Predictive Simulation of Guided Wave Structural Health Monitoring with Piezoelectric Wafer Active Sensors for Military Vehicle Applications

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ABSTRACT
Predictive simulation of the structural health monitoring (SHM) process has a crucial role in the efficient design of effective SHM systems. Predictive simulation is part of the forward problem which calculates the sensor signals that would be recorded for a given structural state and a given excitation. The inverse problem, which is more difficult, has to estimate the structural state from known excitation and known measured signals. This inverse problem is usually solved through an optimization process in which the forward problem is run repeatedly for many times. A fast and accurate forward problem that has adequate sensitivity to damage presence while being insensitive to confounding factors is highly desirable for an efficient solution of the inverse problem. Several examples derived from work performed in the laboratory for active materials and smart structures (LAMSS) of the University of South Carolina, USA will be presented and discussed. The paper ends with conclusions and suggestions for future work.

1 STRUCTURAL HEALTH MONITORING
Structural health monitoring is an emerging technology that aims at offering on-demand bulletins about the structural integrity of critical assets (e.g., military vehicles) without taking them out of service. The availability of such on-demand immediately delivered structural health bulletins would permit the in-field commander to make informed optimal decisions about asset allocation, individual mission profiles, and fleet management.

1.1 SHM Methods
SHM methods can be strain based, vibration based, wave based, etc. Wave-based SHM (aka, acousto-ultrasonics) works in both passive and active modes. It is able to capture the waves produced by an acoustic emission or a damaging event. It can also characterize the damage through diagnostic-wave interrogation. The structural waves are generated and captured with small piezoelectric wafer transducers adhesively bonded to the structure. We call these transducers piezoelectric wafer active sensors (PWAS) [1]. This approach has been successful in emulating the guided-wave NDE methods (pitch-catch, pulse-echo, phased array [1]) as well as in developing new techniques such as the electromechanical (E/M) impedance spectroscopy (EMIS) [2] [3].

1.2 Multi-site Fatigue Damage; Widespread Fatigue Damage (WFD)
Metal fatigue is a natural phenomenon in the aircraft practice. The light-weight requirements of aircraft design are such that all aircraft are subjected to metal fatigue sooner or later. Aircraft structural integrity programs based on periodic NDE inspections exist to ensure that aircraft operation is safe and reliable. Nonetheless, surprises appear: a fatigue issue that has produced several near-accidents (Aloha Airlines 1988 in-flight decompression, Southwest Airlines 2009 and 2011 rapid decompression [4] [5] [6], etc.) is that of multi-site fatigue damage (MSD) and widespread fatigue damage (WFD) [7]. The MSD and WFD phenomena appear in mechanically-fastened splice joints (Figure 1a). What happens is that cracks emanating from adjacent rivet holes
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are joining together to produce ‘unzipping’ of the splice joint (Figure 1b). MSD normally effects co-located items (e.g., fuselage joint fasteners) whereas WFD may affect adjacent elements (e.g. spars or stringers).

![Figure 1](image)

**Figure 1** Widespread fatigue damage (WFD) example: (a) structural splice with multiple fastener holes and cracks prone to WFD; (b) photo of actual WFD phenomenon observed on a row of rivets in an aircraft splice joint [7]

1.3 Early Detection and Prevention of WFD

The WFD phenomenon is related to butterfly cracks emanating from the fastener holes (Figure 1b). A hole placed in a stress field creates stress concentration sites on its sides. These stress concentration sites facilitate the lateral growth of fatigue cracks in a direction perpendicular to the loading direction. Due to their symmetric arrangement lateral from a rivet hole these fatigue cracks are known as ‘rivet-hole butterfly cracks’. The rivet-hole butterfly cracks must be detected early to prevent them reaching a size where the WFD may happen [7].

1.4 How could SHM Prevent WFD through early Detection of Rivet-Hole Butterfly Cracks?

Figure 2a presents a conceptual representation of how PWAS transmitter (T) and receiver (R) transducers could be used to detect the presence of rivet hole butterfly cracks and monitor their growth. The PWAS transmitter pings with a tone burst; the resulting wave packet is scattered by the rivet hole; the scattered field is detected by the PWAS receivers, including the transmitter PWAS which acts in dual mode and now has become a receiver. However, the detection of the butterfly crack is not straight forward because the received signal has multiple packets in it which may partially overlap. The packets in the received signal may be due to:

(a) scatter from the hole itself; a clean “pristine” hole is nonetheless a scatterer with its own scatter pattern. The scatter due to the butterfly crack is superposed on top of the scatter from the clean hole
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(b) reflection from the splice joint edge; this reflection could be normal or oblique depending on the relative arrangement of the transmitter and receiver. Though the edge reflection is expected to arrive later than the hole scatter, it may still be difficult to separate in the signal. One way to deal with this situation is through the differential signal method. In this case, one has at one’s disposal a stored signal representing the pristine structure with no cracks. By subtracting the ‘pristine’ signal from the ‘damage’ signal, one could obtain that component of the signal which is due only to the scatter from the damage. Such an exercise is illustrated in Figure 2b which shows that the reflection from a rivet-hole crack can be separated out quite adequately under laboratory conditions.

