- Title: Probability of Detection Assessment of a Guided Wave Structural Health Monitoring System
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ABSTRACT

This paper summarizes the preliminary findings of a study to generate Probability of detection (PoD) and Receiver Operating Characteristic (ROC) curves for a guided wave (GW) Structural Health Monitoring (SHM) system. PoD curves are used to access a detector's performance as a function of damage size or equivalently the backscattered Energy to Noise Ratio (ENR). ROC curves present statistical representations of the reliability of the method for detecting certain size flaws versus their Probability of False Alarms (PFA). To a large extent, generating meaningful versions of these curves involves multiple repetitions of the same experiments while injecting as much realistic variability as possible. Experiments using representative rotorcraft specimens with crack growth in addition to a riveted stiffener are presented.

INTRODUCTION

SHM systems are permanently integrated within a structure to efficiently detect, locate, and characterize damage. This process involves an information extraction procedure where measurements are processed to determine if damage is present. For GW methods, inspection consists of interrogating the structure with an input excitation and then analyzing the resulting scattered wave field using a signal processing method (detector). In this paper, a single GW mode phased array detector is considered.

Before an SHM systems can be fielding in military or commercial applications, its performance as detector needs to be characterized. While no standards presently exist that are specifically written for characterizing SHM performance, best practice suggests that MIL-HDBK-1823 "Non-Destructive Evaluation System Reliability Assessment", can be leveraged due to the close relationship between many NDE and SHM. The key figure of merit from HDBK-1823A is the PoD(a) curve, which is the probability of detection as a function of damage size (a). Resulting from the PoD(a)

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curve is the $a_{90/95}$ value, which is the damage size that can be detected with a 90% probability of detection and a 95% confidence bound. An important implication for SHM in establishing a PoD(a) curve is the required number of independent test specimens. For SHM applications, testing of many specimens is typically impractical due to the expense associated with the permanent nature of SHM sensor installation. Model assisted probability of detection (MAPOD) then becomes vital to establishing PoD curves for SHM applications. This includes the incorporation of propagation, scattering, and operational/environmental models with experimental data to properly establish PoD. Initial sources of variability include but are not limited to temperature, strain, humidity, installation location, bond quality, and sensor element degradation.

The work presented in this paper is a first step towards establishing PoD values. An active sensing model is used to derive a signal processing detector. The performance of this detector is assessed with experimental PoD curves generated by Monte Carlo methods using a large number experimental test runs, typically between 1,000 and 2,000 experimental runs per test case. Data is collected from multiple damage types with damage size and interrogation orientation varied. Environmental effects are held constant at this point by testing in a controlled laboratory environment.

BACKGROUND

Signal Processing Detector

An ultrasonic GW pulse echo strategy detects damage by interrogating the structure with a waveform and detecting the scattered/echo from damage. An array of M closely spaced transducers with inter element spacing small enough to allow for coherent processing measures the scattered wave field [1]. A scattered signal at transducer m can be modeled as

$$\tilde{s}_{m}[n] = \sum_{\alpha=1}^{P} A^{\{\alpha\}} \exp\left[\phi^{\{\alpha\}}\right] \Pi^{\{\alpha\}}[n,r] \exp\left[j2\pi f^{\{\alpha\}}n\right] \exp\left[-j2\pi f^{\{\alpha\}}\tau_{m}^{\{\alpha\}}\right], \quad (1)$$

where $A^{\{\alpha\}}$ is amplitude, $\phi^{\{\alpha\}}$ is absolute phase relative to the scattering source, $f^{\{\alpha\}}$ is temporal frequency and $\tau^{\{\alpha\}}$ is the relative inter-element phase delay due to the direction of propagation for given a wavevector. $\Pi^{\{\alpha\}}[n,r]$ a boxcar function that represents the time with when wave mode α , scattered from a source a distance of r away, is present at all array transducers. Assuming Gaussian noise, a generalized likelihood ratio test approach can be used to derive a detector that maximizes the probability of detection for a fixed false alarm rate. The resulting detector for array data $\tilde{\mathbf{x}}[n] = [\tilde{x}_0[n] \ \tilde{x}_1[n] \ \cdots \ \tilde{x}_{M-1}[n]$ and a single wave mode, A_0 , is given as [2],

