Detection Sensitivity Analysis for a Guided Wave (GW) Structural Health Monitoring System

Gregory Jarmer and Seth S. Kessler
Metis Design Corporation

Paul Swindell
FAA Technical Center

William Meeker
Iowa State University

IWSHM-2019

ABSTRACT

The paper presents a detection sensitivity analysis for a guided wave (GW) approach to monitoring fatigue crack growth. Piezoelectric beamforming array (PZT) sensors were used to send and receive ultrasonic waves. In this "baselined" method, changes in sensor response are recorded between the installed and test conditions. Propagating cracks create line-of-site obstacles between arrays, thus more energy is reflected (pulse-echo mode) and less is transmitted (pitch-catch mode) between sensor pairs. Any change in acoustic impedance, such as reduction in stiffness or thickness would also cause partial energy reflection, proportional to the relative impedance change. Two test configuration as presented here, including fatigue in 4-point bending and more traditional tension-tension. The purpose of the present study was to evaluate the sensitivity of this GW approach to damage size using the Length at Detection (LaD) statistical approach recently developed specifically to be applied to Structural Health Monitoring (SHM).

INTRODUCTION

Probability of Detection (PoD) as defined in MIL-HDBK-1823A is typical used as the key metric to evaluate the risk involved when using specific non-destructive techniques to inspect structures. As Structural Health Monitoring (SHM) sensors are being considered to guide, supplement or replace strategic time-consuming inspections, a comparable metric must be produced to ensure risk levels are not increased. Following typical approaches for generating PoD can be quite costly for SHM sensors however, as they are permanently installed on the test structure thus requiring new sensors be used for each data point. Traditional PoD also does not allow for repeated inspections—observing a flaw at multiple points in time as it grows on the same structure—as it raises concern that not enough variability is captured. Therefore, new approaches have been proposed to assess the sensitivity of SHM methods for detecting damage that incorporates the statistics associated with repeated measurements, with the hope that in the near future these approaches will be validated to be comparable to traditional PoD.

Gregory Jarmer, Metis Design Corporation, Boston, MA 02114, USA
Seth S. Kessler, Metis Design Corporation, Boston, MA 02114, USA
Paul Swindell, FAA Technical Center, Atlantic City, NJ 08405, USA
William Meeker, Iowa State University, Ames, IA 50011, USA

APPROACH

SHM using a guided wave (GW) approach entails the ultrasonic excitation of structure to produce Lamb waves, and then measuring the transmission and/or reflection of this wave energy's interaction with the surrounding structure at one or more sensor location. In most GW applications found in the literature, piezoelectric ceramic wafers are used as actuators and sensors, often abbreviated PZT representing the most common type of piezoceramic material used. PZT elements expand and contract both in and out-of-plane with high force potential when exposed to a dynamic voltage, and can operate at very high frequencies (typically between 10 kHz and 10 MHz) making them ideal actuators. Conversely, when dynamically strained they provide a potential between electrodes, making them good sensors. During the course of the presented work, a PZT beamforming array was used, seen in Figure 1, where a central 6 mm diameter actuator is surrounded by six 3 mm diameter sensors spaced in 60° increments. The excitation used was a 20Vpp narrowband linear sinusoidal chirp between 50 and 250 kHz.

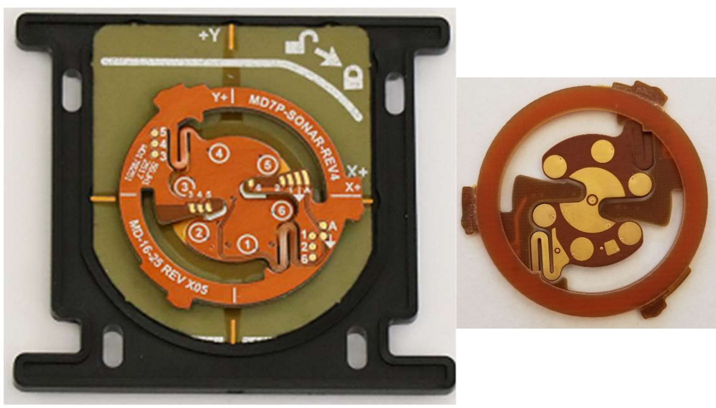

Figure 1: PZT beamforming array on carrier tray (left) and bottom cross section view (right)

