ELSEVIER

Ultrasonics 34 (1996) 405–409

Ultrasonics

Ultrasonic imaging using laser generation and piezoelectric air-coupled detection

W.M.D. Wright [a,*], D.A. Hutchins [a], G. Hayward [b], A. Gachagan [b]

[a] *Department of Engineering, University of Warwick, Coventry CV4 7AL, UK*
[b] *Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XW, UK*

Abstract

A non-contact ultrasonic system using a pulsed laser source and a wideband 1–3 connectivity PZT/epoxy composite transducer as a receiver has been used to produce images of defects in a variety of materials. Using both time and frequency information, through transmission images have been formed of delaminations and machined defects in both carbon fibre reinforced polymer (CFRP) and pultruded glass-fibre reinforced composites. Lamb waves have also been used to reconstruct tomographic images using a filtered back projection algorithm, for defects in thin plates of CFRP and Perspex.

Keywords: Piezoelectric air-coupled transducers; Composites; Imaging of defects

---

1. Introduction

There has been recent interest in the use of pulsed lasers to generate ultrasonic transients [1] for non-destructive evaluation in solid materials, as they are non-contacting. To utilise this benefit fully, a suitable non-contact detector is also required, the most common being some form of optical device [2], which usually requires a sample with good reflectivity. If the material to be tested is electrically conducting, capacitance transducers [3], or electromagnetic acoustic transducers (EMATs) [4] may be used, although they must be in close proximity to the sample. Advance composite materials such as carbon fibre reinforced polymer (CFRP) [5] and pultruded glass reinforced polymer (GRP) [6] composites are usully optically rough and electrically non-conducting, and so an alternative detector is required. Air-coupled ultrasonic tranducers are suitable devices, and may be divided into two main types: capacitance or electrostatic transducers [7,8], which consist of a thin metallised polymer membrane over a contoured conducting backplate, and piezoelectric [9,10] designs, one of which is used in the present work, described below.

A hybrid system of a pulsed CO_2 laser as a source of ultrasound and a 1–3 connectivity piezocomposite air-coupled transducer as a receiver was used to image various defects in polymers and composite materials. Using information in both the time and frequency domains, through transmission images were formed of both delaminations and machined defects in CFRP and pultruded GRP composites. Lamb waves [11] were also used to reconstruct tomographic images of defects in CFRP composite and Perspex, using a filtered back projection algorithm [12].

2. The non-contact system

The equipment used in the system is shown schematically in Fig. 1. Ultrasonic waves were generated in a sample using a Lumonics 'Lasermark' series Model 630 TEA CO_2 laser, delivering 100 ns pulse at 10.6 μm wavelength, with a maximum pulse energy of 8 J. Waveforms detected by the air transducer were amplified using a Cooknell CA6 amplifier, and then captured using a Tektronix 2430A digital oscilloscope. The signals were then transferred for storage and analysis to an IBM PS/2 model 30 286 PC via an IEEE-488/GPIB interface, which was also used to control the linear and rotary

