Hybrid Coherent/Incoherent Beam Forming Diagnostic Approach to Naval Assets

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ABSTRACT

This paper presents a hybrid diagnostic algorithm that leverages a novel piezoelectric-based damage-localization method using ultrasonic waves. The goal of the present research was to monitor a Navy established "challenge problem"—a large (1.8 x 0.9 m) aluminum plate with several geometric features such as cutouts and bolted doublers, which tend to confound most guided wave methods. The algorithms used were a hybrid collection of functions making use of both coherent and incoherent information in the data. Data for each sensor is processed separately, then ultimately summed in a weighted fashion across the test structure. Further logic is also deployed to eliminate anomalies and invalid features. Generally, this process is analogous to active sonar. Damage ("targets") are detected and/or localized by generating ultrasonic elastic waves and observing how they bounce off of potential targets. Because a test structure is arguably far more complex than the open ocean, producing potentially far more "false targets", this approach takes advantage of embedding probabilistic models into the wave propagation/scattering process so that likelihood-based judgments can be made about the damage targets. These judgments may be understood in appropriate performance terms—probability of detection, probability of localization, etc.— which directly supports the uncertainty quantification needed for decision-making.

INTRODUCTION

To benchmarking the state-of-the-art for SHM, the Navy established a "challenge problem" to compare the performance of multiple systems. Engineering drawings were provided for a large (1.8 x 0.9 m) aluminum plate with several unique features such as cutouts, holes and bolted doublers. No other information was provided, other than "damage" would be introduced in multiple locations.

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The overall approach taken by the present investigators was a system optimization problem; attempting to maximize detection capabilities with minimal impact to the test structure. Hundreds of sensors densely spaced over the test structure would certainly have the best opportunity to precisely resolve damage locations; however this would obviously be impractical for real-life naval platforms due to the quantity of instrumentation required (cables, acquisition hardware, etc) and would pose a serious weight penalty risk for aerospace platforms. Therefore a Bayesian risk function was used to assign costs to missed-damage, false-positives, and localization error as well as associating a cost with each sensor.

The actual physical SHM nodes used were the MD7 digital SHM system. This includes distributed digitization hardware, the VectorLocator analog sensing element and a data accumulator. This system efficiently facilitates piezoelectric-based detection by allowing serial connections between sensors to minimize cabling, and by using a pulse-echo mode (same node sends and received the guided wave) the sensors can be spaced much further apart as compared to pitch-catch methods (where one element senses and another remote element receives the response). In particular, the VectorLocator provides not only amplitude information, but also phase using 6 local PZT sensing elements arranged in a circle, thus being able to support both coherent and incoherent-based algorithms.

DIAGNOSTIC ALGORITHMS

Algorithm Approach

Active SHM sensing involves mechanically exciting a structure and in turn measuring the response in order to gain information regarding the potential presence of damage. When one dimension of the structure being excited is relatively small compared to the other two, such as in a plate-like structure, and the wavelength(s) of excitation are of the same order as this dimension, the process is referred to as guided-wave active sensing.

The MD7 digital SHM system works in an analogous fashion to active sonar. One at a time, each MD7 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 guided wave 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 60 KHz. This filtering is performed by passing the signals through a 2nd 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 $T(x)$ (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.

Incoherent vs. Coherent Beam Forming

In the case where the relative phase velocity is different and unknown between transducer pairs, the *envelopes* of the waveforms must be summed together in order to eliminate the dependence on phase. Otherwise, the delayed and summed waveforms run the risk of destructively interfering at the true location of damage and/or constructively interfering away from damage due to these phase mismatches. If we represent the baseline-subtracted acquired waveform from each transducer pair m on node n according to its complex analytic signal $w_{nm}(t)$, then the test statistic for the incoherent ("phase ignorant") detector for damage at x reduces to

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

where $\tau(m, x)$ is the time of flight from transducer pair m to x.

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

$$T_C(\boldsymbol{x}) = \left| \sum_{m=1}^{M} w_m\left(t - \tau(m, \boldsymbol{x})\right) \right|, \qquad (2)$$

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), limiting their coverage of the structure. 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 in each MD7 node, are referred to as phased arrays.

