Damage Quantification of Active Sensing Acousto-ultrasound-based SHM Based on a Multi-path Unit-cell Approach

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ABSTRACT

Assessing the reliability of damage quantification is a critical and necessary process for the evaluation of Nondestructive Evaluation (NDE) or Structural Health Monitoring (SHM) techniques. When it comes to NDE techniques, appropriate processes have been matured and established for asserting the reliability of damage quantification. However, such techniques offer solutions which that can be applied offline, are time consuming, and oftentimes quite expensive. On the other hand, for the case of SHM-based methods, and although several probabilistic methods have been proposed in the state-of-the-art literature, the task of damage quantification of active sensing techniques poses significant challenges that need to be properly addressed. Specifically, a major safety concern in aerospace structures is related to fatigue induced cracks for which accurate and reliable quantification is a critical issue for achieving the design performance and ensuring the aircraft safety. The main challenges associated with the quantification of fatigue cracks originate from the acousto-ultrasonic response discrepancies in similar structural materials that are due to variations in operating and environmental conditions, sensor positioning, damage characteristics (crack location, orientation, and propagation), and the effectiveness of the employed diagnostic algorithms. Recent studies have shown that apart from the operating/environmental conditions, the main sources of variation and uncertainty in the acoustic response are related to the location of the sensors and the damage location and propagation patterns. Trying to address the latter, this study presents an active sensing damage quantification approach that is based on the use of multiple piezoelectric sensors and corresponding acousto-ultrasonic damage propagation paths. Multiple paths from a multiple-sensor configuration unit, referred to as unit-cell, are used along with an adaptive weighted averaging method to mitigate the effects of sensor positioning errors and/or uncertainties associated with crack size and orientation. Several coupon-level experiments have been conducted to validate the performance of the method and investigate the convergence of the accuracy for increasing number of sensors.

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INTRODUCTION

Structural Health Monitoring (SHM) systems utilize distributed, permanently installed sensors at certain structural regions and apply diagnostic algorithms to extract meaningful health information from the sensing data [1-6]. Such sensing data is subjected to various sources of uncertainty associated with all aspects of the inspection environment and operating conditions. In contrast to traditional Non-destructive Evaluation (NDE) procedures, where the factors due to operator pose the dominant uncertainty [7-9], SHM-based technologies are mainly challenged by in-situ effects. These include changing environments (temperature, humidity, and wind), varying operating conditions (ambient loading conditions, operational speed and mass loading, etc.), variation in boundary conditions, sensor and structural aging, and measurement noise amongst others, as well as the sensing network layout itself [10-15]. A SHM system needs to be robust to uncertainties, but sensitive enough to detect the required minimum damage even when sensor data is "corrupted" by these uncertainties. To effectively address various types of uncertainties in SHM, various statistical methods and feature extraction algorithms have been proposed in the literature [10, 11, 16-18].

Typically, SHM methods involve the detection, localization, and quantification of an adverse event that may affect the structural health state (Figure 1). In the current state-of-the-art literature, a significant amount of research is targeted to the development of diagnostic approaches based on various sensor technologies [19-20]. These approaches can achieve a certain level of capability in terms of damage detection. However, the effectiveness of such methods face significant challenges when it comes to tackling the critical task of damage quantification. Typically, SHM involves four functional levels referred to as Technology Classification Levels (TCL) [21, 22]:

- Level I: Detection of the occurrence of damage
- Level II: Identification of the geometric location of damage
- Level III: Quantification of the magnitude or severity of damage
- Level IV: Estimation of the remaining service life/strength (prognosis)

The reliability quantification of SHM systems starts from TCL I, as it is of utmost importance to determine whether a system can detect damage. This topic has been addressed in a recent study by the authors and co-workers [22]. The main conclusions from this work were that the sensor locations and the way damage propagates are the two critical parameters that influence the damage detection capability of the SHM system, if the environmental, ageing and boundary conditions remain constant. In that respect, if the sensor-actuator location uncertainty can be minimized via accurate installation processes, then the damage growth exhibits a similar pattern from one coupon to another, and the damage index (DI) may exhibit similar evolution patterns for identical structures. Therefore, for hotspot monitoring applications (where the approximate damage location and orientation are known), testing of multiple coupons may not be necessary for traditional POD-based analysis under the assumption of accurate sensor installation, appropriate compensation of the environmental and boundary conditions effects, and compensation of aging effects.

