Detection of Hidden Fatigue Crack Growth in Single-Sided Fastened Joints

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ABSTRACT

Aircraft structural elements are usually assembled using single-sided fasteners—pins with flush heads on one end and threads on the opposite end coupled with collars designed to ensure specific torque levels. Common examples include Hi-Lok and Hi-Lite pins. Unfortunately, fastened joints also provide unique opportunities for hidden damage, including fatigue cracks, corrosion and fretting, due to stress concentrations at the hole, friction between fasteners and surrounding material, and moisture that can ingress and become trapped between layers. The complex multi-layered geometry at these joints also forces disassembly to inspect using conventional techniques. Many proposed structural health monitoring (SHM) approaches tackle this problem by modifying the installed condition of the fasteners by placing a sensor between the structure and the collar or fastener head. This paper presents a novel SHM approach that can detect hidden fatigue cracks in multilayer fastened structures without disassembly or modification to the installed condition of the fastener. Piezoelectric elements are integrated post-installation to turn the fasteners themselves into impedance sensors. The coupled electro-mechanical resonance changes in the presence of local damage, which softens the adjacent boundary condition constraining the fastener. Experimental data illustrates a detection capability for finding hidden fatigue cracks of at least 1.5 mm.

INTRODUCTION

Finding fatigue cracks hidden between multiple metallic layers near fastener locations is one of the most challenging detection problems. Traditional non-destructive inspection (NDI) techniques such as Eddy current can detect flaws once disassembled and a probe is inserted into the bolt-hole, but typical SHM methods such as ultrasonic guided waves have difficulty scanning a region with such complex contact points and boundaries that cause reflections. The most common aerospace fasteners are HI-LOK™ and HI-LITE™ (LISI AEROSPACE), which are installed by pressing threaded pins into an interference-machined hole, then tightening the collar using a ratchet until the wrenching element breaks off at a pre-set torque level, while using a hex-key to prevent the rotation of the pin during tightening. The keyhole remains unused post-installation.

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Figure 1. Hi-Lok pins & collars (left), installed Hi-Lok fasteners on an aerospace structure (right)

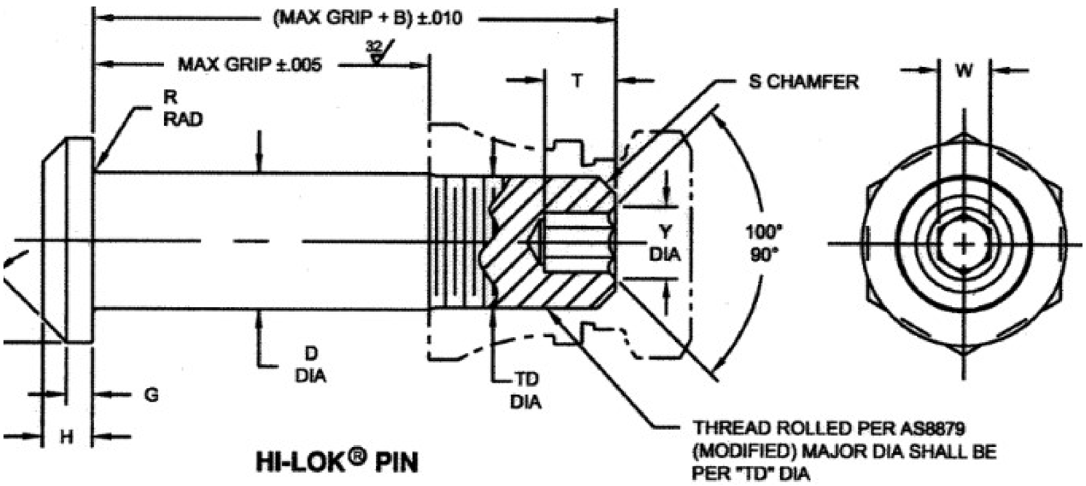

Figure 2. Side & top view of Hi-Lok fastener, highlighting hex-entry for transducers installation

The present work utilizes a novel ultrasonic impedance approach to detect hidden damage, integrating piezoelectric transducers into the fasteners themselves without modifying standard fasteners or their conventional installation procedures. The sensors are mounted inside the volume used for the hex-key (post-installation) thus they do not require any modification of the fastener or fastener installation process. As damage in the form of fatigue cracks or corrosion is incurred adjacent to the fastener it essentially softens the boundary condition, thus the mechanical impedance of the stiffened joint would be changed providing a metric that can be measured. This paper presents a laboratory fatigue test designed to evaluate the detection capabilities of this approach.