---

* Corresponding author. Fax: +44-1203-418-922; e-mail: es770@eng.warwick.ac.uk

SSDI 0041-624X(95)00119-0

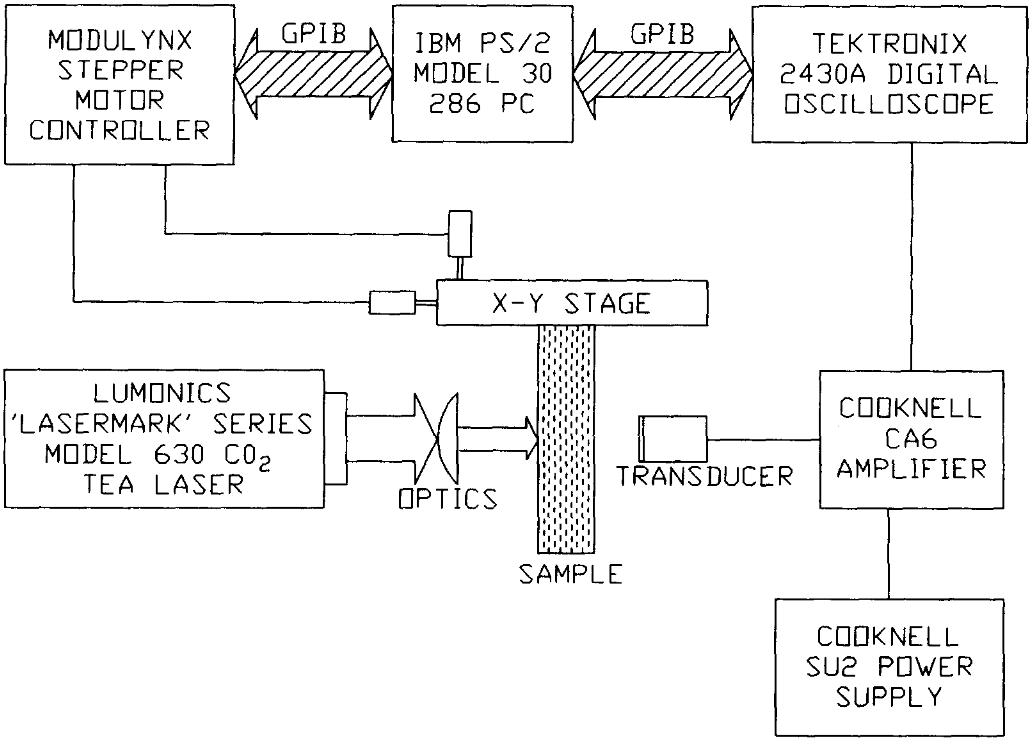

Fig. 1. Schematic diagram of the non-contact system.

stages using a Modulynx stepper motor controller. To produce the through transmission images, the receiver was placed directly behind the laser source on the opposite side of the sample, as shown in Fig. 1, but for the tomographic imaging the transducer was displaced by 80 mm on the same side of the sample as the laser source, and inclined at an angle to the plate to detect Lamb waves, which re-radiate energy or 'leak' into the surrounding air. The air coupled transducer used as a detector was constructed from a 15 mm diameter disc of a 1–3 connectivity piezocomposite. The piezoelectric element, shown schematically in Fig. 2, consisted of square pillars of PZT/5A piezoceramic in a matrix of CIBA-GEIGY CY1300/HY1301 epoxy resin and was manufactured using the standard slice and fill technique [13].

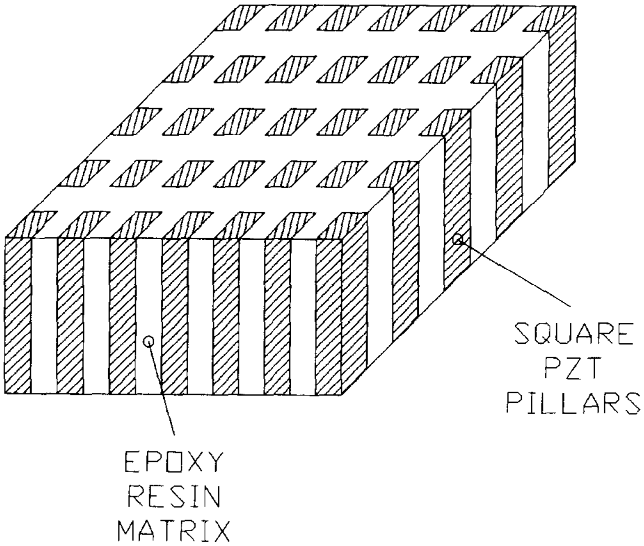

Fig. 2. A 1–3 connectivity piezocomposite transducer element.

3. Through transmission images

Various data processing techniques were used to produce the through transmission images. By selecting a window in the time domain waveform, any change in amplitude or time of flight of a part of the signal could be monitored. By performing a fast Fourier transform (FFT) of each waveform, a similar technique could be employed in the frequency domain. Only a selection of the defects imaged will be presented here. Each scan was 50 mm by 50 mm, with a resolution of 1 mm.

