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Interference Fit Fastener Inspection using Sonic Thermography

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Abstract: This paper reports on an experimental study addressing the application of sonic thermography to the characterisation of interference fit levels in fastened metallic plates. The technique uses high intensity acoustic waves to induce frictional heating at defect locations. In the case of poorly fitted interference fasteners, the acoustic waves induce relative motion between the fastener and host, causing frictional heating which is detected with a thermal imaging system. Results are shown to demonstrate the efficacy of the approach.

Keywords: infrared, interference fit, non destructive evaluation, sonic IR, sonic thermography.

1 Introduction

An unanticipated failure in 2003 of an F-111C wing under full-scale fatigue testing at DSTO revealed serious problems in the build quality of fastener holes in the wing skin and in the interference fit levels of taper lock fasteners. Investigations [1] revealed that deficient surface finish and low interference fit levels at several fastener holes contributed to the premature failure. It is common in the aerospace industry to incorporate interference fit fasteners in mechanically fastened joints to enhance the fatigue performance of these joints. In order for them to be effective a minimum interference level is prescribed. The effect of the interference fit is to allow full load transfer from the structure to the fastener, thus reducing the stress concentration produced by the hole. Another important benefit is that a correctly fitted fastener prevents fretting, a known precursor to crack initiation. An interference fit can be compromised under exposure to high operational loads in cases where a fastener hole is plastically deformed. As a consequence, a need exists for non-destructive means of assessing interference fit levels, both to identify poorly installed fasteners and to detect changes in interference that occur during operation. Currently there are no NDI techniques available to measure interference levels. Sonic thermography has the potential to fulfil this role.

Preliminary investigations [2] have underscored the possibility of quantifying interference fit levels in fastened metallic structures using sonic thermography (ST), a relatively new NDI technique. ST relies on the injection of high intensity acoustic waves into a structure. The excitation can produce frictional heating if the structure includes discontinuities like cracks that comprise contacting surfaces. Although the signature arises from an irreversible mechanical process, the technique is widely considered to be non-destructive and experimental work can be found to support this conclusion [3]. With the advent of sensitive IR imaging systems ST has emerged as a versatile broad-field inspection technique.

This paper outlines the results of an experimental investigation into the application of ST to the quantitative measurement of interference levels in tapered fastener systems. The study specifically focuses on issues relating to the repeatable transfer of acoustic energy into the target structure. Preliminary data is presented to demonstrate a relationship between the increase in temperature caused by acoustic excitation and the interference fit level for tapered fasteners, which provides encouragement for the development of a quantitative assessment capability.

2 Experiment Details

2.1 Experimental Setup

The experimental work was undertaken on a square Al2024 plate with a side dimension of 400 mm and 6 mm thick. A pilot hole drilled in the centre of the panel was expanded using a tapered mandrel to a final nominal diameter of 6 mm, tapered at a rate of 6.35 mm/304 mm (¼"/ ft). A matching tapered fastener was manufactured from high strength steel. The protruding shank of the fastener was threaded to accommodate a nut that could be turned against the plate to control fastener insertion depth and, thus, interference level. Acoustic insulation material was used between the plate and supports to reduce the loss of acoustic energy from the plate [4].

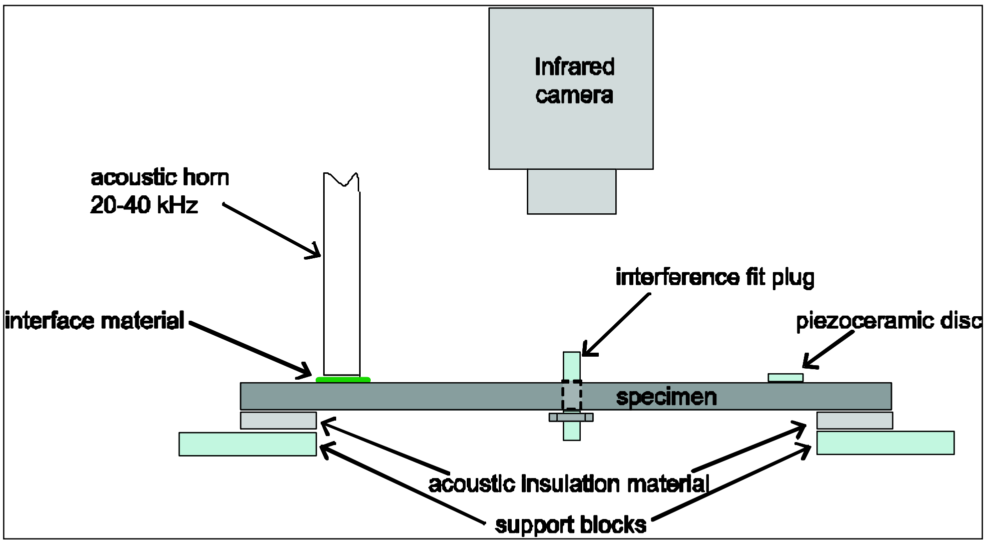

Figure 1. Experimental setup showing specimen, acoustic horn and infrared camera.

