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PREDICTIVE MODELING OF SMART STRUCTURES WITH IN-SITU SENSING CAPABILITY

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ABSTRACT: A methodology for the predictive modeling of smart structures with in-situ sensing capability is presented and discussed. First, the smart structures concept is briefly reviewed. Then, self-sensing smart structures with in-situ sensing capabilities are introduced. Focus is placed on active sensing methods using ultrasonic guided waves in thin-wall structures. The challenges of modeling ultrasonic wave propagation in realistic structures are discussed, and the mesh-size and time-step convergence requirements are discussed. The recently developed hybrid models for modeling ultrasonic nondestructive evaluation using bulk waves are presented and their advantages are discussed. A new approach, the generic hybrid global-local (HGL) approach is presented. It builds upon previous work in hybrid methods and extends them to guided waves in thin-wall structures equipped with piezoelectric wafer active sensors (PWAS) capable of both transmission and reception of ultrasonic guided waves. The features of this proposed HGL approach, which is still under development, are discussed.

SMART STRUCTURES

The concept of smart structures (a.k.a., adaptive structures or intelligent structures) is usually derived through analogy with living organisms which can *sense* the environment, *interpret* the information sensed from the environment, and *react* to it appropriately. For example, sensors in my skin would sense the pricking of a rose's thorns and send the information to my nervous system which will interpret it and instruct my hand to let go and retreat. In order to achieve these functions, the living organisms possess sensing, data processing, and actuation capabilities embedded into their complex bodies. Similarly, a bio-inspired smart structure would be equipped with sensing, data processing, and actuation capabilities. A smart structure is a *multifunctional system* with capabilities well beyond the mundane load-bearing mission of conventional structures (Figure 1). Enabling technologies are active materials, integrated active sensors, fiber optics sensors, fiber optics communication, solid-state actuators, autonomous power and energy harvesting, multifunctional composites, self healing materials, integrated electronics, reasoners, and microcontrollers, etc.

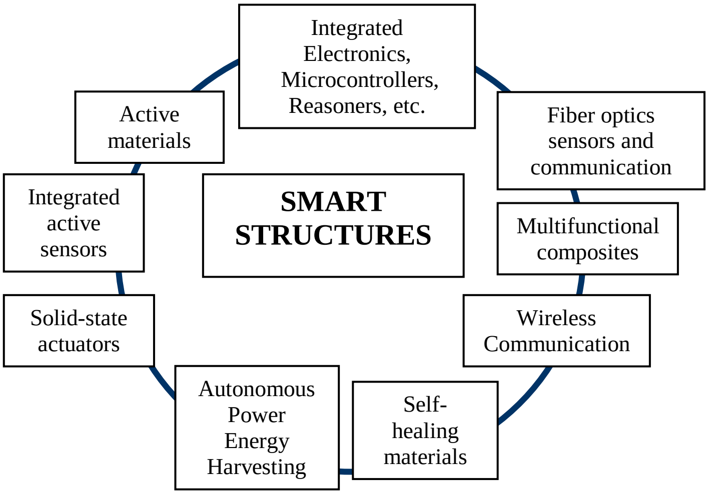


Figure 1. The smart structures constellation: functional attributes and technology enablers

Smart-structure concepts have been developed for many engineering fields. A *smart building* or *bridge* would feel an earthquake and 'brace' itself to sustain it better; afterwards, it would quickly inspect itself to assess and control damage, if any. A *smart aircraft* would feel the effect of flight loads, operational environment, or enemy fire on its load bearing capability and would take corrective actions to arrive safely at destination. A *smart space antenna* would adapt its shape to maintain its focusing accuracy under uneven solar heating and micrometeorite impacts.
A buried *smart pipeline* would monitor its state of corrosion, detect leaks, report its state of structural health, and even attempt self-repair. A *smart automobile* structure would adapt its suspension impedance according to the road type, i.e., make it stiffer for high-speed travelling on high way, while making it more complying for cross-country excursions. A *smart machine tool* will adapt the tool holder, pressure, feed, and impedance to optimize the machining process by increasing material removal rate while reducing chatter and vibration and minimizing energy usage.
Recent advances in smart structures research and implementation can be traced along three major directions: (i) morphing structures; (ii) self-bracing structures; (iii) self-monitoring structures.

