place.

This analysis has been confirmed by examining experimentally the results of a beam deflection measurement with those of a Michelson interferometer. The Michelson interferometer was a homodyne device and has been described elsewhere (13). Stabilization of the interferometer was achieved by means of an electromechanical vibrating mirror, driven by a feedback signal from the output of the interferometer. In this way, compensation for low-frequency noise up to 600 Hz was achieved with an efficiency of 97%.

The calibration equation of the laser interferometer for small displacement y(t) was

$$y(t) = \lambda V(t)/4\pi\ V_0, \qquad (3)$$

where V_0 was the peak output voltage of the interferometer when unstabilized and λ was the laser wavelength (λ = 633 nm).

Equation (3) was obtained with the approximation sin y(t) = y(t), and presents a linear dynamic range of about $\lambda/20$. Beyond this limit, the device is increasingly non-linear. The Michelson interferometer is a displacement sensor sensitive to out-of-plane motions y, while the beam deflection technique monitors the surface gradient, tan Θ, of a perturbed surface. For a Lamb wave travelling in the x direction the relationship between the two physical characteristics is of the form

$$\Theta\ (t) = dy(t)/dx \text{ for small } \Theta, \qquad (4)$$

where y(t) and $\Theta(t)$ represent the waveforms detected by the interferometer

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and the beam deflection techniques respectively. Since x and t are two independent variables the second term of Eq. (4), for a particular monitoring position x_0, may be written as

$$\left(\frac{dy(t)}{dx}\right)_{x_0} = \left(\frac{dy(t)}{dt}\right)_{x_0} \cdot \left(\frac{dt}{dx}\right)_{x_0} \qquad (5)$$

The first term on the right-hand side of Eq. (5) is simply the time differential of the waveform detected by the interferometer. The second term is the inverse of the group velocity of the wave, V_g, which varies because of the dispersive nature of the wave. Since the source-to-detector distance is fixed, the velocity can be calculated for any time of arrival, t, at the detector point. By numerical evaluation, Eq. (5) has been used to predict acoustic waveforms that a beam deflection technique should produce from those derived from a Michelson interferometer measurement. Thus, waveforms from a beam deflection technique have been compared with those from a displacement interferometer. For comparative experiments, probe beams of both the interferometer and beam deflection technique were directed to the same location on the surface of the sample, with both positioned at 24mm from the photoacoustic source.

Lamb wave detection has been studied in a range of polymer materials of different thickness and we report here on data from 125μm-thick samples. The generating laser was a Q-switched Nd:YAG system with a pulse duration of 20ns. A cylindrical lens with a focal length of 20cm was used to produce a linear focus on the surface of the plate, producing preferentially acoustic wave propagation perpendicular to the line. Generation was accomplished in the thermoelastic regime with a laser energy of 40mJ. Due to the good transmission properties of polyester films in the infrared (IR) region, laser energy was only partially absorbed by the sample. After about ten consecutive laser shots, the sample showed some signs of degradation caused by photo-dissociation in the zone of the laser irradiation.

Typical waveforms in the time domain are presented in Fig. 2. Figure 2(a) illustrates a waveform detected by the beam deflection technique. Quantitative calibration arose from the use of Eq. (2), in which following photodetector signal amplification of 200, V_0 was found to be 1.6V when the spot radius of the reflected beam at the plane of the knife edge was approximately 0.50mm. The distance f was 16cm. The waveform consisted of two essential features. After laser excitation at time t = 0, the first feature (at time $\approx$ 10μs) was a signal corresponding to the symmetric Lamb wave. Its amplitude was expected to be small compared to the asymmetric wave. The latter is the second feature (beyond t = 25μm), which as expected, had negative frequency dispersion characteristics. Using Eq. (2) for calibration, we found that its amplitude rapidly increased to a peak-to-peak value of 120μrad.

This waveform was then compared with one taken with a Michelson interferometer, Fig. 2(b). The detection point was coincident with that of the previous detection system, with all other experimental conditions remaining the same. Again, the asymmetric Lamb wave component was clearly monitored, with waveform amplitudes extending beyond 40nm. No symmetric wave was observed, since the interferometer monitored the acoustic motion normal to the surface, combining the motion from both surfaces of the transparent polymer film. A combination of Fresnel reflection from each surface moving in opposite directions (valid for symmetric wave motion) resulted in a null response within the interferometer. This was obviously not the case for the asymmetric wave, which is clearly observed, but with a temporal development out of phase with the waveform detected by the beam deflection technique (Fig. 2(a)). This arises from the difference in physical processes used to detect the ultrasound. Using Eq. (5), the waveform in Fig. 2(b) can be converted numerically to represent the same data in terms of surface gradient, producing the waveform shown in Fig. 2(c). We now see that in the case of the asymmetric waveform, there is close similarity to Fig. 2(a), with once again the predicted beam deflection angle reaching 120μrad peal-to-peak amplitude.