A major safety concern in aerospace structures is related to fatigue induced cracks for which accurate and reliable quantification is a critical issue for achieving the design performance and ensuring the aircraft safety. The main challenges associated with the quantification of fatigue cracks originate from the acousto-ultrasonic response

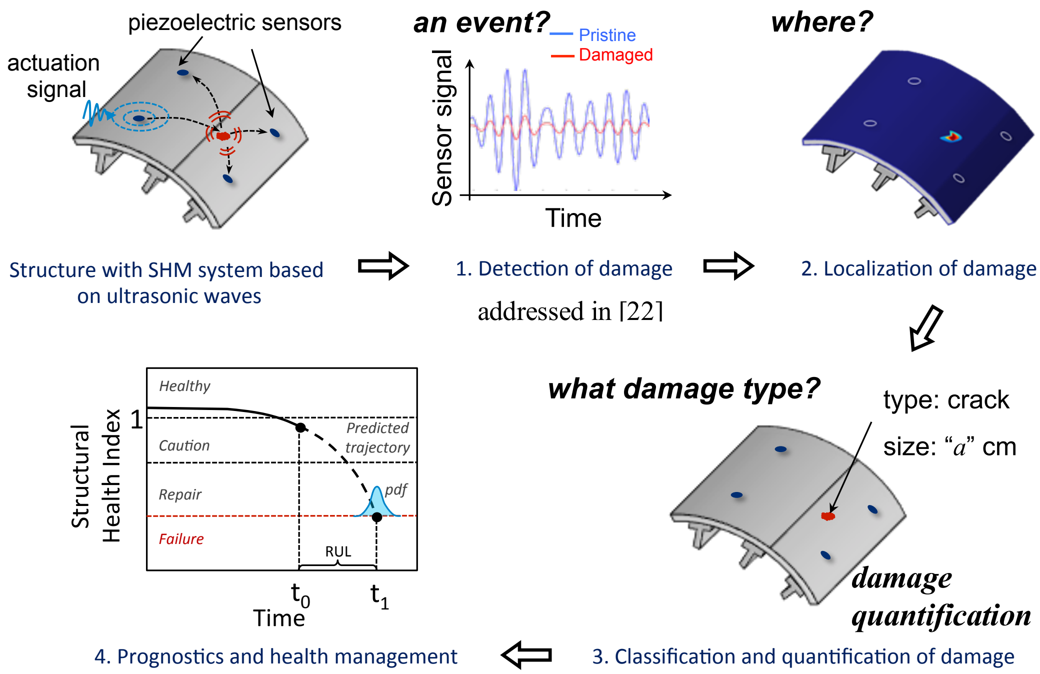

Figure 1. Schematic representation of the technology classification levels (TCLs) for an active sensing acousto-ultrasonic SHM system [22].

discrepancies in similar structural materials that are due to variations in operating and environmental conditions, sensor positioning, damage characteristics (crack location, orientation, and propagation), and the effectiveness of the employed diagnostic algorithms. Recent studies have shown that apart from the operating/environmental conditions, the main sources of variation and uncertainty in the acoustic response are related to the location of the sensors and the damage location and propagation patterns.

However, the sensitivity characterization of active-sensing SHM methods is based on the main operating principles of each technique. Apart from the sensor types and diagnostic algorithms, the reliability and accuracy of an SHM system could be significantly influenced by the sensor/actuator network (number and locations of sensors and actuators). However, the sensor network design depends upon whether the damage location is known (Known Damage Location – KDL) or unknown (Unknown Damage Location – UDL) a priori based on historical data or other preliminary methods of analysis. Hence the sensor network design for KDL (in fact the suspected damage location, also known as "hotspot" monitoring) could be substantially different from those cases where potential damage location is completely unknown, Accordingly, all SHM systems can be classified into four categories as shown in Table I [22].

TABLE I. CLASSIFICATION OF SHM SYSTEMS FOR RELIABILITY QUANTIFICATION.

	S-SHM (Scheduled)	**A-SHM (Automatic)**
Known Damage Location (KDL)	The system will only interrogate periodically a known "hotspot" location. *(similar to NDE)*	The system will continuously interrogate a known "hotspot" location.
Unknown Damage Location (UDL)	The system will periodically interrogate the entire structure for damage.	The system will continuously interrogate the entire structure for damage.