SELF-MONITORING SMART STRUCTURES

Self-monitoring smart structures are equipped with structural health monitoring (SHM) sensors and advanced data processing algorithms capable of structural diagnosis and prognosis. The goal of SHM is to develop a monitoring methodology that is capable of detecting and identifying various damage types during the service life of the structure, monitor their evolution, and predict the remaining useful life with a continuously updating structural model. SHM can be broadly classified into two categories: (a) passive and (b) active. **Passive SHM** (such as acoustic emission, impact detection, strain measurement, etc.) are relatively more mature; however, their utility is limited by the need for continuous monitoring and the indirect way in which damage existence is inferred.
Active SHM aim at directly interrogating the structure on demand using guided wave ultrasonics and other methods. Active SHM resembles conventional nondestructive testing/evaluation only that the sensors are permanently attached to the structure and interrogated automatically without human intervention. Historical SHM data would allow projection of damage progression trends and estimation of remaining useful life. In critical situation, on board processing of SHM data would allow adaptive mission planning to ensure safe return to base.
Smart structures with in-situ sensing capabilities are likely to increase their presence in aerospace because they can offer tangible evidence of the structural performance and state of health (White, 2009). The benefits of monitoring the structural state include design feedback, performance enhancement, on-demand condition-based maintenance, and predictive fleet-level prognosis.

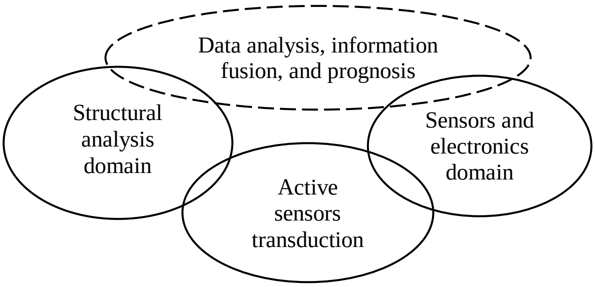


Figure 2. Venn diagram of the multi-domain interaction in a self-monitoring smart structure

On-board structural sensing systems have been envisioned for determining the health of a structure by monitoring a set of sensors over time, assessing the remaining useful life from the recorded data and design information, and advising of the need for structural maintenance actions. Figure 2 shows the Venn diagram of the interrelations inherent in a predictive methodology which will combine the structural analysis domain with the active sensors transduction domain and the sensors and electronics domain. The software domain of data analysis, information fusion, and prognosis is weakly bonded to this predictive methodology concept because it will utilize its signal products, process them, and then feed them back into the process to achieve structural prognosis that will forecast the future behavior of the structure. Figure 3 shows a possible implementation of an SHM system on board a unmanned aerial vehicle (UAV). Some active sensors are distributed in clusters around the structure targeting the „hot spot“ areas where structural problems are expected to happen. Whereas wide-sensing active sensors will be evenly distributed around the structure to detect unexpected structural damage occurences. The sensors signals are fed into data concentrators that perform local processing of received data and distill pertinent critical information that is sent to the on-board processing unit for further data condensation and reasoning. If a critical situation is identified, then immediate remedial action is taken and the base-station is alerted for further instructions that may mean a change in flight plan, mission objectives, or even return to base.

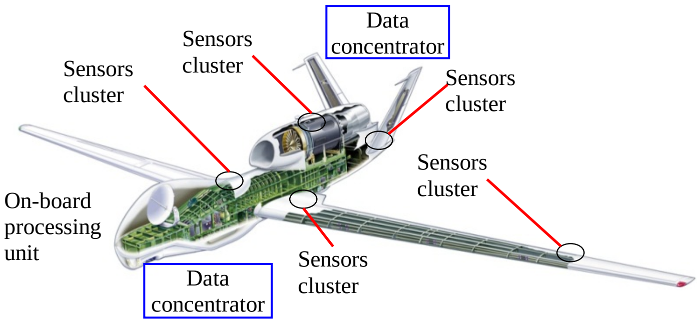


Figure 3. Possible implementation of a structural health monitoring (SHM) system on board an unmanned aerial vehicle (UAV)

Essential to the whole process is the availability of proper structural modeling methodologies and software, as discussed in the next section.

