CHARACTERISATION OF SOFT IMPACT DAMAGE IN COMPOSITE SANDWICH PANELS USING A "PITCH-CATCH" ACOUSTIC PROBE.

Laurence. P. Dickinson & Suszanne Thwaites
CSIRO Telecommunications and Industrial Physics
Sydney NSW 2070

Abstract: This paper discusses an investigation of the detection of low-velocity, soft impact damage in Nomex honeycomb cored, carbon fibre composite sandwich panels using a low frequency acoustic technique. A commercially available probe head was used on an automated scanning table to perform a raster scan on prepared test panels. Various processing techniques were used to analyse the data but it was found that a simple integrated difference algorithm provided a surprising amount of detail about core damage that is virtually invisible on the panel surface. The patterns that emerged from the scans appear mode-like and the complexity looks to be related to impact severity.

1. INTRODUCTION

Carbon-fibre skinned, Nomex (paper-resin) honeycomb cored sandwich panels are widely used in the aerospace industry. During their lifetime these panels are often subjected to myriad impacts including, for example, dropped tools, stones flung up from the runway and hail. It has been found that a particular form of impact that results from collisions with soft-bodied objects travelling at low velocities (eg detached fragments of tyre tread or birds) can create core damage which is invisible on the surface. This damage is frequently very difficult to detect using conventional NDT techniques employed for in-service panel inspection. These techniques include such methods as acoustic, ultrasonic, thermographic and X-Ray. The most common of the above are acoustic where commercially available systems use mechanical impedance, resonance and so called "Pitch-Catch" approaches. This study centres on a Pitch-Catch acoustic, commercially available probe.

2. THE PITCH-CATCH PROBE

The Pitch-Catch probe is one of a number of acoustic probes available with many commercial scanning systems such as those used in the aircraft industry. This instrument works on the general principle of using vibration to detect changes in the mechanical properties of a test piece, associated with some form of defect, in the region local to the probe / panel contact. A "Pitch-Catch" probe refers to the fact that there are two piezoelectric accelerometers spaced a fixed distance of 10 to 20 mm apart. One of these accelerometers acts as a transmitter (hence the "Pitcher"), and the other is a dedicated receiver (the "Catcher"). The accelerometers are symmetrical with regard to drive and receive channels and have contact pins that are a push fit, not bonded to the bottom of the accelerometer housing. Fairly compliant springs are employed to hold each tip against the object being examined, a dry contact – no couplant is used. These springs also provide some isolation from the probe housing and reduce any cross talk between the two tip accelerometers. These features are shown schematically in Figure 1.

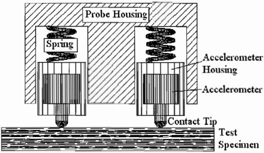


Figure 1 A diagrammatic representation of a Pitch-Catch probe used in the study

Typical use in a commercial system involves transmitting a sinusoidal tone-burst into the panel under examination and the signal received (from the catcher) is digitised. According to operating instructions, the operator is first asked to place the probe on a supposedly "good" section of panel. A series of digitized reference waveforms is then obtained while the burst frequency is incremented over the range 5 kHz up to 40 kHz. A second series of samples is taken over a known defect, which is normally a test panel that has had various defects introduced into it such as milled holes to simulate core damage, or Teflon wafers to represent disbonds. A comparison is then made between the two sets. For example, a single point may be chosen in the time-domain and the amplitude and phase difference between the reference waveform and a waveform from the known defect sampled at the matching frequency are used to indicate that damage is present. The working frequency is chosen such that there is the greatest difference seen between the known defect and the reference panel. This frequency is often in the region of 20 to 25 kHz where the strongest output signal from the probe can be obtained.

Once a working frequency is chosen and a sample waveform is stored of a "good" section of panel, the operator can then pick and place the probe by hand over areas of interest.

3. THE PROBE – UNDERSTANDING ITS BEHAVIOUR

A calibration of the probe by the CSIRO National Measurement Laboratory Acceleration Standards group revealed some interesting behaviour. Figure 2 shows a calibration of one of the probe tips for loaded drive response. The tip was excited with a constant sine wave of 5 volts amplitude and its output was measured on a force transducer mounted on a heavy inertial block. The probe displayed two high Q resonances, one of which is in the range 20 to 25 kHz.

Examination of the probe structure, shown in Figure 1, suggests that a probable source of these resonances is the spring-mass system consisting of the accelerometer mass and the compliance associated with the contact tip. The large spring will also have a resonance associated with it but this is at a much lower frequency, well below the useable range of the instrument. A very rough model for the probe tip is that of a simple vibrating rod loaded with a mass at one end. The termination at the other end will vary considerably depending on the panel impedance and coupling efficiency. From [1] the angular vibrational frequencies of a free-free bar are

$$f_n = \frac{n}{2}\frac{c}{L} \qquad (1)$$

where $n = 1$ for the fundamental resonance, c is the compressional wave velocity and L is the length of the contact tip.