![Diagram](image)

(a) Conceptual representation of how PWAS transmitter (T) and receiver (R) transducers could be used to detect the presence of rivet-hole butterfly cracks and monitor their growth; (b) experimental results of crack detection with the signal differential approach [1], p. 894 (sensor placed @ 100 mm from the cracked hole)

However, for practical applications, several issues must be also considered. The bondline between two plates in typical lap-joints must be included in the analysis. Having a T/R pair and a baseline for each of the many thousands of rivet holes may be impractical and one has to focus on the 'hot-spot' areas.

1.5 Variability and Uncertainty Effects in Processing SHM Data

Although the signal differential method has promise, its practical implementation in SHM work may encounter considerable difficulties due to variability and uncertainty factors. These confounding effects may occur in design, manufacturing, maintenance, repairs, modifications, usage, etc. Since it is known that variability is stochastic in nature [8], boundary scatter/reflection effects may vary stochastically for one structure to another. Variability in what we measure and how we measure leads to uncertainty in the conclusions we draw. External factors, such as environment and operating conditions, may affect the damage sensing capability of the SHM system. Experimental studies of these effects have covered variation in temperature, operational loads, combinations thereof, vibration, and boundary conditions. Ref. [9] indicates that over 20 factors influence the SHM signal from a damage site when inspecting for fatigue cracks in multi-layered structures.
1.6 The Robust SHM System

A robust SHM system is needed to overcome the variability and uncertainty challenges. Such a robust SHM system must have good sensitivity to damage presence and size while being virtually insensitive to variability and uncertainty confounding effects. Of course, such a robust SHM system does not yet exist. In order to achieve it, one needs an appropriate SHM-system design methodology. We propose a model-assisted SHM-system design methodology as illustrated in Figure 3. Such an approach should combine numerical simulation, experimental validation, and statistical data processing. As shown in Figure 3, the SHM design process consists of two arms: the first arm is a predictor arm (forward problem), which generates the signal that the sensors would receive for a given excitation in a given structure under given environmental and loading conditions. The second arm is a detector arm (inverse problem) which would take as input the measured SHM signals and detect if damage exist and characterize its size and location. This inverse problem is the more difficult of the two: besides being ill-posed and possibly non-unique (different factors may produce same apparent signal changes) it is also heavily influenced by the confounding factors mentioned earlier. However, the synergistic pairing of the forward problem (predictor) and inverse problem (detector) indicated in Figure 3 may yield an optimized SHM system design that maximizes sensitivity to damage while minimizing sensitivity to the confounding factors (environment, load, boundaries, etc.)

![Figure 3: Model-assisted SHM-system design methodology conceptualized as predictor-detector pair](image)

1.7 What is it Needed?

In order for the robust SHM system design methodology described in Figure 3 to be achieved, one has to do a large number of design iterations for various combinations of damage types and sizes, loading cases, and ambient conditions. For each case, one would have to use the forward problem to generate a set of signals which would then be fed into the inverse-problem detector to produce a damage characterization outcome. On the one hand, it is apparent that doing the forward problem through actual experiments, thought technically possible, it would require extensive resources and thus become impractical. On the other hand, the approach would be more practical if the forward problem were done in simulation using an efficient but sufficiently accurate computational approach. The search for such an efficient and faithful predictor capable to capture the damage details with sufficient accuracy while being computationally rapid makes the object of the hybrid local approach (HGL) discussed in this paper.
2 HYBRID GLOBAL LOCAL (HGL) ANALYSIS

