Development and Performance Quantification of an Ultrasonic Structural Health Monitoring System for Monitoring Fatigue Cracks on a Complex Aircraft Structure

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ABSTRACT

Aircraft structural components may have known "hot spots" where any initial damage is anticipated to occur or has consistently been observed in the field. Automated inspection of these areas, or hot spot monitoring, may offer significant time and cost savings for aircraft maintainers, particularly when the hot spots exist in areas that are difficult to access or where traditional NDE inspection methods will not work. This paper discusses the development of a hot spot monitoring system for a metallic lug component using ultrasonic elastic waves generated by piezoceramic elements. The development process utilizes a formal SHM system design framework developed by Boeing and AFRL and uses a multi-step approach progressing from simple coupon tests to the full scale component for system validation. A Probability of Detection (POD) approach is being developed to quantify the performance of the SHM system based on the selected operation scenario and demonstrate the capability relative to current Aircraft Structural Integrity Program (ASIP) requirements. Further POD verification and validation plans to address system reliability and operational conditions are discussed.

INTRODUCTION

Under the joint program called SHM for Hot Spots, Boeing and the Air Force Research Laboratory (AFRL) are developing and demonstrating a framework that enables efficient and defendable design of a SHM system for a structural hot spot. A defendable design is a design in which each step is supported by decisions based on the requirements for the system. Aircraft structural components may have known "hot spots" where a particular type of damage is anticipated to occur or has consistently been observed in the field. A specific hot spot application for a military aircraft has been selected to demonstrate this process. Engineering the solution for this particular hot spot began with an in-depth cost benefit analysis to identify a feasible and economical concept of operation for a SHM system for a near-term transition into the current ASIP maintenance process. Although a SHM system can potentially provide additional capabilities, as part of a near-term

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2011	**N/A**	**-**

4. TITLE AND SUBTITLE
Development and Performance Quantification of an Ultrasonic Structural Health Monitoring System for Monitoring Fatigue Cracks on a Complex Aircraft Structure

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boeing Research & Technology, 9725 East Marginal Way South, Seattle, WA 98108

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA580921. International Workshop on Structural Health Monitoring: From Condition-based Maintenance to Autonomous Structures. Held in Stanford, California on September 13-15, 2011 . U.S. Government or Federal Purpose Rights License.

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Aircraft structural components may have known hot spots where any initial damage is anticipated to occur or has consistently been observed in the field. Automated inspection of these areas, or hot spot monitoring, may offer significant time and cost savings for aircraft maintainers, particularly when the hot spots exist in areas that are difficult to access or where traditional NDE inspection methods will not work. This paper discusses the development of a hot spot monitoring system for a metallic lug component using ultrasonic elastic waves generated by piezoceramic elements. The development process utilizes a formal SHM system design framework developed by Boeing and AFRL and uses a multi-step approach progressing from simple coupon tests to the full scale component for system validation. A Probability of Detection (POD) approach is being developed to quantify the performance of the SHM system based on the selected operation scenario and demonstrate the capability relative to current Aircraft Structural Integrity Program (ASIP) requirements. Further POD verification and validation plans to address system reliability and operational conditions are discussed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

transition and demonstration strategy by Boeing/AFRL, the current application focus only on using the SHM system in the same way as the ASIP has utilized current NDI methods but in an autonomous way; inspecting the hot spot locations at a predetermined inspection interval and providing crack detection capability in terms of POD (Probability of Detection). The major benefit of a SHM system over a NDI method in this operation scenario is reducing maintenance cost by minimizing inspection time and eliminating on ground hours for structure dismantle/reassemble. The development process has followed a multi-step approach progressing from simple coupon tests to a full scale component. One advantage of this approach is that it provides opportunities to continuously re-evaluate and enhance the framework process based on the lessons learned from each step. The test articles include dogbone coupons, cantilever beams, lug subcomponents, and a full scale lug component. All of these studies use surface-bonded piezoelectric disks for elastic wave excitation and sensing.

Initial testing was performed on titanium dogbone coupons [1]. This testing demonstrated the potential to detect relatively small cracks. However, actual crack detection was complicated by issues of sensor system robustness and the reliability of “truth” crack length data. Subsequent testing was performed using titanium cantilever beam specimens [2-3]. Sensor robustness and the reliability of “truth” data were improved, but additional testing was required to further refine the techniques, as only limited data was available from the beam testing. Recent experiments include fatigue testing of lug subcomponents with geometry and material properties very similar to the full scale component. Preliminary work demonstrates that damage indices can be correlated to crack length. Building on the results from all of the earlier testing, SHM system development is underway for a full scale lug component to be fatigue tested under spectrum loading. Modeling, experimentation, and signal analysis performed during the development are discussed.