APPROACH

The Fastener Attrition Sensing Transducer (FAST) uses piezoelectric transducers, specifically PZT-5A wafers, to measure damage in close proximity to fasteners by observing changes in electro-mechanical impedance of the PZT-fastener coupled system. As seen in Figure 3, the sensor assembly consists of a PZT element electro-mechanically sandwiched between two flex circuits, with a 32 AWG wire soldered to either flex to establish a positive and negative connection. The entire assembly is bonded to a T-pin that is inserted into the fastener hex-keyhole—serving as an ultrasonic delay line—then sealed with a 2-part machined metal housing. The hardened sensor package is mated with miniature (20 x 15 x 3mm) data acquisition hardware and can be operated in a standalone fashion or be networked on a single cable with a common access point.

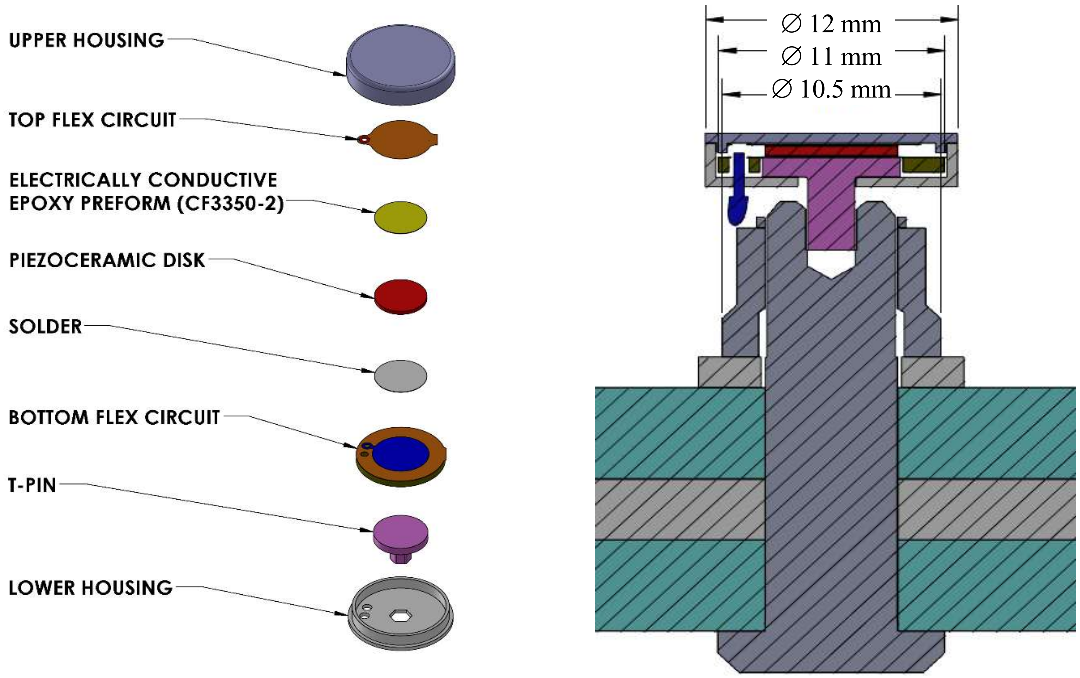

Figure 3. CAD drawing of the assembled FAST sensor

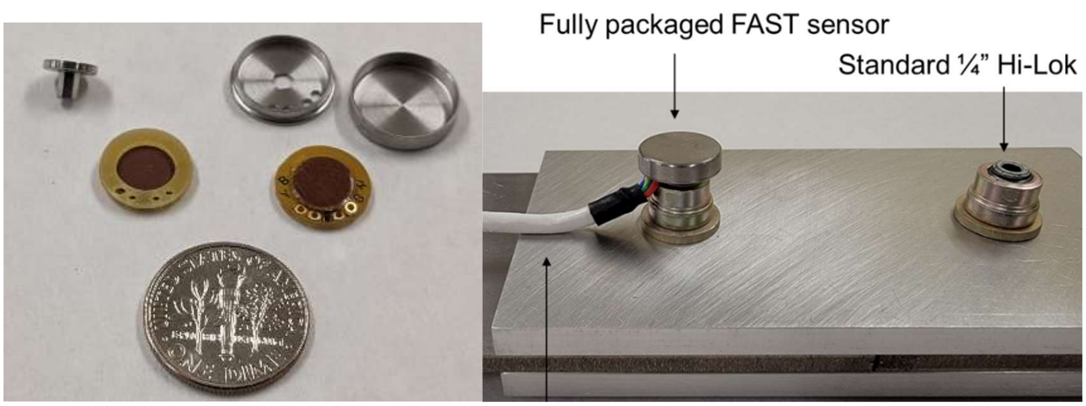

Figure 4. Photographs of unassembled and assembled components of the FAST sensor

EXPERIMENTAL SETUP

A literature survey yielded guidance for tensile fatigue testing on open hole aluminum specimens. Material and geometry were chosen to reproduce the work of Lancombe [1]. Fatigue specimens were machined from 2024-T351 cold-rolled aluminum sheet with the longitudinal axis of the bar oriented to the rolling direction, measuring 200 x 19 x 3 mm with a centered 6 mm hole. Specimens differed from those in the Lancombe study by the inclusion of a 0.25 mm through-thickness laser etched starter notch at the hole inner diameter, cut towards the closer edge of the specimen. A multi-layered assembly was created using two 5mm thick 18 mm square washers joined by a grade 5 titanium fastener (HST12YW8-9) with a threaded collar (HST1087-8). S-N curves provided by Lancombe (Figure 5) gave load guidance of 10.6 kN at R = 0.1 to target 25,000 cycles at 10 Hz. Initial testing on an instrumented specimen however indicated that the load needed to be increased to 16 kN to compensate for the frictional force of the washers acting against the tensile load around the fastened hole.