The hybrid global local (HGL) concept uses a fast and efficient analytical approach in the global domain coupled with a detailed finite element method (FEM) approach in the local domain around the damaged area. In our LAMSS approach, the guided waves are generated with a PWAS transmitter, scatter from a damage, and get picked up by a PWAS receiver (Figure 4). Our HGL methodology incorporates an analytical framework for global guided wave propagation (called Wave Form Revealer or WFR) and a local FEM analysis with nonreflective boundaries (NRB) for the determination of the wave damage interaction coefficients (WDIC) [12] [13] [14]. The travel from transmitter PWAS to the damage and from the damage to the receiver PWAS is modeled with analytical wave propagation formulae, whereas the interaction between the guided waves and the damage is done with FEM discretization [12]. As different from previous investigators [10] [11], the LAMSS approach to the HGL method is to replace the damage with a new guided wave source that generates the scatter field to be added to the analytical solution. The scatter field is defined in terms of wave damage interaction coefficients (WDIC) that are calculate through a local FEM analysis or by other methods.

Figure 4: General 2D set-up for Hybrid Global-Local modeling of structural sensing.

To address guided-wave NDE of aerospace structures, Mal and co-workers envisioned in the late 1990s [10] a combination of closed-form analytical solution in the global domain and FEM solution in the local domain to achieve an efficient simulation of guided wave propagation and interaction with damage in thin plates. Exact displacement continuity and traction balance were imposed at the boundary between the local FEM and global analytical domains through a colocation approach. An HGL application to arbitrary waveguides using the semi analytical finite element (SAFE) method is described in ref. [15].

Our LAMSS group extended the HGL approach to SHM applications using PWAS transducers. We were inspired by the 1990s seminal work of Chang and Mal [10], but we had to substantially modify it in order to avoid the solution of the large over-determined set of complex equations at the global-local interface. In contrast with ref. [10], we adopted a different approach that combines frequency-domain and time-domain solutions and uses a transition overlap between the local and global regions. As different from ref. [10], our approach to the HGL method is to replace the damage with a new guided wave source that generates the scatter field to be added to the analytically calculated 'pristine' field [12]. The scatter field is defined in terms of the complex-value wave damage interaction coefficients (WDIC) that are calculated separately, e.g., through a local FEM analysis [14]. The propagation of the scatter field is also done analytically. Our HGL methodology incorporates an analytical framework for guided wave propagation in the global region (called Wave Form Revealer or WFR).
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which allows for insertion of localized scatterers at user-defined locations to account for damage effects [13].

![Diagram](image)

Figure 5: FEM analysis to determine wave damage interaction coefficients (WDIC) values: (a) overall view; (b) nonreflective boundary details; (c) extraction of WDIC values. Note that pristine mesh should include a hole, though not specifically shown here.

1.1 Global Analytical Solution

In our approach, the guided waves generated by a PWAS transmitter are scattered from a damage and are picked up by a PWAS receiver (Figure 4). The travel from the transmitter PWAS to the damage and from the damage to the receiver PWAS is modeled with analytical wave propagation formulae. Though the guided waves are an elastodynamic phenomenon, their generation is done under electric excitation through the converse piezoelectric effect in the PWAS transmitter, whereas their sensing in the PWAS receiver is done in the form of electric signals obtained through the direct piezoelectric effect in the PWAS transducer. In addition, the finite size of the PWAS transducers produces tuning effects, i.e., at various frequencies, various guided wave modes may be excited or sensed differently depending on the relative ratio between their wavelength and the PWAS size (see ref. [1], Chapter 11).

1.2 WDIC Extraction through FEM Simulation with Nonreflective Boundaries

To calculate the complex WDIC values associated with a particular damage we use a local FEM analysis at the damage site (Figure 5a). Nonreflective boundaries (NRB) are placed on the extremities of the FEM mesh; thus, the analysis can be performed as the damage inclusion was part of an infinite domain without unwanted
reflections from the boundaries. This ensures that no standing waves are created and a pure scatter phenomenon is simulated. An NRB approach that effectively absorbs the Lamb waves at plate free edges [14] has to take into account the fact that Lamb waves result from the superposition of P and S waves that undergo multiple reflections at the top and bottom surfaces of the plate as well as at the plate ends (Figure 5b). Hence, the NRB must inhibit both the end reflections at the plate boundary as well the top and bottom reflections in its near vicinity. In order to achieve this, viscous boundaries were added both at the plate ends and on the top and bottom surfaces near the plate ends; the latter viscous boundaries were smoothed out by adopting a gradually decreasing viscosity parameter from the plate end towards the inner region [14]. The NRB FEM analysis is done in the frequency domain such that the WDICs are generated over a wide frequency range as needed to perform the convolution with the interrogative signal generated by the transmitter PWAS.

Two WFR GUIs were developed, an earlier version for straight-crested guided waves (WFR-1D), and a more recent version for circular-crested guided waves (WFR-2D).

