FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

NON-DESTRUCTIVE TESTING OF COMPOSITES USING LONG WAVES

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A new technique for detecting faults in composite panels has been developed based on measurements of the local phase velocity of low frequency flexural waves. Broadband excitation is used so the method includes source configurations and software to reduce the effect of the reverberant field. An X-Y scanning version has been built employing non-contact methods and a handheld version based on a note book computer has also been constructed. The method has been used on multi-ply panels to determine stiffness matrix elements and lay-up errors. Delaminations and core damage in honeycomb sandwich panels have also been detected via scattering of the waves.

1. INTRODUCTION

Composite materials are rapidly replacing metals in many applications, because of their superior performance and reduced weight. In the aerospace industry in particular, carbon fibre composites are becoming more common. All aerospace structures must be tested at manufacture, and most at regular intervals during service. It has become essential to develop methods of testing which are both cost-effective and practical to implement.

A method has been devised using low frequency acoustic waves, which can detect many typical defects in composite structures. The method supplements manual ultrasonic pulse-echo methods, and the automated "Through Transmission Ultrasound" (TTU) scanners. Unlike the latter, the new method is not limited to structures accessible from both sides, and is also suitable for structures which may be harmed by the water jet couplants of TTU.

2. PHASE VELOCITY

The new method is based on measurement of the phase velocity of acoustic waves travelling in the structure being tested, typically some sort of panel. Continuous broadband vibration is introduced into the panel, and as the resulting waves propagate out from the point of excitation, they are detected by two transducers which are spaced apart by a distance **d**. In principle, the velocity *c* of the wave component of frequency **f** Hz is simply

$$\mathbf{c(f) = 2\pi fd / \phi} \qquad (1)$$

where ϕ is the phase difference measured by the two transducers. Any structural anomalies will change the Local Phase Velocity (LPV) of propagation.

In practice it is not that easy. Reflections from boundaries and from structural discontinuities result in a reverberant field which can completely swamp the propagating wave which we are trying to measure. A major feature of the new method is the development of techniques to overcome the reverberant field.

3. THE REVERBERANT FIELD

It has been shown [1] that a propagating wave in a plate is relatively unaffected by a diffuse field, ie a field such as would be created by a large set of uncorrelated random noise sources arranged around the edge of the plate. The present authors [2] have shown that the reverberant field can be made to resemble a diffuse field if the point source of broad-band excitation is either (a) moved along a line, or (b) replaced by a set of uncorrelated point sources arranged along a line. In either case it is advantageous to arrange the line of excitation to be collinear with the LPV measuring points.

4. WAVE PROPAGATION IN COMPOSITE PLATES

The LPV method uses waves which propagate parallel to the plate surface, but with displacements normal to the surface. The type of propagation depends on the plate thickness **h**. For isotropic plates in which $\mathbf{h < \lambda/5}$, where λ = wavelength of the propagating wave, through-thickness shear strain is negligible and the waves are classic bending waves. Propagation is dispersive in this case, ie the phase velocity varies as the square root of the frequency [3].

For thicker isotropic plates, with $\mathbf{h > \lambda/5}$, shear strain tends to dominate, and the waves propagate at a velocity which is constant with frequency.

Both types of propagation have been encountered and utilised in developing the LPV method. As composite plates are not generally isotropic, the velocity of propagation varies with direction in a plate, and the condition for transition between dispersive and non-dispersive propagation may differ from the above.

5. MEASURING LOCAL PHASE VELOCITY

An X-Y scanner has been built to implement the LPV method. The required broad-band excitation is by a row of jets supplied with compressed air from a standard workshop compressor. The vibration measuring sensors are two Doppler-laser velocity transducers (Polytec OFV352), which are mounted on the armature of the scanner together with the array of jets. Also on the armature are steering mirrors to direct the laser beams to be approximately normal to the panel, and to direct the returning light into the detectors. The scanner can accommodate panels up to 1.5m wide.

The laser beams impinge on the test panel at points separated by a distance **d**, usually about 30 to 50 mm. The signals from each detector are simultaneously sampled with a fast A/D converter. Both signals are Fourier transformed with a programmable FFT analyzer (hp3567A) which then computes the complex frequency response function (**FRF**) between the two transformed signals.

