In Situ Acousto-Ultrasonic Inspection of a Tiger Helicopter Frame-Skin Junction Repair

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ABSTRACT

This report outlines an experimental investigation that demonstrates the application of piezoelectric elements to the in situ diagnostic evaluation of bond-line integrity in a battle damage repair developed for the Tiger Armed Reconnaissance Helicopter. A test coupon capturing the primary structural elements of the repair was subjected to cyclic loading and the performance of the critical bond-line region was assessed using an acousto-ultrasonic interrogation technique. Damage induced in the repair by means of controlled impact was detected through the measurement of perturbations in the acoustic wavefield. Evidence of possible deterioration in the prototype piezoelectric transducer elements trialled in the study raises the need for further evaluation of the resistance of piezoceramic materials to fatigue, a matter being pursued in a separate experimental investigation.

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EXECUTIVE SUMMARY

In situ structural health monitoring technology has the potential to radically transform contemporary aircraft structural management practice. An opportunity to demonstrate this potential recently emerged with the development by the DSTO of a battle damage composite repair for the Tiger Armed Reconnaissance Helicopter (ARH). The repair in question involves the Frame-Skin junction (FSJ) of the central fuselage, a sophisticated structure with poor access for non-destructive inspection (NDI). The installation of a permanent repair in this region is likely to pose a difficult challenge for conventional NDI, raising a strong argument for the integration of diagnostic sensors which could potentially eliminate the need for manual NDI entirely.

This report outlines an experimental investigation that demonstrates the application of piezoelectric elements to the in situ diagnostic evaluation of bond-line integrity in a composite repair for the Tiger helicopter. A test coupon capturing the primary structural elements of the repair was subjected to cyclic loading and the performance of the critical bond-line region was assessed using an acousto-ultrasonic interrogation technique. Damage induced in the repair by means of controlled impact was detected through perturbations measured in the acoustic wavefield. Evidence of possible deterioration in the prototype piezoelectric transducer elements trialled in the study raises the need for further evaluation of the resistance of piezoceramic materials to fatigue, a matter being pursued in a separate experimental investigation.
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1 Introduction

In situ structural health monitoring technology has the potential to radically transform contemporary aircraft structural management practice. An opportunity to demonstrate this potential recently emerged with the development by the DSTO of a battle damage composite repair for the Tiger Armed Reconnaissance Helicopter (ARH). The repair in question involves the Frame-Skin junction (FSJ) of the central fuselage (Wang et al (2006)), a sophisticated structure with poor access for non-destructive inspection (NDI). The installation of a permanent repair in this region is likely to pose a difficult challenge for conventional NDI strategies, raising a strong argument for the integration of diagnostic sensors which could potentially eliminate the need for manual NDI entirely. Previous work has shown that acousto-ultrasonic (AU) techniques are well suited to this type of diagnostic role (Walley & Rajic (2004)). A key practical advantage of the technique is that broad-field diagnostic coverage can be achieved with a relatively low transducer density.

The present study demonstrates the application of integrated AU techniques to the detection and monitoring of structural degradation in a battle damage repair. The acoustic wave field produced in the repair structure by integrated piezoelectric elements is studied with a view to identifying optimal modes of inspection for damage in the critical repair bond-line. AU measurements are made using a dedicated hardware device called the AUSAM (Acousto-Ultrasonic Structural health monitoring Array Module). Developed by the DSTO in partnership with local industry the module integrates piezotransducer system control, powering, and communication in a small (≈100 × 160 × 10 mm) and robust package. The device has 2 drive and 4 receive channels and can operate synchronously with other modules to cater for larger piezotransducer networks. Further details are found in Walley & Rajic (2004).

