SAW Sensor for Fastener Failure Detection

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***Abstract*— The proof of concept for using surface acoustic wave (SAW) strain sensors in the detection of aircraft fastener failures is demonstrated. SAW sensors were investigated because they have the potential for the development of passive wireless systems. The SAW devices employed four orthogonal frequency coding (OFC) spread spectrum reflectors in two banks on a high temperature piezoelectric substrate. Three SAW devices were attached to a cantilever panel with removable side stiffeners. Damage in the form of fastener failure was simulated by removal of bolts from the side stiffeners. During testing, three different force conditions were used to simulate static aircraft structural response under loads. The design of the sensor, the panel arrangement and the panel testing results are reported. The results show that the sensors successfully detected single fastener failure at distances up to 54.6 cm from the failure site under loaded conditions.**

I. INTRODUCTION

NASA is investigating ways to increase aviation safety by monitoring the structural health of aerospace vehicles during flight. Fastener failure is one issue being addressed because it may lead to unplanned costs, fines or catastrophic events. Some areas are more critical than others, a fastener failure may result in a catastrophic occurrence if it fails in a critical area [1]. A $2.9 million dollar penalty has been proposed against American Eagle Airlines by the Federal Aviation Administration (FAA); and one of the primary concerns are loose or missing fasteners [2]. Recently, fatigue was blamed for the failure of two Hi-Locks™ fasteners in a carrier aircraft that caused a fuel leak in the wings [3]. In this case, it was fortunate that the plane was landed safety before a spark could cause a fire. Clearly, the integrity of the fasteners used in aircraft is a critical indicator of aircraft health and safety.

Issues with fasteners are further complicated by companies that deliver counterfeit parts. These fasteners do not meet specifications and therefore are more likely to fail under normal operational conditions. The use of counterfeit parts has multiple impacts: potential loss of life, monetary loss, liability, lack of availability of products for customer use, loss of customer/public trust and image, and brand damage [4]. Seventeen deaths and thirty nine injuries are attributed to counterfeit parts by the FAA from 1973 through 1996 [5]. During the period from 1984 to 1987, 61 aviation accidents were attributed to counterfeit fasteners [6].

Due to the critical importance of monitoring the structural integrity of aircraft, NASA is investigating the use of SAW sensors to passively detect fastener failures. SAW strain sensors have been previously developed, however these do not incorporate high temperature piezoelectric materials that are necessary for harsh environments found in aerospace applications [7]. To investigate fastener failures at high temperature, a SAW strain sensor comprised of an interdigitated transducer (IDT), and two banks of four OFC reflectors has been developed on a Langasite substrate.

II. DEVICE DESIGN

The SAW device uses orthogonal frequency coding (OFC) in a spread spectrum technology manner [8]. The sensor that has been developed has two reflector banks. Each reflector bank is comprised of four sets of gratings. To avoid interference, the reflector banks are positioned on either side of an interdigitated transducer with spacing such that the reflections do not overlap in time (Fig. 1).

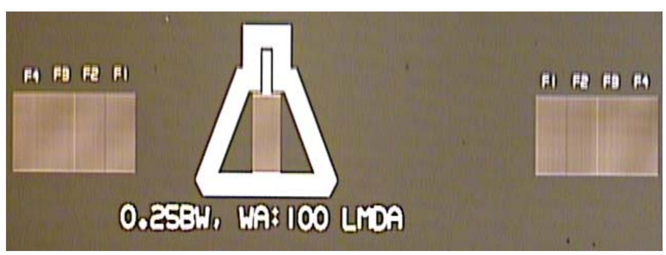

Figure 1. SAW strain sensor comprised of an interdigitated transducer (IDT), and two banks of four OFC reflectors on a Langasite substrate.

The response of each of the four separate frequencies banks are shown in Fig. 2 along with the response of the IDT.

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To meet the constraints of orthogonality, the peak frequency of each reflector occurs at the null for all of the others. Consequently, each reflector will reflect only the frequencies within the main lobe around its peak, and will pass all other frequencies. This aspect of OFC reflectors allows for more consistent amplitude and maximum efficiency of returned energy from the reflector gratings that comprise a reflector bank. The reflector banks are spaced 1.722 mm (left) and 3.710 mm (right) from the IDT. The number of fingers in each grating is 98, 99, 100, and 101. The four gratings have frequencies of 300.05, 303.04, 306.10, 309.28 MHz arranged in order f1, f2, f3, f4, with f1 closest to the IDT (Fig 2.). More diverse frequencies arrangements that make up a reflector bank would allow for more code diversity when uniquely identifying the sensor in a multisensory environment [9].