DESIGN FRAMEWORK

The latest version of the SHM system design framework for a structural hot spot is shown in Figure 1. The framework continues to be updated and matured as lessons learned from earlier implementations are incorporated. Two major additions from the last reported framework are: 1) the design framework is applicable not only for existing structures, but also for new structures where the SHM system is considered as a key design element during any design optimization processes; and, 2) virtual SHM system design and damage detection processes have been incorporated which enables the optimization of SHM system design parameters and performance in virtual domains prior to actual system construction. Some testing and prior knowledge will be used as part of the design optimization/iteration loop. The framework, which includes understanding system level requirements, has been exercised for a hot spot application on a metallic lug component. Based on the system level requirements, wave propagation methods using piezoelectric materials have been selected as the best design approach. The following sections discuss modeling, experimentation, and signal analysis performed during the multi-step development approach.

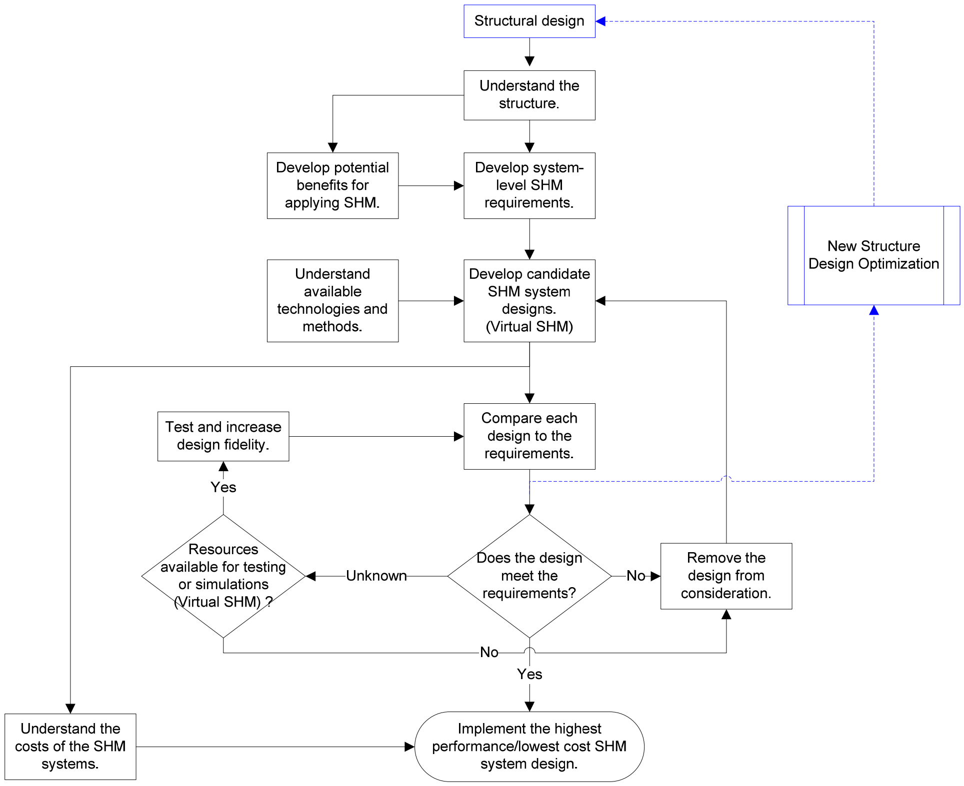
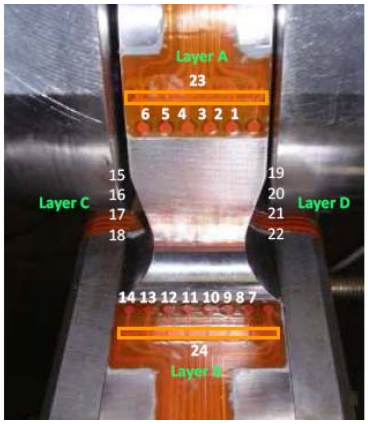


Figure 1. SHM system design framework for a structural hot spot

LUG SUBCOMPONENT TESTING

Results from the previous cantilever beam testing [2-3] showed the potential to detect crack damage, as well as to estimate the current crack length. However, the geometry of the cantilever beams was much simpler than the actual lug component. Therefore, the next step in the SHM development uses a titanium alloy lug subcomponent which has geometry very similar to that of the actual full scale lug component. Figure 2 shows the basic geometry of the lug subcomponents. As shown in the figure, each lug subcomponent is instrumented with four piezoelectric transducer packages, one on the lug portion (Layer A), one on the floor of the structure (Layer B), and two on the sides of the subcomponent (Layers C and D). The sensor packages on the lug and floor of the structure include a strip actuator and sensing disks. Each actuator/sensor package topology and location was designed by understanding stay out zones, areas of maximum strain, performance requirements. Windowed sine burst excitation signals are sent to the strip actuator to generate elastic waves in the beam. The sensing disks capture response that is transmitted through and scattered from the cracks expected to grow near the root of the lugs. Data from the transducer packages on the sides of the subcomponent have been collected but not investigated in detail at this time.