MODELING OF ULTRASONIC WAVE PROPAGATION

Finite element modeling of ultrasonic wave propagation in realistic structures is challenging because a very fine mesh is required in both time and space discretization to achieve a reasonable representation of the high frequency ultrasonic guided waves used in this process. Analytical methods such as ray-tracing (Achenbach et al., 1982), beam/pencil (Gengembre, 2003), Green functions (Achenbach, 1973) can efficiently model wave propagation in simple geometries. Geometric theory of diffraction based on ray tracing was recently extended to efficiently calculate multiple echoes and scatter (Yamada et al., 2009) but it cannot handle complicated defects or structures with complex geometries. Green functions give the displacement field at any point in a uniform elastic medium illuminated by ultrasonic waves using an integral formulation. Analytical Green functions exist for both bulk waves (Achenbach, 1973) and guided waves (Achenbach & Xu, 1999); Green's functions can be also determined experimentally (Etaix et al., 2010). However, scattering of ultrasonic waves from a complex-shaped defect cannot be achieved directly by analytical methods and needs the use of a numerical discretization approach such as finite differences, finite elements, boundary elements, etc.

Commercially available finite element (FE) codes (e.g., ABAQUS-CATIA, NASTRAN, ANSYS, COMSOL, PZFlex, etc.) are capable of capturing the structural details and offer convenient built in resources for automated meshing, frequency analysis, and explicit time integration of dynamic events. Even a relatively rough FE model would yield a 'wave propagation' output that is illustrative and instructive. However, to obtain accurate wave propagation solution at ultrasonic frequencies is computationally intensive and may become prohibitive for realistic structures (Russell et al., 2008; Reynolds et al.,2010). Aldrin et al. (2009) performed FEM studies of the scattering of guided waves from a multi-layer fastener site with cracks emanating from the hole and showed that the presence of a fastener insert can significantly change the scattering pattern if the insert is in full contact with the hole (i.e., stiff interface). However, they showed that considerable computational resources are needed to perform a full FEM simulation of this process, and proposed the use of analytical tools (Aldrin, 2001) that are much faster and more efficient.

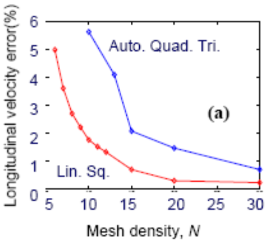


Figure 4: FEM convergence study (Rajagopal, 2009); *N* indicates the number of nodes per wavelength

CONVERGENCE OF FEM WAVE PROPAGATION MODELS

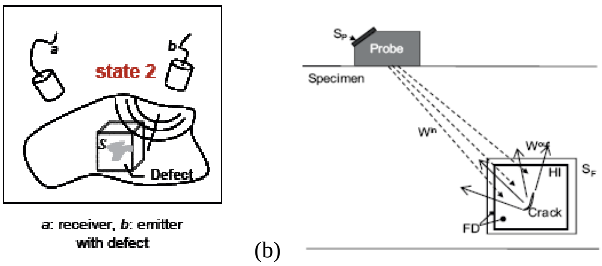
A recent systematic study of FEM convergence (Rajagopal, 2009) has concluded that 25-30 nodes per wavelength, 5-10 nodes per thickness, and 15-20 steps per period would be required to obtain reasonable convergence in ABAQUS explicit code (Figure 3). Good-quality FE analysis can easily run into hundreds of millions of degrees of freedom and millions of time steps in order to satisfy the convergence and accuracy requirements (e.g., the analysis of a 1 m by 1 m specimen at 2 MHz would require at least 500 million degrees of freedom, and would run for many hours). It is apparent that brute-force FE analysis of ultrasonic damage detection is not appropriate for predictive simulation of structural sensing. When parameter studies, variability explorations, and sensor design options must be analyzed, a brute-force ultrasonic FE analysis would simply not do. Improved approaches to the FE method have been studied to increase efficiency while maintaining accuracy during ultrasonic simulation. Boundary element method (Liu, 2009) reduces mesh requirements by restricting the discretization to only the boundary of the domain under investigation, while the bulk of the domain is represented by analytical Green functions. When a crack is present, then the crack boundary should be also discretized since it is a part of the domain boundary. Roberts (2007) used the boundary element method and the appropriate Green functions to model the propagation of ultrasonic plate waves across stiffeners integrally built into the plate. Spectral element method (Doyle, 1997) overcomes the limitations of time domain integration by performing the analysis in the frequency domain; although increasingly popular (Gopalakrishnan, 2008; Lee, 2009), spectral elements have not been yet adopted in the commercial FEM packages.