Problem Statement and Method of Approach

In this study, the problem of damage quantification is addressed for an active sensing KDL S-SHM approach. Active sensing SHM utilizes appropriate transducers that may act both as sensors and actuators. The most common type of such transducers used in state-of-the-art SHM systems are piezoelectric sensors-actuators (PZTs), which can be used both as transmitters and receivers, for monitoring local defects by injecting controlled diagnostic signals into structures and can potentially interrogate large structure areas. In principle, an active system allows damage to be interrogated by injecting controlled diagnostic signals (i.e. guided Lamb waves) into the structure. With the known inputs, the changes in local sensor measurements are associated with the introduction of damage in the structure. Although these techniques have been demonstrated to be provide a promising approach for reliable damage detection, active systems, it has been recently shown that the sensor/actuator location and the damage growth orientation from specimen to specimen are the two major factors affecting the variation of the damage index for SHM under the same environmental and boundary conditions, and therefore the reliability of damage quantification [22].

Trying to address the aforementioned challenges and propose an effective approach for tackling damage quantification for KDL S-SHM, this study presents an active sensing damage quantification approach that is based on the use of multiple piezoelectric sensors and corresponding acousto-ultrasonic damage propagation paths.
The main goal of this study is to enhance the premise that higher damage quantification robustness of active sensing ultrasonic approaches for hotspot monitoring can be achieved via the use of multiple sensors, and thus paths. The main hypothesis for this study can be stated as follows: as the number of sensors and wave propagation paths increases, the uncertainty in the damage index (as defined in [22]) will decrease leading to robust damage quantification. Theoretically, it is assumed that the damage index value will converge to its "real" value as the number of sensors/paths increases, as the addition of new paths will not contribute to any useful information.

Multiple paths from a multiple-sensor configuration unit, referred to as unit-cell, are used along with an adaptive weighted averaging method to mitigate the effects of sensor positioning errors and/or uncertainties associated with crack size and orientation. The second hypothesis of this study can be stated as follows: once the calibration curves have been obtained from the unit-cell of a single coupon, the same mathematical equation can be used for "identical" coupons for hotspot monitoring (the location of crack is known/suspected a priori).

In order to evaluate the stated assumptions, several coupon-level experiments have been conducted to validate the performance of the method and investigate the convergence of the accuracy for increasing number of sensors.

MULTI-PATH UNIT-CELL APPROACH FOR DAMAGE QUANTIFICATION

In this study, a novel multi-path calibration-based quantification approach is investigated and tested to determine the effectiveness of using multiple paths from a piezoelectric pitch-catch sensor configuration, referred to as unit cell (Figure 2). This method employs an appropriately selected weighting factor for constraining the effect of crack orientation in the quantification approach and account for the coupon-to-

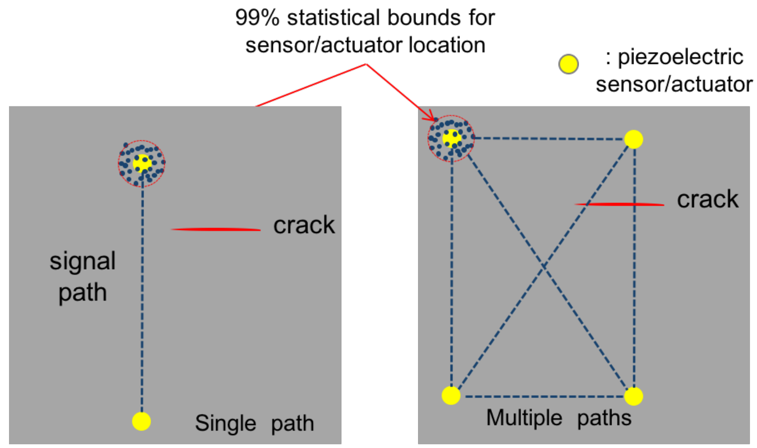

Figure 2. Single-path configuration versus multiple-path configuration that defines a unit-cell for hotspot monitoring.

coupon uncertainties. Employing more paths in the calibration process provides additional flexibility to the active sensing SHM system to auto adjust the weighting factor based on the sensitivity of individual paths used along with the calibration curve.

Definition of Unit Cell

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 enabling an accurate and scalable diagnostic system. The goal is to transfer the system configuration setup obtained from an indicative structural coupon of the structure to larger structural components with identical sensor network topologies, as well as hardware and software components. 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 assuming "identical" installation process and SHM system. The cornerstone of this methodology is based on crack damage quantification using a weighted calibration method. The proposed multi-path unit-cell approach can be scalable from representative coupons to in-service structures to provide a feasible solution for fleet-wide structural health monitoring. As Figure 2 indicates, and in contrast to single actuator-sensor pairs and corresponding single path configurations, the unit-cell approach utilizes multiple actuator-sensor paths for tackling damage detection, localization and quantification. With a minimum of 4 sensors and corresponding 6 paths, any coupon can be configured as shown in Figure 2. As damage is introduced in the structure the path closest to the damage is expected to show bigger changes in the wave scatter energy. As damage size grows, other paths in the unit cell will also start showing changes in their scatter energy.