To get clear phase information from the measurements, a number of stratagems have been adopted. The first of these is the use of a line array of excitation sources, which makes the reverberant field resemble a diffuse field. A second involves taking an average, in the frequency domain, of several sets of readings taken in quick succession.

For the case of "thin" plates (see **4** above), the program plots the phase of the **FRF** against $\sqrt{\mathbf{f}}$, and thence the phase velocity at frequency **f** is computed as

$$\mathbf{c(f) = 2\pi d\sqrt{f} / S} \tag{2}$$

where S is the slope of a line fitted by least squares to the plot of phase ϕ against $\sqrt{\mathbf{f}}$. For "thick" plates, $\mathbf{d\phi/df}$ is nominally constant, so ϕ is plotted against **f** instead, and the phase velocity is

$$\mathbf{c = 2\pi d / S} \tag{3}$$

where S is the slope of a line fitted in this case to a plot of ϕ against **f**.

The phase at each point is computed as the inverse tangent of ***I/R***, where ***R*** and ***I*** are the real and imaginary parts of the **FRF**. A further stratagem is to apply a smoothing function, in the frequency domain, separately to the real and imaginary parts of the **FRF.** This eliminates most of the remaining reverberant effect. Without this step, it is almost impossible to unwrap the propagant phase needed for Eqs (2) and (3).

6. AN APPLICATION TO THIN LAMINATED COMPOSITE PLATES

The local phase velocity was measured and plotted as a function of direction, in 10° steps, on a sample of 3-ply plate 1.2mm thick. Each ply was of carbon fibres woven at 90° to each other (see Figure 3(a)). Excitation and analysis were for the frequency range 5.0 to 17.8kHz, within which the phase varied as $\sqrt{\mathbf{f}}$ as expected, and the phase velocity for **f** = 20kHz was calculated from equation (2). An interactive program was developed to fit a 3x3 matrix to stiffness values calculated from these results, shown plotted in Fig 1 (a) and (b). The continuous curve is for the fitted model. Stiffness along each of the principal in-plane axes was found within approximately 5%, and shear stiffness within 10%. A small asymmetry between the x and y directions was clearly distinguishable.

The same technique was applied to a sample of composite plate, approximately 4mm thick, built up from 12 plies of unidirectional fibres. Relative to the principal in-plane axes, successive layers were oriented at angles +45°, 90°, -45°, 0° etc as shown in Fig 3. Velocity measurements were made as before in 10° steps. At angles between 35° and 55°, velocities were found to vary considerably at different locations on the plate; this has been attributed mostly to very small variations in the distance between outer plies and the neutral plane of the plate. For this reason, the points in Fig 2 are averages over several positions on the plate. Even with such averaging, to achieve the fit of the curve in Fig 2 it was necessary to rotate the angle of plies 3 and 10 in the model from –45° to –49°. These results show the localization capability of the technique.

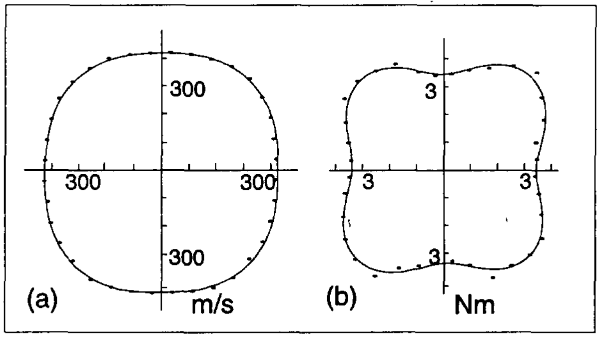


Figure 1
3-ply carbon fibre composite panel
(a) Phase Velocity versus direction,
(b) Stiffness along fibres versus direction

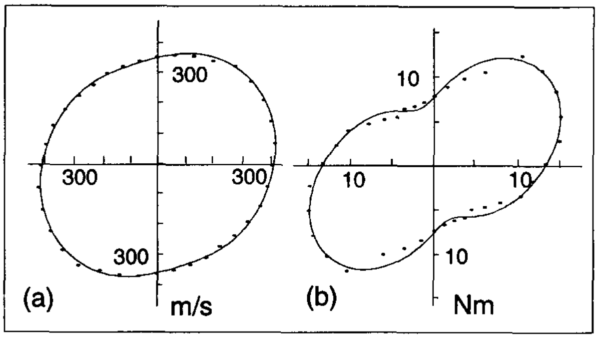


Figure 2
12-ply carbon fibre composite panel
(a)Phase Velocity versus direction,
(b) Stiffness along fibres versus direction.

