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# Review of Guided-wave Structural Health Monitoring

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ABSTRACT—In this paper we present the state of the art in the field of guided-wave structural health monitoring (SHM). We begin with an overview of damage prognosis, and a description of the basic methodology of guided-wave SHM. We then review developments from the open literature in various aspects of this truly multidisciplinary field. First, we discuss different transducer technologies, including both piezoelectric and non-conventional popular and non-conventional piezoelectric transducers. Next, we examine guided-wave theory, tracing its early history down to modern developments. Following this, we detail the efforts into models for guided-wave excitation by SHM transducers. Then, we review several signal processing related works. The next topic in Section 6 is guided-wave SHM system development, and we explore various packaging ideas, integrated solutions and efforts to examine robustness to different service conditions. We also highlight the broad spectrum of applications in which this technology has been tested. We then present some investigations that have attempted to combine guided-wave approaches with other complementary SHM technologies for better system performance. Finally, we propose desirable developments for further advancement of this field.

KEYWORDS: structural health monitoring, guided wave propagation, Lamb wave, damage prognosis, piezoelectric transducer, signal processing, pattern recognition

## 1. Introduction

In recent years, there has been an increasing awareness of the importance of damage prognosis systems in civil, mechanical and aerospace structures. It is envisaged that a damage prognosis system in a structure would apprise the user of the structure's health, inform the user about any incipient damage in real time and provide an estimate of the remaining useful life of the structure. The potential benefits that would accrue from such a technology are enormous. The maintenance procedures for structures with such systems could change from being schedule-driven to condition-based, thereby cutting down on the time period for which structures are offline and correspondingly resulting in cost savings and reducing their labor requirements. Operators could also possibly establish leasing arrangements that charge by the amount of system life used during the lease instead of charging simply by the time duration of the lease. Most significantly, the confidence levels in operating structures would increase sharply as a result of the new safeguards against unpredictable structural system degradation, particularly so for ageing structures. Moreover, most importantly, the safety of the users of the structure is better ensured.

Structural health monitoring (SHM) is a key component of damage prognosis systems. SHM is the component that examines the structure for damage and provides information about any damage that is detected. An SHM subsystem typically consists of an onboard network of sensors for data acquisition and some central processor to evaluate the structural health. It may utilize stored knowledge of structural materials, operational parameters, and health criteria. The schemes available for SHM can be broadly classified as active or passive depending on whether or not they involve the use of actuators, respectively. Examples of passive schemes are acoustic emission (AE) and strain/load monitoring, which have been demonstrated with some success (Rees et al., 1992; Marantidis et al., 1994; Ellerbrock, 1997; Kollar and Steenkiste, 1998; Schoess and Zook, 1998; Hautamaki et al., 1999; Seydel and Chang, 1999; Chiu et al., 2000). However, these suffer from the drawback of requiring high sensor densities on the structure. They are typically implemented using fiber optic sensors and, for environments that are relatively benign, foil strain gages.

Unlike passive methods, active schemes are capable of exciting the structure and, in a prescribed manner, they can examine it for damage within seconds, where and when required. Guided-wave (GW) testing has emerged as a very prominent option among active schemes. It can offer an effective method to estimate the location, severity and type of damage, and it is a well-established practice in the non-destructive evaluation and testing (NDE/NDT) industry. There, GWs are excited and received in a structure using handheld transducers for scheduled maintenance. They have also demonstrated suitability for SHM applications, having an onboard, preferably built-in, sensor and actuator network to assess the state of a structure during operation. The actuator–sensor pair in GW testing has a large coverage area, resulting in fewer units distributed over the structure.

GWs can be defined as stress waves forced to follow a path defined by the material boundaries of the structure. For example, when a beam is excited at high frequency,