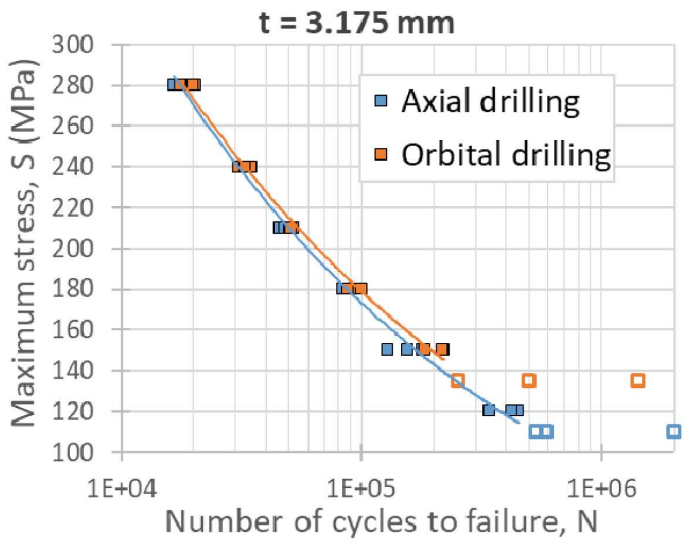

Figure 5. S-N curves found in the Lancombe aluminum open-hole fatigue study [1]

Figure 6. Fatigue specimen apart and assembled (left), instrumented specimen prior to testing (right)

EXPERIMENTAL RESULTS

Prior to blind testing, an instrumented specimen was cycled until failure to calibrate the damage metric. Figure 7 illustrates the admittance magnitude versus frequency for each 500 cycles increment. An offset was introduced in the measurements due to clock jitter, however the shape remained consistent until a crack started to develop, at which point a new resonant peak appeared around 170 kHz. To determine the presence of a crack, the coefficient of determination between 165-175 kHz was calculated, essentially a metric quantifying how much the shape of the resonant response was changing irrespective of the offset value. As seen in Figure 8, for the calibration specimen there was virtually no change in metric until the 22 block (3 data sets were collected per block) representing 11,000 cycles, at which point there was a steady decline for each of the next 5 blocks followed by a large drop for the final 2 blocks collected prior to specimen fracture following block 29 (15,000 cycles). For the remaining blind specimens, loading was paused every 500 cycles for FAST collection and damage metric calculation, and the test was stopped as soon as a change in admittance phase was confidently detected. After the fatigue testing was complete, the specimens were disassembled and the crack length from the starter notch was optically measured, each reported in Table I.