2 Experimental Details

Shown schematically in Figure 1 the coupon comprises a Nomex-cored sandwich panel approximately 45 mm wide, 17.5 mm thick and 450 mm long. The skin is made from 4 plies of a bidirectional carbon-epoxy pre-preg (M18/1/45%/G939) with a layup of [0°, 45°, 45°, 0°]. The elastic properties of the cured laminate are given in Table 1. Three piezoceramic elements are shown installed on the front skin of the coupon. The central element serves as an acoustic source, while the adjacent elements act as acoustic receivers. The elements were bonded to the composite skin using a commercial epoxy adhesive. Preparation consisted of dry abrasion of the surface followed by cleansing with alcohol.

<table>
<thead>
<tr>
<th>Table 1: Elastic properties for skin laminate.</th>
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<td>E_{11} (GPa)</td>
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<td>50</td>
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A 30 mm overlap length results in a joint ultimate strength of about 7000 µe. It was judged that fatigue failure of the joint would require loads that would lead to rapid me-
chanical failure of the piezoceramic elements. Consequently, the loads applied to the coupon were restricted to amplitudes of less than 2000 $\mu\varepsilon$ and failure of the coupon, which under normal circumstances would not occur at this strain, was engineered by subjecting the joint to damage.

**Figure 1:** Schematic of coupon structure (all dimensions are in mm). Surface to which transducer elements are attached is termed the “front” skin. The coupon is symmetrical about its centreline.

Figure 2 shows the coupon installed in the servo-hydraulic machine. The AUSAM device appears in the background and the smaller circuit board in the foreground is a variable gain amplifier used to boost the signal amplitude on the receive channels. A resistance was added across the input terminals of the amplifier, in parallel with the capacitance of the piezoelectric element to form a high-pass filter. This was to mitigate a signal drift problem noticed in preliminary testing. The drift was linked to the operation of the electrical motor driving the servo-hydraulic pump.

A prototype layered piezoelectric element was trialled as part of this study. Shown in Figure 3 the transducer comprises a Pz27 ‘soft’ piezoceramic disc sandwiched between polyimide layers with conductive tracks providing electrical connectivity. A separate experimental evaluation of the performance and mechanical resilience of the package is presently underway, and while preliminary data suggests good resilience, the possibility of mechanical failure could not be discounted even under the restrained loading conditions prescribed here.

A strain gauge was mounted on the coupon approximately 15 mm below the position of receiver B on the back skin to enable the longitudinal strain in the coupon to be recorded. A thermocouple was mounted on the lower hydraulic grip of the testing machine to allow temperature variations to be recorded. Previous work (Rajic et al (2001)) has shown that piezoelectric transduction is measurably affected by a variation in ambient temperature, and that correlated changes in the acoustic response can be identified.

The specimen was loaded sinusoidally at a frequency of 5 Hz. Initially, the load amplitude was set to 2 kN at an R-ratio of 0.1, producing a strain variation in the composite
Figure 2: Photograph of specimen with transducer locations arrowed. Damage induced near top right corner of overlap ply.

Figure 3: Layered piezoceramic transducer.

skin of 580 $\mu$e. After 250,000 cycles the load was increased gradually to achieve a measured strain amplitude in the skin of 2000 $\mu$e where it was held for the remainder of the test, about $4 \times 10^6$ cycles. AU measurements were made throughout the test at intervals of $2 \times 10^4$ cycles with the coupon maintained at a static zero load. The source piezoelectric element was driven at frequencies in the range 20 – 500 kHz, using a narrow band signal comprising a 5 cycle Hanning modulated tone-burst.
A separate periodic assessment of joint structural integrity was made by applying thermoelastic stress analyses to the overlap zone. Since a disbond represents a region of relaxed strain transfer and, through a redistribution of load causes increased strain elsewhere, mapping of the stress field should provide an effective means of detecting a disbond.

