Hybrid Passive/Active Impact Detection & Localization for Aerospace Structures

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ABSTRACT

This paper presents finding from a recent set of formal performance assessments studies, quantifying the ability of a hybrid passive/active SHM system to detect impact damage. The SHM system itself is an integrated device including an array of PZT sensors with a central PZT actuator, analog-to-digital converter, memory and FPGA. In passive mode, the system uses the central PZT element for triggering and the array of PZT sensors to detect and localize acoustic emissions (AE) propagating from the impact source. Subsequently, an active mode is triggered to capture the guided wave (GW) response of the resulting impact damage to a narrowband excitation measured from the same PZT array. In both cases, a phase-coherent beamforming approach is used to process the data. A single node was mounted to a 0.6 x 0.6 m square 2 mm thick aluminum plate with a row of 20 fasteneres, which was then subjected to 36 impact events of ~20 J. In addition, 6 tests were conducted to further predict the presence of a loosened fastener on the assembly. Results of the study indicated that the AE mode was extremely sensitive to small impacts even at a great distance with localization errors on the order of 25 mm. Similarly, while the GW mode errors were closer to 50 mm for localization for ~0.5 mm dents, the error for detection of loosened fasteners was less than 5 mm.

INTRODUCTION

Structural health monitoring (SHM) is increasingly being considered by Aerospace OEM and their operators as a means for unlocking inherent capabilities while reducing overall life-cycle costs. Proper use of SHM can lead to increased asset availability, reduced design factors of safety for lighter weight structure, and prolonged useful operating life. Similarly, SHM can guide condition-based inspection and maintenance, thus minimizing traditional expenses expended preventatively. Aerospace applications are very mass sensitive however, thus sensor networks must be able to detect damage over large area with sparse placement. Furthermore, the ability of a single sensing system to efficiently collect multiple forms of data would provide obvious advantages for detection and mass.

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This paper presents finding from a recent set of formal performance assessments studies, quantifying the ability of a hybrid passive/active SHM system to detect impact damage in representative Aerospace metallic specimens. The SHM system itself comprises of 2-parts: 1) an analog sensor base, and 2) a digital sensor node. The analog base is constructed from 6 piezoceramic 3 mm diameter by 0.5 mm thick wafer elements (specifically PZT-5A) arranged in a ring around a central 6 mm diameter element. In passive mode, the system uses the central PZT element as an event trigger, and the circular array of PZT sensors to measure the acoustic emissions (AE) propagating from the impact source. Similarly, in active mode the ring of PZT sensors capture the guided wave (GW) "echo" response of the resulting impact damage, in this case due to a narrowband excitation originating from the central PZT element. The digital node is a 40 mm diameter by 6 mm thick "puck" that physically surrounds and electrically connects to the analog sensor base to facilitate the active and/or passive testing. Using an integrated arbitrary function generator a 20 Vpp excitation can be provided to the actuator to promote guided wave propagation. A 50 MHz digitizer with digital gains is used to quickly collect synchronous sensor data to be stored in local memory. The entire node is a state-machine, controlled by embedded software on the FPGA. The device weights approximately 12 g and draws about 100 A at 28 V_{DC} while in active mode.

EXPERIMENTAL SETUP

Test Specimen

For the purposes of evaluating the performance of this SHM system under nominal conditions, a simple 0.6 x 0.6 m square aluminum plate selected for testing, 2 mm thick as a representative skin thickness for Aerospace structures. A row of 20 fasteners were evenly spaced across the center for the test article, tightened to the same torque. A single analog sensor based and digital node were bonded the aluminum plate using AE-10 strain gauge adhesive with a 24-hour room temperature cure cycle. The node was placed half way between the edge of the plate and the row of rivets, centered in the transverse dimension of the plate. A flat flexible cable (FFC) was used to connect the node to a small hub unit to provide power and accumulate the resulting data on an SD card.

Figure 1: Digital node and analog sensor based bonded an aluminum plate with FFC attached

Test Matrix

A relatively simple test matrix was conducted to evaluate system performance. A total of 36 low-velocity falling-mass impacts were imparted to the test article, each at ~20 J of energy with a ~1 cm semi-spherical impact head. The plate was simply supported around its entire perimeter with a wooden frame and impacted on the side opposite the installed node and FFC. The impacts were randomly distributed around the specimen, keeping at least 2 cm from the node itself, with half being on the same side of the fastener line as the node and the other half on the opposing side. The test procedure comprised of setting an automated trigger level for the node armed in passive mode to collect AE data upon impact, to be followed by collection of active GW data in response to a 50 kHz an excitation. In addition to these impact events, 36 active GW tests were manually triggered scattered throughout the impact test matrix to check for false positives. Finally, in the middle of the impact testing 6 GW tests were conducted with a loose (hand tightened) fastener.

