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Title: Monitoring of Bolted Joints using Piezoelectric Active-sensing for Aerospace Applications

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Cover page

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ABSTRACT

This paper is a report of an initial investigation into tracking and monitoring the integrity of bolted joints using piezoelectric active-sensors. The target application of this study is a fitting lug assembly of unmanned aerial vehicles (UAVs), where a composite wing is mounted to a UAV fuselage. The SHM methods deployed in this study are impedance-based SHM techniques, time-series analysis, and high-frequency response functions measured by piezoelectric active-sensors. Different types of simulated damage are introduced into the structure, and the capability of each technique is examined and compared. Additional considerations encountered in this initial investigation are made to guide further thorough research required for the successful field deployment of this technology.

INTRODUCTION

A lug joint is one of the most critical structural elements in aerospace applications. This connector-type structure has been responsible for several incidences, including the crash of AA587 on November 2001. Consequently, some of Boeing's hotspot programs and the Arizona State University's damage prognosis MURI program have focused on tracking and monitoring the integrity of lug-assemblies [1].

During operation, a lug joint will experience significant fatigue loads and environment variations, and as a result, several damage conditions could be initiated in this structure, including fatigue cracks and connection (joint) failures. As an initial investigation, this study focuses on monitoring of joint failure modes of a lug assembly using piezoelectric actives-sensors.

The SHM techniques employed in this investigation are impedance-based

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structural health monitoring techniques, high-frequency response function-based, and time-series predictive model-based methods. The guided wave approaches are not investigated because the lug assembly examined in this study has a relatively smaller dimension and several bolted joints, potentially acting as wave scattering sources. The experimental setup, procedure, and results, along with future issues are outlined in the following sections.

THE TEST STRUCTURE: A UAV LUG ASSEMBLY

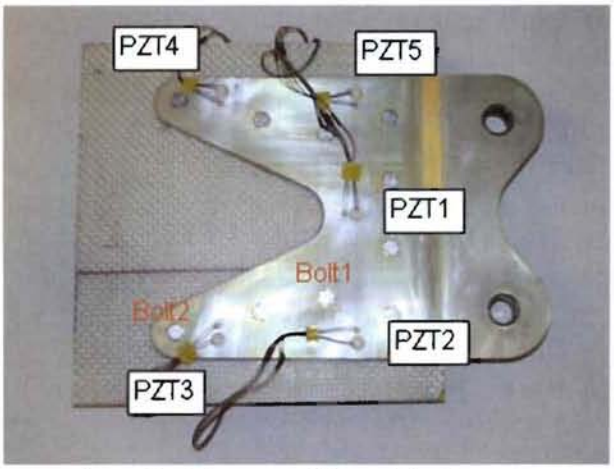

Figure 1. A lug assembly used in this study

The lug assembly was fabricated from 25-mm thick Al 7075-T651 plate, shown in Figure 1. The overall size of the lug is approximately 375 x 270-mm. One side of this structure is bonded with a 345 x 245 x 30-mm composite plate using 10 bolted joints (AN6C21A) at the torque level of 220 in-lb. The typical failure modes for this lug-assembly were identified as a fatigue crack at the tip of the lug and the wing, the loosening mode of joint failure, and fatigue crack initiation at bolt holes. Total 10 piezoelectric transducers (five 12.7-mm diameter and five 6.3-mm diameter) were installed on one surface of the lug as shown in the figure. A redundant number of transducers were installed, rather than optimal, for this feasibility study.

IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

The basic concept of the impedance method is to use high frequency vibrations to monitor local regions of a structure for changes in the structure's mechanical impedance that would indicate permanent or imminent damage [2,3,4,5]. This process is possible using piezoelectric sensor/actuators whose electrical impedance measurements can be used to identify changing parameters such as resonant frequencies or modal damping, allowing for the detection and location of damage. The impedance method can be implemented with relatively low power compared to other active-sensing SHM techniques. The impedance method also has applications in sensor self-