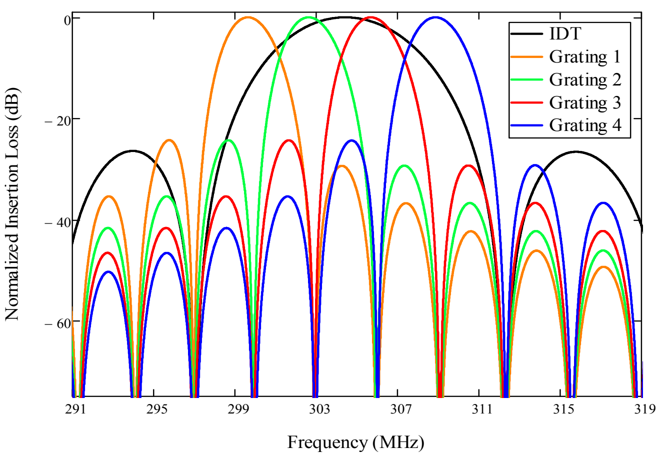

Figure 2. The normalized frequency response of each OFC grating and the IDT response.

The IDT must be broad band and encompass the frequency content of all four reflectors so it has effectively 23 finger pairs, a center frequency of 304.61 MHz, and a null bandwidth of 13.25 MHz for the main lobe. The reflectors have a null bandwidth of ~3.061 MHz each. The reflector and IDT fingers are 100 λ or 899.83 µm. The IDT sampling is $3f_0$, where f_0 is the synchronous frequency, so there are 6 fingers per wavelength.

Langasite ($La_3Ga_5SiO_{14}$) was chosen for the substrate because it has the potential for high temperature operation. Langasite does not have any phase transitions lower than its melting point, therefore it does not lose its piezoelectric properties until 1470 °C [10]. SAW devices operate down to cryogenic temperatures (77 ºK) as well [11]. SAW devices are also inherently radiation hardened up to 10 MRads, so ionizing radiation is not a concern [12]. These properties make SAW technology very attractive for harsh environment locations like those that are found in aerospace applications. Langasite crystal with an Euler orientation of (0, 138.5, 26.6) and a Rayleigh wave velocity of 2741 m/s was used for these devices. Another important property of this material is the piezoelectric coupling coefficient (k^2) which is 0.32% or twice the value found in crystalline quartz. Although the final goal is to have wireless devices, an antenna design was not ready when the testing was required to be performed. Therefore, the prototype sensors have wire connections for this experiment.

III. Experimental Setup

A panel with bolted side stiffeners was used to simulate repeatable fastener failure. This panel is similar to panels suggested by Worden for Structural Health Monitoring (SHM) [13]. The aluminum panel is 25” wide and 37” long. The panel is 0.09” thick, and is made from 6051 aluminum. The side stiffeners are made of 1” “L” shaped 6051 aluminum extrusions that are 0.0625” thick. The bolts are spaced 2” apart. The root of the panel was mounted to steel plate using 26 bolts and a 24.75” x 2” x 3” base plate of aluminum on top of both the panel and side stiffeners. A 24.75” x 1” x 0.5” steel plate was attached to the end of the panel to distribute the force from hanging weights (Fig. 3).

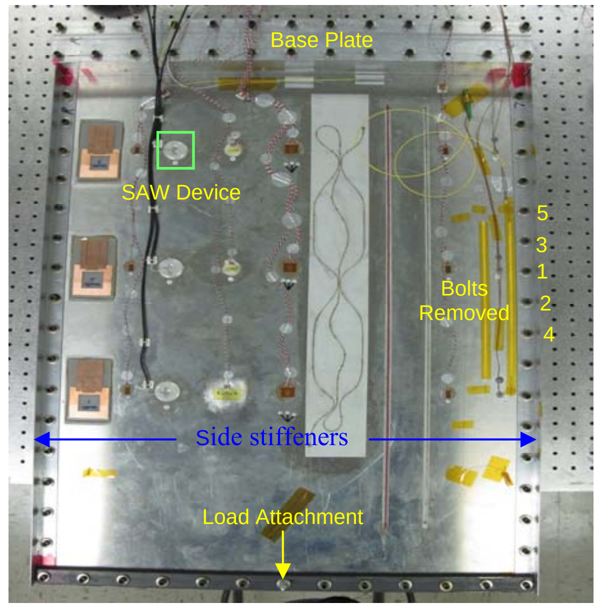

Figure 3. Test panel with bolted side stiffeners. The SAW sensor location is denoted by the green box.