The interference level is defined here as

$$i = \frac{(h_0 - h_i)}{48} \times \frac{100}{d} \qquad (1)$$

where h_0 is the height of the fastener measured above the plate at nil interference, h_i is the height of the fastener above the plate after interference and d is the diameter of the hole.

A commercial acoustic horn was used to excite the plate. The horn was set to a fixed nominal output power of 555 W, applied to the sample for a duration of 1 s. The amount of power delivered to the sample depends on the acoustic load impedance and is recorded by the horn controller. The output trace was recorded for each inspection.

Infrared imagery of the plate was acquired using a cryogenically cooled Indium Antimonide focal plane array detector with a temperature sensitivity of 20 mK. The acoustic horn and infrared imager were controlled through a single software interface allowing for synchronous operation. The ideal metric for heat production at the interface between the fastener and the plate is the interface temperature. To assist in noise rejection, the temperature adjacent to the interface was averaged over an annular region with an internal radius defined by the hole and an external radius twice that of the hole radius.

2.2 Repeatability of thermal signatures

Initial experimental work revealed that one of the critical issues in developing a quantitative capability is achieving repeatable acoustic energy transfer to the sample. The acoustic horn is designed primarily for welding plastics and therefore metal structures are generally a poor acoustic impedance match. As well as reducing power transfer to the structure, the mismatch gives rise to a semi-chaotic impact mechanism, known as acoustic chaos [5], which is thought to be at least partly responsible for the poor repeatability observed in experimental work on metal subjects. A compliant interface layer between the horn tip and structure can often mitigate the poor impedance match and increase transfer and repeatability significantly. A critical aim of the study was to identify interface materials with the requisite properties for efficient and repeatable transfer of acoustic energy into the sample. Figure 2(a) shows the horn tip velocity measured using a laser vibrometer for an excitation lasting 1s. The amplitude spectrum of the time trace is shown in the inset, revealing a dominant 20 kHz component. Smaller components occur at the harmonics: 40, 60 and 80 kHz, but are not seen at the chosen scale. The trace also reveals a linear ramp up to full power over a period of 150 ms.

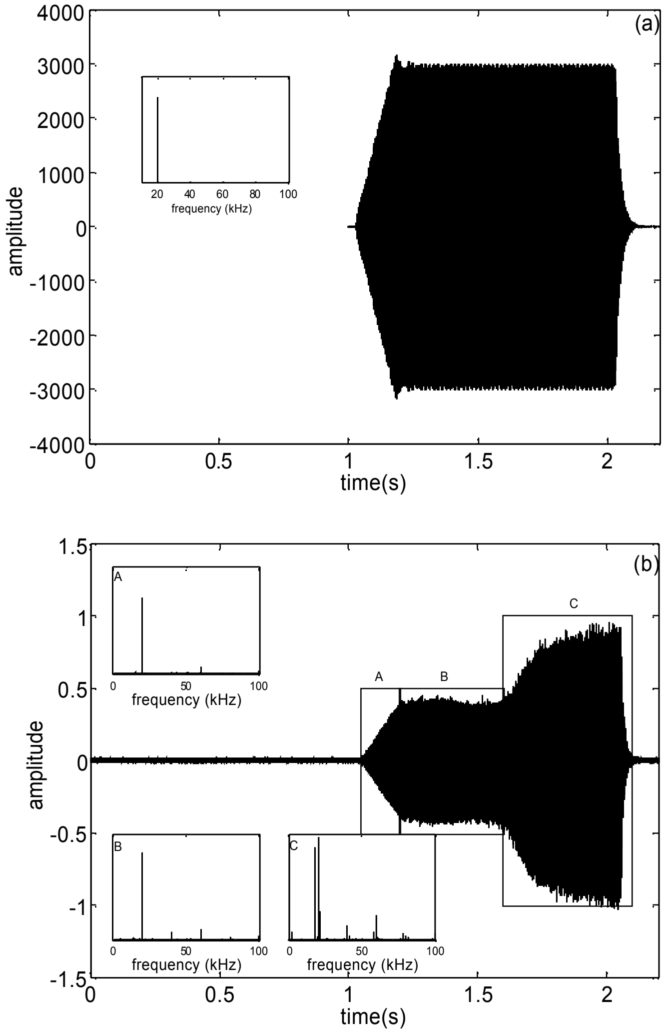

Figure 2. (a) Horn tip velocity measured by laser vibrometry for a 1 s excitation. The inset shows the amplitude spectrum of the time history. (b) Plate vibration measured using a piezoceramic disc element, with corresponding amplitude spectra shown inset.