3 Results and Discussion

The first impact event was applied after the coupon had been exposed to $3.04 \times 10^6$ cycles. To this stage no sign of structural deterioration in the sample had been detected in the thermoelastic scans. With the sample still fixed in the hydraulic grips, a controlled impact was applied in the region of the upper left corner of the overlap zone using a round indenter (top impact location in Figure 2). The incident energy was estimated to be of the order of 10 J. The event was repeated (impact 2) after a further $4 \times 10^4$ cycles. A final impact was applied at $3.4 \times 10^6$ cycles at a location about 15 mm below the first site. Having exposed the specimen to nearly 4 million loading cycles, and with no obvious sign of incipient failure, a wedge was driven 5 mm into the bond-line at the upper right corner. Failure of the joint occurred $85 \times 10^3$ cycles later.

![Figure 4: Signal power as a function of loading cycles at a 60 kHz drive frequency. Impact events are labelled.](image)

For brevity, discussion of the acousto-ultrasonic data will focus mainly on the 60 kHz case with some reference to the 120, 240 and 500 kHz drive frequencies as well. These serve to adequately highlight the main trends observed in the test.

Figure 4 shows the trace of signal power in the dominant wave mode measured at
receivers A and B for a 60 kHz drive. Only the signal at receiver A shows evidence of the effects of the applied damage. The significance of the perturbations prior to the impact events will be discussed shortly. It is useful however to first remark on the substantial background variations evident in both receiver signals.

The most noticeable trend is a persistent decline in signal power, amounting to a $35 - 40\%$ reduction over the duration of the test. The precise cause is unknown and the limited data available from this study allows only for speculation. For instance, a decline in the transduction efficiency of the source element, caused either by degradation of the adhesive bond or of the piezoelectric properties would produce a weakened response. However, an exception to the trend occurs in the 500 kHz case at about $1.3 \times 10^6$ loading cycles (Figure A1), which is inconsistent with this explanation. Another possibility is that the acoustic trend may reflect benign structural change in the coupon. Strong acoustic interaction between the skin and honeycomb was observed in some measurements, so it is conceivable that changes in the core might give rise to altered dynamic behaviour measured at the skin. Further comment on this interaction will be made shortly.

![Figure 5: Signal power at receiver A for a 60 Hz drive and the temperature measured at the lower hydraulic grip of the machine.](image)

The other noteworthy feature is a cyclic variation in signal with a period of approximately $5 \times 10^5$ cycles, which is diurnal and suggests an environmental origin. This was confirmed by an examination of the temperature record for a small segment of the test which revealed the strong inverse correlation with signal power shown in Figure 5. Although receivers A and B are nominally identical in structure and were installed in the same manner the latter exhibits a noticeably weaker temperature dependence. The closer proximity of receiver B to the hydraulic actuator of the testing machine, the primary source of heat in the experiment, should expose it to a larger temperature variation, so an argument based on heat conduction alone cannot explain the observation. Part of the temperature dependence may stem from the effect of thermal expansion and contraction in the coupon itself. Again, the core could play an important role.

Reconsider now the signal perturbations relating to the events labeled in Figure 4. The attenuation caused by impact 2 is shown in Figure 6. Strong selectivity is observed with
Figure 6: Receiver A baseline response compared to signal after 2nd impact - 60 kHz drive frequency.

respect to the second and larger of the two wave packets featured in the baseline response. A Hilbert transform of the temporal signal provides a more useful description of the attenuation. Given the real valued response $u(t)$, an analytical signal $Z(t) = u(t) + jg(t)$ is formed where the Hilbert transform $g(t)$ is defined as,

$$g(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{u(\tau)}{t-\tau} \, d\tau$$

(1)

The envelope of the signal power, defined as $|Z(t)|^2 \equiv u(t)^2 + g(t)^2$, is shown in Figure 7. Using the delay between the drive and response maxima in the envelope functions, the group velocity of the two wave packets are approximately 2500 and 1100 ms$^{-1}$ respectively; low values that are typical of antisymmetric modes. Whether the two packets are indeed separate modes is unclear.