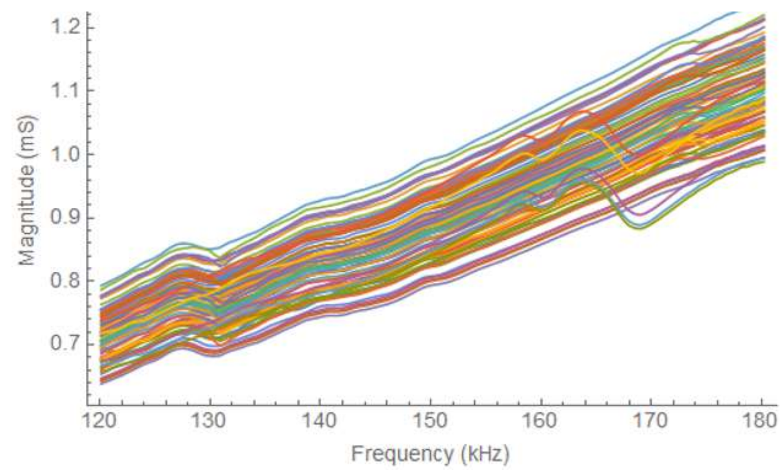

Figure 7. Calibration specimen admittance magnitude vs frequency, each line represents 500 cycles

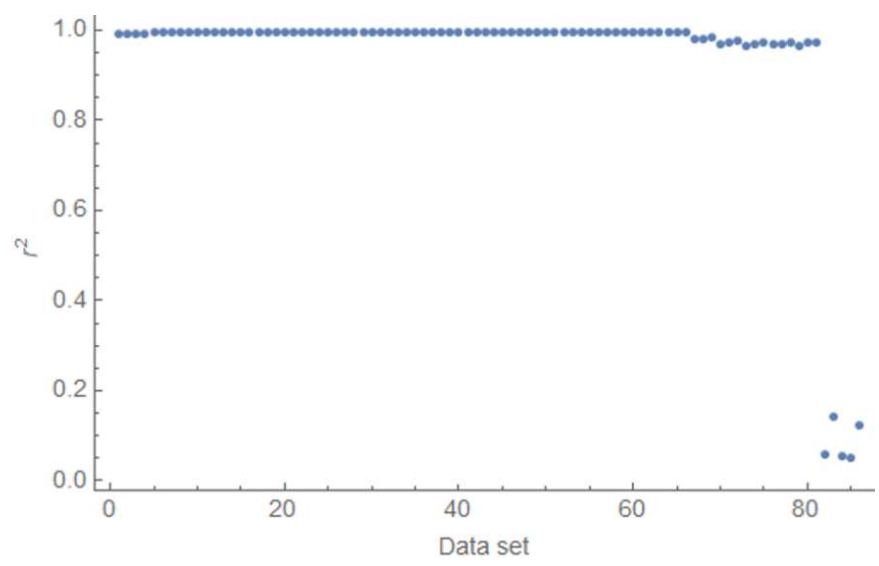

Figure 8. Calibration specimen coefficient of determination with a crack developing at 11,000 cycles