In conclusion these results indicate that the optical beam deflection technique may be used for quantitative measurement of ultrasonic Lamb waves.

3. LAMB-WAVE MODELLING

Arising from an analysis of frequency dispersion behaviour of laser-induced Lamb waves, the literature has already shown how signal analysis leads to evaluation of film thickness and elastic moduli (3). However, a complete modelling of the elastic motion is not so successful.

Our recent work has studied solutions presented by Medick (7) and Weaver and Pao (8). They have studied the applicability of classical plate wave theory in describing the response of a semi-infinite flat plate to a sharp, transient loading applied over a small surface area. Fig. 3 shows one of the anomalies presented by one of these solutions (7). The mathematical model is able to display the typical frequency dispersion and amplitude behaviour seen in experimental waveforms, but produces finite amplitude solutions of the asymmetric wave at times, t, corresponding to times much less than those corresponding to the Rayleigh wave speed. Whilst this is unrealistic, good agreement can be obtained at larger times. An example of ultrasonic waveforms is shown in Figure 4, where this time the sample has been changed to aluminium which has better defined physical characteristics than is usually the case with polymers. Figure 4 shows predicted waveforms, and experimental waveforms. As is shown we can see that on some occasions, good agreement can be obtained.

4. CONCLUSIONS

The beam deflection technique has been shown to have an excellent capability for detecting photoacoustic Lamb waves in thin transparent or opaque film. It can be used for quantitative as well as qualitative measurements. This all-optical inspection technique may be developed into an on-line system. However, whereas analysis of waveforms has already led to the estimations of film thickness and elastic moduli, it is not yet possible to derive a complete prediction of waveform shape. Further investigations are required to enable waveforms to be analysed as an inverse scattering problem, leading to an accurate and complete assessment of the films physical characteristics.

5. REFERENCES

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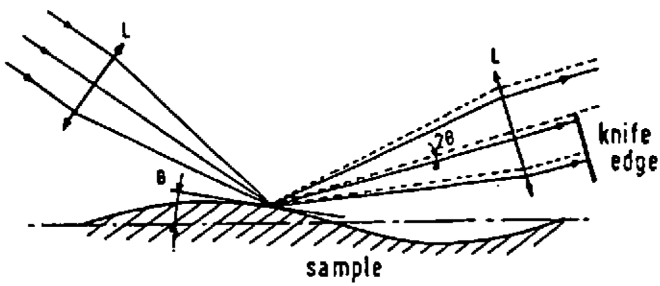

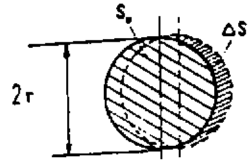

Figure 1 Schematic Diagram of the Beam Deflection Technique
L: Lens S_0: Area of the reflected beam cross-section
ΔS: Variations of area due to an ultrasonic signal
2r: Laser beam diameter at the knife-edge
θ: Gradient at surface due to ultrasonic signal.

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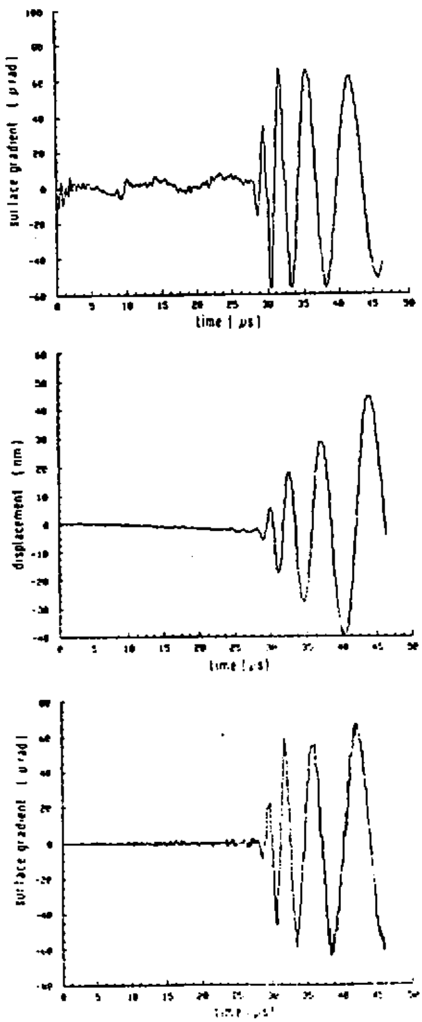