WFR-2D assumes circular-crested guided waves, hence the solution involves Bessel and Hankel functions [16]. Figure 6a shows the WFR-2D main interface which calculates in real time the sensing signals as well as the propagation solver.

2 GUIDED WAVE PREDICTIVE SIMULATION IN ISOTROPIC THIN-WALL STRUCTURES

The modeling of the guided waves generation by a PWAS transmitter, their propagation throughout the thin-wall structure, and then their sensing by the PWAS receiver is well documented [1]. For implementing the HGL approach to simulate guided wave propagation in isotropic thin-wall structures, we used these well documented results to build a fast and efficient MATLAB simulation environment that has come to be know as WaveForm Revealer (WFR) [13]. Two WFR GUIs were developed, an earlier version for straight-crested guided waves (WFR-1D), and a more recent version for circular-crested guided waves (WFR-2D).

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Figure 6: WFR-2D GUI: (a) WFR-2D main interface; (b) damage information platform; (c) S0 WDICs module; (d) A0 WDICs module; (e) T-PWAS properties module; (f) spatial propagation solver.
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the dispersion curves and tuning curves. The parameter control panel allows users to modify the material properties, structural thickness, damage location, and transmitter/sensing locations. The excitation control panel provides excitation waveform, frequency, and arbitrary excitation loading options. Users can also selectively choose the excited wave mode of interest. Figure 6b shows the damage information platform for inputting wave-damage interaction coefficients (WDICs). Figure 6c and Figure 6d show the sub-panels for loading S0 and A0 WDICs. The PWAS properties panel allows users to define PWAS geometric and material properties (Figure 6e). The spatial propagation solver (Figure 6f) calculates the transient time-space wave field and produces a wavefield image that can identify the damage location like a conventional ultrasonic C-scan. Examples of how WFR-2D can be used to simulate pitch-catch and pulse-echo SHM of metallic airframes are discussed in ref. [17]. The detection of rivet-hole butterfly cracks in an aluminum skin lap joint is analyzed and the design of optimum PWAS installation is presented in ref. [17]. Experimental validation of these prediction is possible if research funding is made available.

3 GUIDED WAVE PREDICTIVE SIMULATION IN LAMINATED COMPOSITES

Guided wave propagation in laminated composites is much more complicated than in metallic structures; it has made the object of extensive research [18]. The first obstacle to be overcome is the dispersion-curve calculation that generate dispersion curves for phase and group (energy) velocities, the steering angle between them, and the modeshapes across the thickness.

3.1 Dispersion curves in anisotropic composites

Guided wave dispersion curve calculation in anisotropic composites is substantially more difficult than in isotropic metallic plates. Due to composite anisotropy, the Lamb and SH waves are no longer separable. In some special cases, e.g., propagation along the principal directions in a unidirectional composite, the familiar symmetric and antisymmetric Lamb waves (S0, S1, S2, …; A0, A1, A2, …) and the SH guided wave (SHS0, SHS0, SHS2…; SHA0, SHA1, SHA2, …) are decoupled and can be identified. However, decoupling is not possible in the generic case and all the displacement components are present in the modeshape.

A solution for guided-wave propagation in a laminated anisotropic composite can be obtained analytically through one of the three major approaches: global matrix method (GMM), transfer matrix method (TMM), and stiffness transfer method (STM) [19]. The DISPERSE software based on the GMM approach has been commercially available since 2003 [20]. Certain numerical convergence issues may be encountered when using these analytical methods. Alternatively, one can use the semi-analytical finite element (SAFE) method [21][22], which is numerically robust and stable (but does not exactly match the stresses in the laminate at the lamina interfaces). In LAMSS, we have used a combination of an unified analytical formulation and a SAFE formulation [23][24][25] to create a user-friendly software available for download from our website [26]. The phase velocity and group velocity dispersion curves as well as the steering angle between them can be readily displayed for a selection of precalculated layups together with the guide-wave modeshapes.

