RECEPTION OF LASER GENERATED ULTRASOUND FROM A CFRP PLATE BY AN AIR MATCHED PIEZOELECTRIC COMPOSITE TRANSDUCER

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INTRODUCTION

Laser generated ultrasound is being investigated [1,2] for testing structures made of both conventional metals and carbon fibre reinforced polymer (CFRP). Laser interferometers are widely used in such work to detect the normal surface motion caused by ultrasonic pulses. Interferometers offer non-contact, remote and high-fidelity detection, together with a potential to cover large areas rapidly by optical scanning. However their cost is high and only in testing large and/or expensive structures may the cost be justified. A lower cost alternative , but with some compromise on the virtues of an interferometer, would be to use an air transducer as a receiver.

Air transducers to date have, from an NDT perspective been limited to low (50-200KHz) frequencies but, with new developments both their frequency and bandwidth is increasing. The transducer used here has a fundamental resonance at 640KHz with 200KHz bandwidth and devices operating at frequencies from 1-2MHz with higher bandwidth are currently under construction.

Our primary interest is in the use of laser ultrasound for testing CFRP and in Scudder and Hutchins [3] the ease with which a laser source generated antisymmetric (A_0) plate waves in thin CFRP was observed. Thus it was envisaged that as these waves propagate along the plate they would re-radiate waves into the fluid, air, in which the plate was immersed. The re-radiated waves would be received by a suitable air transducer making a laser ultrasonic analog of an immersion system for the generation and reception of plate waves in materials.

The A_0 plate wave generated by the laser source travels with velocities from 200 m/s at low frequency (10KHz) up to 1800 m/s at high frequency (500KHz). So re-radiation should occur over angles consistent with this velocity range.

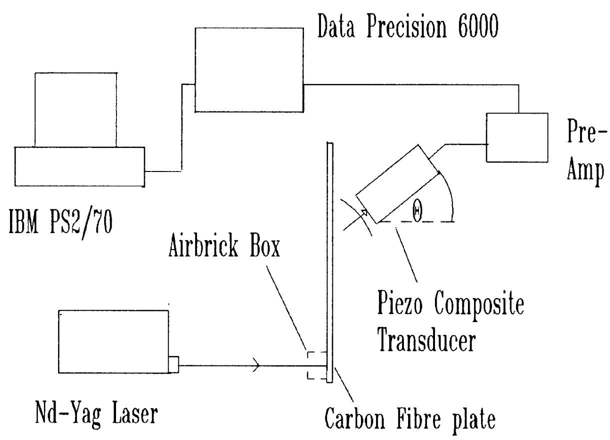

Fig.1 Experimental equipment.

EXPERIMENTAL EQUIPMENT AND METHOD

Experimental Equipment

The sample in this experiment was an 8 ply (1mm thick) unidirectional CFRP plate made by compression moulding hand laid plies of carbon fibre (Enka Tenax HTA 12k tow)/epoxy resin (ICI 7716H) pre-preg.

Equipment for the experiment is shown in Fig.1. Unfocussed pulses from a Lumonics Nd-YAG laser (λ=1063nm, pulse energy=30mJ) produced ultrasonic plate waves from a position at the edge of the plate. With the laser beam being 3mm in diameter and the low total pulse energy no material was ablated from the sample. To further minimise any surface damage all waveforms were taken with a single laser pulse.

The air transducer was mounted on a rotary table so its angle to the plate surface could be varied. Initially the transducer was orientated with its face parallel to the plate surface and its face centre separated 80mm along the fibre direction from the source centre. When parallel, the distance from the transducer face to the plate surface was set at 10mm. Waveforms were taken at angles of the transducer axis to the plate normal of 0° to 22.5° in 2.5° steps.

<u>Construction and Frequency Response Characteristics of the Air Transducer</u>

The active element of the transducer is made from thin rectangular PZT pillars embedded in an epoxy matrix. To create the pillars a solid PZT element is cut in perpendicular directions with a circular saw and the gaps between the pillars filled with epoxy resin. This structure has lower stiffness and density than solid PZT and hence a better impedance match to air. A silicone rubber layer a quarter of a wavelength thick at the transducer's fundamental frequency acts as a further matching element.