Fig. 3 shows images of defects in CFRP, formed using the change in signal amplitude. Fig. 3(a) was a 25 mm square delamination, in a 16 ply unidirectional composite plate, which was formed by replacing the central eight plies with layers of Teflon tape during manufacture. Fig. 3(b) shows a 10 mm diameter cylindrical hole machined to half the thickness of a 32 ply cross-ply composite plate. The size and shape of each defect can be clearly resolved. Fig. 4 shows images of a 10 mm diameter flat hole machined to a depth of 1 mm in a 10 mm thick pultruded GRP composite, formed using

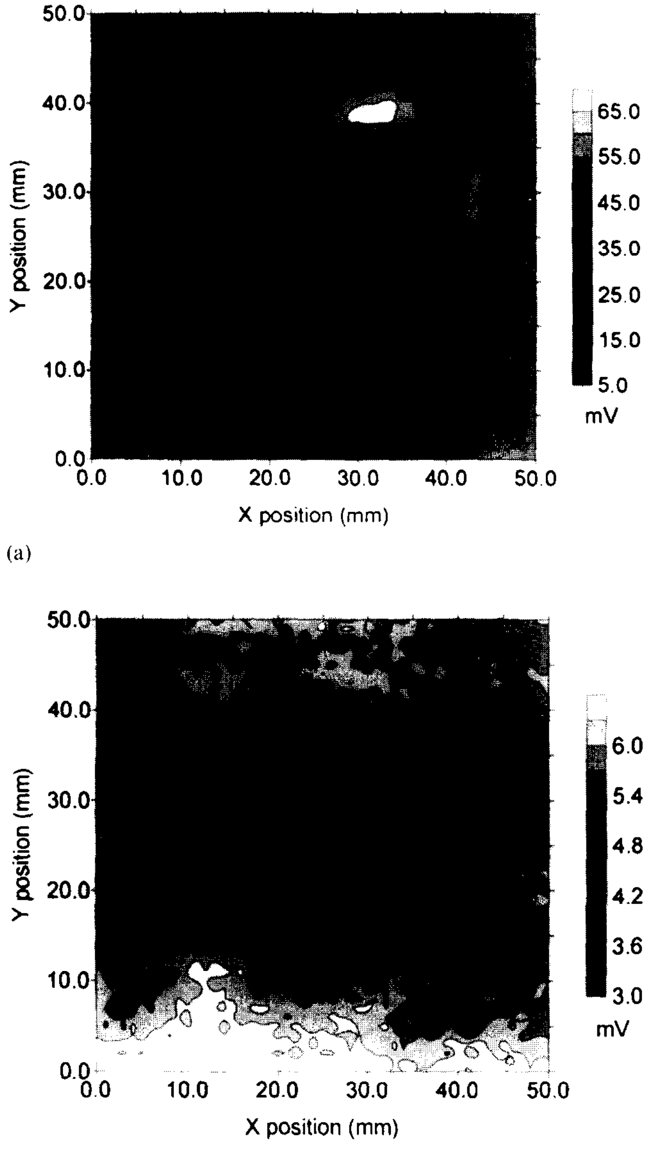

Fig. 3. Images of defects in CFRP, using change in signal amplitude, for (a) a 25 mm square delamination in a 16 ply unidirectional composite plate, and (b) a 10 mm diameter flat hole machined to half the thickness of a 32 ply cross-ply composite plate.

(a) signal amplitude; (b) shift in time of flight; (c) FFT amplitude; and (d) frequency shift. The defect is clearly discernible using each method, as is a resin rich area running horizontally through the image.