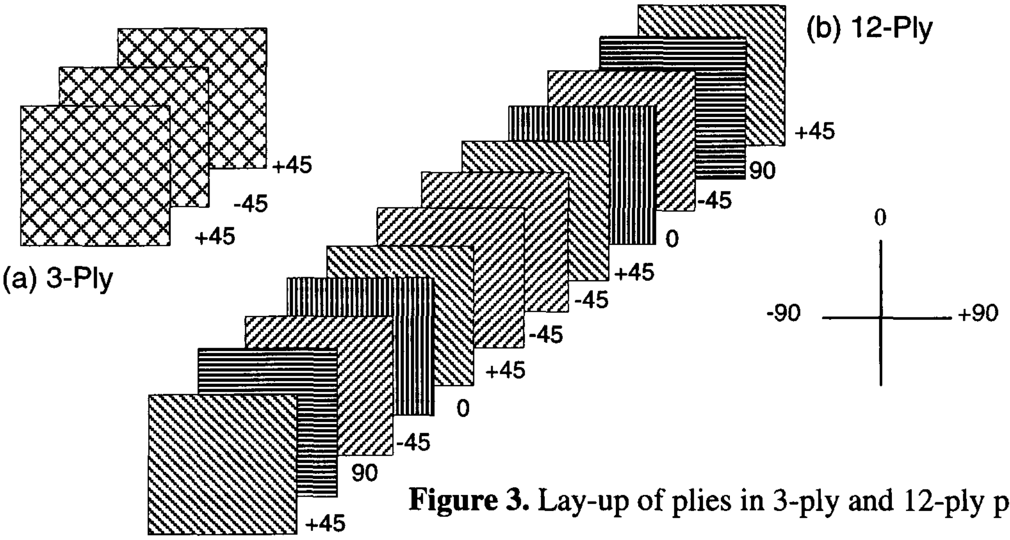


Figure 3. Lay-up of plies in 3-ply and 12-ply panels

7. APPLICATION TO NOMEX HONEYCOMB SANDWICH PANELS

A typical structure in aerospace components is a composite panel with outer skins of 3 to 10 plies of carbon fibre, sandwiching a core of epoxy coated paper in an hexagonal arrangement ("nomex") as shown in Fig 4. The most common defects in such "honeycomb sandwich" structures, also shown in the figure, can occur either in manufacture or in service. Crazed or crushed core, in particular, can be produced by an impact which may leave little visible external damage.

LPV measurements were made on samples of panel which had 10mm nomex cores with skins of 3-ply and 4-ply woven carbon fibre. It can be shown [4] that, for panels such as these, the waves are dominantly shear for frequencies greater than about 1 kHz, thus non-dispersive propagation can be expected and the appropriate equation is (3).

Excitation and analysis was for the frequency range 5 kHz – 30 kHz. Fig 5 shows (outer points) velocity data from a set of measurements at 10° steps. The form of the obvious orthotropic symmetry is due to the double thickness of the honeycomb core walls in the direction of the bond lines, shown in Fig 4. This can be contrasted with the symmetry for the skin alone, shown for two different frequencies in the two inner sets of points.

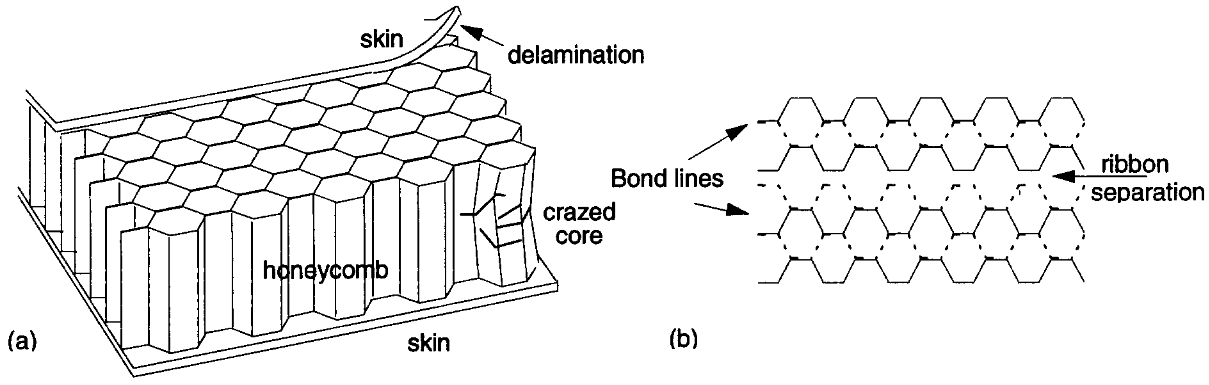


Figure 4. "Honeycomb Sandwich" panel, showing typical defects.