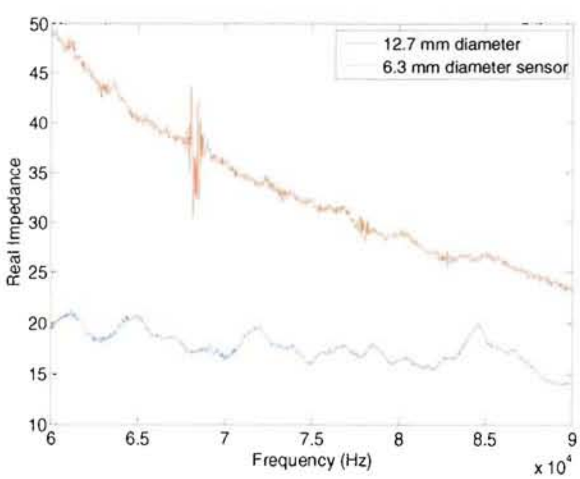

Figure2. Major components of the WID3

diagnostics in determining the operational status of piezoelectric active-sensors used in SHM [6].

Figure 2 shows the impedance responses in the frequency range of 60-90 kHz measured by the transducers located at the top of the structure (PZT5). As can be seen, the impedance response measured by a 6.3-mm diameter sensor is dominated by a strong contribution of the piezoelectric capacitive impedance (shown as a downward sloping), and fails to clearly identify unique structural responses. This capacitive impedance should not be used for SHM because it is much more sensitive to temperature or other operational variations than structural changes. The response measured by a 12.7-mm diameter shows a better coupling between the structure and the sensor than that of the smaller sensors. However, with a relatively massive structure and a higher damping present (probably caused by the bonded composite plate), the response does not appear to those typically found in metallic structures. The impedance excitation from the PZTs does not seem to be sufficient enough to modulate the structural responses necessary to SHM, and/or the sensing region of each sensor would be confined to an extremely small area.

Further tests indicates that the impedance measurements made before and after the induced damage (will described in the next section) show some variations, however, these variations are not significant enough to conclusively indicate structural damage. In order to efficiently use the impedance method for this specific application, the frequency range for interrogation should be kept much higher, higher than a few hundred kHz ranges. However, this approach was not taken because of the practical implementation issues. Current impedance hardware developed by authors has a frequency range only up to 100 kHz [7]. Although not successful in SHM, the impedance method will be used for sensor diagnostics and validations processes [6] for our research effort, along with other SHM techniques described in the next section.

FRFS/ TIME SERIES PREDICTIVE MODELS FOR SHM

It is a well known fact that frequency response functions (FRFs) represents a unique dynamic characteristic of a structure. From the standpoint of SHM, damage will alter the stiffness, mass, or energy dissipation properties of a system, which, in turn, results in the changes in the FRF of the system [8]. Additionally, time series predictive models, such as autoregressive model with exogenous inputs (ARX), can be used as a damage-sensitive feature extractor. An ARX (p,q) model is fit to the data to capture the input/output relationship, which is intended to enhance the damage detection process by utilizing the information associated with a "known" input provided by a piezoelectric active-sensing system [9]. In order to overcome some limitations imposed by the impedance methods, FRF-based and the time series-based approaches are investigated.

For this study, time histories were sampled at a rate of 51.2 kHz, producing 4096 time points using a commercial dynamic signal analyzer. An amplified random and chirp signals (10+V) were used as the input for the tests. Several sensor-actuator combinations were used to measure the required data for SHM. Only the results with the random inputs and with one sensor-actuator pair (PZT 1 as an actuator, PZT 4 as a sensor) are shown in this report.