DIAGNOSTIC ALGORITHMS

Algorithm Approach

Acousto-ultrasonic SHM sensing involves exciting a structure (either mechanically or from an external source) and in turn measuring the response in order to gain information regarding the potential presence of damage. The previously described SHM system works in an analogous fashion to sonar. In passive mode, a foreign object being propelled against a plate-like structure generators a wide-band excitation source. In active mode, the node actuates a series of narrow-band, ultrasonic mechanical pulses, or “pings”, using its central actuation transducer. These pulses propagate through the structure, reflect and scatter at geometric features, such as plate boundaries, as well as at potential damage, and are then sensed by the six local sensing elements. The recorded responses are used to determine the range(s), bearing(s), and size(s) of potential damage in the structure relative to each node. In traditional active sonar applications, bearing is often determined in one of two ways. The first is to physically arrange the sonar array to maximize its sensitivity in one direction, and then mechanically orientate, or steer, the array to scan multiple directions. The second approach is to artificially introduce delays in the acquired, digitized responses in order to electronically steer the array through a processes known as beam forming. For the current application, the latter approach has two distinct advantages: 1) the position of the array elements (i.e. sensing transducers) can be fixed so there are no moving parts, and 2) a single actuated pulse and sensed response can be used to simultaneously scan for damage in every direction. This directional scanning through electronic steering forms the basis of the present investigators approach to ultrasonic imaging.

Signal Conditioning

Before being used for image generation, the waveforms are conditioned in order to reduce influence of both mechanical and electronic noise sources. After retrieval from the data collection hub, the waveforms are band-pass-filtered to a 30 KHz band centered about the actuation frequency of 50 KHz. This filtering is performed by passing the signals through a 2^{nd} order Butterworth filter in the forward direction and then again in the reverse direction. This forward and reverse filtering eliminates any signal phase distortion introduced by the filter. In order to make the reflections from damage visible relative to normal geometric reflections, measurements recorded when the structure was in a known damage-free state, commonly referred to as "baselines", are subtracted from the live measurements.

Constructing the 2D scans

Optimal detectors can be derived according to statistical likelihood tests on the measured responses for the presence and location of damage. Depending upon the specific objective(s), such detectors provide a means of combining measurement data to build a set of test statistics $T(\boldsymbol{x})$ (sometimes referred to as "damage features") that can be compared to a threshold (determined by a risk analysis) in order to make decisions regarding the existence and/or location of damage on the structure. In most cases, where localization is of prime importance, the time of flight from the actuator to the potentially damaged region to the sensor for a given wave number can be reasonably estimated based on an average group velocity computed from the (likely heterogeneous) material and geometric properties along the propagation path. With this in mind, a common localization detection approach for each region in a structure is one that delays and sums the measurements from the different transducer pairs so that they will additively combine at the true location of damage, resulting in an "image" of highly constructive scatter relative to the background noise. However, the relative average phase velocities from each transducer pair to each region of the structure can be more difficult to predict. This leads to two basic forms of detectors based on the statistical model of the measurements: coherent and incoherent beam forming.

Coherent Beam Forming

Each sensor base involves a single actuating transducer surrounded by six sensing transducers. Across the transducers in each node, the average phase velocity along the path to any given region is approximately equal, allowing for coherent beam forming. In the case where the relative phase velocity between transducer pairs is the same, the delayed waveforms can be combined coherently, without enveloping, which is referred to as coherent beam forming. The test statistic for the coherent detector can then be expressed as

$$T_{\mathrm{C}}(\boldsymbol{x}) = \left| \sum_{m=1}^{M} w_m \left(t - \tau(m, \boldsymbol{x}) \right) \right|, \tag{1}$$

where the magnitude is taken after summation rather than before.

Coherent beam forming is ideal since the summation of the delayed waves tend to destructively combine at all locations except the true location of damage. However, in order for the average phase velocities along the path to each region of the structure to be the same, the transducers must be very closely spaced (less than a characteristic interrogation wavelength apart). In practice, for narrowband signals, the time delays are substituted by computationally faster phase shifts. As such, arrays of sensors that make use coherent beam forming, such as those packaged here, are referred to as phased arrays.