ACTIVE ULTRASONIC GUIDED WAVE INSPECTION DAMAGE METRIC

Signal processing consisted of bandpass filtering the acquired signal, then constructing a narrowband signal with a center frequency of 80 kHz, found to be the most sensitive to changes in crack length. A baseline waveform from an uncracked condition is subtracted from the filtered signal. The detector is a phased array beamformer for the A_0 guided wave. The theoretical dispersion curves were solved numerically giving the relationship between temporal frequency and wavelength. Mathematically, beamforming is the operation that applies the appropriate phase shift for an assumed propagation direction to coherently align and then sum the array signals:

$$\mathbf{B}(\mathbf{k}') = \sum_{m=0}^{M-1} \exp\left(j\left(\mathbf{k}'^{\mathrm{T}} - \mathbf{k}^{\mathrm{T}}\right)\mathbf{p}_m\right)\tilde{y}(t)\exp(j\omega t) \quad \text{where} \quad |\mathbf{k}| = \omega / c_p \tag{1}$$

Here $\mathbf{k}$ is the wavenumber, ω is temporal frequency and c_p is the phase velocity for the A0 wave. Beamforming is performed over all possible arrival angles for a signal coming from the crack and the maximum value over this range is taken as an estimate of the crack size. This series of operations is repeated for every pitch-catch (PC) and pulse-echo (PE) pair for each dataset collected at a given cycle number. Estimates from the two pairs of array paths are then averaged yielding a damage metric vs. cycle.

PROOF OF CONCEPT EXPERIMENTAL SETUP

A 4-point bend fixture was used to grow a natural crack from a 1.5 mm EDM notch by applying an 80% yield load at 1 Hz to 300 x 25 x 3 mm aluminum bars. A digital microscope was used to capture truth data at ~1.5 micron resolution (16 pixels per 25 micron), and the entire setup was synchronized with LabVIEW, such that at pre-specified cycle numbers resistance data and an optical image could be captured. A total of 8 identical specimen were cycled at room temperature for 50,000 cycles with GW data collected in the unloaded positions every 1,000 cycles along with an image capture of the crack extending from the tip of the EDM notch (usually optically detectable around 25 micron between 22,000 and 28,000 cycles). Along with each measurement, also collected were time, temperature, and load.