An estimate of the modal content was deduced from Rayleigh-Lamb theory applied with respect to the skin structure alone, and compared to a more detailed experimental spectral reduction of the dynamic response. This comprised laser vibrometric measurement of the skin out-of-plane velocity on the undamaged half of the coupon. Scans were made along the line of symmetry on the front skin over a length of 118 mm, extending from the source element toward receiver B. Taken at an interval of 1 mm the measurements were converted to a spectral representation to isolate the propagating modes. The reduction was applied separately to the data from the double and single skinned sections (Figure 1) of the coupon. Figure 8 compares the experimentally revealed modes to the Rayleigh-Lamb solution computed using the material properties given in Table 1. Theoretical solutions are shown corresponding to the single and double skin thicknesses (1 and 2 mm respectively).

The comparison excludes the presence of symmetric modes in the structure, and implicates two distinct antisymmetric modes possibly corresponding to the two skin thicknesses. The measured difference in wave-number is roughly consistent with that predicted by theory. However, the theory consistently overstates the wavelength relative to the observed
values suggesting the skin is flexurally more compliant than the assumed properties suggest. Considering that the reinforcing effects of the honeycomb core and the adhesive layer are not factored into the analysis, and would conceivably have the effect of stiffening the skin, the finding is not intuitive. While the analysis suggests the disturbance shown in Figure 7 is antisymmetric in nature, the selective suppression of the slower component indicates a different origin. The mechanism is not clear but is likely to relate to the transition from a double skin in the repair section to the single skin of the parent structure.

The scale of attenuation is noteworthy. Reductions in signal power of 50% following the first impact and 70% following the second are significant compared to the background variations previously discussed and indicate a high sensitivity to damage in the joint. On
a cautionary note, had the damage evolved more progressively, for example on a time scale similar to that of the background trend, discrimination would be far more difficult. Resolving the cause of the background decline should be a priority for any further work.

A confirmation that joint damage occurred in response to the impact events is furnished by the thermoelastic stress scans shown in Figure A2. Small perturbations in the stress field around the impact zone suggest reduced strain transfer indicative of a damaged bond. While impact 3 is seen to have led to a large thermoelastic indication, the acoustic response in Figure 4 is only weakly affected. Moreover, changes due to impact 3 oppose those caused by the first two impact events. This serves to underscore that the interaction of guided-waves with the reinforced structure of the coupon is complex. Interestingly, insertion of a wedge into the bond-line caused a further increase in signal transmission, but the ensuing joint failure, which occurred about 60,000 cycles later, led to complete signal loss - a more intuitive result. Figure 4 shows that joint failure produced a slight increase in signal power at receiver B, caused by increased reflection from the damaged joint.

### 3.1 The Role of Nomex Core in the Wave Dynamics of a Reinforced Structure

In light of the extensive use of Nomex reinforced composite skinned panels in the construction of the Tiger ARH, it was thought useful to examine in slightly more detail the acoustic transfer characteristics of the panel, and in particular whether acoustic energy in one skin is coupled to the other by the core. The question has significant practical relevance since coupling of this nature could provide for complete diagnostic coverage of a sandwich structure based on a single-sided transducer installation.

Evidence of coupling was sought by applying laser vibrometry to the undamaged half of the coupon. Scans of approximately 118 mm in length were taken on the front and back skins between the source transducer and receiver B. Drive frequencies of 60, 120 and 240 kHz were considered.

Figure 9 compares the response measured along mirrored paths on the two skins. Acoustic coupling through the core is evident in all three cases. The mechanism is thought to depend critically on an antisymmetric wave-mode and its flexural deformation which reacts against the core. The strain induced in the core is transferred to the back skin with a transport delay that is presumably determined by the properties of the core. This in part explains why the velocities measured in the two skins are not 180° out of phase - the expectation for a perfectly rigid core.