Hybrid Beam Forming

Each sensor node 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. From node to node, however, the average phase velocity is generally not equal and as such the scattered signals must be combined incoherently. This hybrid approach enables both effective imaging through coherent beam forming within each node as well as effective coverage of large areas through the placement of multiple nodes.

$$T_H(\boldsymbol{x}) = \left\| \sum_{n-1}^{N} \left| \sum_{m=1}^{6} w_{nm}\left(t - \tau(n, m, \boldsymbol{x})\right) \right| \right\| \qquad (3)$$

Figure 1 shows a graphical representation of the summation process. The scans on the left are the result of coherent summation of the individual sensing-tranducers' measurements with appropriate time delays while the image on the right shows the result of the incoherent summation of multiple MD7 nodes. Figure 2 show a summary of results from these three imaging approaches for detecting a 6 mm magnet (black circle) added to a 1 m square plate. 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 the MD7 system when compared to traditional ultrasonic guided wave systems.
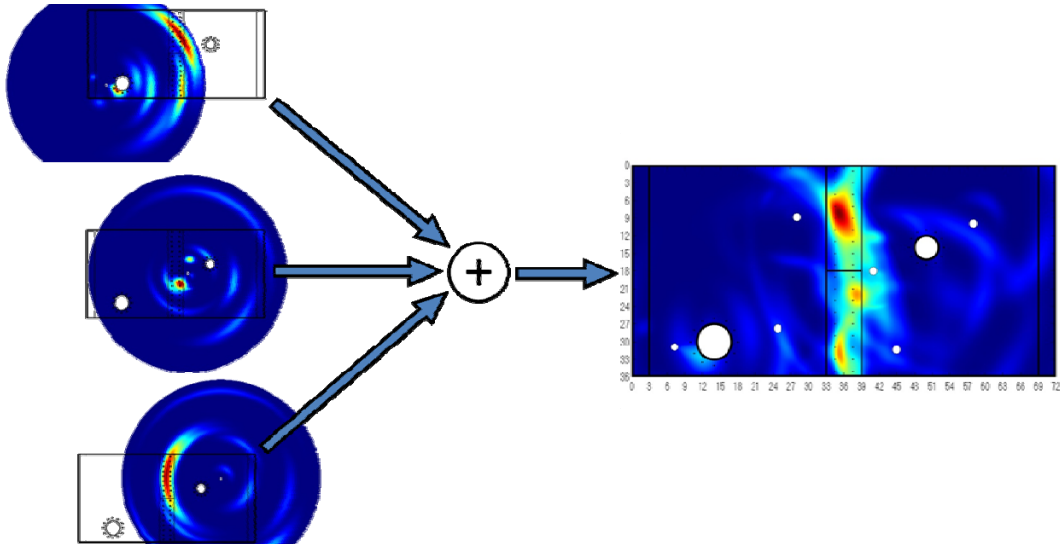
Figure 1: Summation of multiple single-node radial scans to produce full structure scan
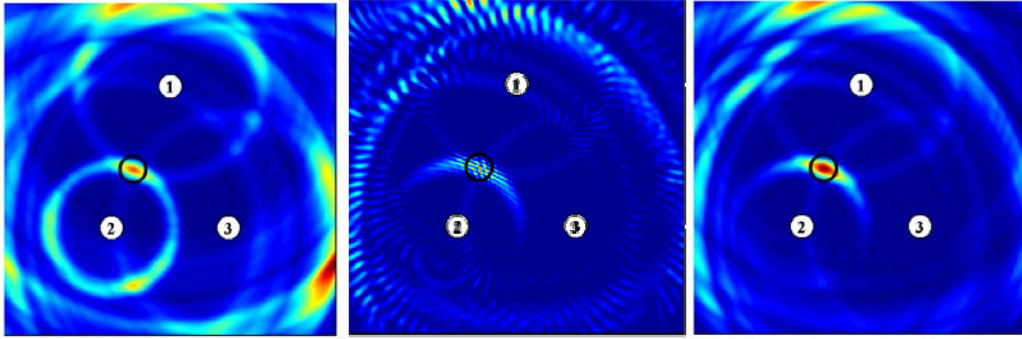

Figure 2: Incoherent (left) coherent (right) and hybrid (bottom) imaging using three nodes.

