

Demonstration of Model Assisted Reliability Assessment Protocol on a Proposed Low Frequency Vibration Based Damage Sensing Case

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ABSTRACT

This paper describes the progress on demonstrating a methodology for reliability assessment for structural damage sensing (SDS) systems. In particular, it presents the initial results obtained from the application of a protocol designed for utilizing empirical data, models, simulations, and uncertainty analyses for statistically characterizing SDS reliability for a damage detection case. The manufactured test article representing an aircraft structure of medium complexity consists of three plates connected by two lap joints with fasteners. Fatigue crack damage around the fastener holes was simulated by manually created thin cuts at selected locations. The test fixture design provides the capability to vary critical parameters of the system with a focus on force loading boundary conditions, joint fastener torque conditions, and temperature. The initial demonstration on this test article and fixture uses a low frequency vibration based damage detection method. Frequency domain metrics were utilized for studying changes in structural dynamics due to mechanical loading, thermal loading, and actual damage. For the demonstration, key factors that affect the capability to sense the effects of damage were assessed through controlled studies of (a) loading and unloading, (b) fastener torque, (c) boundary condition variation, (d) temperature variation and temperature gradients, (e) sensor bond quality and operation performance, (f) ambient noise, and (g) sensitivity to flaw growth. The design of the full validation study and the current results of the implementation are presented, highlighting general protocol feasibility while identifying remaining challenges for full demonstration and broad use of the methodology and protocol.

INTRODUCTION

The successful deployment of systems for health monitoring of structures clearly depends on appropriate verification and validation (V&V) of these structural health monitoring (SHM) systems. The V&V method must explicitly evaluate all

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Report Documentation Page		Form Approved OMB No. 0704-0188
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1. REPORT DATE SEP 2011	2. REPORT TYPE N/A	3. DATES COVERED -
4. TITLE AND SUBTITLE Demonstration of Model Assisted Reliability Assessment Protocol on a Proposed Low Frequency Vibration Based Damage Sensing Case		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) Materials and Manufacturing Directorate, Air Force Research Laboratory, WPAFB, Ohio 45433		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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15. SUBJECT TERMS		

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

aspects of the SHM system that can affect its capability to detect, localize, or characterize damage. Moreover, it must evaluate the effects that usage and environmental conditions have on these capabilities over time. The current U.S. Air Force practice for maintaining aircraft structures follows the Aircraft Structural Integrity Program methods, as documented in MIL-STD-1530C [1]. A very important component of the damage tolerance approach and the calculation of risk that are intrinsic to the ASIP methodology is the assessment of the reliability of Nondestructive Evaluation (NDE) methods that are used for periodic inspection of structures. MIL-HDBK-1823A provides guidance on probabilistic methods for NDE reliability assessment and introduces the possible use of models to complement experimentation for the necessary probability of detection (POD) determination [2]. As SHM methods depending on permanent, on-board mounted damage sensing systems continue to be proposed and developed for complementing ground-based NDE inspections for aircraft structural integrity purposes, it is necessary that the reliability of these damage sensing systems be assessed with a rigor that is suitable and sufficient for the function that they are expected to perform within the ASIP methodology, be it damage detection alone or damage detection, localization, and characterization [3]. For damage detection, this necessarily results in the need for a POD determination. For localization and characterization, the metrics for SHM reliability and their evaluation process are the subject of current research and development [4].

This presentation will describe the progress in demonstrating a methodology for reliability assessment for SDS systems. In particular, it will show the results obtained from the application of a protocol designed for utilizing empirical data, models, simulations, and uncertainty analyses for statistically characterizing SDS reliability for a damage detection case [5].

EXPERIMENTAL STUDY SETUP

The system used for this initial demonstration of the protocol is a system for detecting the presence of damage using permanently mounted transducers. A test article representing an aircraft structure of medium complexity was designed and built (see Figure 1). The test article consists of three plates connected by two lap joints with fasteners. In addition, a fixture was built for supporting the test article. Fatigue crack damage around the fastener holes can be simulated by manually created thin cuts at selected locations. The final version of the test article and fixture, shown in Figure 1(c), differ from those in the design shown in Figure 1(a) in that (1) the two bottom support beams were manufactured out of steel instead of concrete to reduce weight and facilitate transportation and (2) the line loading attachment was manufactured but not used, and therefore it is not shown in Figure 1(c). The test fixture design provides the capability to vary critical parameters of the system with a focus on force loading boundary conditions, joint fastener torque conditions, and temperature. To study the effect of mechanical loads on the performance of the onboard damage sensing system, the assembly includes a capability for changing the configuration of the article support to the fixture so that selectable loads can be applied to the structure.