A piezoceramic disc transducer was bonded to the surface of the plate in order to measure the acoustic energy spectrum in the plate. Figure 2(b) shows the output of the piezoceramic element for an excitation applied using a felt interface between the horn and plate. Segment A corresponds to the ramp up of the horn output and within this period the frequency content is dominated by the 20 kHz drive signal, as shown in inset A. Segment B is characterised by a period of steady amplitude, where the signal is again dominated by a 20 kHz component but with stronger harmonics. Finally, in section C, the amplitude is observed to grow and the signal comprises a broader spectrum of frequencies.

The ramp up noted in section A clearly relates to the performance of the horn since its duration is consistent with an equivalent ramp-up evident in the vibrometry data for the horn tip. The transition in behaviour from section B to C is thought to relate primarily to a change in the properties of the felt interface layer. The felt is initially compressible, containing a large volume of entrapped air, which impedes acoustic energy transfer to the specimen. Section B is surmised to correspond to a phase where the felt is gradually compressed to a point where the compliance of the layer is markedly reduced thus allowing for increased energy transfer to the sample (section C). The appearance of additional frequency components would support the contention of a loss in interface compliance since this loss would permit the establishment of a vibro-impact mechanism where the horn tip and plate separate and then impact on elastic rebound. This type of behaviour is not likely to be conducive to repeatable transfer of energy to the sample and may account for at least some of the variation noted in the experimental work.

Figure 3(a) and Figure 4(a) show the normalised temperature traces measured adjacent to the tapered fastener for an interference level of slightly less than 0.2% for felt and petroleum jelly (PJ) interface layers respectively. The results indicate substantial variability in the case of the felt interface. In contrast, the PJ interface produces greater repeatability and much less apparent noise. The cleaner response is primarily due to the higher signal strength, which is approximately twice that for the felt interface.

The inset images in Figure 3(a) and Figure 4(a) show the thermal response recorded over the target region prior to insonification (t=0s) and at the stage where the average temperature adjacent to the fastener reaches its maximum value (t=1.0s). The PJ interface shows greater definition of the fastener/hole interface as compared to that of the felt interface, reflecting the much stronger thermal response.

Figure 3(b) and Figure 4(b) show plots of the horn acoustic power output, as detected by the horn controller, for the two layer types. The felt layer shows substantial variability in the delivered power with a peak amplitude ranging from 80 to 110W. This is low compared to the prescribed input power of 555 W, and is the result of a poor impedance match at the interface. The results for a PJ layer indicate markedly better performance. For the same prescribed input power the horn delivers 200 to 250 W. Interestingly, while the repeatability of the acoustic power input is only marginally improved for the PJ layer, the resulting thermal traces show vastly better consistency. This is thought to be a consequence of the suppression of the vibro-impact mechanism, which the PJ interface evidently does not support.

It is instructive to comment briefly on the form of the power traces shown in Figure 3(b) and Figure 4(b). The ramp up over the first 200 ms corresponds to the linear development of horn output observed in both the laser vibrometry of the horn tip and the piezotransducer output. For the felt interface, the period from 150 to 300 ms, is thought to correspond to the progressive compression of the felt, as remarked earlier. From roughly 300 ms onwards the power level increases and develops a low frequency oscillation. This is thought to correspond to a low frequency structural mode in the plate excited by the vibro-impact mechanism described earlier. A similar oscillation is observed in relation to the PJ interface but occurs only in the ramp-up stage and is transient.