RESULTS

This section presents results from experiments conducted by the principal investigators (Figures 4-6) and the Navy (Figures 7-8). As seen in the Figures, the hybrid beam forming algorithm was reliable for detecting at least two introduced features with reasonable localization accuracy (~5% error). For the cases with many new features introduced simultaneously, the algorithm was reliable for detecting more than half of the features (favoring the larger changes), with comparable accuracy. The same processing procedure was carried out on every dataset when producing all images in this section and all adjustable parameters remained fixed. Only the color scale was shifted from image to image. To support a statistical decision-making framework, the color in all images represents the number of standard deviations the image values lie above the mean of the images generated from a database of damage-free data. As such, dark blue corresponds to one or fewer standard deviations from the mean while the image value corresponding to dark red is indicated by "SCALE" in each figure caption (in units of standard deviations from the mean). Using node-to-node propagation times, the group velocity was determined to be approximately normally-distributed according to:

$$v \sim N\left(2760 \text{ m/s}, 76200 \left(\text{m/s}\right)^2\right). \tag{4}$$
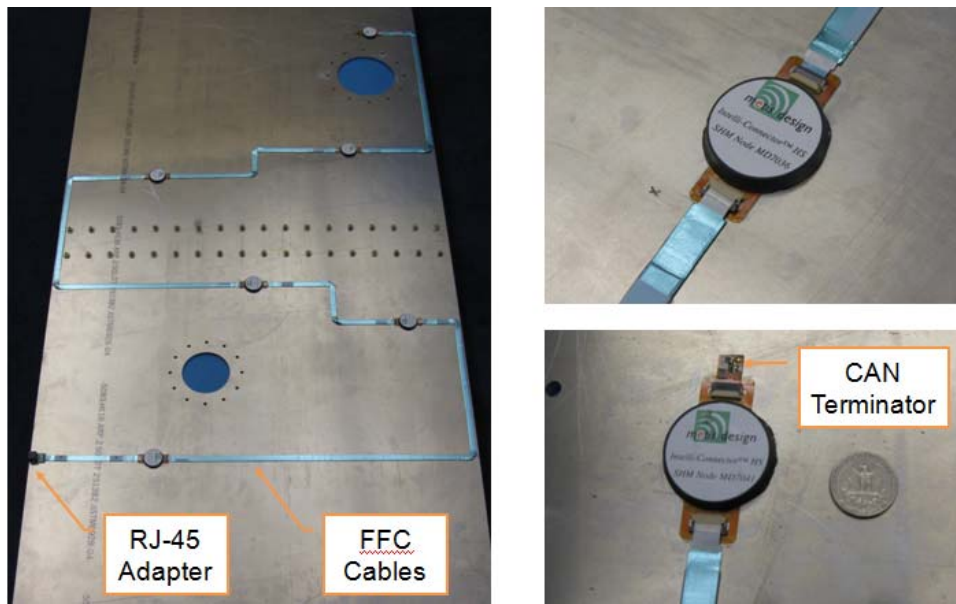
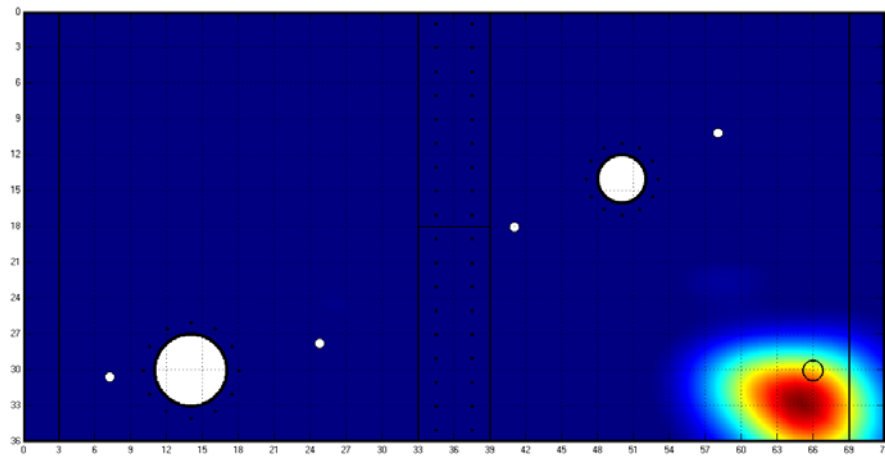Figure 3: Photographs of the installed MD7 system on the Navy test structure.