Three-dimensional finite element simulations of healthy and cracked lug subcomponents have been performed. Model detail, waveform fidelity, and processing time tradeoffs are considered, leading to selection of model parameters



(a)

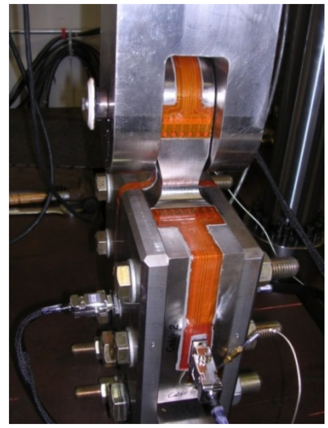
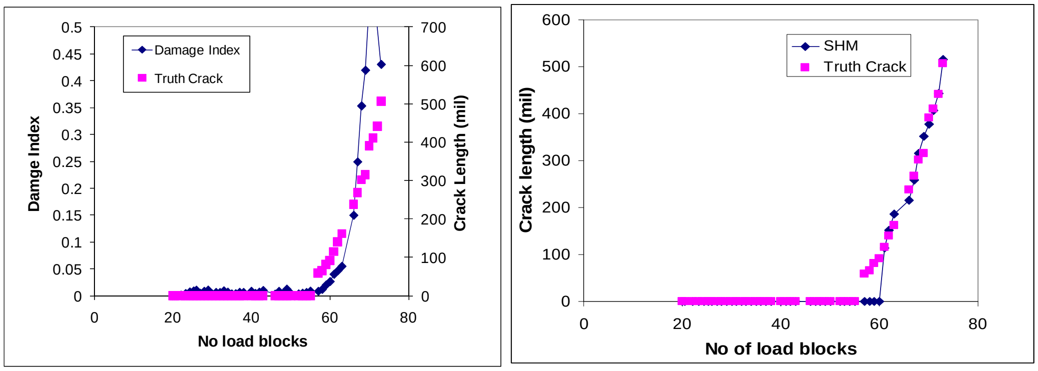

(b)

Figure 2. (a) Basic geometry of instrumented lug subcomponent test article and (b) lug subcomponent mounted in test fixture

to support simulations of excitation and response signals. The model was run to simulate the healthy condition and for corner crack conditions up to 0.50 inch long. A damage index is created based on scatter signals formed from the difference between the healthy and damaged responses. The simulated damage indices from sensors on the same edge as the crack provide a good indication of damage, particularly for larger cracks. A similar process is used for the experimental data analysis, where scatter signals are formed from consecutive data sets and utilize a field of view defined for each sensor on the lug subcomponent.

Experimental testing was performed at Metcut Research, a commercial mechanical test facility. After instrumentation, each subcomponent was mounted in an MTS and cycled with aircraft-specific spectrum loading. After each half spectrum, the cycling is halted and elastic wave measurements are taken. Excitation signals are applied at the actuators and the responses are recorded at sensors using Acellent's commercially available ScanWizard data acquisition system. The experimental data are stored on a laptop computer over the duration of the tests. Four of the five test articles have grown cracks. The "truth" data is based on visual crack length measurements.

Using collected measurements and "truth" data from the lug subcomponent testing, as well as the results from the cantilever beam testing, several damage indices have been computed. SHM damage indexes (DIs) are designed to be low when no crack is evident and grow larger as the crack grows. The DI calculations are based on differential measurements between consecutive data sets and utilize a field of view defined for each sensor on the lug subcomponent. In order to minimize potential false positives from the current crack estimation method, a new algorithm has been developed for detecting crack initiation that would be followed by subsequent crack growth algorithms should any cracks be detected. To determine if a crack exists, a "detection threshold" is established such that any measured DI value above this threshold indicates a crack and any DI value below this threshold indicates the absence of a crack. Figure 3 shows preliminary results of crack initiation and subsequent crack growth estimates using independent training and test data.