Another way to reduce the FE computational needs would be have coarser meshes in the ‘clean’ parts of the structure and finer meshes around the structural features and the damage regions. However, it has been found that the variation in acoustic impedance in the transition zones between coarse and fine meshes results in a large amount of coherent noise (Rajagopal et al., 2009). Studies to adjust the material properties such as to facilitate a gradual variation of acoustic impedance have not been successful in the 2-D wave-propagation domain (Drozdz et al., 2007; Drozdz, 2008).

HYBRID MODELING METHODS FOR ULTRASONIC WAVE PROPAGATION

Several investigators have recently proposed to combine the efficiency of analytical methods with flexibility of discrete methods. Researchers at the French Commissariat for Atomic Energy Gengembre, 2004) have developed the CIVA computational framework, which combines the *Champ-Sons* semi-analytical wave propagation model in the clean global region with the *Athena* FEM in the local region containing a defect.

The general concept of this approach is shown in Figure 4a. Researchers at the Japanese Central Research Institute of Electric Power Industry (Lin, 2009) have developed a hybrid approach combining numerical FEM and analytical ray tracing method (Figure 4b). In these hybrid analyses, the FE mesh was usually confined to a small box region around the crack. The coupling conditions between the analytical region and the FE region were identified as a major challenge. Auld’s reciprocity theorem (Auld, 1979) is used to couple two analysis states, one which is focused on global wave propagation, and another which deals with the interaction with the defect. In order to minimize the spurious diffractions at the global-local interface, Lin et al. (2009) used a two-step transition layer with variable viscosity (FD in Figure 4b). The hybrid-method results were compared with conventional FE analysis; it was found that the signals predicted by the two methods were similar, while the number of elements use by the hybrid method was only 1/3rd of those used by the conventional FE, whereas the computational time was 1/10th. These hybrid approaches have been used to simulate the ultrasonic NDE process of detecting cracks in solid components using bulk waves and conventional NDE transducers. Validation and verification studies have yielded good agreement with full-power finite element analyses and with experiments (Mahaut et al., 2006; Lonne et al., 2006; Raillon et al., 2009).



(a) (b)

Figure 5 The hybrid method applied to the modeling of UT testing of a crack in a massive component: (a) French approach (Gengembre et al., 2004); (b) Japanese approach (Lin et al., 2009)

The hybrid methods (Gengembre et al., 2004; Lin et al., 2009) could not be directly applicable to thin-wall structures because they were developed for solid parts interrogated with bulk ultrasonic waves, as appropriate for nuclear energy applications, whereas aerospace structures have a thin-wall construction and require guided waves for wide-area SHM applications. At present, only a few attempts have been made to develop the hybrid approach to the modeling of ultrasonic guided waves damage detection in thin-wall structures. In pioneering work, Mal et al. (1999, 2000) extended the hybrid method to the study the interaction of guided waves with damage in thin plates. Notches and thickness removal (simulated corrosion) were analyzed with straight-crested 1-D models. For cracks emanating from rivet holes, a 2-D model employing circular crested guided waves and Bessel function was used. The damaged region was modeled with an FEM mesh that extended six times the plate thickness from the center of the hole. No systematic error analysis and convergence studies were reported. The model was validated with experiments and the comparison was quite good. More recently, Lanza di Scalea and his group at UCSD have used the HGL approach for the calculation of wave scatter from defects in 1D waveguides (Srivastava et al., 2007;