Figure 4: Calibration test with 6mm magnet in lower corner. Nodes 1-4 in use. SCALE: 36
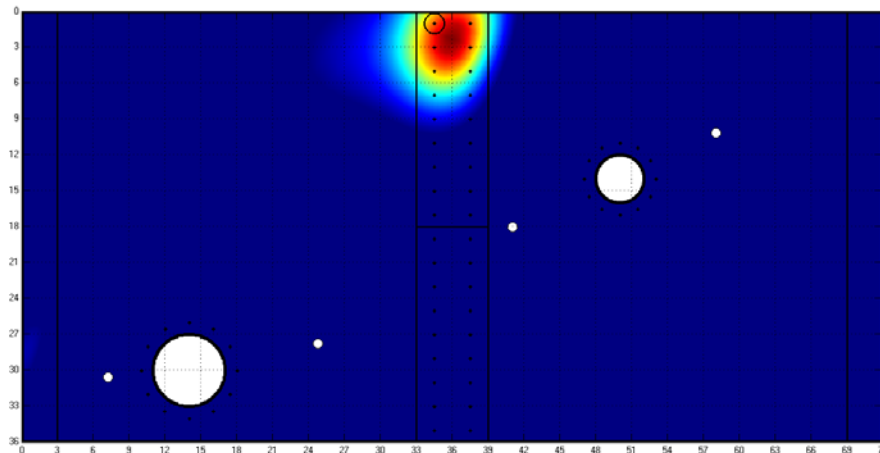Damage detected with localization error ~5 cm.

Figure 5: Calibration test with loosened top bolt. Modes 1-4 in use. SCALE: 9.71

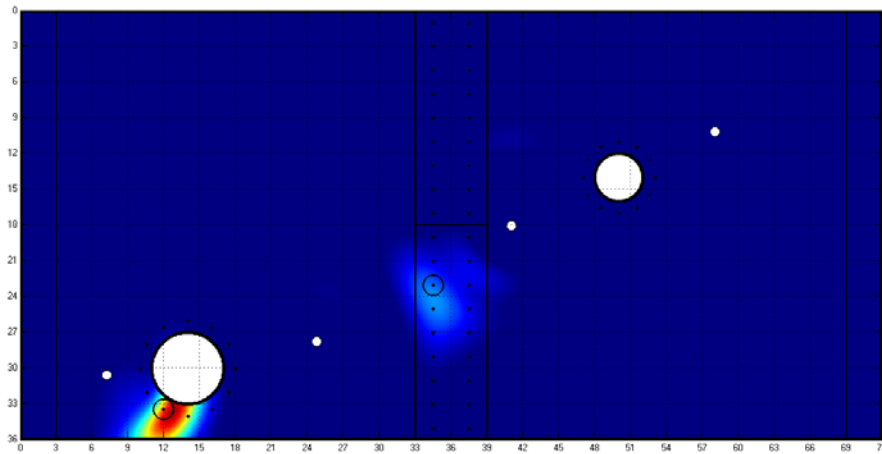Damage detected with localization error ~3 cm