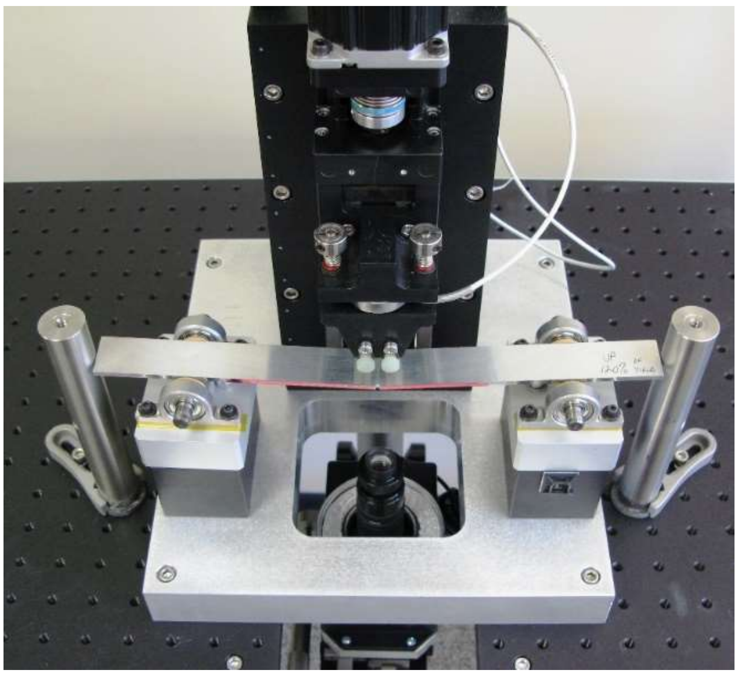

Figure 2. 4-point fatigue bend test fixture

PROOF OF CONCEPT EXPERIMENTAL RESULTS

Using equations 1, a damage index (DI) was estimated for a given set of GW sensor response files. Figure 3 shows all of the DI points for the specimens plotted against the optically measured crack length. Here a threshold value was set at a DI value of 100. SHM system detection sensitivity was calculated by Prof. Bill Meeker at Iowa State University. Figure 4 shows the Gaussian distribution results of the Length at Detection (LaD) method for computing detection sensitivity. According to this analysis, which just considers data up until the interpolated threshold crossing values, the $a_{90/95}$ value is 0.25 mm, seen in Figure 5. For this experiment, data was only processed for the PC approach. While the detection sensitivity was good, it can be seen that the data fell into two groups post detection, with some DI values following a linear trend with the other set levelling out. It is thought that these trends are related to the paths the crack took both in-plane and through-thickness as they grew across the specimen, and how the guided wave then interacted with that damage shape.

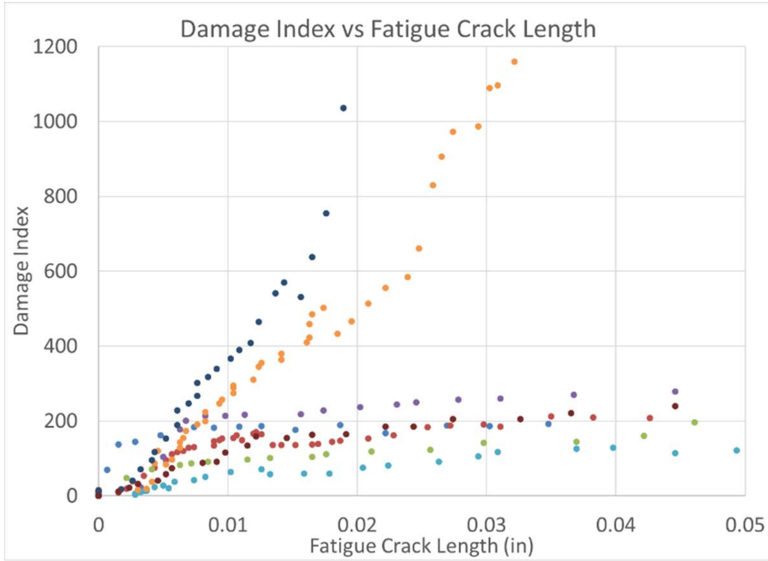

Figure 3. Predicted crack vs measured crack length for all specimens at all temperature ranges