$$T\left(\tilde{\mathbf{x}}\right) = \max_{r,\beta} \frac{2}{\sigma^{2} \left(\left(KM\right)^{2}\right)} \left[\left|\mathbf{h}_{1}^{H}\tilde{\mathbf{x}}\right|^{2}\right]$$
(2)

where
$$\left|\mathbf{h}_{1}^{H}\tilde{\mathbf{x}}\right|^{2} = \left|\sum_{n=0}^{K-1} \tilde{x}_{B}[n] \exp\left[-j2\pi fn\right]\right|^{2}, \tilde{x}_{B}[n] = \sum_{m=0}^{M-1} \tilde{x}_{m}[n] \exp\left[j2\pi f\tau_{m}^{A_{0}}\right].$$
 (3)

 $|\mathbf{h}_{1}^{H} \tilde{\mathbf{x}}|^{2}$ is a periodogram at known frequency f and $\tilde{x}_{B}[n]$ is a phased array beamformer for wave mode A_{0} . The detector in (2) coherently combines the scattered mode at each sensor (beamforms) and then sums the estimated power of the mode as known frequency f. A search is performed over possible range, r, and bearing, β , combinations and the resulting maximum taken.

EXPERIMENTAL SETUP

Aluminum Sandwich Panel

The first specimen investigated was a sandwich panel with thin aluminum plate facesheets and Nomex Honeycomb core, with a total thickness of ~0.25". Two beamforming sensor arrays were located at 0° and 90° and a radius of 5 inches from the crack initiation site, as seen in Figure 1. The crack was formed by first inducing a 0.015" starter hole, and then micro-milling a slot in various steps to increase the crack size. Measurements were taken at crack sizes of 0.015", 0.050", 0.075", 0.100", 0.250", 0.500", and 1.000". A 4.5 sine wave excitation signal under a Hanning window at 45 kHz was used to interrogate the structure, and resulting data was collected synchronously on all channels at 10MHz.



Figure 1: Aluminum sandwich panel with honeycomb core experimental layout.

Aluminum Plate with Riveted Stiffener

The second specimen was a 36"x36" aluminum 0.125" thick plate with a riveted stiffener spanning the centerline. Single beamforming sensor arrays were bonded symmetrically on either side of the stiffener, as seen in **Figure 2**. As seen in the figure, locally distributed data acquisition hardware was integrated with both sensor arrays, with an older generation being installed over the array to the left of the stiffener, and the latest generation hardware over the array to the right. Damage was induced by the removal of an individual rivet from the stiffener, either the centermost rivet or one that was 1" above or below the center. A 4.5 sine wave excitation signal under a Hanning window at 100 kHz was used to interrogate the structure, and resulting data was collected synchronously on all channels at 10MHz.



Figure 2 Aluminum plate with riveted stiffener experimental layout.

SIGNAL PROCESSING APPROACH

The detector from (2) was applied to data, and the resulting output mapped to a two dimensional diagnostic image of the structure. Figure 5 is an example of a diagnostic map for the riveted stiffener specimen. The total scattered energy is then estimated by summing around the peak value of the image map (i.e. maximum over (r, β) . Optimal baseline subtraction was employed by selection of a baseline condition that minimizes the mean square error. The performance of the detector is compared via ROC curves, where each point on a curve corresponds to a value of (P_{FA}, P_D) for a given threshold value γ' . Experimentally this is accomplished with a sliding threshold value, where at a given threshold, the output of the detector is determined under H_0 (no damage) and H_1 (damaged) measurements. The number of detector output values that exceed the threshold under each hypothesis are counted and then the PoD and false alarm rate estimated by dividing the count value by the number of observations. This is repeated for each set of data.