A frequency response for the transducer was measured by using it to receive the ultrasonic pulse from a point , ablative regime laser source through an 18cm thick aluminium block. The transducer was on the opposite side of the block from the source and with its face centre directly opposite the source point. Even though the frequency content of the laser ultrasonic pulse is reduced by diffraction and attenuation it has sufficient bandwidth to show the air transducer's frequency response. A transducer waveform recorded using the above method is shown in Fig.2a. The aluminium used is thick enough to ensure the longitudinal (L) arrival emerges without distortion by later reflections in the block. Fourier transforming the longitudinal arrival gives the frequency response in Fig.2b with the fundamental resonance at peaking at 640KHz and harmonics at about 1.8MHz.

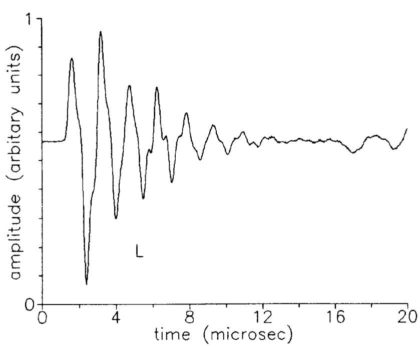

Fig.2a Time domain response of air transducer to laser ultrasonic pulse.

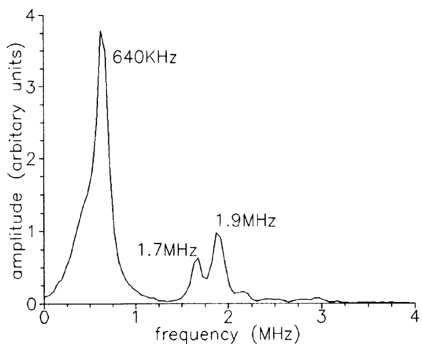

Fig.2b Fourier transform of arrival L (2a).

Both the fundamental and harmonic consist of two closely spaced resonances with these separating clearly (1.7 and 1.9MHz) in the harmonics case.

Effect of Direct Airborne Wave From Source to Receiver

The outward expansion of the source surface generates an airborne wave which propagates direct to the receiver. By covering the laser heated area with a thin piece of CFRP generation in the main plate is prevented and the airborne wave alone generated. Waveforms were taken at an angle of 15° with and without the CFRP cover to show this effect.

Using an acoustic absorber between source and receiver the direct airborne wave can be suppressed. To demonstrate this a box was constructed from furnace airbrick, a strong ultrasonic attenuator, to enclose the source area (see Fig.1). A hole in one face of the box allows the pulse to enter and the opposite box face is absent allowing the pulse to irradiate the plate. Generating the airborne wave only (protecting the surface with extra CFRP layer) waveforms were taken with and without the airbrick box in place.

EXPERIMENTAL RESULTS AND DISCUSSION

Variation of Received Signal With Transducer Orientation

Presented in Fig.3 are the typical waveforms , taken at 15°, showing air and plate borne waves and airborne waves only. Fig.3a shows a short pulse at 80μS as the first arrival followed at 100μS by low frequency components which grow increasingly complex. Fig.3b shows the first airborne arrival is at 190μS so after this time the signal in 3a is unreliable. Because of this, only the first 175μS of each signal is presented in Fig.4 which shows the waveforms taken as the transducers angular direction was varied. This 175μS time window develops as a result of the higher propagation velocity (≈1800m/s) of the plate wave relative to airborne waves (≈330m/s).

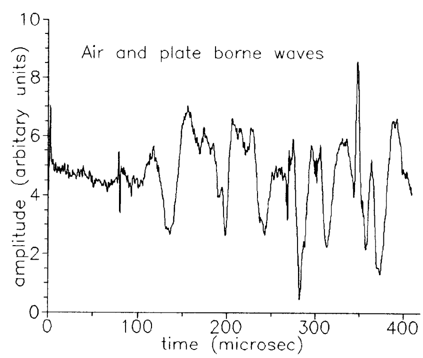

Fig.3a Air and plate borne waves.