The initial demonstration on this test article and fixture uses a vibration based damage detection method. An ETrema brand Terfenol-D magnetostrictive actuator

was used for band-limited pseudo-random excitation up to 1200 Hz, and the dynamic response of the plate was recorded using eight 50mV/g single-axis accelerometers set to measure out of plane motion and provide input to change detection algorithms. The accelerometers were placed at locations that attempt to maximize the ability to detect change in the modal dynamics of the structure even in the presence of modeling errors. M-Bond 200 adhesive was used for semi-permanently affixing the accelerometers to the bottom of the assembly. Four bonded foil 350-ohm strain gages were also installed on the test article for tracking the state of stress under mechanical loading. Finally, thermocouples were also used for studying the effects of heating due to excitation of the damage detection system and the effects of the operational temperature. The layout of the sensors is presented in Figure 2. A LabVIEW data acquisition system was used for acquiring the required data. Variations in operational temperature were simulated by testing the system inside a carefully controlled Thermotron SE-1200 environmental chamber.

The method for inducing damage involved notching the area of the ‘skin’ under a fastener. To initially isolate damage to the skin alone, the test article design includes machined relief slots in the joining plate at the fastener locations, but the final induced cut stages went beyond these relief slots. A change metric based on the area under the curve representing the difference between two frequency responses and an R-square metric were used for assessing changes in structural dynamics due to mechanical and thermal loading, actual damage, and combinations thereof, and therefore attempting to detect damage presence and growth. The frequency band of interest was from 200 to 1200 Hz.

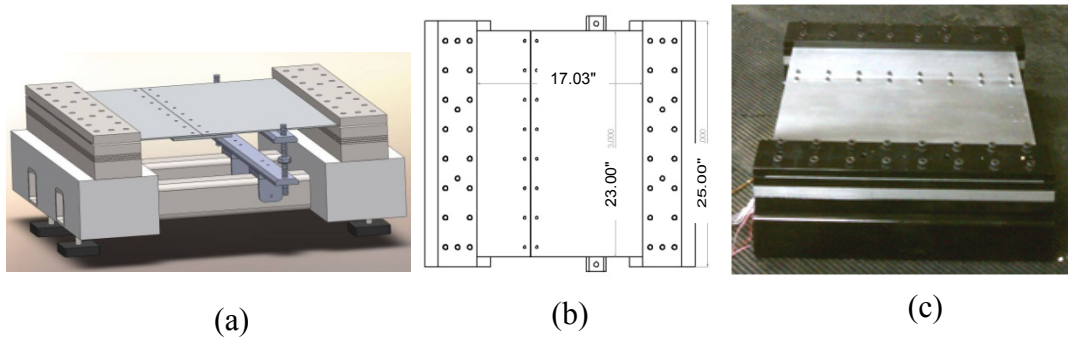


Figure 1 Test fixture assembly: (a) concept diagram, (b) top view, (c), photograph

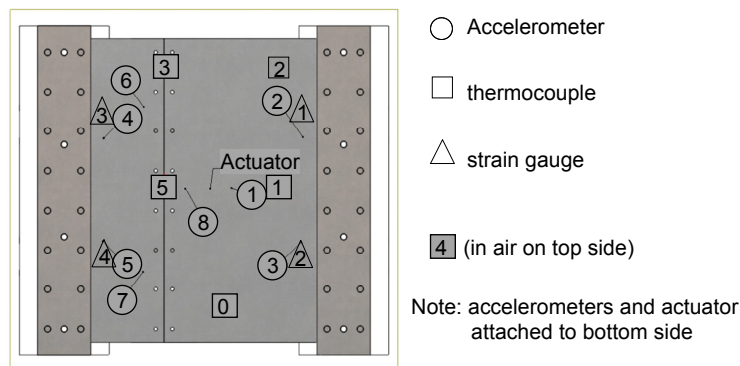


Figure 2. Location of sensors on the test article

FACTOR EVALUATION STUDIES

The initial experimental demonstration followed the proposed protocol. Before designing the validation test matrix, the following key factors were assessed through controlled studies: (a) mass loading and unloading, (b) fastener torque, (c) boundary condition variation, (d) temperature variation and temperature gradients, (e) sensor bond quality and operation performance, (f) ambient noise, and (g) sensitivity to flaw growth.