Multi-path Calibration and Quantification

Specifically, when it comes to damage quantification, the goal of the proposed approach is to mitigate the effects of sensor positioning errors and uncertainties associated with crack orientation and propagation.

The key points of the unit cell are the following:

1. In a unit cell, paths closer to the damage are show dominating DI values.
2. As damage size grows, the DI values for individual paths change/evolve.
3. Appropriate weight factors based on dominating DI paths are used for back estimating the actual damage size.

The goal of the unit cell is the mitigation of the effects of sensor/actuator positioning variations and uncertainties that can be associated with crack orientation and propagation.

The damage quantification approach comprises two steps. First, for a representative coupon with several sensors that define the unit cell, the DIs associated with the paths showing the highest scatter energy changes are correlated to actual damage size measurements using a fitted hyperbolic tangent shaped curve via nonlinear least squares minimization. This step corresponds to the unit cell calibration and in implemented via a properly designed offline process. Second, the calibration curve is used through an online process to estimate the actual damage size on target coupons with nominally identical sensor network configurations and hardware. The DIs from paths from target coupons is used to calculate weighting factors along with calibration curve. More details on steps of the multi-path unit-cell calibration and quantification process can be found in reference [23].

EXPERIMENTAL CASE STUDY

In the Section, an experimental study is presented for the preliminary evaluation and assessment of the proposed approach. The experiments were conducted on four identical aluminum coupons of dimensions 12” × 6” × 0.09” AL 6061 with a 0.5’’ diameter hole drilled at an offset of 2’’ from one of the longest edge of the plate. The geometric configuration is shown Figure 3. Four single-PZT SMART Layers® (type PZT-5A) from Acellent Technologies were attached on the plate, as shown in Figures 3 and 4, using Hysol 9394 adhesive. PZT actuator/sensors were ¼” in diameter and 0.39’’ in thickness. The case study aims at investigating the performance of the multi-path unit-cell approach in quantifying Electrical Discharge Machining (EDM) generated crack damage in four aluminum coupons. Figure 4 presents the four identical aluminum

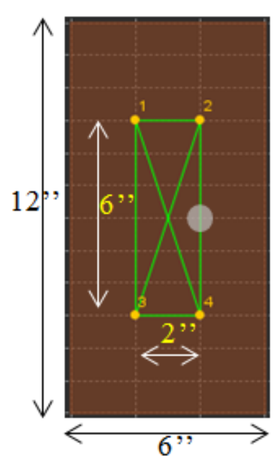

Figure 3. Dimensions of aluminum coupon equipped with four PZT-5A type piezoelectric sensors on the surface using Hysol 9394 adhesive.

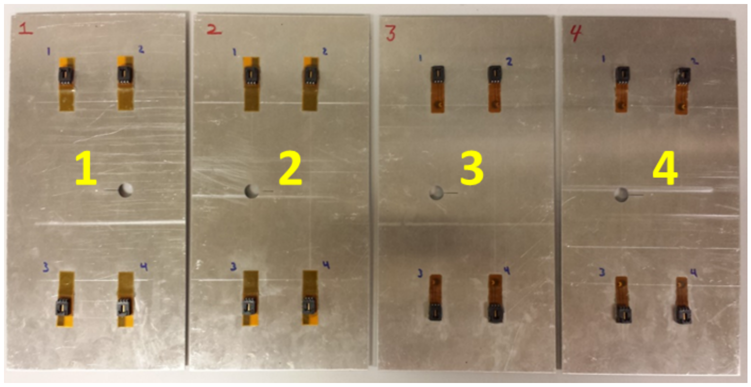

Figure 4. Four identical aluminum coupons each outfitted with four piezoelectric sensors. Coupon 1 was used for the generation of the calibration function via EDM-cut notches. Coupons 2, 3, and 4 were used for the evaluation of the multi-path unit-cell approach.

coupons used in the experiments. The four sensors can generate a total of six wave propagation paths in pitch-catch configuration. Ultrasonic wave propagation data are recorded from each coupon for increasing crack length via the ScanGenie hardware from Acellent Technologies. Coupon 1 was used for the generation of the hyperbolic calibration function, i.e. damage index versus crack size function, whereas Coupons 2, 3, and 4 were used for the assessment of the calibration and quantification approach.