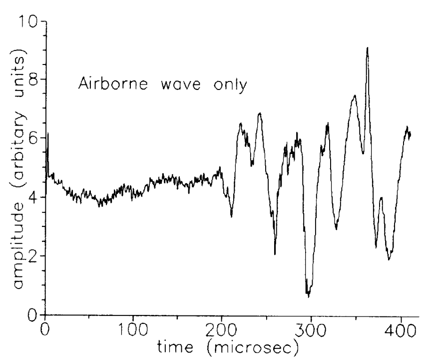

Fig.3b Airborne waves.

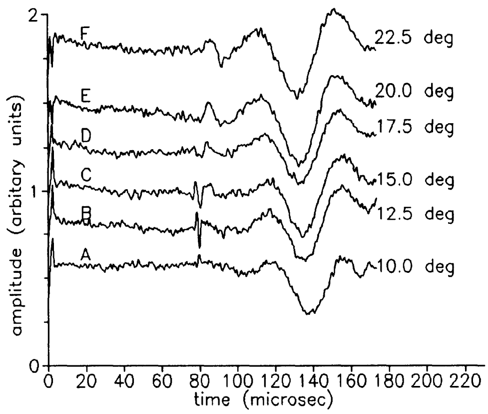

Fig.4 Received waveform as function of transducer angle.

Waveforms taken from 0°to 10° are not shown in Fig.4 as no significant changes occurred in this range. At 10°, the first indication of the 80μS arrival appears and at 12.5° it becomes clear reaching a maximum amplitude. At larger angles the width and time of arrival of this pulse increase, until it merges with the low frequency components present at all angles. The identity of this pulse and other arrivals has been established in Fig.5 by comparing waveform 4c with that taken in Scudder and Hutchins [3] using a high-fidelity transducer. The high fidelity waveform shows the laser source produces two plate wave modes; a non-dispersive S_0 (in Fig.5 it is 10x original amplitude for clarity) and a dispersive A_0. Placing the start of the high-fidelity waveform at the time taken for the re-radiated wave to cross the plate to transducer air gap, we see that the pulse at 80μS and

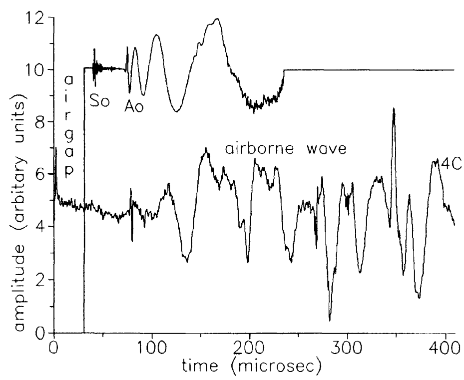

Fig.5 Comparison of high-fidelity and air transducer waveforms.

the low frequency components are the A_0 plate waves first arrival and low frequency components respectively.

The air transducer fails to pick up the S_0 plate wave as it is smaller than the current systems noise level which is significant. Averaging a number of pulses would improve the signal and with development the noise from the air transducer and its associated electronics could be minimised. Good correlation between the A_0 waveforms from the high-fidelity and air transducers comes from the frequency response of the air transducer being well matched to the frequency content of the plate wave which Scudder and Hutchins [3] found to be from 20-500KHz.

With the identity of the arrivals established their behaviour with increasing angle can be explained. A_0 waves have a phase velocity dispersion curve of the form of Fig.6. At low frequencies the velocity rises from zero levelling off at higher frequencies. As the angle (θ) between the transducer axis and the plate normal is increased the transducer detects waves re-radiating at shallower angles to the plate surface. The relation between the angle (θ) and plate wave velocity means such waves are propagating at lower velocity, hence the greater arrival time, in the plate. Fig.6 shows that this lower velocity is at a lower frequency so the initial pulse width must increase. An alternative phrasing is that the dispersive nature of plate wave propagation spreads the frequency content out in time (Fig.5). Then as the angle of the air transducer increases it picks up a lower velocity range creating a short time window moving along the waveform picking up lower frequencies as it does so.