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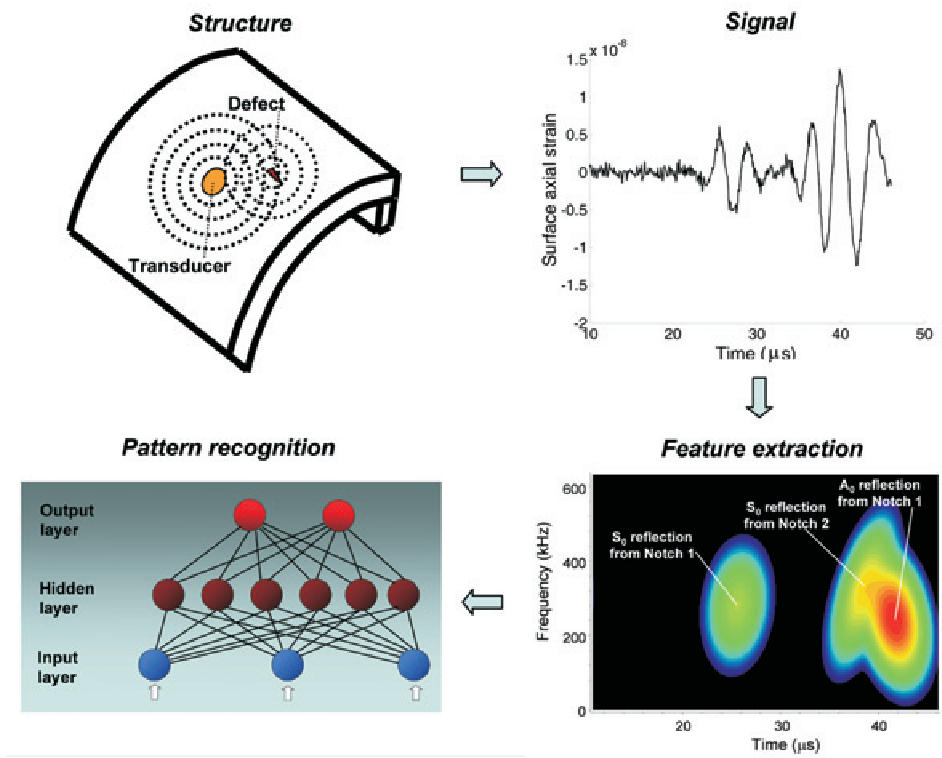



Figure 1. The four essential steps in GW SHM

stress waves travel in the beam along its axis away from the excitation source, i.e. the beam "guides" the waves along its axis. Similarly, in a plate, the two free surfaces of the plate "guide" the waves within its confines. In GW SHM, an actuator generating GWs is excited by some high-frequency pulse signal (typically a modulated sinusoidal toneburst of some limited number of cycles). In general, when a GW field is incident on a structural discontinuity (which has a size comparable to the GW wavelength), it scatters GWs in all directions. The structural discontinuity could be damage in the structure, such as a crack or delamination, a structural feature (such as a stiffener) or a structural boundary. Therefore, to be able to distinguish between damage and structural features, prior information is required about the structure in its undamaged state. This is typically in the form of a baseline signal obtained for the "healthy state" to use as reference for comparison with the test case. There are two approaches commonly used in GW SHM: pulse–echo and pitch–catch. In the former, after exciting the structure with a narrow bandwidth pulse, a sensor collocated with the actuator is used to "listen" for echoes of the pulse coming from discontinuities. Because the boundaries and the wave speed for a given center actuation frequency of the toneburst are known, the signals from the boundaries can be filtered out (or alternatively the test signal can be subtracted from the baseline signal). Then, signals from the defects are left (if present). From these signals, defects can be located using the wavespeed. In the pitch–catch approach, a pulse signal is sent across the specimen under interrogation and a sensor at the other end of the specimen receives the signal. From various characteristics of the received signal, such as delay in time of transit, amplitude, frequency content, etc., information about the damage can be obtained. Thus, the pitch–catch approach cannot be used to locate the defect unless a dense network of transducers is used. In either approach, damage-sensitive features are extracted from the signal using some signal-processing algorithm, and then a pattern recognition technique is required to classify the damage and estimate its severity. Figure 1 illustrates these steps involved in GW SHM. Another crucial point to note is that GW SHM always involves the use of some threshold value to decide whether damage is present in the structure or not. The choice of the threshold is usually application-dependent and typically relies on some false-positive probability estimation.

The critical elements of GW SHM are the transducers, the relevant theory, the signal-processing methodology, the arrangement of the transducer network to scan the structure, and the overall SHM architecture (i.e. issues related to supporting electronics, robustness and packaging). In this paper, we scrutinize each of these aspects and present a review of the efforts by various researchers. We discuss some examples of field applications in which GW SHM has been implemented. We then explore the compatibility of GW-based SHM with other schemes. We conclude with a summary and a discussion about developments desirable in this area. However, before these elements are broached, it is useful to consider some background on GWs and some basics for GW analysis in structures.