Figure 6: Calibration test with 3 mm notch & loosened bolt. Nodes 1-4 in use. SCALE: 29.0
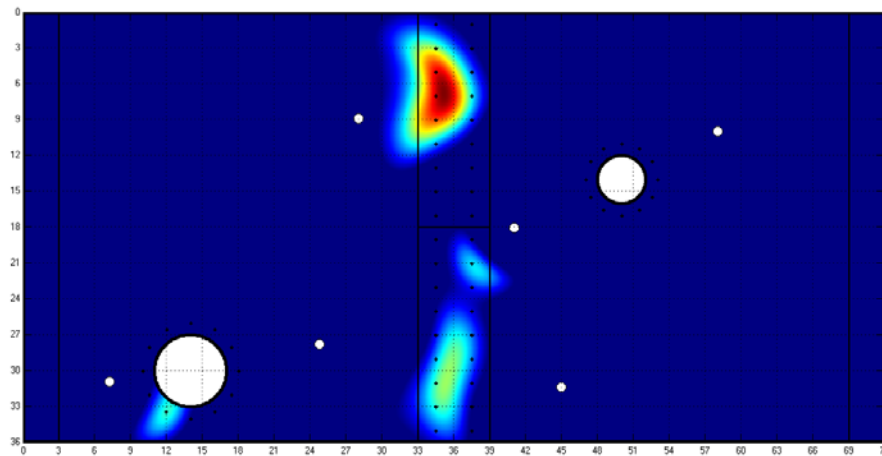Both damage detected, localization errors of ~1 cm for both cases.

Figure 7: Navy test with 6 "blind" damage locations. Nodes 1-6 in use. SCALE: 5.62
Identified 4 locations: 3 mm notched hole, two 1.5 mm drilled holes and loosened bolt.
Missed 2 locations: 3 mm shallow punch indentation and 0.3 mm bolt hole enlargement
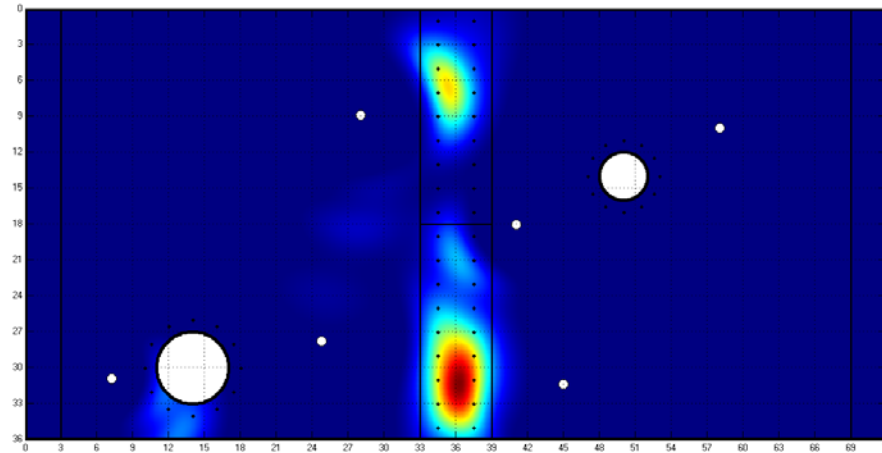

Figure 8: Navy test with 8 "blind" damage locations. Nodes 1-6 in use. SCALE: 40.1.
Identified 5 locations: 6 mm notched hole, 1.5 mm & two 3 mm drilled holes and loosened doubler.
Missed 3 locations: 1.5 mm notched hole, 3 mm drilled hole and ball-drop impact.

CONCLUDING REMARKS

During the course of this research, aluminum test plates were instrumented for efficient damage detection using the MD7 digital SHM system (total system weighs only 160 g including all sensors and hardware). A Bayesian risk minimization approach was taken to determine optimal sensor placement to minimize false positives while providing the desired coverage [9]. Guided wave-based damage detection & localization algorithms were implemented, and it was found that by combining phase-coherent and incoherent algorithms, through a process similar to active sonar, greater accuracy could be achieved. In the end, the project is believed to be quite successful in identifying multiple damage locations over a wide-area in a blind test scenario with a limited number of sensors, to demonstrate a system that could be scaled practically to cover a true Navy application. While the incorporation of additional sensors would have resulted in significantly more accurate results, it was felt that the 6-sensor system would provide enough detail while minimizing the impact to the structure (cost, mass, power, complexity, etc).

ACKNOWLEDGMENTS

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