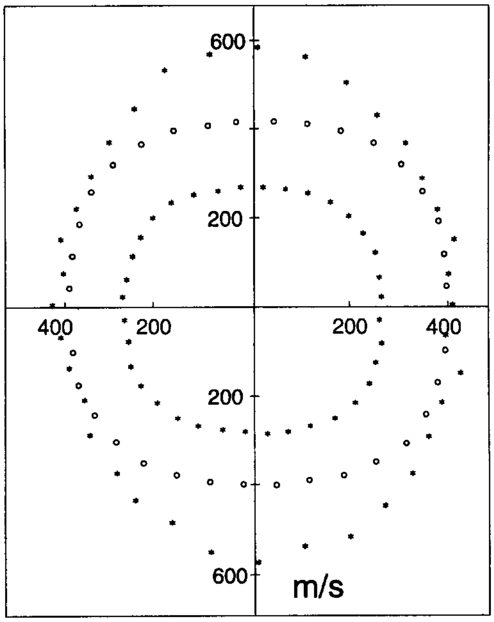


Figure 5. Phase velocity versus direction, honeycomb sandwich panel (outer set of points)

Core damage in panels such as these decreases the core shear stiffness, thus reducing the phase velocity locally. LPV measurements from either face of these panels were able to unambiguously locate artificially produced core damage, as in Fig 6.

Artificially produced delaminations were also detected using the LPV scanner. They could be distinguished from other forms of damage by characteristic patterns of variation in the apparent LPV, as the scan approached and passed over the defect. Fig 7 shows this for a scan collinear with the exciter jets and the detectors: the central dip locates the defect. For the dotted trace, the characteristic peaks and troughs either side of the fault show that the delamination is under the skin on the face being measured. The solid line shows the same delamination measured from the opposite face of the panel; the asymmetry is characteristic. These features have been shown [4] to be due to scattering from the defect, producing distortions of the otherwise rectilinear phase/frequency plot. Fitting a line to such a plot does not give the true LPV, but it clearly distinguishes this type of defect.

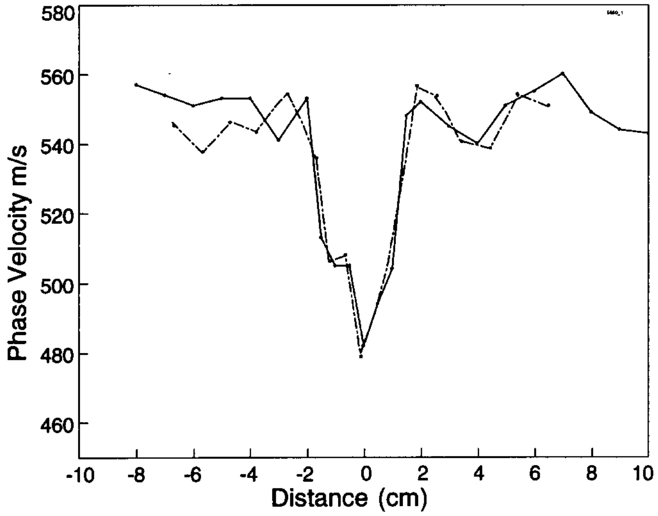


Figure 6. LPV scan across a crushed core defect, measured on the two sides of the panel.