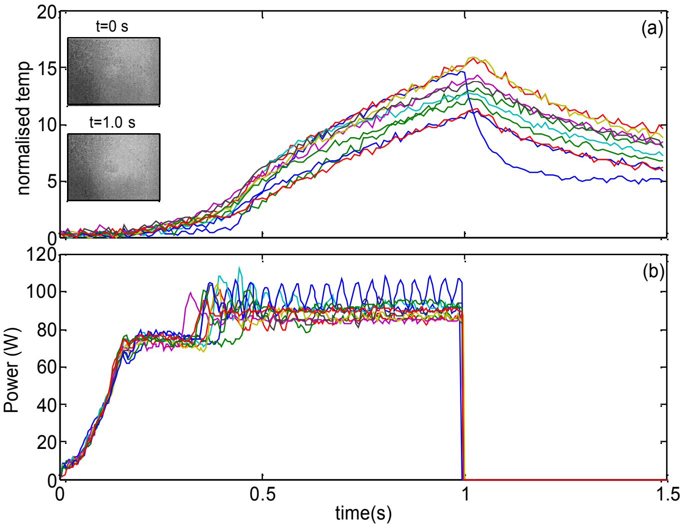

Figure 3. (a) Temperature and (b) acoustic power evolutions for insonification through a felt interface. The inserted images show the raw sonic thermograph at the time indicated.

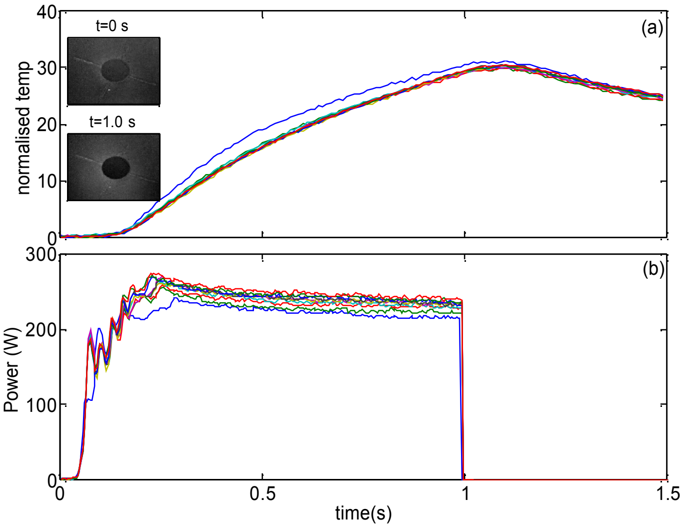

Figure 4. As in Figure 3, but for a PJ interface.

3 Characterisation of fastener interference level

Figure 5 maps the variation in the average temperature calculated around the fastener-hole interface, as mentioned in Section 2.1, as a function of fastener interference level. The curve suggests that quantitative measures of interference are possible, but within a relatively narrow range of interference levels. The form of the curve is largely intuitive. It suggests that below a threshold of about 0.15% the contact stress between the fastener and host is low producing only a weak frictional heat source. As the interference level is increased, the frictional forces obviously grow, and this drives increased heat production. At some point, evidently around 0.25% in the example considered here, the frictional force between the fastener and plate is sufficiently high to restrict relative motion, which impacts on heat production. As the interference increases the level of heat production continues to decline.

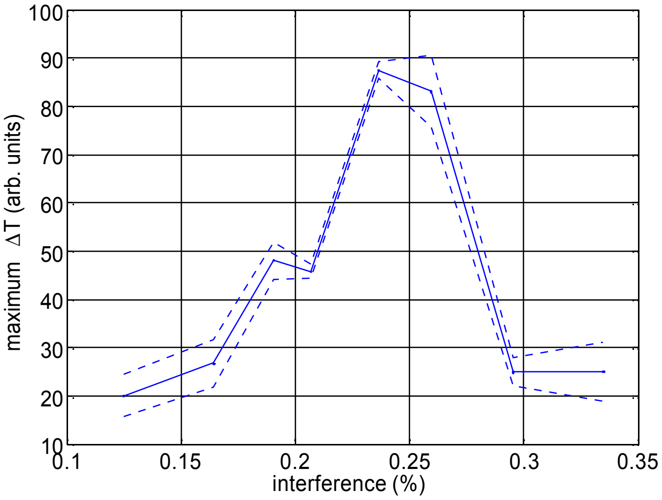

Figure 5. Average maximum temperature during insonification versus % interference fit for a PJ interface, for 10 insonifications. The dotted lines indicate one standard deviation.

Work continues on developing the technique. From a practical perspective the critical challenges are to improve the repeatability of the acoustic excitation and to expand the range of "inspectable" interference levels, ideally up to a maximum of 0.85%, which corresponds to yield in Al2024.

4 Conclusions

Experimental work has demonstrated good correlation between the interference fit level of a tapered fastener in an aluminium alloy plate and the thermal signature produced adjacent to the fastener during high intensity acoustic excitation of the plate. Repeatability of the acoustic excitation remains a critical experimental issue, however work conducted thus far has revealed that optimisation of the interface offers an encouraging basis for improvement.

Acknowledgments

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