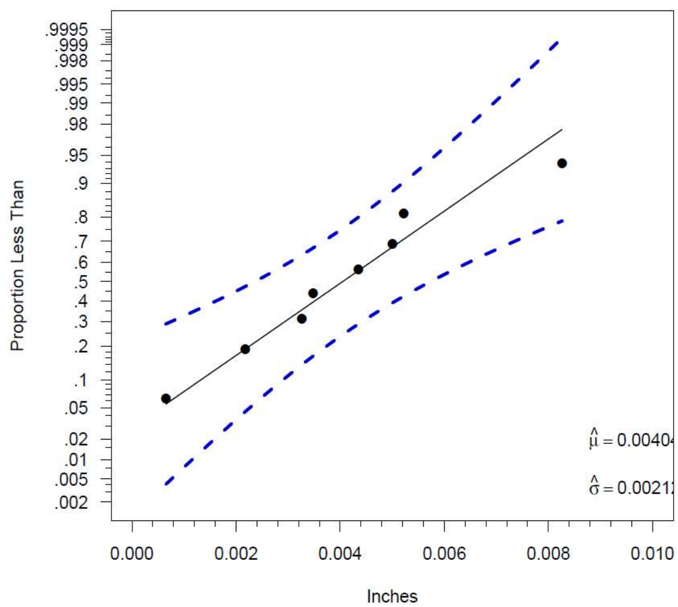

Figure 4. Gaussian distribution probability plot for LaD approach

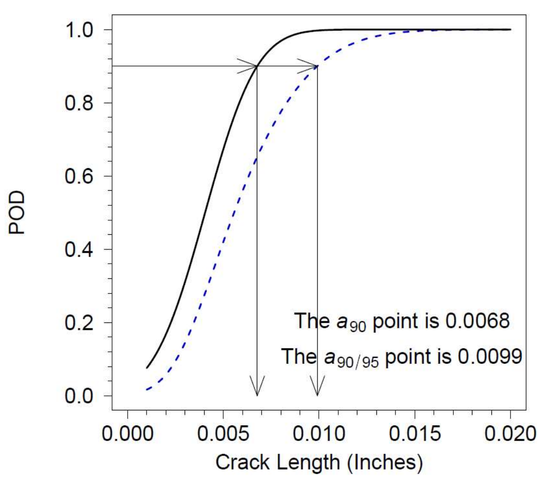

Figure 5. POD estimate using LaD approach

BLIND VALIDATION EXPERIMENTAL SETUP

In collaboration with the FAA William J. Hughes Technical Center, a series of fatigue tests were performed to further evaluate the new detection sensitivity statistical approach being evaluated. A dozen 600 x 40 x 2 mm specimens were water-jet cut from a large plate of Aluminum-Lithium alloy provided by the FAA, as seen in Figure 6. A 5 mm edge notch was electrical-discharge machined (EDM) into each following ASTM E647. Sacrificial specimens of similar dimensions were used by the FAA to determine the appropriate load, load rate, and approximate cycles to initiation and failure. Each specimens were instrumented with a pair of PZT sonar arrays that were offset by 90 mm from the EDM notch on one side, and 115 mm on the other. A 22 x 22 mm CNT crack gauge was also bonded to the middle of the bar to collect resistance data on the specimens, however this data is presented in a separate paper.

Subsequently, natural fatigue cracks were grown through 35,000 tension-tension cycles, representing ~3 mm of crack growth, with data being collected every 1,000 cycles. Data was collected using proprietary microminiature acquisition hardware integrated with the arrays, and was processed using Equation 1 to predict crack length. A total of 12 specimens were tested, however three of the sensors were inadvertently damaged by the FAA and yielded invalid data, thus were excluded from this study. True crack data was only provided for a single specimen for calibration purposes, and the rest of the data was processed blindly with ultrasonic response versus cycle data.

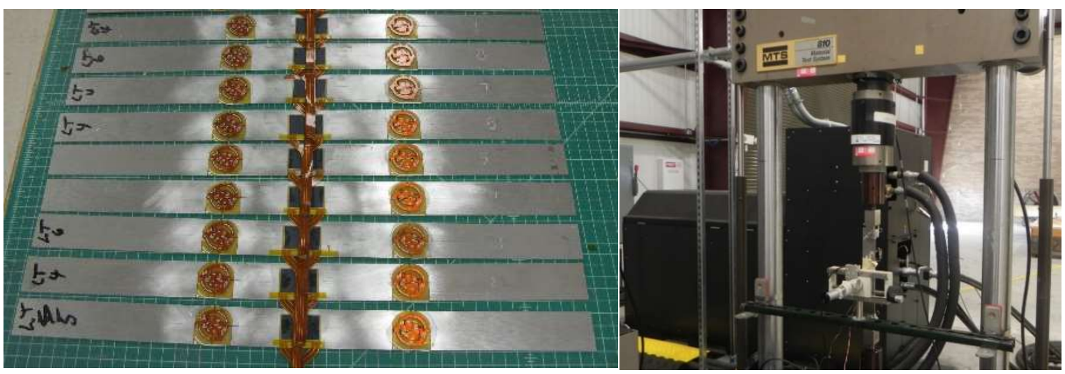

Figure 6. Al-Li tensile-tensile fatigue specimens instrumented with ultrasonic PZT arrays (left). MTS setup for fatigue crack growth and optical measurement of actual crack length (right)