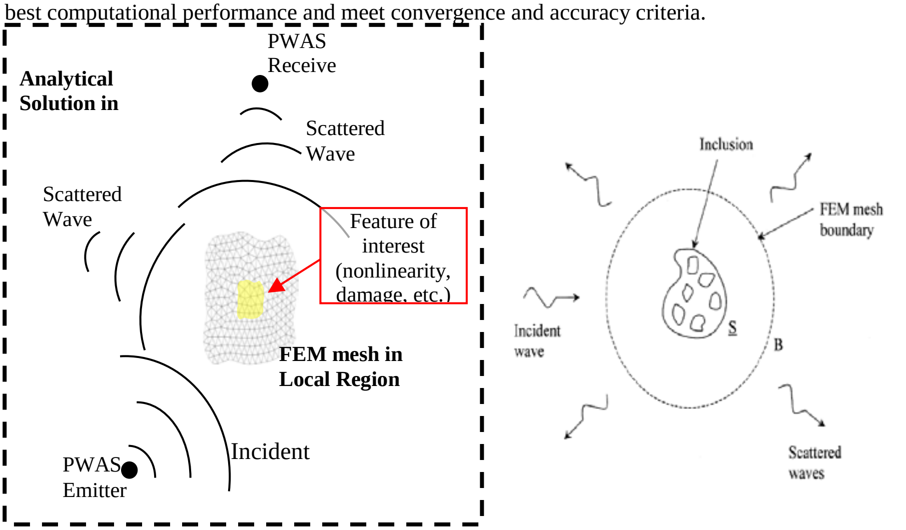
Srivastava, 2009). The effect of notches and corrosion in metallic rails, and delamination in composite stiffeners and spars were studied.

PROPOSED HYBRID GLOBAL-LOCAL (HGL) APPROACH

We propose to build upon early pioneering work **(**Aldrin, 2001; Gengembre et al., 2004; Lin et al., 2009; Mal & Chang, 1999, 2000) and develop a **generalized hybrid global-local (HGL)** approach that will allow computationally-efficient multi-scale multi-domain modeling of structural sensing. The HGL approach will use **local FEM discretization** only in the critical regions (structural joints, discontinuities, flaws, damage, etc.) while using **global analytical solutions** (e.g., Green's functions) in the uniform outside region. The efficiency of the method resides in the fact that only local regions of interest will be meshed and solved with the FEM technique, whereas the uniform outside field will be solved analytically. Continuity and equilibrium conditions between the inner solution (FEM) and the outer solution (analytical) are imposed on the mesh boundary.

We intend to develop the HGL method for multimode guided waves under full 2-D conditions as appropriate to aerospace thin-wall structures (Figure 5a). The waves originating from a transmitter PWAS propagate in circular wave fronts towards the local region containing the damage under investigation. The incoming waves enter the local region through the global-local (HG) boundary and interact with the damage generating a complicated scattering pattern. The scattered waves exit the local region through the GL boundary and are picked up by the receiver PWAS (as well as by the transmitter PWAS acting in pulse-echo mode). It is expected that a major part of our effort will be concentrated on developing the **proper interfacing formulation** for the fully 2-D analytical solution of guided wave propagation in circular-radial geometry in interaction with a generically shaped FEM local region.

The coupling of the local and global regions will be done by generic matching of the ultrasonic field (complex velocities and tractions) on both sides of the domain boundary (Figure 5b). The incident field is calculated analytically and then injected into the FEM boundary. The FEM response is calculated for two states ('pristine' and 'damage') and then ejected through the FEM boundary into the global domain to travel to the receiver sensor. We are aware that the coupling between the analytical and FEM regions plays an essential role in the solution accuracy. For example, the size of the FEM region must be selected sufficiently large to allow the entire incident ultrasonic field to enter before wave diffraction from the damage reaches the FEM region boundary. We would study carefully these aspects and apply algorithmic optimization to achieve best computational performance and meet convergence and accuracy criteria.



(a) (b)

Figure 6 Generalized setup of the hybrid global-local (HGL) method modeling of structural sensing: (a) overall model including PWAS transmitters and receivers; (b) Saint Venant's principle is used to define the local region (after Mal & Chang, 2000)

FEATURES OF THE PROPOSED GENERIC HGL MODEL

Building upon early pioneering work **(**Aldrin, 2001; Gengembre et al., 2004; Lin et al., 2009; Mal & Chang, 1999, 2000), we will incorporate features in the HGL approach to make generic and applicable to a variety of structural sensing situations. The **FE meshing** will be generic, whereas previous investigation used mostly rectangular mesh and regular boundaries. Unlike previous work that used FEM boxes, the **shape of the local region** will be **generic**, i.e., a reproduction of the shape of interest but scaled up to match Saint Venant's principle (5 to 10 length scales). **Generic local regions** can be constructed not only around structural damage but also around the transducers and the salient structural features to capture special effects (e.g., nonlinear behavior). Reduced-order **nonlinear models** will be included in the local region.