4. Tomographic imaging using Lamb waves

For tomographic imaging, a series of views or 'projections' of the slowness (inverse of velocity) function through the object in angular steps of α was built up using parallel 'rays' of Lamb waves a fixed distance d apart, as shown in Fig. 5. Each ray contains the line integral of the slowness function between the source and receiver. The filtered back projection algorithm used [12] states that the Fourier transform of a projection of this slowness function, at an angle θ through the object, is also the two-dimensional Fourier transform of the actual slowness function at that same angle through the centre of the object. The inverse of this transform, required to obtain the slowness function, reduces to a back projection of all the projections convolved with a 'kernel' function or filter. Each scan had 51 rays which were 1 mm apart, and 37 projections through 180° in steps of 5°. Fig. 6 shows the reconstructed slowness tomographic images (obtained using time of flight variations) for (a) a 5 mm diameter hole through a 1 mm thick sheet of Perspex; and (b) for the 10 mm diameter

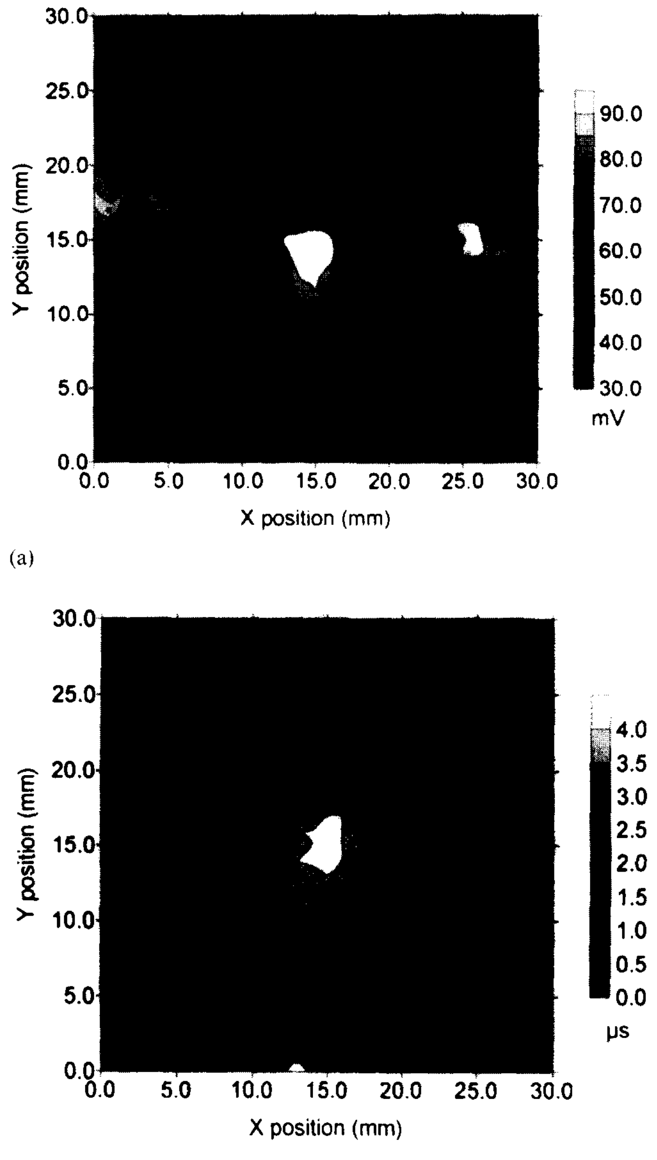

Fig. 4. Through transmission images of a 10 mm diameter flat hole machined to a depth of 1 mm in a 10 mm thick pultruded GRP composite, formed using (a) signal amplitude; (b) shift in time of flight; (c) FFT amplitude and (d) frequency shift.