This frequency is considerably lowered by the mass on the end. The end-correction to the length is given approximately by the factor $(1+M/m)^{-1}$ where M is the added mass and m is approximately half the tip mass.

Assuming that the tip material is Nylon, c is in the range 1600 to 2670m.s^{-1}. If this is inserted into equation 1 with measured values for m, M and L, the fundamental loaded resonance frequency is in the range 22 to 36 kHz in agreement with the peaks seen in Figure 2. Little useful information can be obtained if the working frequency for the probe is chosen to be close to these frequencies.

To illustrate the effect of these resonances on the probe response when in use on a panel, the probe was driven with a step excitation. The dark line in Figure 3 shows the spectrum of the output over a good region of panel and the light coloured line shows the spectrum over a known impact site.

The two dominant peaks in both spectra above 20 kHz are artefacts of the probe more that any effect of the panel. However there is a marked peak unique only to the sample over the damage at a much lower frequency of about 11 kHz. On the basis of these results, a sine burst in the region of 11 kHz is the optimum test excitation to use for this type of panel and form of defect. To further reduce the effect of the probe characteristics, and those from mounting mechanism noise, a 2 kHz and 13 kHz band pass filter should also be used.

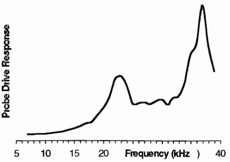


Figure 2 Calibration of one of the probe tips for drive response

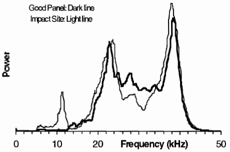


Figure 3 Spectra of probe's output with impulse excitation over an area of good panel and an impact site

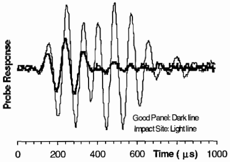


Figure 4 Response of the probe driven with a 2 cycle, 11kHz tone burst over an area of good panel and an impact site.

Figure 4 shows a time waveform taken from the probe's response while being driven with a 2 cycle, 11kHz sine burst with the band pass filter on the receive channel. The waveform from the region over the impact site (light coloured line) shows a pronounced resonance at approximately 11 kHz, as expected from the results in Figure 2. This paper does not examine the mechanisms behind these local panel resonances, but they are discussed in [2] & [3] where plate modes were explored and a relationship between damage area and impact severity was drawn.

4. PRODUCTION OF TEST SAMPLES

Information obtained from panel manufacturers and aircraft testing laboratories suggests that the type of defects present in the test panels provided with commercial NDT systems, a few of which were mentioned in a previous section, are uncharacteristic of damage the panel is likely to encounter in its service life. Of much more interest is impact damage that crushes or "crazes" the paper honeycomb core but leaves no visible indication on the panel's surface. We have conjectured [2] that skin failure may be bypassed in the damage process if the projectile's surface is non-rigid. The impact then occurs over a longer time and alternative mechanisms of energy dissipation such as full panel strains and vibration modes can occur. The strain may then be sustained elastically by the skin.

A series of test panels with known characteristics and damage profiles was essential for this investigation. In particular, damage imposed on these panels needed to be controlled and repeatable. To this end a drop impact apparatus was designed that allowed adjustable impact head (commonly referred to as the "tup"), mass and velocity. The apparatus was built around an 84mm diameter Perspex tube, through which the tup falls and is guided by Teflon runners. A system was also devised to catch the tup after the initial impact to prevent multiple strikes. This consists of an optically triggered shutter at the base of the tube that is closed when the tup has hit the panel and has travelled past the end of the tube on its rebound. To provide a non-rigid impact surface, the tup was covered in 6mm thick extruded rubber, Durometer (A) hardness of approximately 65, that was machined to give it a rounded profile.

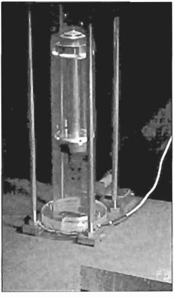


Figure 5 Apparatus to create repeatable low velocity, soft-bodied impacts. A 2.5kg, 69mm diameter tup is shown about to strike a test panel

5. AN AUTOMATED SCANNING SYSTEM

Although the probe we obtained was intended for hand held use, some trials repeatedly placing the probe by hand onto the same spot showed that the received waveform can vary considerably, due to pressure exerted on the tips and contact angle, occasionally leading to false positives. To overcome this, a holder based on a gimbal joint was designed for the probe. This holds the probe perpendicular to the panel surface with a constant pressure exerted on the tips. The holder was attached to a computer controlled moving gantry that enabled the probe to be moved in the X and Y directions with a resolution in position of 1 mm. A programmable signal generator was used to produce a tone burst of a few cycles of a sine wave with a peak of 8 volts to drive the transmit tip. A band-pass filter was included to reduce the effect of the mechanical resonance of the probe (> 15 kHz) and the mechanical resonance of the scanning table (< 1 kHz). A digital oscilloscope was used to digitize the returned waveform, which was then downloaded to a computer and saved in its entirety to disk for future analysis.