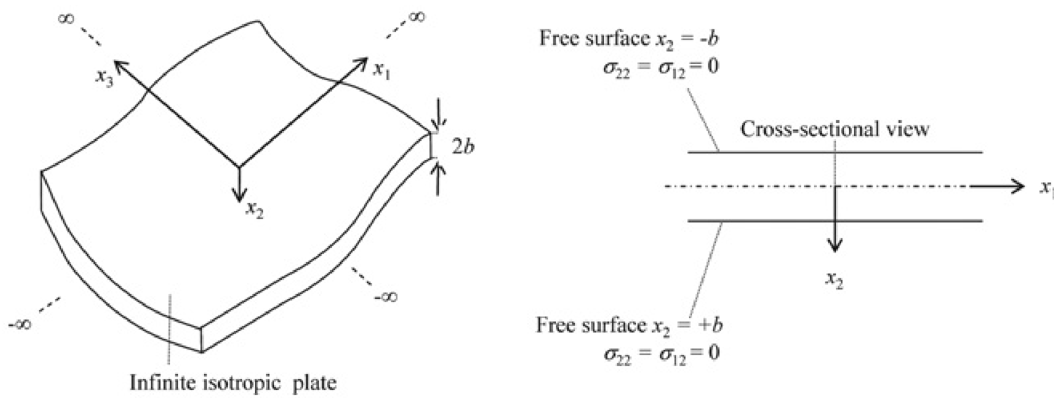



Figure 2. The 2D plate for which dispersion relations are derived

## 2. Fundamentals of Guided Waves

### 2.1. Early Developments

There are several application areas for guided elastic waves in solids, such as seismology, inspection, material characterization, delay lines, etc., and consequently these have been a subject of much study (Achenbach, 1984; Auld, 1990; Graff, 1991). A very important class among these is that of Lamb waves, which can propagate in a solid plate (or shell) with free surfaces. Because of the abundance of plate- and shell-like structural configurations, this class of GWs has been the subject of much scrutiny. Another class of GW modes is also possible in plates (i.e. the horizontally polarized shear or SH-modes). Other classes of GWs have also been examined in the literature. Among these are Rayleigh waves, which propagate close to the free surface of elastic solids (Rayleigh, 1887). Other examples are Love, Stoneley and Scholte waves that travel at material interfaces (Stoneley, 1924; Love, 1926; Scholte, 1942). Lamb waves were first predicted mathematically and described by Horace Lamb (1917) about a century ago. Gazis (1958, 1959) developed and analyzed the dispersion equations for GWs in cylinders. However, neither was able to produce GWs experimentally. This was first achieved by Worlton (1961), who was probably also the first person to recognize the potential of GWs for NDE.

### 2.2. Guided-Wave Analysis

To understand GW propagation in a structure, it is useful to consider briefly a simple configuration (i.e. an isotropic plate). Assume GW propagation along the plate $x_1$-axis, as shown in Figure 2. As the plate is two-dimensional (2D), variations along the 3-axis (normal to the plane of the page) are ignored ($\partial/\partial x_3 = 0$). Furthermore, displacements along the 3-axis are also assumed to be zero. The governing equation of motion is

$$(\lambda + \mu)\nabla\nabla \cdot \boldsymbol{u} + \mu\nabla^2\boldsymbol{u} = \rho\ddot{\boldsymbol{u}} \tag{1}$$

where $\boldsymbol{u}$ is the displacement vector, and $\lambda$ and $\mu$ are Lamé constants for the isotropic plate material, while $\rho$ is the material density. Using Helmholtz decomposition,

$$\boldsymbol{u} = \nabla\phi + \nabla \times \mathbf{H} \quad \text{and} \quad \nabla \cdot \mathbf{H} = 0, \tag{2}$$

splitting the displacement vector into a scalar and vector potential. The equations of motion in terms of the Helmholtz components can be shown to be

$$\nabla^2\phi = \frac{1}{c_1^2}\phi \quad \text{and} \quad \nabla^2 H_3 = \frac{1}{c_2^2}H_3. \tag{3}$$

The other Helmholtz vector components $H_1$ and $H_2$ turn out to be zero. Here $c_1 = \sqrt{(\lambda + 2\mu)/\rho}$ and $c_2 = \sqrt{\mu/\rho}$ correspond to the bulk longitudinal and shear wave speeds, respectively. Because GW propagation along the $x_1$-axis is considered, solutions will be of the form:

$$\phi = f(x_2)e^{i(\xi x_1 - \omega t)} \quad \text{and} \quad H_3 = h_3(x_2)e^{i(\xi x_1 - \omega t)}. \tag{4}$$