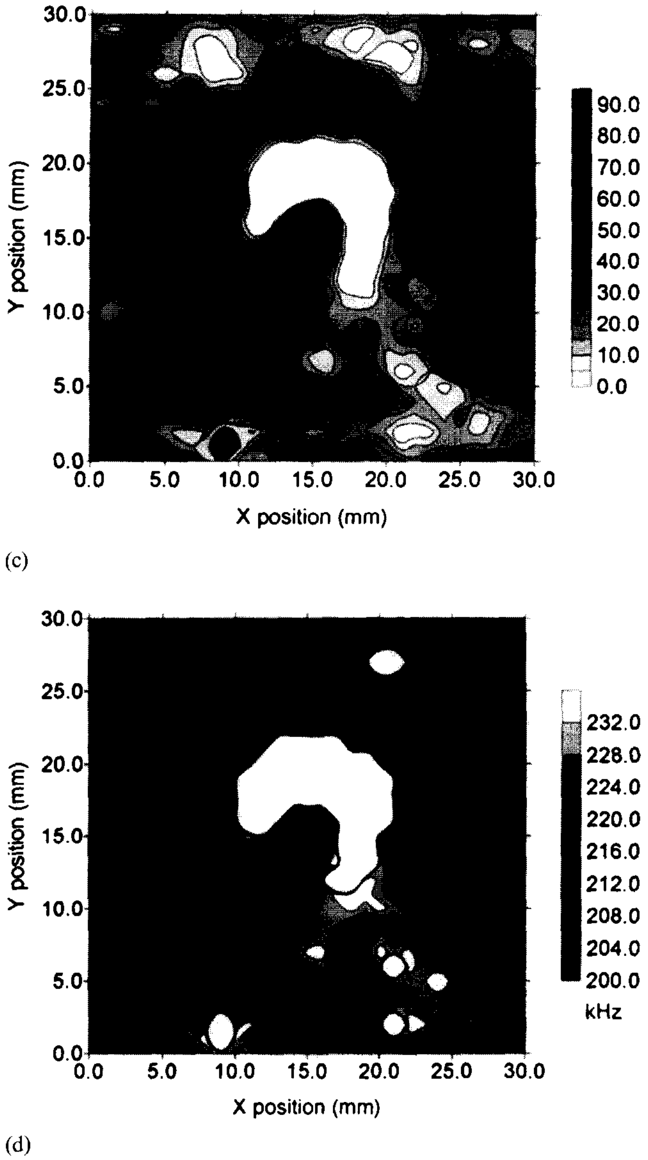

Fig. 4 (continued).

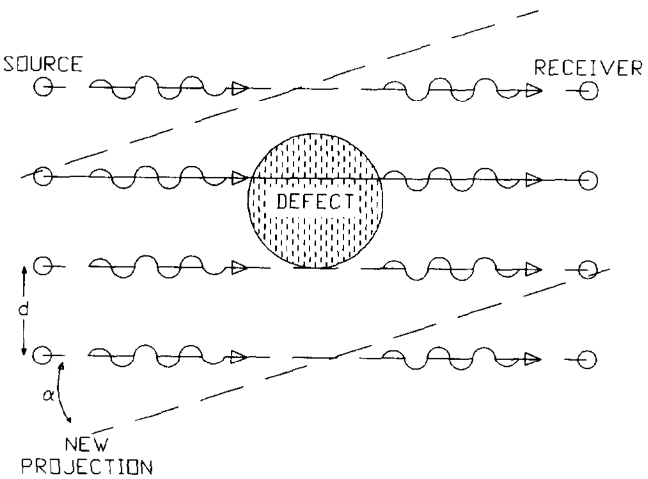

Fig. 5. Tomographic image reconstruction technique.