The A_0 waves first arrival is detected at 10° and its velocity can be found with the relation ($C(Ao)=C_{air}/\sin\theta$) between the plate wave velocity ($C(A_0)$) and angle (θ). Using a literature value for the velocity of sound in air (C_{air}=330 m/s) a speed of 1900m/s is calculated. This correlates well with the 1800m/s measured in Scudder and Hutchins [3] for this arrival.

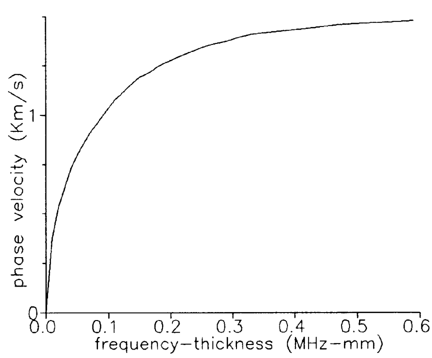

Fig.6 Phase velocity dispersion curve for Ao plate wave.

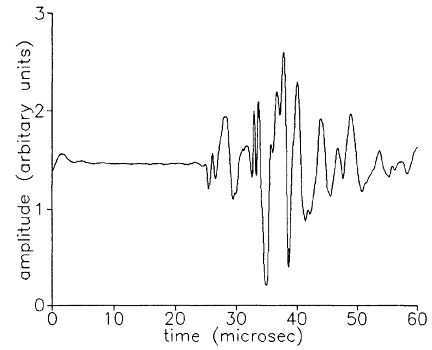

Fig.7a Airborne wave without airbrick attenuator.

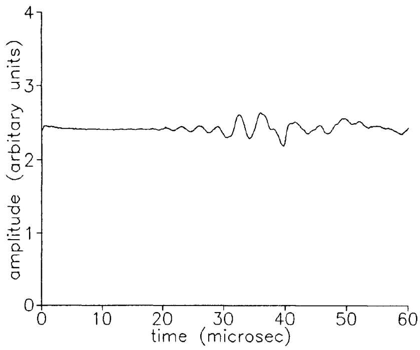

Fig.7b Airborne wave with airbrick attenuator.

Detection of the low frequency components of A_0 at all angles is slightly puzzling as in principle detection of these should be at angles over 20°. This may be caused by the larger amplitude and diffraction of the mode at low frequency enabling the air transducer receive it even when its alignment is not optimised. For converse reasons the high frequency component may only be received at the correct orientation of the transducer.

Attenuation of Direct Airborne Wave

In Fig.7 the waveforms taken to show the effect of the airbrick attenuator are displayed. The direct airborne wave has been reduced by 75% using the airbrick box. With this level of reduction it becomes possible to see the signal received from the plate but the distortion is still obvious. A better option may be to shield the transducer with a tube of attenuating material as the hole through which the laser pulse enters the airbrick box allows some of the airborne wave to escape.

SUMMARY AND CONCLUSIONS

This experiment demonstrated the feasibility of a laser ultrasonic analog to a conventional immersion system for the generation and reception of plate waves in thin composite materials. A non-ablative laser source produced the plate waves and a piezo-composite air transducer received the re-radiation from the sample. The identity of the received signal was demonstrated to be the A_0 plate wave and the waveform behaviour as the transducer direction changed explained by reference to the dispersion curve of that mode. Good correlation between the time domain waveforms of air and high-fidelity transducers arose from the frequency response of the air transducer being well matched to the frequency content of the plate waves. Velocity calculated for the first A_0 arrival from the angle at which it first appears correlates well with that from previous measurements on the same plate. The problem of the interference caused by the direct airborne wave was demonstrated and a possible method for suppressing this by an attenuating shield for source and/or receiver suggested.

It is envisaged that improved air transducers which are currently in development may make a significant improvement to the utility of this system when combined with optimised receiver electronics. Further studies in using air transducers as receivers for laser generated ultrasound are planned.

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