(a) (b)

Figure 3. Preliminary results from (a) crack initiation detection algorithm and (b) subsequent crack growth estimation algorithm

PROBABILITY OF DETECTION APPROACH

One necessary precondition for certifying a SHM system for flight is being able to provide a rigorously obtained Probability of Detection (POD) curve. The POD curve provides information about the smallest crack size that can be reliably detected by an inspection system.

There are two significant questions that must be answered about the performance of a SHM system in terms of POD. The first question is: What is the smallest size crack that can reliably be detected? This crack size is expressed as $a_{90/95}$ where the ‘a’ refers to the crack length, ‘90’ refers to the detection rate, and ‘95’ refers to the confidence level. The confidence level is a statistical concept that quantifies the uncertainty in the estimation. Taken together, this means that there is 95% confidence that the system will detect *at least* 90% of the cracks of length $a_{90/95}$.

The general process for obtaining these measures is briefly described below. Typically one would establish a relationship between an inspection system’s output (usually termed â) and the “true” measured crack length, a. For these studies, the relationship is established between the SHM system’s DI, which will be called â, and the measured crack length, a. This relationship is established using linear regression as follows. Let $x = f(a)$ and $y = g(\hat{a})$ where f and g are either linear or logarithmic functions selected such that x and y are linearly related. The linear or logarithmic representation of the DI, y, is then estimated as:

$$y = \beta_0 + \beta_1 x + e \qquad (1)$$

where β_0 and β_1 are coefficients to be solved for and e is the residual error which is normally distributed with a zero mean and a variance δ^2.

The selection of an appropriate detection threshold, y_{th} , is described below. Let $\Phi(z)$ be the standard normal cumulative distribution function and let $Q(z)$ be the survivor function, equal to $1-\Phi(z)$. The POD function can then be derived as:

$$POD(a) = P\left(y > y_{th}\right) = 1 - Q\left[\frac{f(a) - u}{\sigma}\right] = \Phi\left[\frac{f(a) - u}{\sigma}\right]$$
$$where \quad u = \frac{\left(y_{th} - \beta_0\right)}{\beta_1} \quad and \quad \sigma = \frac{\delta}{\beta_1} \qquad (2)$$

This formula provides the probability of detection for any given crack size, a. Statistical techniques can be used to calculate the 95% confidence interval of this POD curve and the $a_{90/95}$ point can be selected. One option for generating the POD curve is to use software based on MIL-HDBK-1823A "Nondestructive Evaluation System Reliability Assessment" available for free download [4]. An example POD curve based on 41 SHM system crack size estimates and their corresponding visual inspection crack size measurements calculated with the MIL-HDBK software is shown in Figure 4. Note that the $a_{90/95}$ value required by the ASIP for the target application is 0.1". These preliminary results indicate the potential for this SHM system design to meet this level of performance.

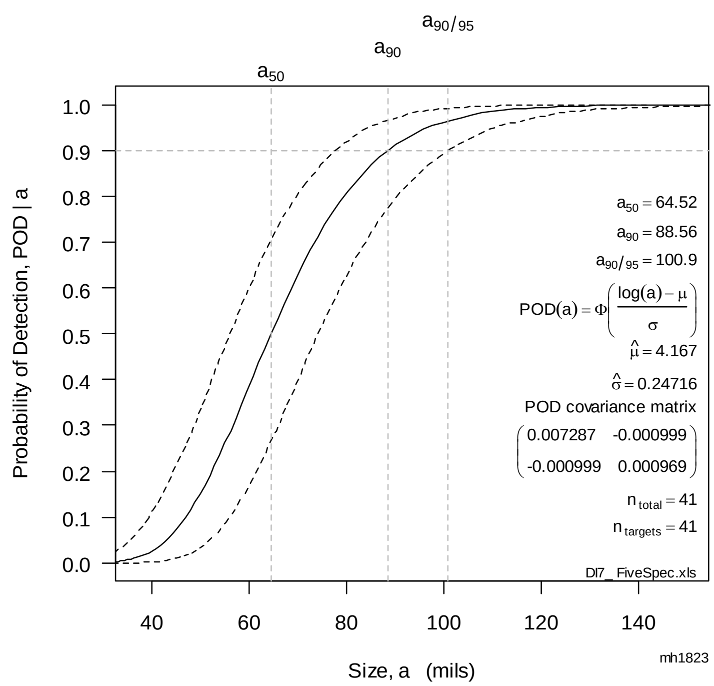


Figure 4. Sample POD curve based on 41 crack size measurements

The second major question involves determining the probability of a false alarm (i.e. how often the system indicates a crack when one does not exist). The probability of false alarm is denoted as *p(FA)*. Calculation of *p(FA)* is accomplished by collecting and characterizing a given SHM system in the situation where no crack exists. Due to in-situ environmental effects, DI measurements taken when no crack exists will have an average value greater than zero. This background noise can be characterized by a specific probability density function (DI Noise PDF) using statistical techniques. This PDF allows the calculation of the probability that a given 'no crack' DI value exceeds the detection threshold as shown in Figure 5 as the shaded 'Probability of False Alarm' area of the DI Noise PDF. The shaded portion represents the proportion of times a 'no crack' DI value will exceed the detection threshold. Similarly, integrating the portion of the DI scatter PDF that lies above the detection threshold provides POD(a) since that portion of the function represents the proportion of times a DI for a given size crack will exceed the detection threshold.

