Fatigue crack quantification approach based on multi-path unit-cell concept in sensor network

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Abstract

A major safety and maintenance concern in aerospace structures are fatigue induced cracks for which quantification is a very critical component for achieving design performance. Such incipient damages, once initiated, can grow extremely fast and can lead to catastrophic failure of the structure. Traditional nondestructive inspection (NDI) techniques offer solutions which are offline, time consuming and quite expensive. Structural Health Monitoring (SHM) techniques are known to overcome some of these drawbacks. However, in SHM the challenges associated with quantification of fatigue cracks come mainly from the differential structural acoustic-ultrasonic response in similar material due to system installation errors or are caused by environmental usage conditions. Studies have shown that these variations in acoustic response come primarily from sensor positioning and the characteristics of crack e.g. orientation, crack length etc. This study presents a robust, multipath and scalable unit-cell approach for quantification of fatigue cracks. Multiple paths from a sensor configuration with a four sensor unit called a unit-cell is used along with an adaptive weighted averaging method to mitigate the effects of sensor positioning errors and/or uncertainties associated with crack orientation for quantification in SHM systems. Coupon tests that have been conducted to verify and validate the performance of this unit-cell approach for quantification purposes.

1 INTRODUCTION

In structural health monitoring (SHM), a diagnostic is typically performed by employing distributed sensors for sensing ultrasonic data and thereafter processing it through intelligent algorithms for determining structural changes (such as defects, degradation etc.) that may have taken place in the structure [1-10]. Performance of such a diagnostic system relies a lot on the quality of data, which unfortunately is quite susceptible to contamination due to uncertainties in system installations, surrounding conditions etc. Therefore major challenges associated with the accuracy of a SHM-based system come from changing environments (temperature, humidity, loading etc.), variation on sensor coupling, structural aging, measurement noise etc. and also from sensor system installation itself. The corruption in diagnostic data due to uncertainties can be mitigated to some extent by adopting baseline compensation in the analysis. This however poses a challenge for the scalability of the technique especially where calibration is required for quantifying the damage. A practical
SHM technique needs to be scalable with calibrations that can be learned and adopted from representative coupons of the hotspot regions in the structure. The calibrations estimated from representative coupons need to be adopted for fleet wide management. For a robust and accurate SHM system, it is essential that it should be adaptive to unknown condition by filtering out the effect of data corruption due to uncertainties and still be sensitive enough to detect the smallest critical size defects. To this end, various statistical tools and feature extraction algorithms are used to characterize the structural anomalies [11-15].

In previous work by the authors [16-18] extensive simulations and tests were performed to study the major factors listed below that could affect the sensitivity of the SHM system for monitoring a structure. Factors affecting SHM system accuracy and reliability are as follows:

- Variation in mechanical properties of structures
- Variation in adhesive properties
- Variation in mechanical and electrical properties of PZT
- Variation in sensor locations
- Uncertainty in damage orientation
- Variation in Adhesive thickness

Damage Index (DI) has been devised as an estimation of differential changes between baseline and current data. Based on this study, out of several factors influencing the DI values, the two most dominating ones are the (1) the sensor/actuator location and (2) damage growth orientation. The study was conducted by testing multiple coupons with single paths (2 sensors) only as described below:

1. Effect of variation in actuator-sensor location

In order to simulate the effect of variations in sensor network placement, five engineers attached sensor on 30 coupons as shown in Figure 1. Sensor locations on the 30 coupons were measured to estimate sensor location variation. Extensive numerical simulations were performed to understand the effect of variations in sensor placement on the damage sensitivity, it was found that for a sensor location variation (%): $\pm 1.57*r$, $\pm 1.57*r$ ($r$-is radius of PZT) there is a 10.84% variation in DI as shown in Figure 2.

Figure 1: Variation in sensor locations in 30 test coupons.
Figure 2: Effect of variation in sensor location on DI.

(2) Effect of variation in crack orientation

In order to study the effect of variations in crack orientation on the DI, damage cuts were used to simulate variations in loading direction. Figure 3 shows the variation in DI. It can be observed that crack orientation has a large effect on the variation of DI as shown in Figure 3.

Figure 3: Effect of variation in crack orientation on DI

The main conclusion from the study was that the sensor locations with respect to the damage location and the way cracks propagate are the critical parameters that influence the DI, if the environmental conditions remain constant. In that respect, if the sensor-actuator location uncertainty can be minimized via accurate installation processes and the damage growth exhibits a similar pattern from one coupon to another, the DI versus damage location behavior may be preserved for identical structures. Therefore, for specific locations on structures where damage is expected to appear, also referred to as “hotspot”, multiple coupons and experiments may not be necessary for traditional Probability of Detection (POD)-based analysis under the assumption of accurate sensor installation, appropriate compensation of the environmental effects, and effective model-assisted and numerical
simulation approaches.

For most practical situations, the sensors can be accurately positioned by employing the SMART Layer [19] however; the nature of crack orientation cannot be assured. For the case of a one sensor path (2 sensors only) configuration there are 3 unknowns (in terms of sensor location, actuator location and the crack orientation) for which there are only one path DI that is available for calibration. Therefore it is interesting to study if including DI information from multiple paths can be useful in mitigating the effect of crack orientation induced uncertainty for calibration.

In this study, a novel calibration based quantification approach was investigated and tested to determine the effectiveness of using multiple paths from a 4-sensor configuration called a unit-cell with a weighting factor for constraining the effect of crack orientation in the calibration based quantification from coupon to coupon. Employing more paths in the calibration process provides more flexibility to the system to auto adjust the weighting factor based on the sensitivity of individual paths used along with the calibration curve.