BLIND VALIDATION EXPERIMENTAL RESULTS

Figure 7 plots the predicted crack length based on the GW sensor output versus the actual measured crack length for all specimens using PC results. This is similar to Figure 3, except in this case a predicted crack length was provided by solely using a linear scaling factor derived from the non-blind specimen to calibrate the Equation 1 output into millimeters. Truth data was measured optically, and was provided after crack predictions versus cycle count had already been submitted to the FAA. Subsequently, the blind results along with the true crack data was provide to Prof. Bill Meeker at Iowa State University to evaluate using the LaD approach. As seen in Figure 9, these analysis resulted in $a_{90/95}$ value of 1.9 mm. Figures 10-12 present an analogous set of plots for PE, in this case yielding an $a_{90/95}$ value of 3.3 mm due to the higher scatter in the DI data seen in Figure 10; though this method has the advantage of only using one sensor array.

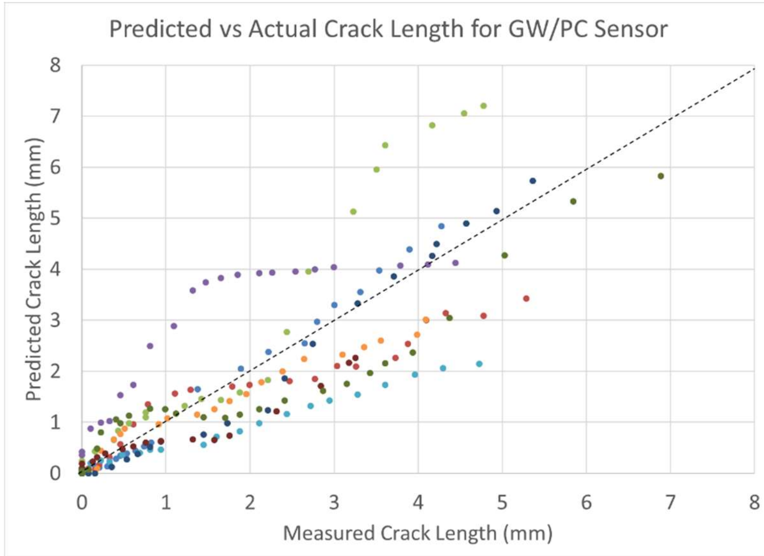

Figure 7. Predicted crack vs measured crack length using GW Pitch-Catch for all specimens

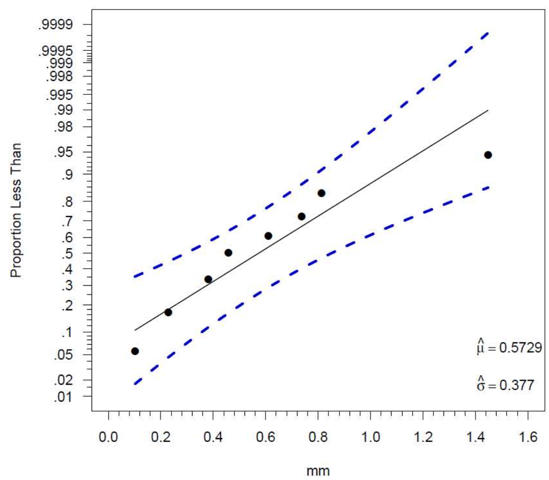

Figure 8. Gaussian probability plot for LaD approach applied to FAA blind test data using GW PC