(a)

(b)

(c)

Figure 2 Typical Waveforms of Lamb Waves Detected With
(a) - A Beam Deflection Technique
(b) - A Michelson Interferometer
(c) - Modelled on the Basis of the Waveform of Figure 2(b)

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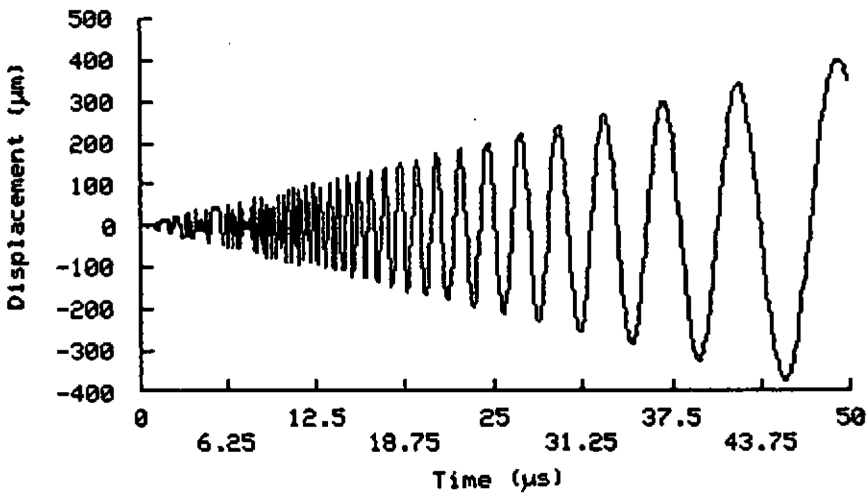

Figure 3 Lamb Wave Response Predicted from a Theoretical Model Assuming an Impulse Point Source of Excitation

Parameters Used in Theoretical Predictions Were: plate thickness = 100µm, Poisson Ratio = 0.345, Young Modulus = 6.9×10^{10}Pa and the Density = 2689kgm^{-3}

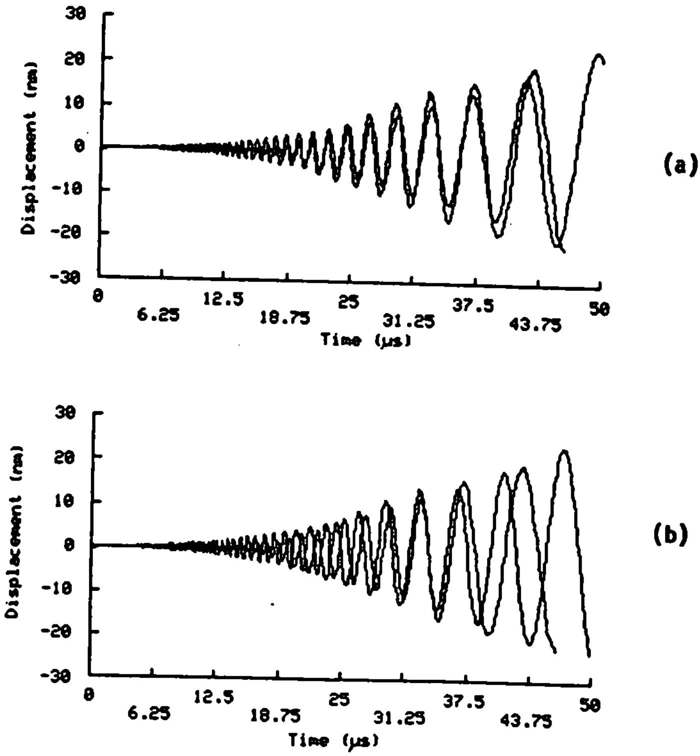

Figure 4 Theoretical and Experimental Waveforms in a 100µm Thick Aluminium Plate. Parameters Used in the Theoretical (Source to Detector Distance = 34mm) Predictions were; Poisson Ratio = 0.345, Youngs Modulus: 6.9×10^{10}Pa, and the Density = 2689kgm^{-3}; except that in (a) The Sample Thickness was Assumed to be 100µm and in (b) The Thickness was Assumed to be 90µm