2 SCALABLE METHODOLOGY

Given the variability and uncertainties in structural boundary conditions, material properties, sensor placements, sensor PZT properties, adhesive thickness etc. it is desired to devise a methodology for making the diagnostic system accurate and scalable. The system configuration setup obtained from a small coupon test should be extendable to a large structure. The proposed unit-cell based SHM system approach is a step in this direction. The focus of this methodology is based on crack damage quantification using a weighted calibration method.

In this investigation, the proposed unit-cell approach that is scalable from representative coupons to in-service structure was tested to provide a solution for challenging fleet-wide structural health monitoring. A weighted calibration based damage quantification technique that can quantify fatigue cracks in real structure through a unit-cell based calibration procedure that uses representative coupons of the structure was developed.

3 SHM THROUGH AN INNOVATIVE UNIT CELL APPROACH

In this investigation it was found that by using more DI paths it is possible to minimize the uncertainty caused by variability factors and therefore the results may be transferable from one specimen to another specimen of the same type ("identical" installation process and SHM system).

3.1 Unit Cell approach

Unit-cell approach utilizes multiple actuator-sensor paths for detection, localization and quantification. The quantification method mitigates the effect of sensor positioning error and uncertainties associated with crack orientation.

With a minimum of 4 sensors and corresponding 6 paths, any coupon can be configured as shown in Figure 4. As damage is introduced in the structure the path closest to the damage will start showing changes in scatter energy. As the damage size grows, other paths in the unit cell will also start showing changes in their scatter energy.
Figure 4: Configuration Unit-Cell

<table>
<thead>
<tr>
<th>One Sensor-One Actuator</th>
<th>A Sensor/Actuator Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each pair of sensor/actuator generates one single DI (damage index)</td>
<td>Multiple paths generate multiple DIs (see 4 node network)</td>
</tr>
<tr>
<td>1 DI (one path) with three variables</td>
<td>6 DIs (6 paths) with five variables:</td>
</tr>
<tr>
<td>1. Sensor location</td>
<td>1. 4 Sensor/actuator locations</td>
</tr>
<tr>
<td>2. Actuator location</td>
<td>2. Crack orientation</td>
</tr>
<tr>
<td>3. Crack orientation</td>
<td></td>
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</table>

3.2 Calibration and quantification approach

There are two steps in this approach. First, for a representative coupon with 4-sensors the DI associated with paths showing huge scatter energy change are correlated to actual damage size measurements using a best fitted hyperbolic tangent shaped curve by least square minimization to generate a calibration. This is done as an offline process. Second, the calibration curve is used through an online process to estimate the damage size on target coupons with similar configurations. The DI from paths from target coupons is used to calculate weighting factors along with calibration curve. Figure 5 shows the calibration process.

4 A CASE STUDY: COUPON WITH 4 SENSORS AND EDM NOTCH

A case study is presented here to show the performance of the proposed weighted calibration technique for quantifying fatigue crack damage in the metallic coupons. As shown in Figure 6, four identical coupons with the same sensor placement were developed. Coupon#1 was used for estimating a calibration curve as shown in Figure 7.

A comparative analysis is carried out to present the effect of adding multiple paths to error in the estimation of crack size. As shown in Figure 8, coupon 1 is used to generate the calibration curve which is used to estimate the crack size on coupon4. The error in estimation is plotted against the number of paths used in calculating the calibration curve which shows that after three paths there is not much improvement in estimation. This demonstrates that
adding more than one path improves the robustness and accuracy.

Figure 5: Calibration based on quantification approach

Figure 6: Four identical coupons used for calibration.
The coupon 1 was used to generate a calibration and tested back for validation on the same coupon. The result is shown in Figure 9.

Similarly the calibration from coupon 1 data is applied on coupon 2, 3 and 4 and results are presented in Figure 10.
5 SCALABILITY OF APPROACH

The proposed unit-cell approach is scalable for use on any size and type of platform. For example, as shown in Figure 11, unit-cells can be composed of various types on a structure. Once calibration is done on one structure, the information can be used for damage detection and quantification on similar structures without any re-calibration.

6 SUMMARY AND CONCLUSIONS

Several uncertainties could affect the damage detection sensitivity of any practical SHM system. Extensive numerical and experimental tests were carried out to understand the two major factors that affect damage detection sensitivity (1) variation in sensor locations, and (ii) crack orientation. Practically these two uncertainties can be minimized but cannot be
eliminated. Development of any practical SHM technique that minimizes the effect of these uncertainties on detection sensitivity and maximizes the accuracy of damage characterization is required. In this paper, a unit-cell SHM design approach that is scalable and adaptable for fleet-wide structural health monitoring was investigated. The focus was on crack damage quantification based on a weighted calibration method in the context of using a unit-cell based SHM system approach. A unit-cell based SHM system was developed that accurately detects, locates, and quantifies damage in representative airframe structural coupons. Test data from coupons were used to verify and validate the performance of the unit-cell based SHM system for damage detection and characterization. The results can be summarized as follows:

- The unit-cell approach offers a scalable mechanism to extend the calibration approach to more complex structures for quantification.
- The effect of variability associated in sensor positioning and crack orientation from coupon to coupon can be mitigated by using a multi-path unit-cell approach for quantifying fatigue crack based on calibration.
- Based on the test results, the calibration based quantification module provides good results for the coupon test data cases.

There are several advantages with this technique such as:

- Scalability
- Multiple wave propagation paths
- Crack in any orientation is sensed by any of paths
- Increases damage detection capability
- Reduces the uncertainty in the damage quantification

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