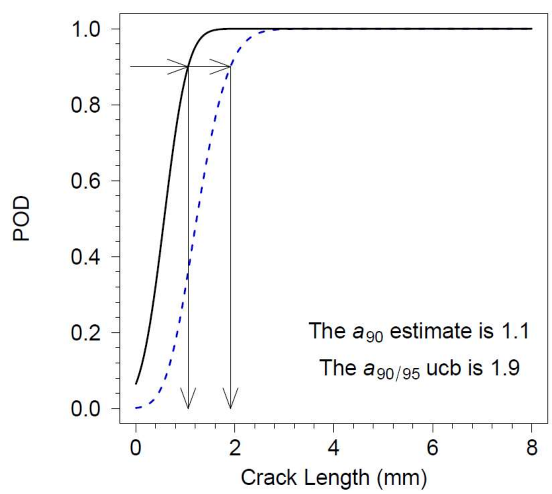

Figure 9. Detection sensitivity estimate using LaD approach using GW Pitch-Catch

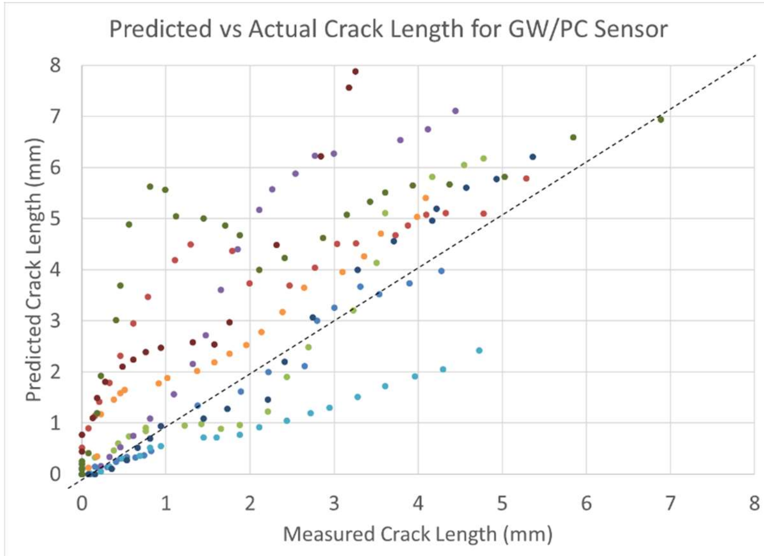

Figure 10. Predicted crack vs measured crack length using GW Pulse-Echo for all specimens

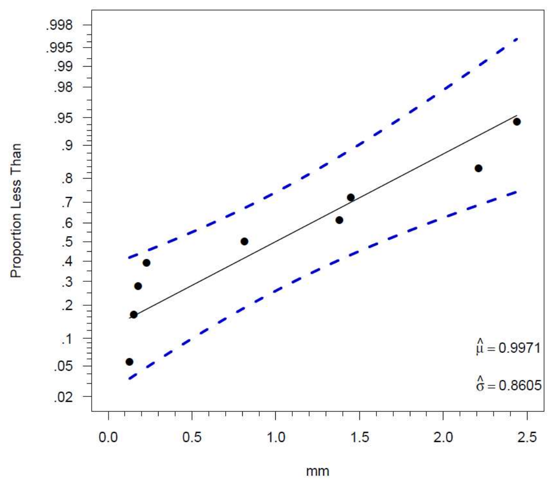

Figure11. Gaussian probability plot for LaD approach applied to FAA blind test data using GW PE