Initially, a series of experiments was performed on Coupon 1 and data were recorded for increasing crack length that was generated via EDM. The EDM method was selected to minimize the damage orientation uncertainty within a well-controlled environment to allow for the first critical evaluation of the method. It is to be noted that in real situations the crack orientation will be quite uncertain around the rivet hole boundary. It is therefore decided to use a well-controlled EDM cut and investigate the sensitivities of multiple paths angled differently with respect to predetermined crack direction. This aspect is also important to study, when it comes to the design of sensor networks with optimally placed sensors and maximum coverage, to monitor fatigue cracks that may appear in random orientations given the high uncertainty associated with operational and environmental conditions. Ongoing work addresses more realistic damage types generated by fatigue experiments in metallic coupons.

Figure 5 presents the damage index profile from all four independent coupons against different instances of crack notch sizes. As evident from these profiles, the wave propagation path from actuator 2 to sensor 4, which crosses the EDM cut crack at almost 90°**,** is the most sensitive one among all other six paths in this four-sensor unit cell. The next two most sensitive paths are 2 to 3 and 1 to 4 which cross the EDM notch crack at an angle of 71.6°. The remaining paths are not sensitive with respect to growing crack size. This is expected from the fact that the damage index increases as much as the propagating energy gets obstructed by the crack presence. Therefore, it can easily be inferred that monitoring crack growth around a hole with just two sensors is a very challenging situation, as the detection sensitivity depends significantly on the angle between the sensor path and the crack orientation (with 90° being the best-case scenario).

As shown in Figure 6, Coupon 1 with all four-sensor wave-propagation path data is used to generate the calibration function which is subsequently used to estimate the crack sizes in Coupons 2, 3, and 4. The estimated calibration function is depicted in the left subplot of Figure 6, while the estimated versus the actual crack size results are

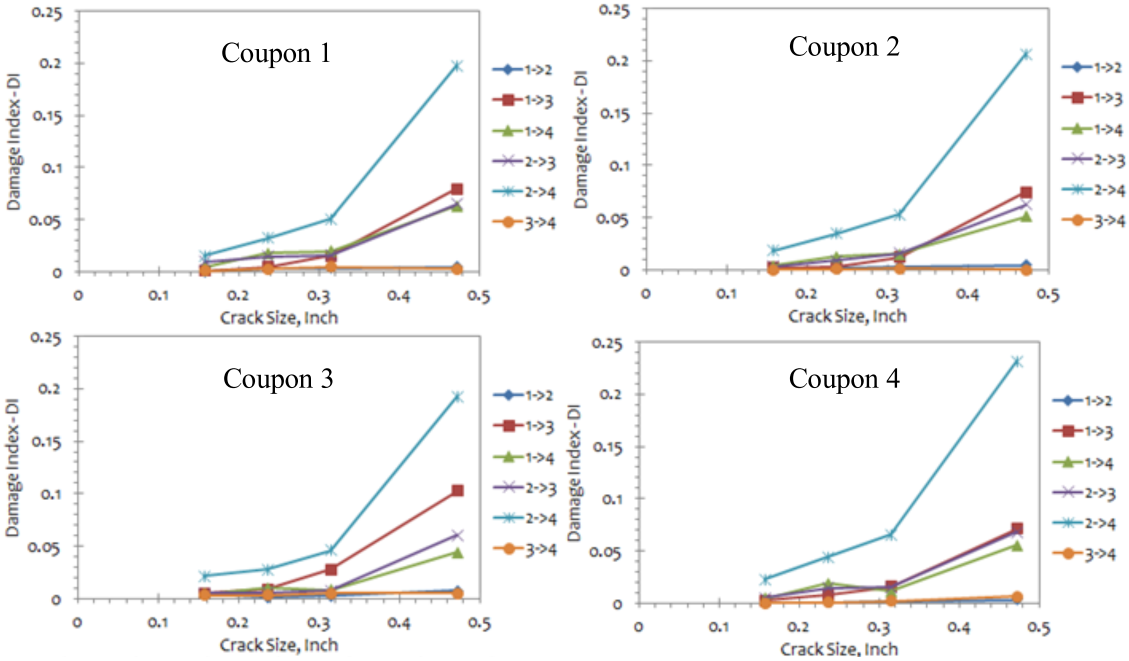

Figure 5. Damage index profiles for all four aluminum coupons. The various actuator-sensor wave propagation paths are shown with different symbols.

shown in the right subplot of Figure 6 for convergence and verification. Remarkably, the results show an excellent agreement between the estimated and actual damage sizes.