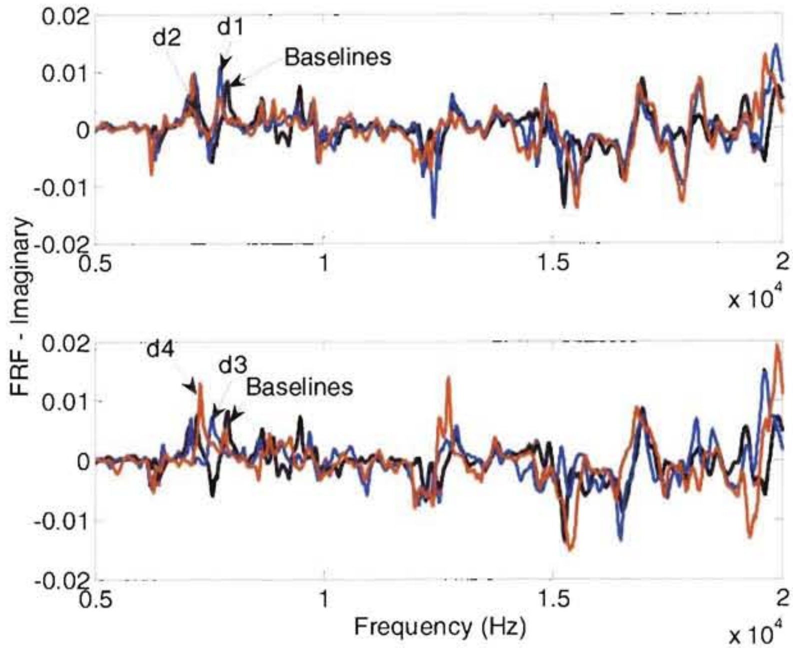

Figure 3: Frequency Response functions measured at different structural conditions

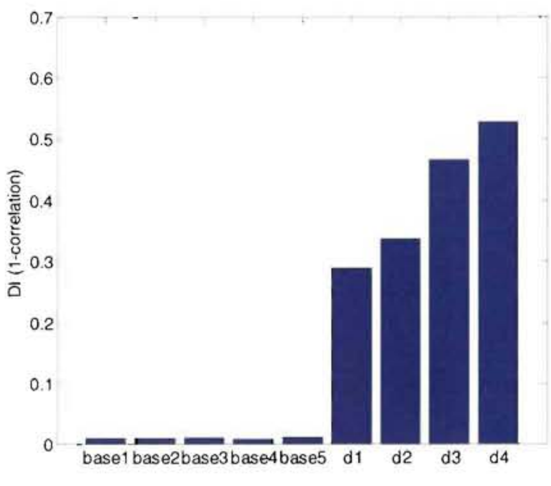

Figure 4. Damage Metric Chart

The FRFs (in the frequency range of 5-20 kHz) obtained from the piezoelectric transducers with 4 levels of damaged conditions are shown in Fig 3. The damage was simulated by loosening bolts in two locations. It can be seen from the figure that, with increasing the level of damage, the FRF signatures shows a relatively large change in shape and is clearly indicative of imminent damage. For the first level of damage (d1: loosening bolt 1 to 100 in-lb), the FRF showed pronounced variations as compared to previous baseline readings. The baselines were taken under different boundary conditions, and they are more repeatable and have higher SNR than the electromechanical impedance measurements. With the next three stages of damage (d2: loosening bolt 1 to 20 in-lb; d3 and d4: loosening bolt 2 to 100 in-lb and 20 in-lb, these conditions were imposed cumulatively), the FRF showed a distinct change in the signature pattern, i.e. new peaks and valleys appear in the entire frequency range. These changes occur because the damage modifies the apparent stiffness and damping of the lug assembly. A correlation-based damage metric chart is illustrated in figure 4. The damage metric chart is constructed after each measurement has been taken in order to give some indication of the conditions of a structure through comparison with the reference measurement. As can be seen in the figure, with an increase in the extent of damage, there is a corresponding increase in the damage metric values. This chart provides a quick insight into the extent of damage and provides for quantitative comparison between different data sets. This figure also indicates that, for monitoring of joint failure modes, one sensor-actuator pair is sufficient to monitor the entire lug assembly. The results with other sensor-actuator combinations are similar. It should be also noted that, for this test, the level of damage still could be categorized as an incipient stage.

In addition to FRFs, SHM techniques based on time series predictive models were also implemented. These techniques have some advantages that i) the process can be embedded into low-power, low-cost digital signal processor, ii) the methods are sensitive to nonlinearity detection, and iii) there are many signal processing algorithms available for SHM.