The IVHM project is investigating many sensor technologies for improving aircraft safety. The panel has many sensors installed in addition to the three SAW sensors. Fiber optics strain sensors, fiber optic strain rosettes, fiber optic thermography sensors, fiber optic shape sensors, carbon nanotube strain sensors and SansEC sensors and conventional sensors were all installed. Future work will include a comparison of the various sensors against each other for this application. The SAW sensors have a plastic cap installed over them for protection (Fig. 3).

The procedure for simulating fastener failure is similar to one that has been used before [14]. First, baseline strain is taken with all of the bolts torqued to 130 in/lb and no load on the panel. Next, the designated load is placed on the panel. Then one bolt is removed and data is taken. The bolt is not replaced. This step is repeated until all five bolts have been removed. The load is removed, the bolts are then put back and re-torqued, and the full sequence is repeated for another loading condition (i.e. 0kg, 1kg, 2kg).

The SAW sensor measurements were made with an Agilent 4396B 1.8 GHz, Network/Spectrum/Impedance

Analyzer under the control of a computer running Labview. The vector analyzer excites the SAW device across a frequency range and simultaneously measures the S parameters, specifically the reflection coefficient S_{11}. The programmable features of the network analyzer were used to setup a small frequency range, and then to locate a specific amplitude level of -13.9 db. Once this level is located, the network analyzer is instructed to return the frequency of the measurement at that level. This technique reduced the amount of noise in the frequency measurement as compared to the use of peak or trough amplitudes. In that case, the small amplitude variations can be interpreted as erroneous frequency shifts. Initially a baseline value is taken when the panel has all of the bolts in place and is unloaded. The frequency data was then stored on the computer and used in calculations to determine the strain value. After receiving the frequency value from the network analyzer it is subtracted from the baseline and multiplied by the conversion factor of 0.002855 seconds to convert it into strain.

IV. RESULTS AND DISCUSSION

The sequence of bolt removal was chosen to detect the sensitivity of the sensor to damage. It was initially expected that three bolts would need to be removed before a significant frequency shift from the sensor would be detected. Data was taken following the removal of a single bolt for completeness. The experiment proved that SAW sensors are more sensitive than was expected. For the static conditions of the experiment, extremely small strains could be detected. The maximum variation for the six cases of bolt removal within each of the three loading runs is less than 2 με. The averaged results for the three loading cases of the panel testing are given in Fig 4.

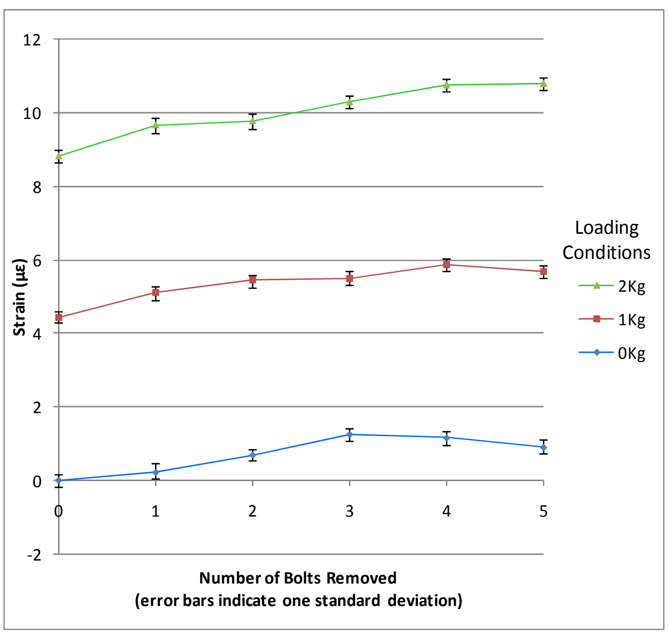

Figure 4. SAW sensor strain data for three load conditions and for 6 cases of bolt removal, with bars indicating the one standard deviation.

The error bars indicate one standard deviation for the 100 data points taken for each test condition. Standard error could be shown instead, but the error bars would not be distinguishable from the symbols used in the plot. Except for the condition of one bolt being removed without any loading the SAW sensor could clearly delineate a single bolt being removed. The average strain value measured for a single bolt being removed is 0.588 με.

Although the data presented in Fig. 4 can be used for detection of fastener failure, opportunities exist for improving the SAW sensor's performance. The variation of the data for a given condition is larger than expected. The average noise for the values measured is ±0.389 με. This value is probably a little high, SAW devices have been developed with sensitivity as low as 0.013 με [15]. The mean strains for the three loading cases are given in Fig 5, with bars that indicate the spread of the data values.