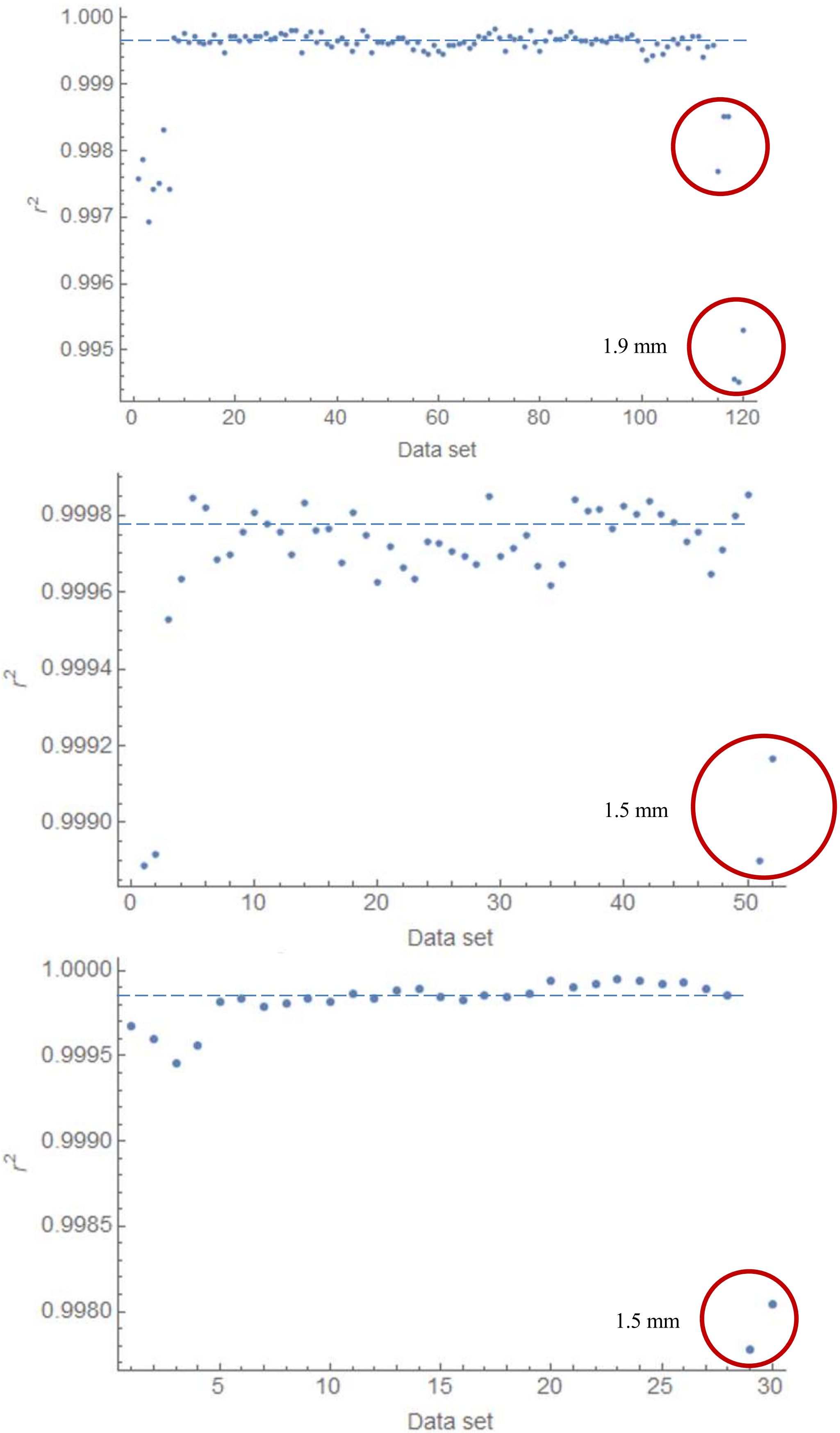

Figure 9. Coefficient of determination plots from blind fatigue specimens A, B and C