Figure 2 shows a graphical representation of beam forming results. The scans are the result of coherent summation of the individual sensing-tranducers' measurements with appropriate time delays for detecting a 6 mm magnet (black circle) added to a 1 m square plate with Vaseline as a shear couplant. As shown, with coherent beam forming, a single node can identify both range and bearing of wave-scattering damage. Sensing systems that are not capable of coherent beam forming, such as traditional single-element sparse transducer arrays, can only identify range to a target, forcing them to rely on multiple widely-spaced, sensing elements in order to triangulate the damage location. This significantly reduces the necessary instrumentation footprint of this system when compared to traditional ultrasonic GW systems.

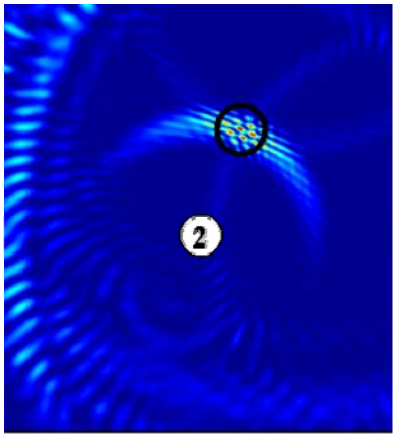

Figure 2: Phase coherent imaging on an aluminum plate with a magnet target

EXPERIMENTAL RESULTS

Passive Mode Detection Results

The system showed excellent sensitively to impact events, detecting all 36 impact using the pre-programed trigger threshold level. For each AE result, a phase coherent scan was produced, which was distilled to a single pair of Cartesian coordinates at the maximum likelihood centroid of the scan. **Figure 3** displays a scatter plot of these raw localization prediction, re-centering all of the impacts to a common origin for comparison purposes. As seen in the figure, the predictions are relatively closely clustered near the origin relative to the size of the overall plate, and the mean error for localization using this AE method was ~ 25mm. No real trend was observed for results obtained for one side of the fastener line versus the other side.

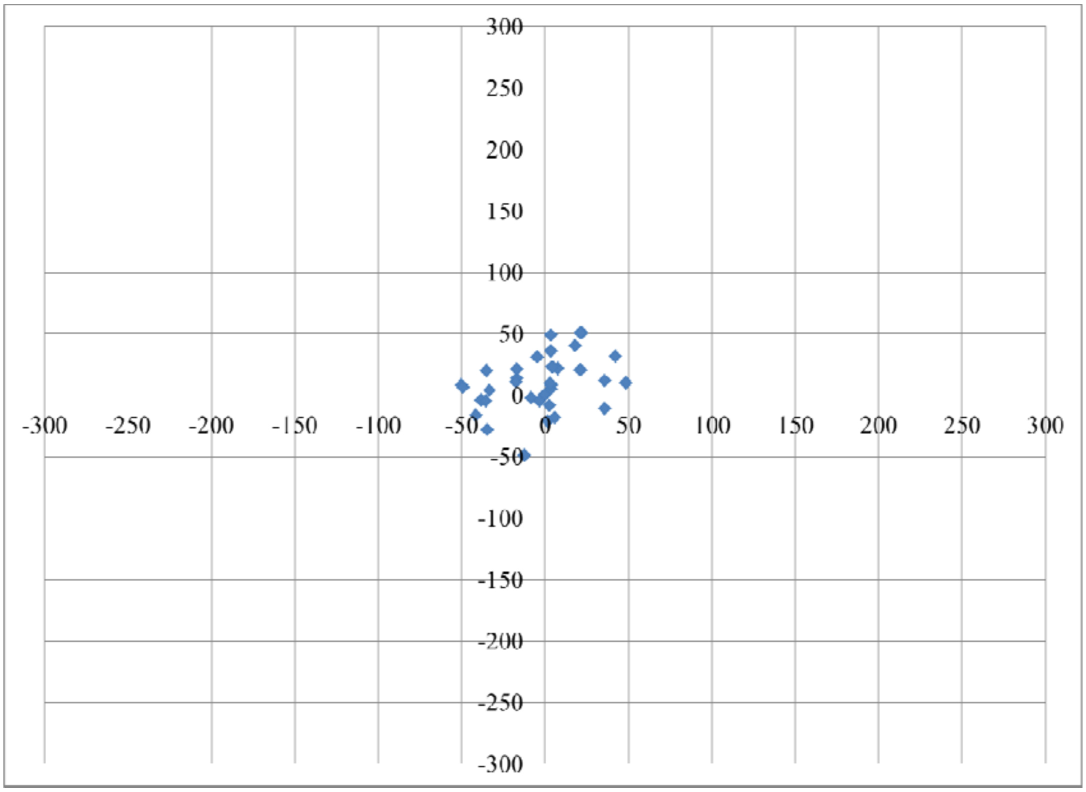

Figure 3: Passive AE impact detection results, re-centered to a common origin. Mean error ~ 25 mm