A simple indicator, I, summarising the result at each sample position was formed by summing the point by point difference between the reference waveform and the test waveform according to the following expression,

$$I = \frac{1}{n}\sum_{i=1}^{n}\left|\varphi_i(t) - \varphi_{Ri}(t)\right| \qquad (2)$$

where φ is the sampled waveform, φ_R is the reference waveform and n is the total number of points in the waveform (default 500).

This method makes use of the entire waveform and reflects how 'different' the panel is at the current scan location when compared to a good region of the panel. A relatively small value of I represents little deviation whereas a large value is a significant difference. Organizing these indicator values into a 2D matrix and applying some artificial colour coding produces an image that can aid further analysis of the raw data. Subsequent sectioning of the panels demonstrated that this image provides a clear indication of any damage the panel has sustained to its core, and the impact area boundary to within ±1 mm, without any false positive indications. Some clues to the nature of the damage itself can also be seen.

6. SCANNING RESULTS

Figure 6 shows a scan performed on a section of 22 mm thick Nomex core, carbon fibre skinned aircraft panel similar to that used in the elevators of a Boeing 777. The panel had been prepared with 12 soft-bodied impacts ranging from a 5 cm drop height of a 25 mm diameter 1.8 kg tup to a 120 cm drop. All but the 5 cm impact can clearly be seen in the images. Only those impacts for heights greater than 20 cm could be seen as visual indentations on the skin surface. Later examination of the panel by cutting it open with a very fine diamond saw revealed no damage had resulted from the 5 cm drop.

The images in Figure 6 employ two different forms of colour coding to represent the 2D index values to highlight several aspects of the scan. The first shows the mode-like

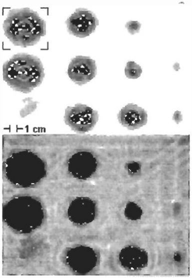
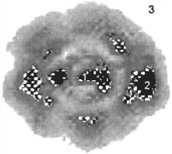


Figure 6 Two representations of a scan performed on a 22 mm thick Nomex cored, carbon fibre skinned panel that has been damaged by soft impacts from a Δ25 mm, 1.8 kg impactor dropped from heights of:
90, 50, 20 and 5 cm - Top row
120, 60, 30 and 10 cm - Middle row
10, 70, 40 and 15 cm - Bottom row



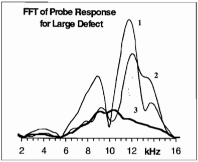


Figure 7 Enhanced image of the large soft-bodied impact highlighted in Figure 6 and a selection of associated FFTs performed on the sampled waveforms.

behaviour of the skin over the impact sites. The second image in Figure 6 highlights the background interference pattern in the areas adjacent to the damage. These are mainly due to interference caused by the panel defects and panel boundaries. Other details that also would normally be seen in the scans are structures such as joins in the skin ply and changes in thickness of the core, although none of these were present in the panel sample shown above. The diffuse indication, seen around the second 10 cm drop position at the lower left corner, is probably due to some defect already present in the panel.

Figure 7 shows a detail from this scan with some examples of the waveform spectra gathered. In the Figure, position 1 represents the approximate centre of the impact area, position 2 is on the edge of the impact site and position 3 was taken over an undamaged part of the panel. These spectra confirm the modal origin of the structure in response to the effect of the probe.

The mottled texture of the image in Figure 7 is probably due to the image enhancing techniques used rather than the structure of the panel.

7. CONCLUSION

Due to the nature of its design, the "Pitch-Catch" type probe can have undesirable mechanical properties leading to regions of large resonances within its stated operating range. An operator can easily be misled into thinking that these resonances are a suitable working region, as the output from the probe is a maximum, but the cost is significantly reduced detection reliability.

With the use of aggressive filtering and intelligent selection of excitation burst frequency and wave shape, the probes can be reliably used for detecting significant core damage in composite honeycomb where no surface damage is visible.

Ideally, a redesigned probe allowing use at frequencies greater than 20 kHz would open up scope for specific damage type identification such as skin delamination as opposed to core crushing. This would probably involve redesign of the probe contact tips and mounting.

8. ACKNOWLEDGMENTS

The authors would like to thank Norm Clark (CSIRO retired), and Neville Fletcher (ANU retired) for their valuable contributions during the course of this study.

This work was carried out as part of a collaborative research agreement between CSIRO and the Boeing Commercial Aircraft Group.

9. REFERENCES

[1] L. E. Kinsler, A. R. Frey, A. B. Coppens & J. V. Sanders. "Fundamentals of Acoustics", 3rd Edition. Wiley. 1982

[2] Suszanne Thwaites & Laurence. P. Dickinson "Detection of Invisible Damage in Honeycomb Sandwich Panels", Proceedings 6th International Congress on Sound and Vibration, Denmark. 1999

[3] Suszanne Thwaites & Laurence. P. Dickinson "NDT of Honeycomb Sandwich Panels using a Pitch-Catch Probe", CSIRO research report. Telecommunications and Industrial Physics. 1998