Both the detection threshold, y_{th}, and p(FA) can be calculated explicitly as a function of one another. As an example, assume the noise has been analyzed and found to have a normal distribution with mean μ and standard deviation σ. For a given probability of false alarm, the detection threshold can be calculated as:

$$y_{th} = \mu_{noise} + \sigma_{noise}\Phi^{-1}\left(1 - p\left(FA\right)\right) \quad (3)$$

Conversely, the probability of false alarm can be calculated as:

$$p\left(FA\right) = 1 - \Phi\left(\frac{y_{th} - \mu_{noise}}{\sigma_{noise}}\right) \quad (4)$$

where Φ represents the normal cumulative distribution function.

As shown in equations above and Figure 5, background noise is one of the major factors that determines false positive rates and overall performance of a SHM system. Understanding key noise contributors and developing solutions to mitigate them are the focus of future design improvement and performance characterization efforts.

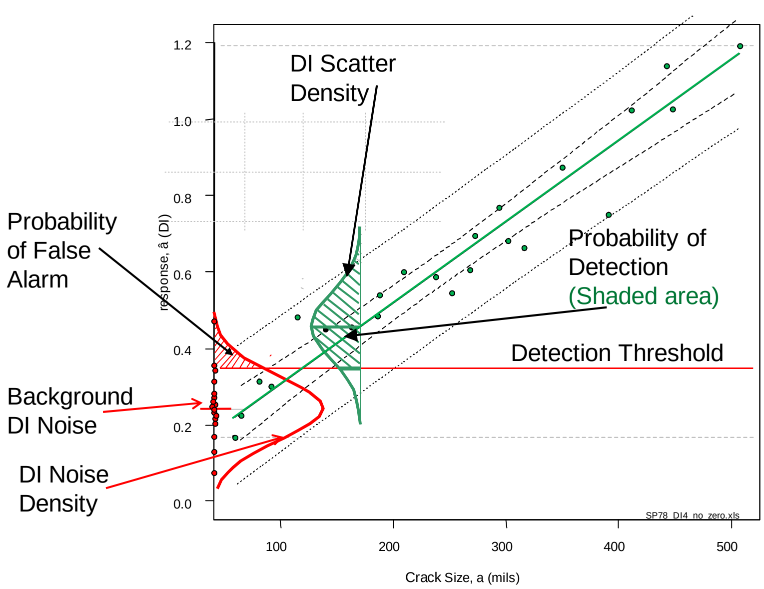


Figure 5. Sample p(FA) calculation based on background noise

CONCLUSIONS

A specific hot spot application of military aircraft has been selected by exercising the SHM design framework starting with an in-depth cost benefit analysis to identify a feasible and economical concept of operation for a SHM system for a near-term transition into the current ASIP maintenance process. Although a SHM system can potentially provide additional capabilities beyond that of traditional schedule based nondestructive inspections, as part of a near-term transition and demonstration strategy by Boeing/AFRL, the current application focused on meeting the existing ASIP POD criteria autonomously. The major benefit of the proposed system in this operation scenario is realized by reducing maintenance cost by minimizing inspection time and eliminating on ground hours for structure dismantle/reassemble. The development process has followed a multi-step approach progressing from simple coupon tests to a full scale component. A method for estimating POD is being developed to quantify the performance of the SHM system. Initial results demonstrate the capability to meet the ASIP requirement for the specific hot spot chosen. More rigorous approaches for validating SHM performance and design of experiments are being pursued to address and quantify the variability of SHM system response. Understanding the issues associated with in-situ effects such as temperature and load variation over time and structure-to-structure and sensor-to-sensor variability will aid the future development of more robust and higher performance SHM system designs.

ACKNOWLEDGEMENTS

The authors would like to thank all members of the Hot Spot Monitoring team for their continuing contributions. Major contributors supporting the lug subcomponent and full scale component tests include Bob Weiss and LeAnn Polin of Boeing, Seth Kessler of Metis Design, and Shawn Beard of Acellent Technologies.

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