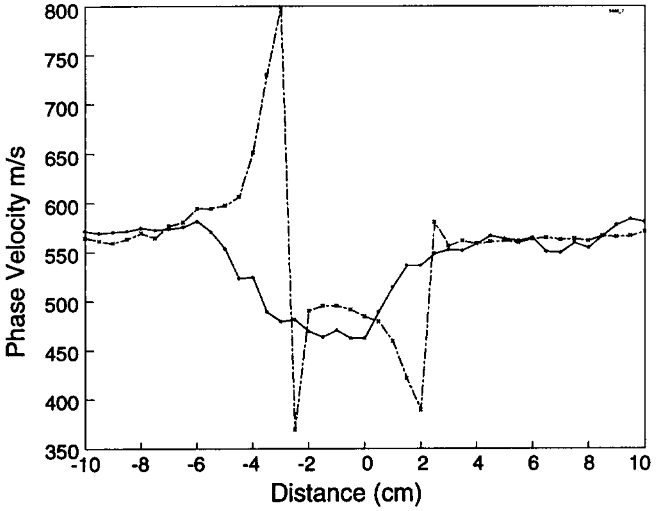


Figure 7. LPV scan across a delamination on -----same face,____on opposite face of panel.

8. A PORTABLE LPV DEVICE

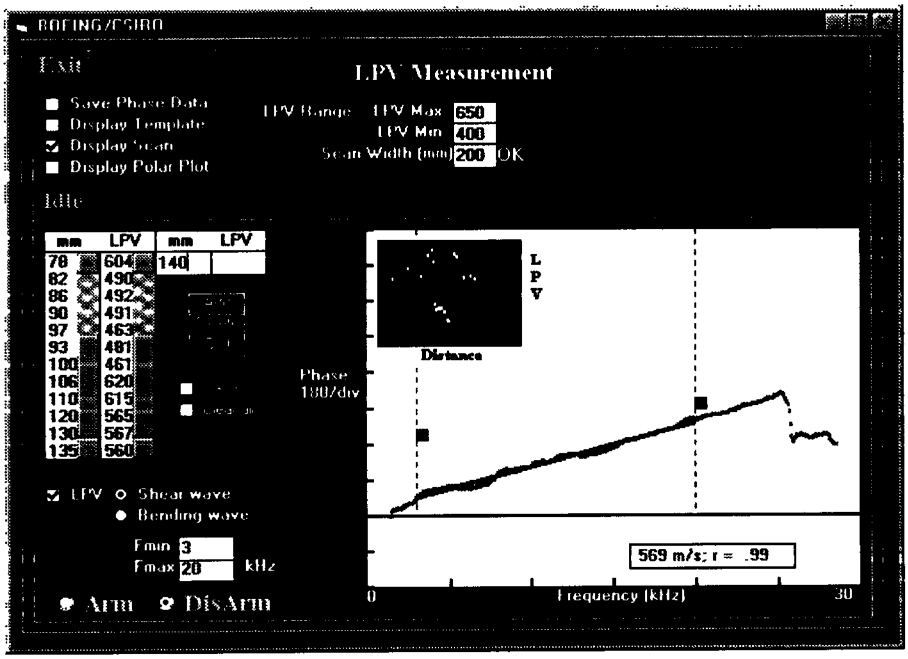
A portable instrument has been developed to enable the LPV technique to be used in the field (or on the tarmac). The main physical components are a laptop computer, a PCMCIA DAQ card, and a measuring probe, which has become known as a "ferret" (Fig 8).

The ferret is a light, hand-held device which incorporates a row of air-jet exciters; these are fed by a hose from a compressor or a cylinder of compressed air. In the front half of the ferret are two ultra-light accelerometers (Endevco 2250-10), attached to self-aligning tips which contact the surface of the test object. The accelerometers are supported in nylon mounts designed to minimize unwanted transmission of waves between the accelerometers, through the ferret body. Behind the accelerometers is surface-mount conditioning electronics. The mounted accelerometers and electronics are matched for phase for frequencies up to 25 kHz. A thumb-operated start button turns on the compressed air, which in turn activates a switch to trigger the data collection and processing.

The data acquisition card (INES DAQi148) incorporates two 14-bit A/D converters synchronized for simultaneous data collection from the two accelerometers. The card can run at up to 330 kS/s per channel, but for this application it is run at 60 kS/s.

Figure 8. Hand-held LPV probe.

All the data processing is carried out by routines in a Visual Basic program developed as an essential part of this instrument. The processes include Fourier transforms, frequency response, averaging, smoothing, phase unwrapping, line fitting, velocity calculation, plotting and screen displays. LPV analysis is generally carried out within the range 2 to 25 kHz, but these limits can be adjusted if necessary.



