Predictive Simulation of Guided Wave Structural Health Monitoring in Metallic and Composite Structures

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Abstract
Predictive simulation of structural health monitoring (SHM) 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 are presented. Both metallic and composite structures are discussed. For metallic structures, classical guided wave theory in cylindrical coordinates is used. For composite structures, a new approach using a combination of analytical methods and the semi-analytical finite element (SAFE) approach is presented. The paper ends with conclusions and suggestions for future work.

Figure 1: The SHM steps from damage detection to remaining useful life (RUL) estimation [1]
1 Introduction

Structural health monitoring (SHM) sets forth to determine the health of a structure by monitoring a set of structural sensors. The SHM system registers if a damaging event has occurred, localizes and quantifies the structural damage, and monitors the damage progression over time (Figure 1). By assessing the remaining useful life (RUL), the SHM system may advise on the need for structural actions, such as repairs or load reduction. At present, SHM is seen as a complement to existing nondestructive evaluation (NDE) practices. Built-in SHM systems capable of detecting and quantifying damage would increase the operational safety and reliability, reduce the number of unscheduled repairs, and bring down overall maintenance costs.

SHM methods can be either vibration based [2] [3] or wave based [4] [5] [6]. Wave-based SHM (aka, acousto-ultrasonics) works in both passive and active modes. It is able to capture the waves produced by a damaging event (passive sensor diagnosis, PSD [4]) as well as characterize the damage through diagnostic-wave interrogation (active sensor diagnosis, ASD [4]). The structural waves are generated and captured with small piezoelectric wafer transducers adhesively bonded to the structure [7] [8] [9]. We call these transducers piezoelectric wafer active sensors (PWAS) [10]. This approach has been successful in emulating the guided-wave NDE methods (pitch-catch, pulse-echo, phased array, etc.) as well as in developing new techniques such as the electromechanical (E/M) impedance spectroscopy (EMIS) [11].

![Figure 2: Model-assisted SHM-system design methodology conceptualized as predictor-detector pair](image)

1.1 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 2. Such an approach should combine numerical simulation, experimental validation, and statistical data processing. As shown in Figure 2, the SHM design process consists of two arms: the first arm is a predictor arm (forward problem), which generates the signal that that the sensors would receive for a given excitation in a given structure under given ambient 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. The 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. However, the synergistic pairing of the forward problem (predictor) and inverse problem (detector) indicated in Figure 2 may yield an optimized SHM system design that maximizes sensitivity to damage while minimizing sensitivity to the confounding factors (environment, load, boundaries, etc.)

1.2 What is it Needed?
In order for the robust SHM system design methodology described in Figure 2 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 would require extensive resources and thus become impractical. On the other hand, it would be more practical to do the forward problem 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 efficient makes the object of the hybrid global local (HGL) approach discussed in this paper.

2 Hybrid Global Local (HGL) Analysis
The HGL concept can be traced back to Goetschel et al. [12] that used different FEM mesh sizes and variable granularity to simulate the elastic bulk wave propagation in the global domain and the interaction of waves with scatterers in the local domain. Further developments of the bulk-waves HGL approach [13] have culminated with the full-scale CIVA simulation package that has been used extensively in the nuclear industry [14]. For NDE and SHM of thin-wall structures, as specific to aerospace applications, the guided-wave approach offers specific benefits over the bulk-wave approach. However, the multi-modal character of the guided waves makes such problems an order of magnitude more difficult than the bulk-wave problems.

![Figure 3: General 2D set-up for Hybrid Global-Local modeling of structural sensing.](image-url)
To address guided-wave NDE of aerospace structures, Mal and co-workers envisioned in the late 1990s [15] 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. [16].

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 [15], 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. [15], 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. [15], 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 [17]. The scatter field is defined in terms of the complex-value wave damage interaction coefficients (WDIC) that are calculated separately [18]. 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) which allows for insertion of localized scatterers at user-defined locations to account for damage effects [19]. The damage scatterers are described as complex-numbered WDIC values. A local FEM analysis at and around the damage site is used for WDIC determination.

2.1 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 3). 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. [10], Chapter 11).

2.2 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 4a). 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 [18] 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 at the plate ends (Figure 4b). 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 [18]. 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.

![Figure 4: FEM analysis to determine wave damage interaction coefficients (WDIC) values: (a) overall view; (b) nonreflective boundary details; (c) extraction of WDIC values](image)

### 3 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 [10]. 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 known as WaveForm Revealer (WFR) [19]. 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 [20]. Figure 5a shows the WFR-2D main interface which calculates in real time the sensing signals as well as 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 5b shows the damage information platform for inputting wave-
damage interaction coefficients (WDICs). Figure 5c and Figure 5d show the sub-panels for loading S0 and A0 WDICs. The PWAS properties panel allows users to define PWAS geometric and material properties (Figure 5e). The spatial propagation solver (Figure 5f) 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. [21]. The detection of rivet-hole butterfly cracks in an aluminum skin lap joint is analyzed and the design of optimum PWAS installation is presented.

4 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 [22]. 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.

4.1 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, as illustrated in Figure 6.

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) [23]. The DISPERSE software based on the GMM approach has been commercially available since 2003 [24]. Certain numerical convergence issues may be encountered when using these analytical methods. Alternatively, one can use the semi-analytical finite element (SAFE) method [25][26][27], which is numerically robust and stable but does not exactly match the stresses in the laminate at the lamina interfaces.

In our LAMSS research group, we have used a combination of an unified analytical formulation and a SAFE formulation [28][29][30] to create a user-friendly software available for download from our website [31]. As illustrated in Figure 6, the phase velocity and group velocity dispersion curves as well as the steering angle between them together with the guide-wave modeshapes can be readily displayed for a selection of precalculated layups.

Figure 6: Phase velocity, group velocity, and steering angle for 30-deg propagation in a [0/90/0/90]s crossply CFRP laminate. Modeshapes at 1000 kHz are also presented [31].
4.2 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 [30]. Figure 8 shows the case study of a unidirectional 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.

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.

Figure 9: Measurement of damping attenuation in a woven CFRP composite plate [33]

4.3 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. [33]. 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 [32]. 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 [32]
4.4 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 4). However, the types of damage encountered in composite structures are fundamentally different from those found in metallic airframes. Chapter 5 of ref.[22] describes a large variety of composite damage situation that are now being taken into consideration in our studies.

5 Summary, Conclusions, and Future Work
This section summarized the paper, presents conclusions and makes future work suggestions.

5.1 Summary
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) 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.

5.2 Conclusions
This paper has shown that the HGL approach can be 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).

5.3 Future work
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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