A comparative study is carried out to illustrate the inefficiencies and inaccuracies due to uncertainties in crack orientation and sensor positioning when limited actuator-sensor paths are used, versus the unit-cell multi-path approach. Figure 7 presents that damage quantification results for Coupons 2 (top subplots), 3 (middle subplots), and 4 (bottom subplots) for varying number of sensors. The left row shows the results for two sensors, the middle row for three, and the right row for four sensors (in this case the only available path has been used). Each subplot shows the estimated crack length based on the calibration function –obtained from Coupon 1– in the vertical axis versus the actual crack length in the horizontal axis. A perfect damage estimation would fall on the diagonal lines within each plot (slope equal to 1).

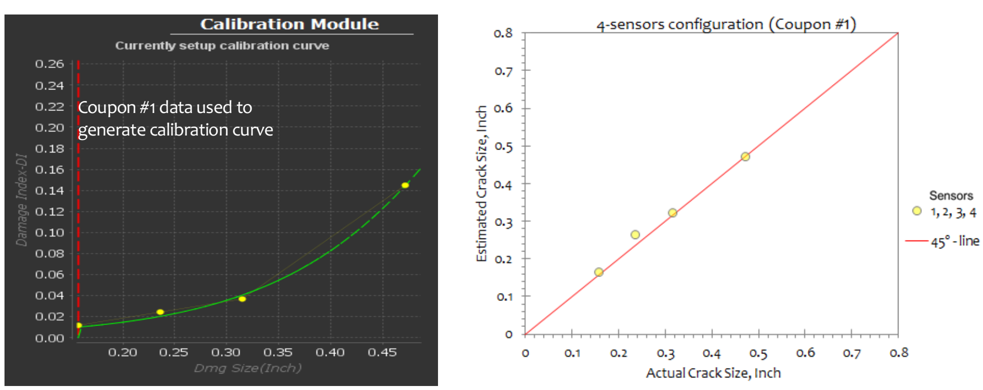

Figure 6. Calibration-curve (left) and estimated crack length versus actual crack length (right) based on the hyperbolic calibration function of Coupon 1.

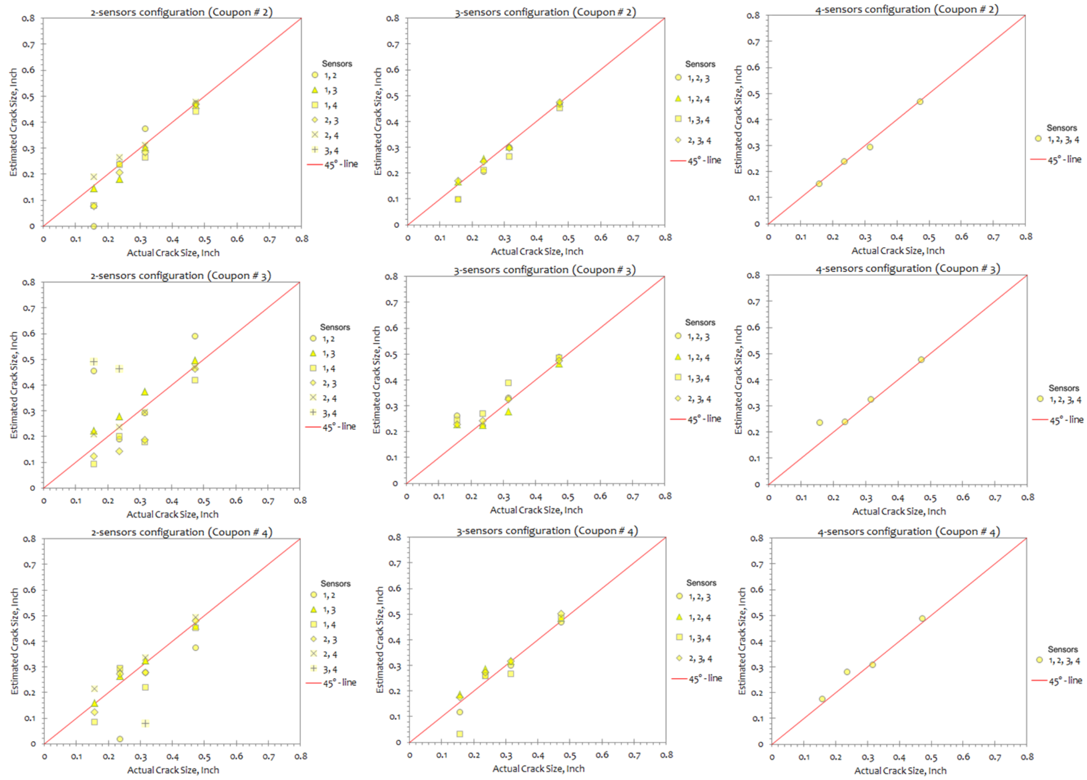

Figure 7. Experimental damage quantification results for Coupons 2 (top), 3 (middle), and 4 (bottom). The three columns present the results for two (left), three (middle), and four (right) sensors, respectively. The calibration function has been estimated from Coupon 1.