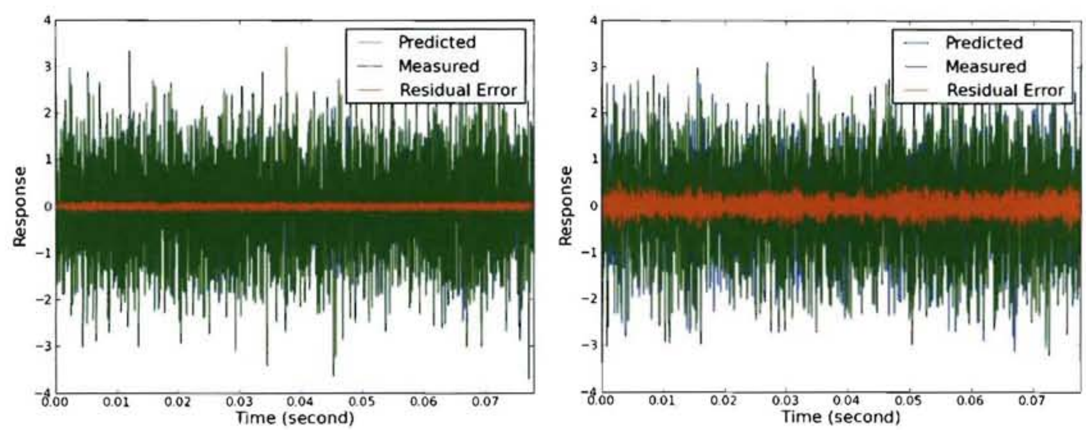

Figure 5. The Predicted and actual responses measured by PZT1 for undamaged (left) and d3 conditions (right)

One SHM approach taken in this study is the use of residual errors. An ARX model estimated from a baseline condition is used to predict newly measured responses. Structural damage introduces either linear deviation from the baseline conditions or nonlinear effects in the signals. As a result, the model developed with the baseline data will no longer accurately predict the response of the damaged system, resulting in increase in residual errors.

Figure 5 illustrates the ARX predicted and actual responses for both undamaged and d3 conditions. As can be seen, there are large increases in residual errors when damage was introduced. Figure 6 illustrates the root-mean-squared-error (RMSE) of the residual errors estimated from all structural state conditions. As can be seen, there is a corresponding increase in RMSE values with induced damage. Several damage identification procedures are also applied to AR and X parameters using principle component analysis (shown in Figure 6), correlation analysis, and Mahalanobis distance measures. All of these results show a clear and accurate classification of each structural condition.

SUMMARY

The results collected from the experimental tests shows the performance of piezoelectric active-sensing technologies to detect connection damage in a lug-assembly. By employing relatively higher frequency ranges, these methods are sensitive to small defects in the structure, and at the same time, the effects of extraneous low-frequency inputs from operational conditions can be reduced. It should be noted however that the damage considered in this study contains bolted joint failures only; this is mainly because they are easy to simulate, control, and enable repeatable tests. Future study should aim at fatigue crack initiation and growth using these methods. Furthermore, the effect of loadings and temperature changes on the methods should be considered, and they are currently being investigated by the authors.

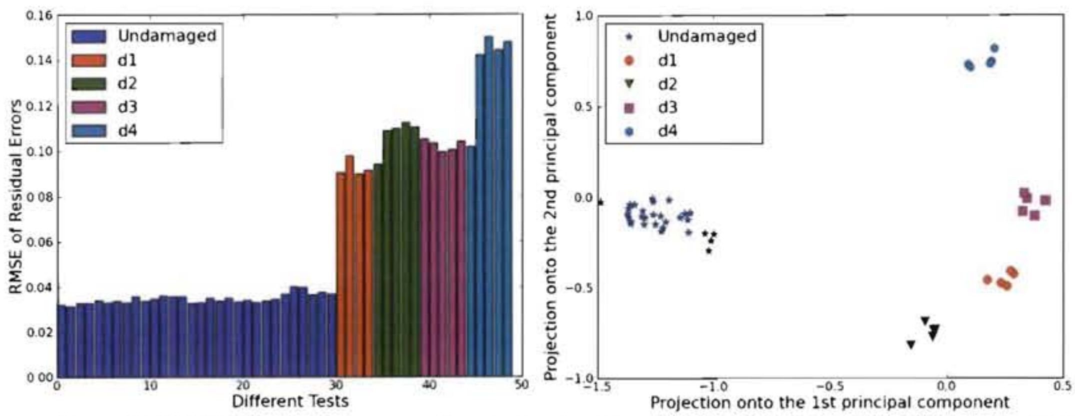

Figure 6. RMSE of residual errors of each structural condition (left). AR parameters of the ARX (50,48) predicted model projected onto the first two principal components (right).

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