Active Mode Detection Results

The system showed good sensitively to impact damage, detecting all 36 dents following AE detection, which were each approximately 0.5 mm deep. Similar to the AE results, for each GW case, a phase coherent scan was produced, which was distilled to a single pair of Cartesian coordinates at the maximum likelihood centroid of the scan. **Figure 4** displays a scatter plot of these raw localization prediction, re-centering all of the impacts to a common origin for comparison purposes. As seen in the figure, while not as tightly clustered as the AE results, the GW predictions are still relatively closely scattered near the origin relative to the size of the overall plate. The mean error for localization using this GW method was ~ 50 mm. Again, no real trend was observed for results obtained for one side of the fastener line versus the other side. It is hypothesized that some of the error in the GW method may be accumulated due to the fact that each subsequent impact introduced additional scatterers into the structure; while they would be subtracted from subsequent scans, they would still redistribute the ultrasonic energy propagating through the structure into an inhomogeneous pattern.

Aside from detecting the impact damage, the GW algorithm was also able to correctly identify 36 scans collected between impact events as no-damage conditions (i.e. no false positives), based upon threshold levels set through comparison of many baseline scans. The final GW result was the identification of loosened fasteners across the plate. For each of the 6 cases tested the loosen fastener was correctly identified, and localized within less than 5 mm mean error, as seen in **Figure 5**. This essentially translates to localization within ±1 fastener position.

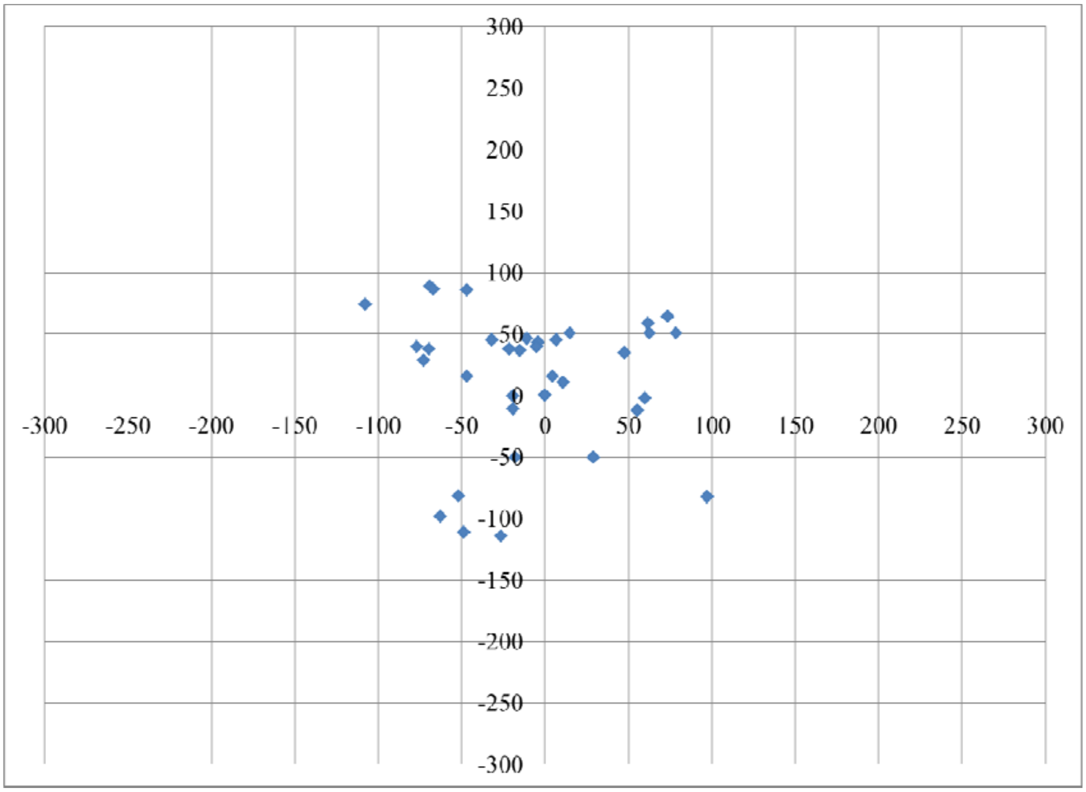

Figure 4: Active GW impact detection results, re-centered to a common origin. Mean error ~ 50 mm