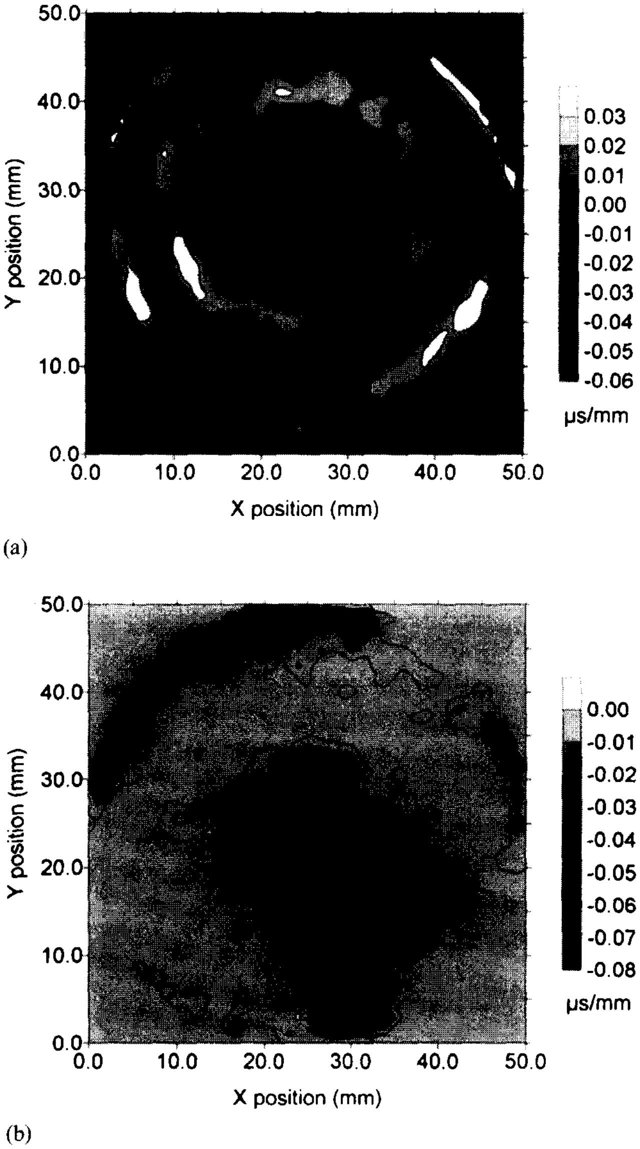

Fig. 6. Reconstructed slowness tomographic images (using time of flight variations) for (a) a 5 mm diameter hole through a 1 mm thick sheet of Perspex; and (b) for the 10 mm diameter flat hole in 32 ply CFRP.

flat hole in 32 ply CFRP imaged earlier. Again, each defect is clearly discernible.

5. Conclusions

It has been shown that a hybrid non-contact ultrasonic system using a pulsed CO_2 laser and piezocomposite air-coupled detector was successfully used to image a variety of defects in composite materials. Through-transmission images of delaminations and machined defects in CFRP and pultruded GRP have been produced, and the reconstruction of tomographic images using Lamb waves demonstrated the flexibility of the system for future ultrasonic non-destructive testing applications.

References

[1] D.A. Hutchins, In: Physical Acoustics – Principles and Methods, Vol. XVIII (Eds. Mason W.P. and Thurston, R.N.) (Academic Press, New York, 1988) 21.

[2] J.-P. Monchalin, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. UFFC-33 (1986) 485.

[3] W. Sachse and N.N. Hsu, In: Physical Acoustics – Principles and Methods, Vol. XIV (Eds. Mason W.P. and Thurston, R.N.) (Academic Press, New York, 1979) 277.

[4] R.B. Thompson, In: Physical Acoustics – Principles and Methods Vol. XIX (Eds. Thurston, R.N. and Pierce, A.D.) (Academic Press, New York, 1990) 157.

[5] P.K. Mallick and S. Newman, (Eds.) Composite Materials Technology: Process and Properties (Hanser, Munich, 1992).

[6] R.W. Meyer, Handbook of Pultrusion Technology (Chapman and Hall, New York, 1985).

[7] H. Carr and C. Wykes, Ultrasonics 31 (1993) 13.

[8] D.W. Schindel, D.A. Hutchins, L. Zou and M. Sayer, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. UFFC-33 (1995) 485.

[9] W. Manthey, N. Kroemer and V. Mágori, Meas. Sci. Technol. 3 (1992) 249.

[10] W.A. Smith and B.A. Auld, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. UFFC-38 (1990) 40.

[11] I.A. Viktorov, Rayleigh and Lamb Waves – Physical Theory and Applications (Plenum Press, New York, 1967).

[12] A.C. Kak and M. Slaney, Principles of Computerised Tomographic Imaging (IEEE Press, New York, 1988).

[13] J.A. Hossack and G. Hayward, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. UFFC-38 (1991) 618.