Initial tests used a simple R-squared change metric to assess the change in the frequency response between accelerometer 1 and accelerometers 2-7 as a function of mass loading and unloading. The structure was mass loaded in steps of 8.6 lbs. The change metric was found to be highly sensitive to this loading and, more importantly, the change metric was shown to be not reversible. For example, completely unloading the structure did not result in the metric returning to zero. Since mass loading and unloading frequently occurs in aircraft structures, the reasons for this irreversibility must be understood before application of dynamic response changes from a baseline state to detect damage could be used in cases where mass loading of this relative magnitude is expected. Possible sources for this variability are varying contact conditions between the plates and fasteners and/or varying temperature conditions during the study.

A fastener torque study was performed using a select set of fasteners at torque levels of 75, 100, 50 and 0 in-lbs, representing normal torque, high torque, low torque, and 'hand tight' conditions. Changes from 75 to 50 in-lbs had very little effect on the frequency response function (FRF). Changes from 75 to 100 in-lbs had more effect, but not much more significant. Changes from the normal torque to the hand tight condition had a much bigger effect, as expected. Repeated removal and reinstallation of fasteners will be included in the final validation study.

Thermal loading studies were performed by varying the ambient temperature from -20°F to 150°F. During this study, the significant thermal capacity of the panel end conditions fixtures was found to produce significant thermal gradients across the test article. During heating and cooling periods, temperature gradients as high as 45°F across the test specimen were observed. For validation studies, an estimate of expected gradients 'in the field' is needed. An assumption will be made for the validation study that temperature gradients in the region of interest will be limited to +/- 10°F.

Failure of accelerometer bonding was observed several times during thermal testing. These failures occurred during the prolonged high temperature runs at 150°F. The bonds for strain gauges and adhesive tape for the thermocouples held up well during testing. Reaffixing the fallen and slightly loose accelerometers greatly improved their coherence estimates. Coherence is viewed as a viable metric to monitor bond quality over time. While vibration-based damage detection systems are proposed as global methods with some sensor redundancy, relying on a single reference sensor will result, upon bond degradation, in either highly degraded performance and/or complete failure of the damage detection system well before the structure end-of-life is reached. Sensor and sensor bonding reliability must therefore be accurately assessed as part of a validation study.

The noise generated by the environmental chamber and by other equipment in the laboratory posed an opportunity for studying the effects of ambient noise on the

detection capability. Coherence levels were observed to change depending on whether the unit was cooling or heating and the ‘throttle’ level of the chamber, and on whether the chamber door was open or closed. An excitation amplification study was performed using coherence estimates to determine the optimal excitation amplifier gain in the various conditions: (1) chamber on, door closed, (2) chamber off, door open, and (3) chamber off, door closed. The amplifier gain yielding optimal coherence was different for the various conditions, and therefore a compromise level yielding high coherence for all conditions was selected for all subsequent runs. For the validation study, both ‘chamber on’ and ‘chamber off’ conditions will be acquired with the objective of including in the analysis the effects of varying noise conditions that are expected in the field.

An initial study on the effect of damage growth was performed to ensure adequate sensitivity during the final validation study. Customized XActo™ blades were used to make cuts in the aluminum plates. The resulting notch width was estimated to be approximately 0.012" +/- 0.002". Cuts were initially made at 0.063" (1/16") increments up to 0.25". For the first series of cuts up to 0.25", Figure 3 presents a history of the AREA damage metric during Damage Study 1, for the chamber off and fastener torque at 75 in-lb condition. During this initial series, sensitivity to notch length increases was observed, but the trend was small relative to noise, and not quite linear. Greater sensitivity to the larger cuts was observed and clear sensitivity to notches on the order of 0.63" was demonstrated. Also, a significant increase in the damage metric was observed after the two week delay between the end of the 0.25" notch cut and the start of the 0.31" notch cut.