EXPERIMENTAL RESULTS

Aluminum Sandwich Panel

The ROC curve for the node that is 90° with respect to the crack formation is show in Figure 3. It has increasing detection performance as the crack size grows. A noticeable jump in performance occurs after a crack size of .025 inches. The ROC curve for the node that is 0° with respect to the crack formation is show in Figure 4. It has nearly 100 percent detection for all crack sizes except the hole at .015 inches. For this case, the crack back-scatters a substantial amount of energy compared to the undamaged case but this performance could change with the crack tip orientation.



Figure 3 ROC curve for node parallel to notch growth in aluminum sandwich panel.



Figure 4 ROC curve for node perpendicular to notch growth in aluminum sandwich panel.

Aluminum Plate with Riveted Stiffener

A0 LAMB MODE SNR COMPARISON

Figure 5 shows image maps for the A0 lamb mode at an actuation frequency of 60 kHz where MD7 node 101 (left) and MD7Pro node 76 (right) are operating in pulse echo mode. The reflected wave from the left and right boundary is shown imaged as the colored regions where the color scale for both images is equal to allow comparison of the reflected signals. At 60 kHz the pulse echo wave from the newer MD7Pro optimized hardware has a larger amplitude compared to the MD7 node.



Figure 5 Example image boundary reflection image maps. MD7 node left and MD7 Pro right.

The signal to noise ratio of the induced A0 mode is determined by measuring the scatted wave amplitude from the edge boundary and from an open area of the plate that contains no scattering/boundary reflections. Applying this process and sweeping over frequency values in 10 kHz steps from 40 to 250 kHz allows the A0 lamb mode/piezo actuator transfer function to be experimentally determined, Figure 6. The SNR ratio is highest for lower frequencies and after 150 kHz begins to decrease.



Normalized SNR Estimate A₀ Mode

Figure 6 Experimental signal to noise ratio curves for A0 Lamb mode.

POD AND LOCATION ESTIMATES

The ROC curve is given in Figure 7 for node 76 at frequencies of 40,60,80 and 100 kHz, with node 101 having similar results. 80 and 100 kHz have perfect detection performance. Frequencies larger than 100 kHz were not investigated due to the spatial aliasing restrictions. Mean square error and the standard deviation of the error between the estimated and true damage location is given in Table 1 for 80 and 100 kHz. The scattering from S0 to A0 mode conversion (S0 mode propagating to the damage location and then mode converting to A0 and backscattering to the node) was present at all frequencies and was often on the same order of magnitude as the direct A0 scattered mode. This has the effect of skewing the location estimate statistics since the imaging algorithms estimate the damage location based upon A0 to A0 time of flight.

All F	Rivet Locations (in.)	80 kHz	100 kHz	
MD7 Pro	MSE	2.11	1.55	
	STD	0.36	0.09	
MD7	MDE	1.78	2.29	
	STD	.23	0.25	

TABLE I. MEAN SQUARE ERROR AND STD OF DAMAGE LOCATIONS



CONCLUSIONS

Experimental PoD and ROC curves were generated by Monte Carlo methods using a large number of experimental test runs for a notch in an aluminum sandwich panel with honey comb core and removed rivets from a fastened stiffener. The detection and localization performance was show to be a function of frequency and orientation relative to damage. Strain and temperature conditions were controlled in a laboratory environment for this preliminary work. Future work will focus on the effect of these non-ideal variables on PoD. This includes the testing of specimens under varying temperature and strain in addition to investigation of other factors of influence such as repeatability of sensor bond line and independence of repeated sampling on an individual test specimen. Additionally, a model assisted PoD methodology based upon the active sensing model derived in the signal processing section is being developed with the ultimate goal of incorporating experimental measured wave propagation and directional damage scattering characteristics. PoD and ROC curves are essential for assessing the reliability of SHM methods, which must be conducted in order to field these technologies within any commercial or military application.

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