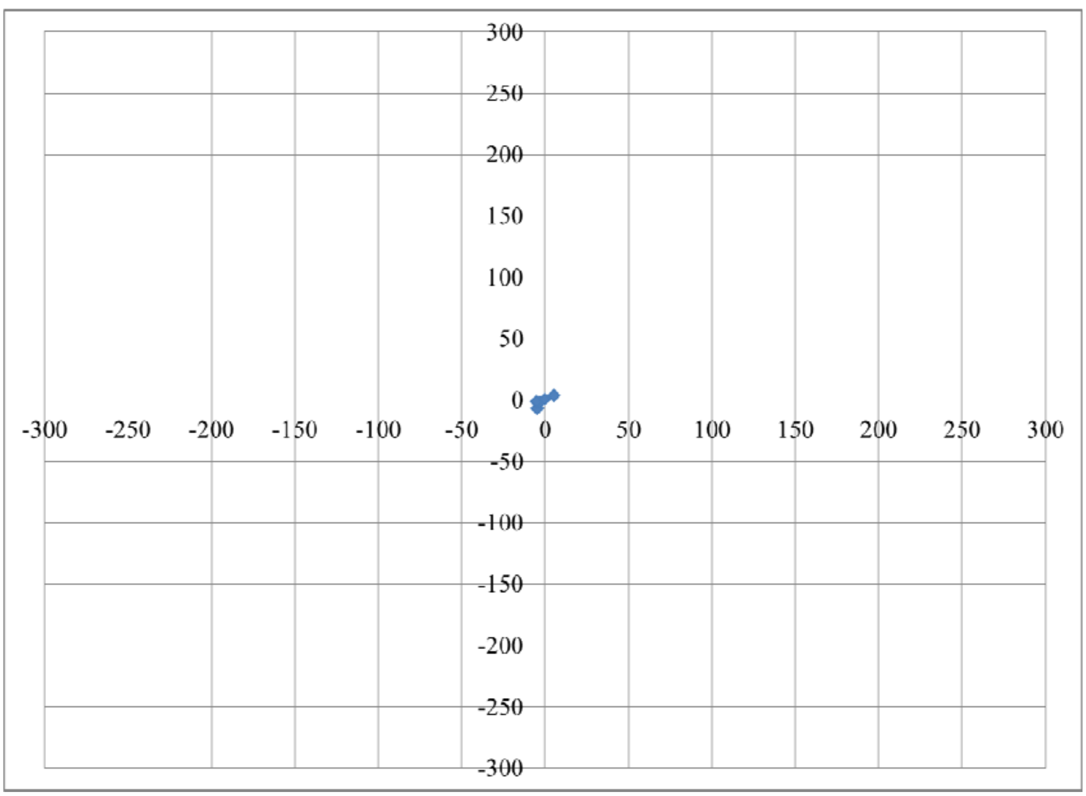

Figure 5: Active GW fastener detection results, re-centered to a common origin. Mean error ~ 5 mm

CONCLUDING REMARKS

This paper present results for a controlled experiment investigating the use of an SHM system for hybrid passive/active operation. An aluminum plate was instrumented with a single sensor, which was subjected to 36 impact events. For each event, triggered AE data was collected as well as GW data for the resulting damage. In addition 36 false positive “checks” were collected, as well as 6 scans with loosened fasteners. All data was collected using a common sensor array. In passive mode, the system uses the central PZT element for triggering and the array of PZT sensors to detect and localize AE propagating from the impact source. Subsequently, an active mode is triggered to capture the GW response of the resulting impact damage to a 50 kHz excitation measured from the same PZT array. In both cases, a phase-coherent beamforming approach is used to process the data. Results of the study indicated that the AE mode was extremely sensitive to small impacts even at a great distance with localization errors on the order of 25 mm. Similarly, while the GW mode errors were closer to 50 mm for localization for ~0.5 mm dents, the error for detection of loosened fasteners was less than 5 mm.

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