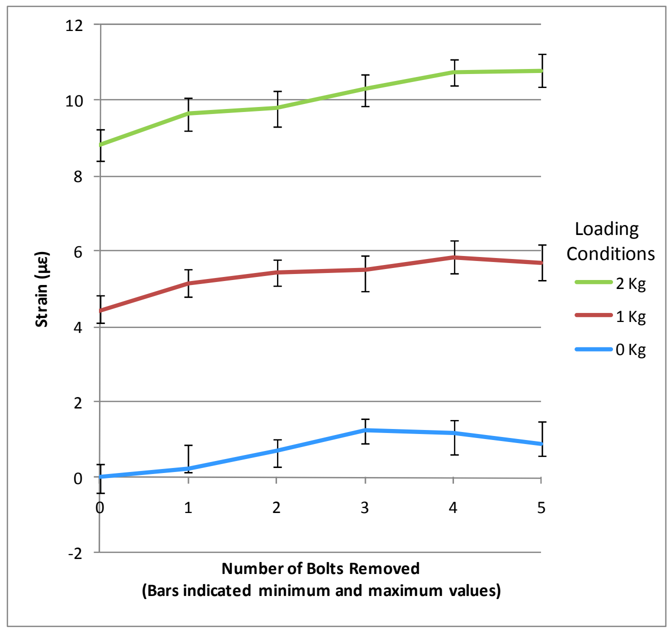

Figure 5. SAW sensor strain data for three load conditions and for 6 cases of bolt removal with bars indicating the minimum and maximum values.

The data appears to be nonlinear as a result of changes in the asymmetrical strain patterns in the panel as bolts are removed. The SAW devices are extremely sensitive even to bolt removal, even when the bolt is 46.4 cm to 54.6 cm away from the SAW sensor. The preliminary data demonstrates that for loaded conditions the SAW sensor can detect single fastener failures. For the unloaded condition the removal of a single bolt is difficult to resolve; the measured strain difference was only 0.221 με. However, the removal of two or more bolts was easily identified. The SAW sensor measured 0.695 με, when the second bolt was removed. During aircraft operation, it may not be necessary to detect single fastener failure "Since mechanical joints in aircraft structures contain a large number of bolts, the above fatigue results suggest that the joint will be able to carry load even after one or several bolts have failed. This gives time for the bolt failure to be discovered during inspection, before catastrophic failure will occur, giving more reasons why joints should be designed in such a way that the failure mechanism in fatigue loading is bolt failure" [16].

The test arrangement was not optimized to reduce the noise level. Shortening the cabling would help, also better cable shielding would reduce the level of electrical noise. During testing the SAW sensors exhibited sensitivity to static electric charges. The addition of a grounding strap to the panel helped but did not completely eliminate the issue. After the testing was completed, some of the instrumentation was found to be on isolated grounds. The improper grounding scheme may have given rise to ground loops. Future testing should incorporate a better grounding scheme without any isolated grounds and optimization of cabling to reduce electrical noise if optimal sensitivity is to be determined.

The sensor could also be used to detect cracks in aircraft structures [17]. A system with a resolution of 1 με has been demonstrated for crack monitoring before and after repairs [18]. Strain gages have also been used for loading and fatigue monitoring of aircraft. While the data shows the feasibility of SAW strain sensors, more work is needed to characterize the SAW sensor for aeronautical applications.

CONSLUSIONS

A SAW sensor has been developed that incorporates OFC reflectors. The sensor is capable of detecting single fastener failures under static loaded conditions (1 kg, 2 kg) for aerospace applications. The average noise for the SAW sensor on the panel is ±0.389 ppm. In general terms when the loading on the panel increased, a larger response was recorded. The average value for single fastener with zero load is 0.221 με, for 1 kg it is 0.695 με, and for the 2 kg case it is 0.848 με. The larger the loading on the panel, the greater the strain change when a fastener fails. The maximum variation during bolt removal for the three loading cases is less than 2 με. The SAW devices are so sensitive that removing bolts 46.4 cm to 54.6 cm away from the SAW sensor could be detected. Extremely small strains were detected during static loading. The average strain value measured for a single bolt being removed under zero load is 0.588 με. Increased sensitivity may enable crack detection.

Future work will include the comparison of the SAW sensor to other technologies such as fiber optic strain sensors and carbon nanotube strain sensors. More work is needed to characterize the SAW sensor for both static and dynamic loading conditions before it will be applicable for commercial aircraft applications.

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