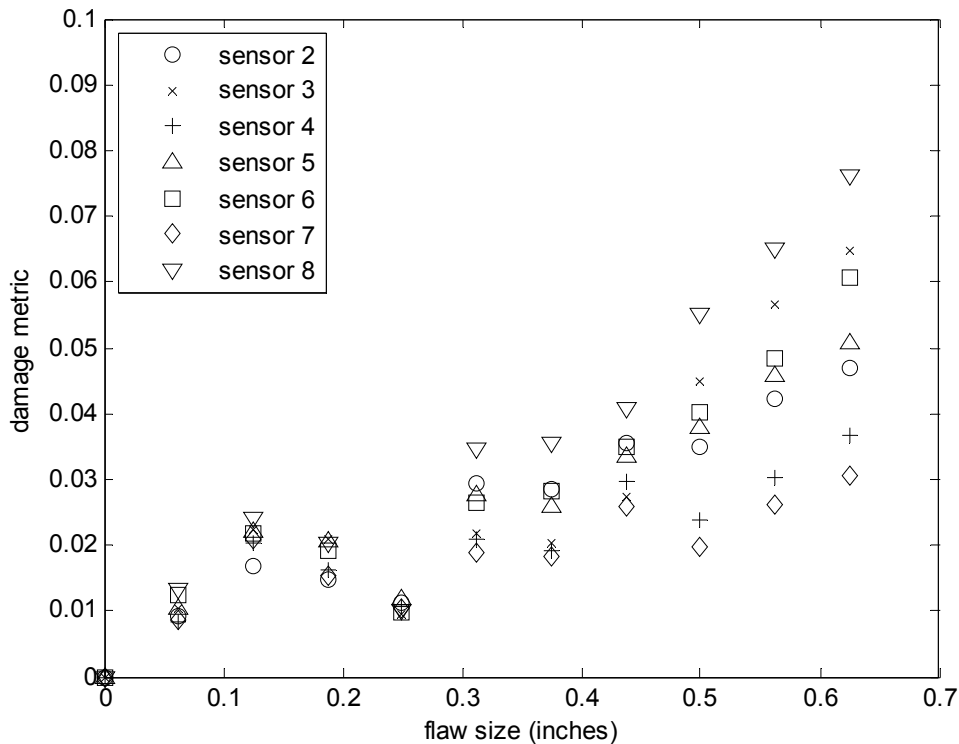


Figure 3. AREA damage metric, Damage Study 1, 200 Hz - 800 Hz

EXPERIMENT DESIGN FOR VALIDATION STUDY

The design of the validation study only included a single stage demonstration using laboratory testing of a relevant structure and under expected environmental conditions. The validation study consisted of growing flaws by artificially cutting the structure at two fastener site locations, site #2 (fastener 11) and site #3 (fastener 7), as shown in Figure 4. A series of environmental and joint boundary conditions were studied after each flaw growth scenario: temperature variation ($\pm 40^{\circ}\text{F}$), temperature gradients, loading and unloading of 10 lb mass, a simulated maintenance action at a set of fasteners (see Figure 4) including the case of minor loosening, and reinstallation and replacement of accelerometers. During the flaw growth period, a series of tests were performed including testing before and after flaw growth, and after fastener installation. Temperature chamber states of ‘on’ and ‘off’ with the ambient temperature set to $T = 72^{\circ}\text{F}$ were acquired for all test conditions. Five averages were taken for all SDS system data acquisitions. After any environmental condition change or change to the test fixture, testing was also performed with the ambient temperature returned to $T = 72^{\circ}\text{F}$. At the time of this writing, the results of these experimental measurements are being analyzed.

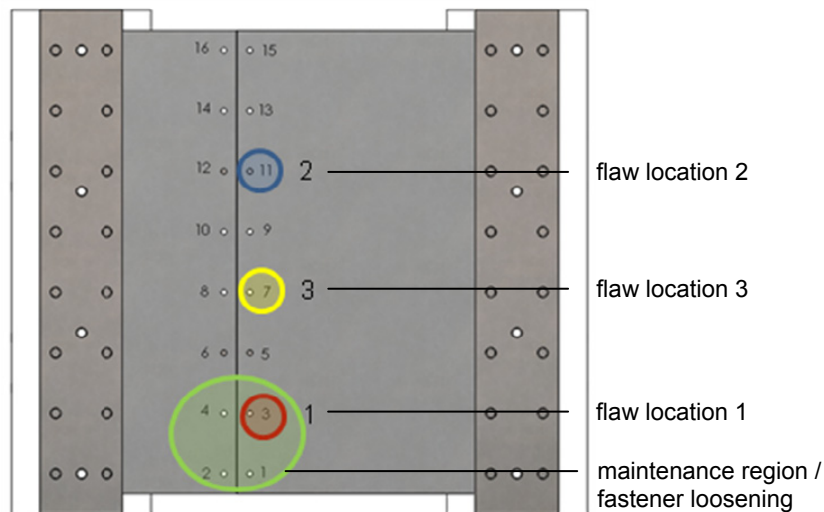


Figure 4. Locations for flaw growth and simulated maintenance actions

PROBABILITY OF DETECTION ANALYSIS

A summary description of the approach being followed for obtaining a probability of detection model for on-board damage detection cases follows. Conventional probability of detection (POD) evaluation for many quantitative NDE applications first uses empirical data to evaluate statistical relationships between the measurement response, $\hat{a}$, and the primary flaw size variable, a . Through application of a detection criterion as part of the NDE procedure, this statistical ‘ $\hat{a}$ versus a ’ model can be used for evaluating the POD curve and probability of false call (POFC) rate, which together are usually referred to as “a POD model”. The detection system can be abstractly represented by a set of random variables a_i that