☐ Save Phase Data
☐ Display Template
☑ Display Scan
☐ Display Polar Plot

LPV Range LPV Max 650
LPV Min 400
Scan Width (mm) 200 OK

mm	LPV	mm	LPV
78	604	140	
82	490		
86	492		
90	491		
97	463		
93	481		
100	461		
106	620		
110	615		
120	565		
130	567		
135	560		

☑ LPV ○ Shear wave
● Bending wave

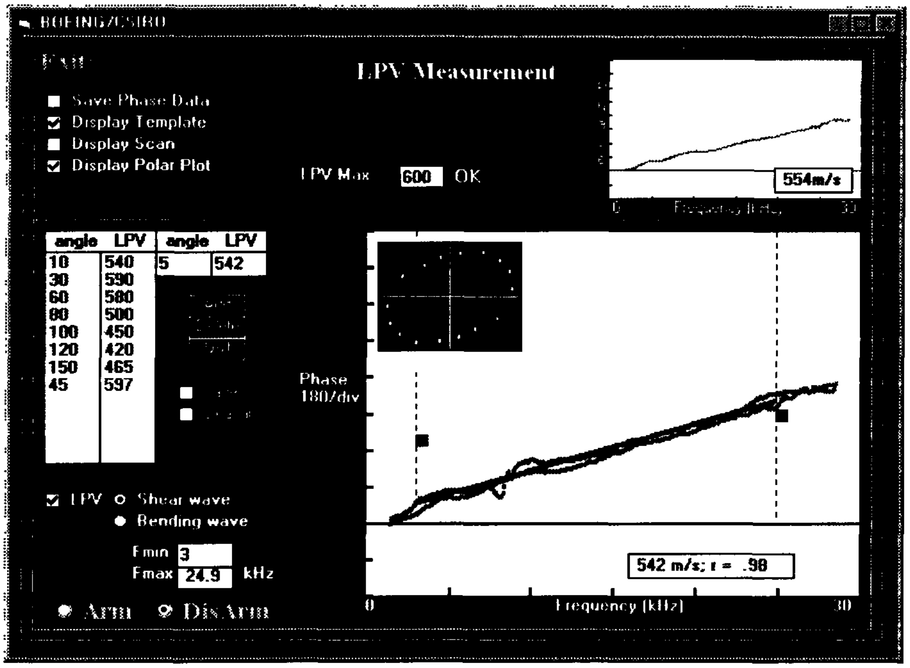
Fmin 3
Fmax 20 kHz

569 m/s; r = .99

Figure 9. Screen display of portable LPV instrument for rectilinear scan of a composite panel.

Fig 9 is a typical screen display. The main section shows a phase/frequency plot for the most recent measurement on a panel. Inset shows results, as velocity/distance, at several points stored from a scan across a core defect. A phase/frequency plot can be stored as a template, from a measurement on a supposedly fault-free section of the panel. This template can be displayed in the main section for rapid comparison with the latest measurement. Fig 10 is similar, but the inset shows results of LPV versus angular direction in a panel.

The computer used for the prototype was a "Fieldworks" ruggedized laptop, but many other laptop or notebook computers would be suitable, provided that they can accommodate a type II PCMCIA card and supply sufficient current to drive the electronics.



■ Save Phase Data
☑ Display Template
■ Display Scan
☑ Display Polar Plot

LPV Max 600 OK

angle	LPV
10	540
30	590
60	580
80	500
100	450
120	420
150	465
45	597

angle	LPV
5	542

☑ LPV ○ Shear wave
● Bending wave

Fmin 3
Fmax 24.9 kHz

● Arm ○ DisArm

Figure 10. Screen display for a scan of LPV versus direction in a composite panel

9. CONCLUSION

A new method, Local Phase Velocity (LPV), has been developed for non-destructive testing of composite panels using plate waves at frequencies less than 50 kHz. The method complements existing ultrasonic techniques for detecting defects. An X-Y scanner has been constructed to perform automated non-contact scans over panels up to 1.5 m wide. A portable device has also been developed to implement the method.

10. ACKNOWLEDGEMENTS

The following people provided valuable assistance to this project: M.Basaglia, A.Batten, P.Dencher, L.Dickinson, B.Meldrum, and D.Whitnall. The work was carried out as part of a collaborative research agreement between CSIRO and the Boeing Commercial Airplane Group, and with the cooperation of two of Boeing's Australian suppliers – Hawker de Havilland (Aust) and AeroSpace Technology Australia.

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