Multi-domain analysis will be used to capture the conversion/transduction between electrical, mechanical, and ultrasonic domains. In preliminary work, we have experimented with ANSYS and ABAQUS multi-physics capabilities and obtained acceptable results. We were able to simulate both pitch-catch/pulse-echo wave propagation as well as E/M impedance standing waves using direct excitation of the piezoelectric wafer bonded to the structure using meshing of the entire problem, which required extensive computational resources. In the proposed work, we will **contain meshing to only the areas of interest, while maintaining the multi-physics capabilities**.

STRUCTURES AND MATERIALS CONSIDERED IN THE HGL SIMULATION

Unlike the previous work **(**Aldrin, 2001; Gengembre et al., 2004; Lin et al., 2009; Mal & Chang, 1999, 2000), our approach will be sufficiently generic to be easily generalized to various structural and material types (metallic, ceramic, composites, hybrids, etc.). It will be also open for generalization to other sensing principles besides piezoelectric ultrasonics. Once the HGL method is in place, we will be able to simulate different damage types that may occur in metallic and composite structures such as loose bolts in joints; disbonds in adhesive joints; degradation and delamination in composite material; corrosion in metallic materials; impact damage in composite material (cracks, delamination and fiber breakage); cracks in metallic components, etc. Analysis of integral rib stiffeners will periodic layout would be easily incorporated. The actual case studies to be considered will be selected through consultation with potential users.

CONVERGENCE AND ACCURACY CONTROL

If damage is not present inside the FEM region, then no wave scatter should take place. However, it is quite possible that numerical artifacts associated with the FEM discretization in the local region and with the GL interface would generate scatter even in a damage-free situation. The existence of such false-scatter artifacts will be an indication of deficient numerical modeling that needs to be corrected. Therefore, a possible figure of merit of the HGL modeling will be the relative smallness of the residual wave scattering in the case of a damage-free local region. Another possible figure of merit of our modeling would be the energy balance between incoming and outgoing wave fronts. During our preliminary studies, we have identified convergence differences between the ABAQUS and ANSYS codes when analyzing the same geometric discretization with the same element type. Therefore, investigation of FEM convergence and development of convergence guidelines for multi-physics FEM simulation and HGL approach will play a major role in our investigation.

CONCLUSIONS

This paper has presented a proposed predictive methodology for multi-scale multi-domain modeling of smart structures with in-situ sensing capability. Such methodology would be able to predict the signal response of the structural sensors as a function of the structural state and/or the presence of structural flaws or damage, in linear and nonlinear regimes. The modeling is multi-scale because it has to incorporate (a) the macro-scale structural features; (b) the micro-scale flaw/damage; (c) the mezo-scale interfaces between structural parts and between sensor and structure. The modeling is multi-domain because the analysis is integrated over several physical domains, i.e., (a) structural mechanics; (b) electromechanical transduction in the sensors; (c) guided waves ultrasonics; (d) power and signal electronics, etc.

To achieve this proposed methodology for predictive modeling of smart structures with in-situ sensing capability, we are proposing a hybrid global-local (HGL) approach which achieves the

integration of an analytically described ultrasonic field in the global region with a numerical discretized response in a local region around a structural feature, a damage site, sensor attachment, or other local region of interest. Multi-physics elements are used to model with the piezoelectric transduction in the sensors and actuators. The focus is on the study of guided wave propagation in thin-wall structures and their interaction with the structural damage/defects. The outcome of this endeavor will go beyond the state of the art with the following attributes: (a) 2-D thin-wall structure global domain; (b) guided waves; (c) local-global boundary of generic shape based on Saint-Venant's principle; (d) generalized matching condition on the global-local boundary; (e) zoom-in/zoom-out capabilities.
At present this HGL methodology is under development and actual results will make the object of future presentations.

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