act as inputs to a measurement model. Input variables can be categorized as being controlled (e.g. flaw size and material properties) or uncontrolled (e.g. liftoff, flaw morphology, and measurement noise). Detection consists of the measurement model output $\hat{a}$ being classified (or “called”) according to pre-specified rules (e.g. a threshold). There are a number of mathematical formulations that can be utilized for statistically characterizing how well this system detects values of the input variables of interest using the particular classification rules. The model-assisted POD (MAPOD) approach proposes to replace a conventional statistical fit in the measurement model with a complete physics-based model, f , calibrated for a given set of experimental conditions. This relationship is given by

$$\hat{a} = \beta_0 + \beta_1 f(a_i) + \varepsilon, \quad (1)$$

where β_0 and β_1 represent the model calibration parameters, and ε represents the residual error between the model and the experimental data. Estimating the statistics of β_0 , β_1 , and ε necessitates specific experimental sampling requirements. Variations due to flaw size and environmental (noise) conditions, for example, are represented in the model as probability distributions of the input variables. Surrogate models derived from numerical simulations can be practically implemented to facilitate repeated calls to the model f . Hybrid models incorporating both empirical and physics-based components can also be implemented to address all key factors including those that cannot be adequately simulated.

In this study, the primary variable associated with the critical flaw size is crack (notch) length, a_1 . Controlled secondary variables in the study include mean temperature (a_2), temperature gradients (a_3), ambient noise level (a_4), structure loading and unloaded (a_5) and minor boundary condition variation / fastener loosening (a_6). A response surface methodology can be applied here to estimate the effect of each secondary factor on the damage metric response. Random events such as sensor failure (or complete sensor disbond) (b_1), sensor bond degradation (b_2), sensor replacement (b_3) and local maintenance actions (b_4) can also be considered in the POD evaluation. Assumptions concerning their frequency (with uncertainty bounds) can be made and empirical models representing their effect can be evaluated and applied in conjunction with the proposed scope and details of the SDS application (inspection frequency, SHM service cycles, etc.)

To complete the POD evaluation, an assessment of the detection model under varying input conditions including uncertainty propagation is necessary. In prior work [6], a second-order probabilistic approach has been developed to propagate both aleatory uncertainty, due to inherent randomness in system behavior, and epistemic uncertainty, due to a lack of knowledge about values expected to be fixed. Using this approach, epistemic variables are specified as intervals on values of parameters such as the means and standard deviations of random variables. Monte Carlo analysis is thus performed using outer and inner loops. The outer loop varies the values of distribution parameters of selected epistemic variables while the inner loop samples from the distributions. A MAPOD case study incorporating second-order probability analysis using Monte Carlo simulations has recently been demonstrated [7].

CLOSING REMARKS

This work has presented initial results of a demonstration featuring the application of the proposed validation protocol to a vibration-based structural damage sensing system. Protocol steps emphasize the importance of assessing the key application characteristics and evaluating the significant factors that control performance and reliability. Results of the initial steps of the validation protocol which evaluate the various factors that affect system capability are presented. Finally, a brief description of the statistical analysis required for processing the experimental data and combining it with models to yield a probability of detection model is included. The paper highlights general validation protocol feasibility while identifying remaining challenges for completion of this validation study in particular and for broad use of the validation protocol in general. Completion of this demonstration study, including a POD model, is expected in late summer 2011.

ACKNOWLEDGEMENTS

This work was supported by the NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, through contract FA8650-09-C-5204 with Radiance Technologies, Inc. The authors would like to thank Hank Rinehart, Wes Tharp, Louie Elliot, and Michael Pearson of Radiance Technologies for administrative and logistics support and for assistance with design and manufacturing of the test article and fixture. We gratefully acknowledge the logistics support of AFRL/RXSS, the University of Dayton Research Institute, and the National Institute of Aviation Research at Wichita State University

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