From Figure 7, it may be observed that for the two-sensor configuration the results from Coupons 2, 3 and 4 (subplots in left columns) show a significant variation in estimated crack size since there are six possible paths (with two-sensor combinations) available from four sensors placed around the hole. This emphasizes the practical difficulty in defining the most sensitive sensor positions with respect to crack initiation (in this case the hole) if only two sensors are to be used. In the present study, since the crack is done using EDM cut and has a well-controlled orientation, the estimation from path 2 to 4 (crossing crack length at 90°) showed good results. However, in practical situations the crack may be oriented in any direction around the hole. Therefore, as a next step, the unit-cell approach with three sensors is used to estimate the crack size for Coupons 2, 3, and 4. For a three-sensor unit-cell there are four possible sensor combinations, i.e. (1, 2, 3), (1, 2, 4), (1, 3, 4), and (2, 3, 4), for which the results are shown in the middle column of Figure 7. The estimation is shown to converge more along the diagonal line (slope 1) compared to the two-sensor combination paths. Thereafter, the unit-cell with four sensors is used (consisting all six paths) to generate the results. As observed from the rightmost column in Figure 7, the results are well converged on the diagonal line (slope 1) for all coupons. This affirms that for effectively monitoring an uncertain fatigue crack around a hole, the use of more than two sensors may eliminate the effect of the uncertainty in crack orientation.

For the case of Coupon 2 (middle rightmost subplot) it may be observed that the damage size estimation for smaller cracks is not as accurate as the estimation for larger cracks, which is to be expected. As the damage propagates and the crack length increases the diagnostic methods can increase the accuracy of the damage detection and quantification. On the other hand, expectedly, the size estimation for the smaller cracks is more challenging.

CONCLUDING REMARKS

In this paper, a novel multiple-path unit-cell damage quantification approach for active sensing hotspot SHM systems was introduced. The method is based on the concept of unit cell, that is a sensor network topology for hotspot monitoring that can be "identical" within the same family of structures and/or structural components. The use of the unit-cell approach enables the effective transfer and deployment of appropriately calibrated damage quantification functions obtained from experiments in a single representative coupon to nominally identical coupons. The main assumption of the approach is that as the number of sensors and paths increases, the uncertainty in the estimation of the damage size will decrease leading to robust damage quantification.

In addition, the method can mitigate variations in the actuator-sensor locations due to installation inconsistencies via the use of multiple paths that allow the convergence of the damage size estimation. However, the method in its current form does not account for varying environmental and boundary conditions, that is the subject of ongoing work. For hotspot monitoring applications (where the approximate damage location and orientation are suspected a priori), testing of multiple coupons may not be necessary, as in the case of traditional POD-based approaches, under the assumption of accurate sensor installation, appropriate compensation of the environmental and boundary conditions effects, and compensation of aging effects.

The unit-cell approach was shown to accurately detect and quantify damage in four representative metallic coupons, each outfitted with four piezoelectric sensors. Test data recorded from a series of experiments, where damage was initiated in the form of EDM notches, were used to evaluate the performance of method. 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 effective damage quantification.
- The effect of variability associated in actuator-sensor placement, path length variations, PZT properties, and adhesive thickness from coupon to coupon can be mitigated for quantifying cracks based on proper calibration using multi-path unit-cell approach.
- Based on preliminary results from several coupon data, the quantification approach was shown to provide good results for most of the coupon test data cases.

REFERENCES

1. Ihn J.B., Chang F.-K. 2004. "Detection and Monitoring of Hidden Fatigue Crack Growth Using a Built-in Piezoelectric Sensor/Actuator Network, Part I: Diagnostics," *Smart Materials and Structures*, 13:609-620.
2. Ihn J.B., Chang F.-K. 2004. "Detection and Monitoring of Hidden Fatigue Crack Growth Using a Built-in Piezoelectric Sensor/Actuator Network, Part II: Validation through Riveted Joints and Repair Patche," *Smart Materials and Structures*, 13:621-630.
3. Lonkar K., Chang F.-K. 2014. "Modeling of piezo-induced ultrasonic wave propagation in composite structures using layered solid spectral element," *Structural Health Monitoring*, 13:50-67.