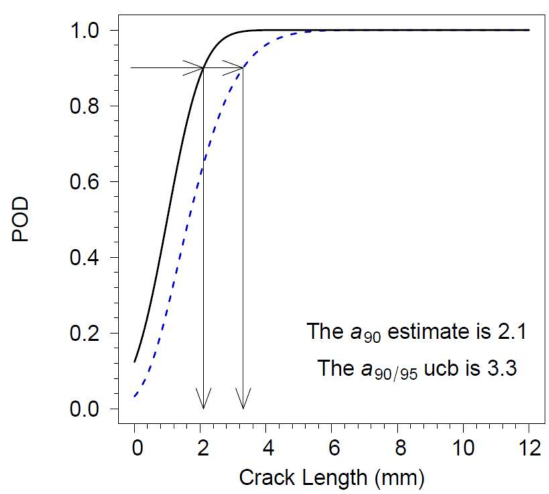

Figure 12. Detection sensitivity estimate using LaD approach using GW Pulse-Echo

CONCLUSIONS

This paper presents an ultrasonic guided wave approach to monitoring fatigue cracks using an array of PZT sensors. Theoretical dispersion curves were solved numerically giving the relationship between temporal frequency and wavelength, and beamforming algorithms were used to apply the appropriate phase shift for an assumed propagation direction to coherently align and then sum the array signals. A series of 8 specimen were tested in 4-point bend fatigue to demonstrate the principal. These results showed reliable detection of cracks <1 mm in length. A second test was conducted blindly with the FAA on 9 specimens, which similarly showed sensitivity of ~2 mm for natural cracks growing from EDM notches in tensile-tensile fatigue specimens. For each set of data, statistical analysis was performed using the newly formulated LaD approach to determine detection sensitivity as a proposed alternative to PoD formulation via MIL-HDBK-1823A. In the future, we plan to collect a much larger set of data in order to further validate these proposed detection sensitivity models.

ACKNOWLEDGMENTS

This research was performed at the Metis Design Corporation in Boston, MA, and the FAA Technical Center Atlantic City, NJ, sponsored by the USAF under SBIR contract FA8501-15-C-0025 and by the FAA under ANG-TT-CRDA-0352.

REFERENCES

1. Jarmer G, Flynn E, and M. D. Todd, "Multi-wave-mode, Multi-Frequency Detectors for Guided Wave Interrogation of Plate Structures," Structural Health Monitoring, p. 1475921713513972, Dec. 2013.
2. S. M. Kay, Fundamentals of Statistical Signal Processing Detection Theory. Prentice Hall Publishers, 1998
3. Kessler S.S. and A. Raghavan. "Co-Located Triangulation: Single Node Damage Position Identification." Proceedings of the Sensors, Signal and Information Processing Workshop, 11-14 May 2008, Sedona, AZ.
4. Kessler S.S. and A. Raghavan. "Vector-Based Localization for Damage Position Identification from a Single SHM Node." Proceedings of the 1st International Workshop on Prognostics & Health Management, 6-9 October 2008, Denver, CO.
5. Kessler S.S. and A. Raghavan. "Vector-based Damage Localization for Anisotropic Composite Laminates." Proceedings of the 7th International Workshop on Structural Health Monitoring, 9-11 September 2009, Stanford University.
6. Dunn C.T., Raghavan A. and S.S. Kessler. "Analytical Axisymmetric Coupled Piezo-Elastodynamic Models for Guided-Wave Structural Health Monitoring." Proceedings of the 7th International Workshop on Structural Health Monitoring, 9-11 September 2009, Stanford University.
7. Kessler S.S., Flynn E.B. and M.D. Todd. "Hybrid Coherent/Incoherent Beam Forming Diagnostic Approach to Naval Assets." Proceedings of the 8th International Workshop on Structural Health Monitoring, 12-15 September 2011, Stanford University.
8. Flynn E.B., Todd M.D., Dunn C.T., and S.S. Kessler "Identifying Scatter Targets in 2D Space using In Situ Phased-Arrays for Guided Wave Structural Health Monitoring." Proceedings of the 8th International Workshop on Structural Health Monitoring, 12-15 September 2011, Stanford University.
9. Kessler S.S. and E.B. Flynn. "Hybrid Passive/Active Impact Detection & Localization for Aerospace Structures." Proceedings of the 9th International Workshop on Structural Health Monitoring, 10-12 September 2013, Stanford University.
10. Jarmer G. and S.S. Kessler S.S. "Probability of Detection Assessment of a Guided Wave Structural Health Monitoring System." Proceedings of the 10th International Workshop on Structural Health Monitoring, 10-12 September 2015, Stanford University.
11. Jarmer G. and S.S. Kessler. "Application of Model Assisted Probability of Detection (MAPOD) to a Guided Wave SHM System." Proceedings of the 11th International Workshop on Structural Health Monitoring, 12-14 September 2017, Stanford University.
12. Johnson D.H. and D. E. Dudgeon. Array Signal Processing. 1st ed. Prentice Hall Signal Processing Series. Upper Saddle River, New Jersey: Prentice Hall Publishers.