3.2 Guided wave propagation in composites

Guided wave propagation in a composite laminate (Figure 7) is defined in terms of the energy velocity direction $\phi$ (aka ray direction) and phase velocity direction $\theta$ which is normal to the guided wave crest. A SAFE formulation was adopted to predict the guided waves excited by a surface-mounted PWAS transmitter [25]. Figure 8 shows the case study of a unidirectional carbon-fiber reinforced polymer (CFRP) plate which has a very high degree of anisotropy between the x and y directions. As illustrated in Figure 8b, the guided waves propagating in different directions have drastically different packet contents.
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Figure 7: Guided wave propagation in a composite laminate [25]

Figure 8: Prediction of guided waves generated by a PWAS in a unidirectional CFRP composite plate: (a) schematic representation; (b) wave packets traveling in 0, 45, 90 deg directions [25]

Figure 9: Measurement of damping attenuation in a woven CFRP composite plate [28]
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The wave propagating in the 0-deg direction (i.e., along the fibers) has a dominant quasi-A0 packet and a residual quasi-S0 packet propagating at much higher speed. The wave propagating in the 90-deg direction (i.e., across the fibers) has a much slower but stronger quasi-S0 packet as well as a strong but slower quasi-A0 package. The wave propagating at the intermediate 45-deg direction has quasi-S0 and quasi-A0 packets with a behavior intermediate between the 0-deg and 90-deg situations. In addition, one notices the presence of a strong quasi SHS0 packet which is a phenomenon which was not at all possible in metallic plates because the circular PWAS transducer considered here cannot excite shear strains. The excitation of the SHS0 wave is entirely due to the anisotropic behavior of the composite plate.

3.3 Damping effect on PWAS tuning and higher frequency excitation

The damping effects are usually ignored in the modeling of guided wave propagation in metallic thin-wall structures. However, damping cannot be neglected in composites due to the energy dissipation properties of the polymeric matrix that binds together the high-strength fibers in the composite construction. Figure 9 shows experimental measurements of damping attenuation in a woven CFRP composite plate as reported in ref. [28]. It is apparent that damping attenuation is an important factor. Figure 10 shows the effect of damping on the tuning between PWAS transducers and quasi-S0 guided waves in a woven CFRP plate [27]. Comparison between measurements and predictions is presented. It is quite apparent that damping effects impose a high-frequency limitation on guided wave excitability. In the 2-mm composite presented in Figure 10, excitation beyond 700 kHz was hardly possible.

![Figure 10: Tuning between a circular PWAS transducer and a quasi-S0 wave in a woven CFRP composite: (a) experimental measurements; (b) theoretical prediction using a damping model of guided wave propagation [27]](image)

3.4 Wave damage interaction in composites

Wave damage interaction coefficients (WDIC) needed in the HGL method can be calculate from a small FEM model in a way similar to that used in modeling the wave-damage interaction in metallic structures (Figure 5). However, the types of damage encountered in composite structures are fundamentally different from those found in metallic airframes. Chapter 5 of ref.[18] describes a large variety of composite damage situation that are now being taken into consideration in our studies.

4 SUMMARY, CONCLUSIONS, AND FUTURE WORK

This paper has presented a novel hybrid global local (HGL) approach for predicting guided wave propagation in interaction with damage that combines a global analytical model in the pristine structure with a local FEM discretization at and around the damage. The application of the HGL concept to metallic and composite structures has been presented. In the case of metallic structures, a convenient graphical user interface (GUI)
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utilizing analytical guided-wave propagation formulae was presented. In the case of composite structures, it was shown that guided wave propagation is much more complicated than in metallic structures due to anisotropic stiffness properties and internal damping of the laminated composite materials. The prediction of guided-wave propagation in anisotropic composites, which requires extensive numerical calculations, was solved through a hybrid approach that combines the convenience of the SAFE approach with the accuracy of the exact analytical approaches. The effect of damping on wave propagation and PWAS tuning in composites was illustrated.

This paper has shown that the HGL approach can be theoretically applied to both metallic and composite structures. It was found that composites anisotropy makes the phase velocity, group (energy) velocity, and the steering angle between them strongly dependent on the propagation direction. It was also found that internal damping strongly alters the tuning curves between guided waves and PWAS transducers and also drastically limits the guided-wave excitability to below 1 MHz. One novelty of our approach is that damage effects are introduced as new wave sources placed at the damage location and characterized by complex-valued wave-damage interaction coefficients (WDIC). Another novelty of our approach is that the WDIC values are calculated over a wide frequency range simultaneously through a frequency domain harmonic FEM analysis with nonreflective boundaries (NRB). It was found that fast and efficient predictive simulation of guided-wave structural health monitoring is possible via the HGL approach. The major conclusion of this work is that the HGL approach is highly efficient and hence recommended for the analysis of large structures in which damage has a localized nature. It would also be very useful in large-scale laboratory experiments.

Considerable future work is required to fully integrate the composites behavior into the HGL approach. In addition, a library of damage situation specific to composite structures needs to be developed.

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