4. Sharif-Khodaei Z., Aliabadi M.H. 2014. “Assessment of delay-and-sum algorithms for damage detection in aluminium and composite plates,” *Smart Materials and Structures*, 23:075007.
5. Flynn E.B., Todd M.D., Croxford A.J., Drinkwater B.W., Wilcox P.D. “Enhanced detection through low-order stochastic modeling for guided-wave structural health monitoring,” *Structural Health Monitoring*, 11(2):149-160.
6. Giurgiutiu V., Soutis C. 2010 “Guided wave methods for structural health monitoring,” In Encyclopedia of Aerospace Engineering, John Wiley & Sons, Ltd.
7. MIL-HDBK-1823. 1999. *Nondestructive evaluation system reliability assessment.* U.S. Department of Defense.
8. Matzkanin G., Yolken H. 2001. *Probability of detection (POD) for Nondestructive Evaluation (NDE)*. Austin: Texas Research Institute.
9. Wall M., Burch S.F., Lilley J. 2009. “Review of models and simulators for NDT reliability (POD),” *Insight - Non-Destructive Testing and Condition Monitoring,* 51(11):612-619.
10. Kopsaftopoulos F.P., Fassois S.D. 2013. “A functional model based statistical time series method for vibration based damage detection, localization, and magnitude estimation,” *Mechanical Systems and Signal Processing*, 39(1-2):143-161.
11. Kopsaftopoulos F.P., Fassois S.D. 2010. “A vibration model residual based sequential probability ratio test framework for structural health monitoring,” *Structural Health Monitoring*, 14(4):359-381.
12. Roy S., Lonkar K., Janapati V., Chang F.-K. 2014. “A novel physics-based temperature compensation model for structural health monitoring using ultrasonic guided waves,” *Structural Health Monitoring*, 13(3):321-342.
13. Chang F.-K., Larrosa C., Janapati V., Roy S., Lonkar K. 2011. “A Robust Health Management System for Composite Airframe Structures,” NRA Final Report to National Aeronautics and Space Administration (NASA). Stanford University, Department of Aeronautics and Astronautics.
14. Larrosa C., Chang F.-K. 2012. “Real Time In-Situ Damage Classification, Quantification and Diagnosis for Composite Structures,” *In the 19th International Congress on Sound and Vibration*, Vilnius, Lithuania.
15. Giurgiutiu V. 2010. “Development and testing of high-temperature piezoelectric wafer active sensors for extreme environments,” *Structural Health Monitoring*, 9:513-525.
16. Yadav S. K., Banerjee S., Kundu T. 2013. “On sequencing the feature extraction techniques for online damage characterization,” *J Intel Mater Sys Struc*, 24:473-483.
17. Yadav S. K., Banerjee S., Kundu T. 2011. “Effective damage sensitive feature extraction methods for crack detection using flaw scattered ultrasonic wave field signal,” *Proceedings of the 8th International Workshop on Structural Health Monitoring,* 1:167-174.
18. Yadav S. K., Banerjee S., Kundu T. 2010. “Artificial neural network based local damage detection in aging steel bridge joints,” *Proceedings of 3rd Asia-Pacific Workshop on Structural Health Monitoring.*
19. Salowitz N., Guo Z., Kim S.-J., Li Y.-H., Lanzara G., Chang F.-K. 2014. “Microfabricated Expandable Sensor Networks for Intelligent Sensing Materials,” *IEEE Sensors Journal*, 14:2138-2144.
20. Salowitz N., Guo Z., Kim S.-J., Li Y.-H., Lanzara G., Chang F.-K. 2013. “Screen Printed Piezoceramic Actuators/Sensors Microfabricated on Organic Films and Stretchable Networks,” *In Structural Health Monitoring 2013 - A Roadmap to Intelligent Structures*; Stanford, CA.
21. Rytter A. 1993. *Vibration based inspection of civil engineering structures*. PhD Thesis, Aalborg: Aalborg University, Department of Building Technology and Structural Engineering.
22. Janapati V., Kopsaftopoulos F., Li F., Lee S.-J., Chang F.-K. 2016. “Damage detection sensitivity characterization of acousto-ultrasound-based structural health monitoring techniques,” *Structural Health Monitoring,* 15(2):143-161.
23. Janapati V., Yadav S.K., Kumar A., Ikegami R., Habtour Ed 2016. “Fatigue crack quantification approach based on multi-path unit-cell concept in sensor network,” *8th European Workshop on Structural Health Monitoring, Bilbao, Spain.*