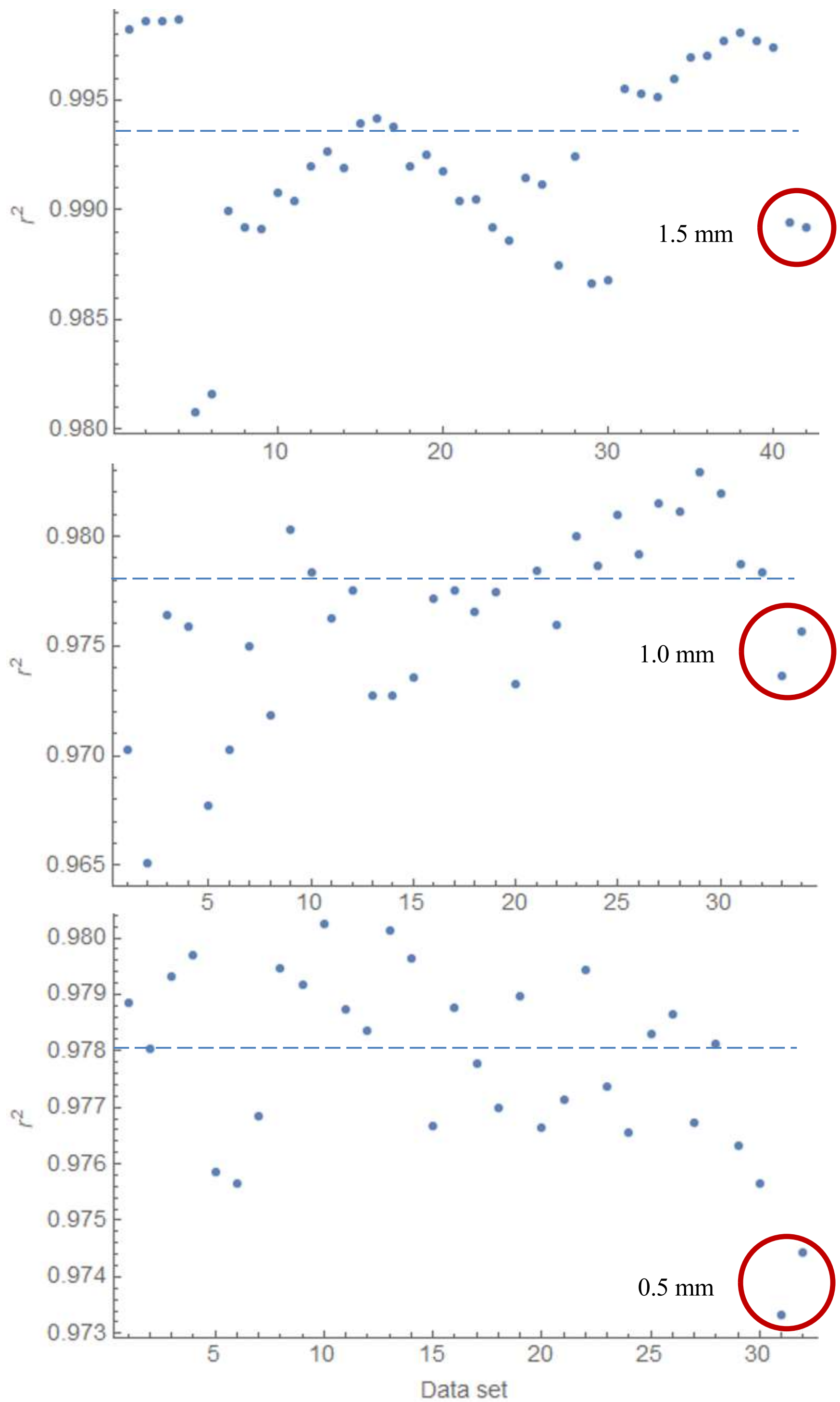

Figure 10. Coefficient of determination plots from blind fatigue specimens D, E and F

Table 1. Summary of fatigue cycles induced on all tested specimens and measured crack lengths

Specimen ID	Fatigue Cycles @ 16 kN	Measured Crack length (mm)
A	16,000	1.9
B	10,000	1.5
C	6,340	1.5
D	9,500	1.5
E	7,500	1.0
F	7,000	0.5

DISCUSSION AND FUTURE RESEARCH

Fatigue cycling was stopped for specimens A, B, C and D following very clear and significant changes in the damage metric seen in Figure 9 and 10. The corresponding crack length measured was 1.9 mm for A and 1.5 mm for the other three specimens. Testing was stopped for specimens E and F following a more subtle change in damage metric below the noise floor, resulting in cracks measuring 1.0 and 0.5 mm. More consistent results could have likely been obtained if data was collected more frequently, for example every 100 cycles, however this was impractical due to the variable nature of the crack initiation, which could have resulted in very long tests in some cases. The overall length at detection average was 1.3 mm (0.05"). The presence of jitter still allowed for small cracks to be detected with the FAST system, but likely more sensitivity (<0.5 mm) could be achieved without the jitter as observed in prior proof-of-concept testing using an impedance analyzer rather than microelectronics. For this experiment data was streamed and processed offline, however the eventual intent is to embed the damage metric algorithm, and just output the coefficient of determination, which would cut test time from 30 seconds down to 1 second per FAST sensor.

CONCLUSIONS

This project aimed to provide a means for detection of early onset of fatigue cracks hidden in fastened joints that does not require disassembly for inspection. PZT elements were bonded to ultrasonic delay lines to be inserted into HI-LOK fastener hex-keyholes, and impedance testing was conducted using microelectronics to monitor coupled electro-mechanical resonance. A coefficient of determination damage metric was calculated to quantify the degree of change due to crack propagation. Following a calibration specimen, blind fatigue tests were conducted on aluminum specimens fastened together with square washers to simulate a multi-layered structure with hidden damage. Of the six specimens, evidence of damage was very clearly indicated using the damage metric for four specimens resulting in measured fatigue cracks between 1.5 and 2 mm, and the remaining specimens were stopped at the initial subtle signs of damage metric change, which resulted in measured cracks between 0.5 and 1.0 mm. The overall average hidden fatigue crack detected was 1.3 mm (~0.05"). FAST sensors provide the potential to increase aircraft availability by eliminating the need to disassemble joints.

ACKNOWLEDGEMENTS

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