The transport delay through the core can be deduced from the Rayleigh-Lamb equations. Nomex core is manufactured from Kevlar-based paper dipped in phenolic resin, and has a published Young’s modulus of 0.9 GPa and a mass density of 724 kg m$^{-3}$ (Zhang and Ashby (1992)). A value of 0.3 is assumed for the Poisson’s ratio. The analysis does not cater for the geometric structure of the cell, and instead assumes propagation in an infinite sheet. Its thickness is equivalent to the cell wall thickness of 142 $\mu$m. Calculations yield the group velocity spectra shown in Figure 10. Only the fundamental symmetric and antisymmetric modes occur at the frequencies considered in this work. Assuming the axial loading of the core preferentially excites the symmetric mode, the relevant group velocity
Figure 9: Out of plane velocity measured 80 mm from the source element toward receiver B on the front skin and at the mirrored location on the back skin. From top to bottom, graphs correspond to 50, 120 and 240 kHz drive frequencies respectively.
is about $1160 \text{ms}^{-1}$. The speed of the symmetric mode varies negligibly across the target frequency range, and also with respect to cell wall thickness, an important point since the cell walls in the Nomex core have two thicknesses, as shown in Figure 11. Given a core length of 15 mm the propagation delay is about 12.90 $\mu$s. Advancing the vibrometry measurement on the back skin by this amount yields the third trace in each subplot in Figure 9. The shift fails to produce the expected phase relationship. This may in part be caused by inaccuracy in the group velocity, which could stem from errors in the mechanical properties and/or the radical simplification of the cell geometry. The assumption of an infinite sheet is intuitively weak but nonetheless an unavoidable simplification for this preliminary study. More detailed numerical modelling would reveal the precise nature of wave propagation through the core.

![Figure 10: Group velocity spectrum for Nomex paper of 142$\mu$m thickness.](image)

![Figure 11: Nomex honeycomb cell dimensions.](image)

It is instructive to examine the response in the back skin with the core bisected to mechanically decouple the skins. A through-cut was made in the core mid-way between the skins beginning at the right edge of the source transducer (in shown in Figure 1) and ending approximately 5 mm beyond receiver B. Figure 12 compares the out-of-plane velocity measured on the back skin before and after bisection of the core. Measured 80 mm from the source, the response is much weaker in the bisected case, as expected.
The residual disturbance is thought to originate from an antisymmetric wave initiated in the back skin through the uncut core behind the piezoelectric element.

![Graph showing surface normal velocity before and after bisection of core.](image)

Figure 12: Response in the back skin before and after bisection of core.

## 4 Conclusion

An experimental investigation has shown that surface-bonded piezoelectric elements provide a useful basis for the diagnostic evaluation of bond-line integrity in a battle damage repair developed for the Tiger Armed Reconnaissance Helicopter. A test coupon reproducing the primary structural elements of the repair was manufactured for the study. While subjecting the sample to cyclic loading, the critical bond-line region was assessed using an in situ acousto-ultrasonic interrogation technique. Damage induced in the repair by means of controlled impact was detected through perturbations measured in the acoustic wave field. Evidence of possible deterioration in the prototype piezoelectric transducer elements trialled in the study raises the need for further evaluation of the resistance of piezoceramic materials to fatigue, a matter being pursued in a separate experimental investigation.

The discovery of strong acoustic coupling between the composite skins has important practical implications. For example, it could permit the inspection of both skins in a honeycomb sandwich panel using transducers installed on one skin. It also raises the possibility of achieving diagnostic coverage of both skins using transducer elements embedded in the core. The reduced load in the core would profoundly increase transducer life and stability. Both concepts are being pursued in the sequel to this study.

## Acknowledgements

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References


Appendix A  Supplementary Data

**Figure A1:** Signal power as a function of loading cycles for drive frequencies of 120 (top), 240 (middle) and 500 kHz (bottom).
Figure A2: Thermoelastic response amplitude in the repair zone. Specimen under cyclic loading (tension-tension) at 5 Hz.
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Aircraft structures, Tiger helicopters, Nondestructive testing, Inspection, Ultrasonics, Composite materials, Piezoelectric materials

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