This leads to the following differential equations for $f$ and $h_3$

$$\frac{d^2 f}{dx_2^2} + \alpha^2 f = 0 \quad \text{and} \quad \frac{d^2 h_3}{dx_2^2} + \beta^2 h_3 = 0, \tag{5}$$

where

$$\alpha^2 = \frac{\omega^2}{c_1^2} = -\xi^2 \quad \text{and} \quad \beta^2 = \frac{\omega^2}{c_2^2} = -\xi^2. \tag{6}$$

The solutions to these differential equations are

$$f(x_2) = A\sin\alpha x_2 + B\cos\alpha x_2 \quad \text{and}$$
$$h_3(x_2) = C\sin\beta x_2 + D\cos\beta x_2 \tag{7}$$

where $A$, $B$, $C$ and $D$ are constants. Because the boundaries at $x_2 = \pm b$ are free, traction-free conditions must be imposed there. Thus

$$\sigma_{22} = \sigma_{21} = 0 \quad \text{at} \quad x_2 = \pm b. \tag{8}$$

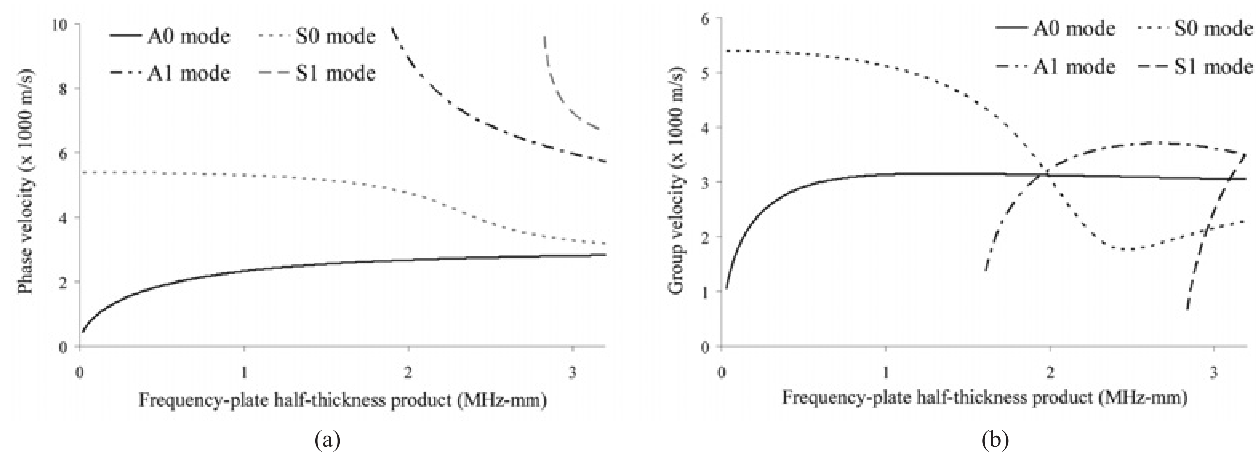



Figure 3. Dispersion curves for Lamb modes in an isotropic aluminum plate structure: (a) phase velocity; (b) group velocity

The tractions in terms of the Helmholtz components are

$$\sigma_{22} = (\lambda + 2\mu)\nabla^2\phi - 2\mu\left(\frac{\partial^2\phi}{\partial x_1^2} + \frac{\partial^2 H_3}{\partial x_1 \partial x_2}\right)$$
$$\sigma_{21} = \mu\left(2\frac{\partial^2\phi}{\partial x_1 \partial x_2} + \frac{\partial^2 H_3}{\partial x_2^2} - \frac{\partial^2 H_3}{\partial x_1^2}\right). \quad (9)$$

From Equations (4), (7), (8) and (9), we obtain

$$\begin{bmatrix} -(\xi^2 - \beta^2)\cos\alpha b & 2i\xi\beta\cos\beta b \\ -2i\xi\alpha\sin\alpha b & (\xi^2 - \beta^2)\sin\beta b \end{bmatrix}\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$\begin{bmatrix} -(\xi^2 - \beta^2)\sin\alpha b & -2i\xi\beta\sin\beta b \\ 2i\xi\alpha\cos\alpha b & (\xi^2 - \beta^2)\cos\beta b \end{bmatrix}\begin{bmatrix} A \\ D \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad (10)$$

For these matrix equations to be true for non-trivial values of the constants, the determinants of the two matrices must vanish. These lead to the Rayleigh–Lamb equations for the plate, which are

$$\frac{\tan\beta b}{\tan\alpha b} = \left[\frac{-4\alpha\beta\xi^2}{(\xi^2 - \beta^2)^2}\right]^{\pm 1}, \quad (11)$$

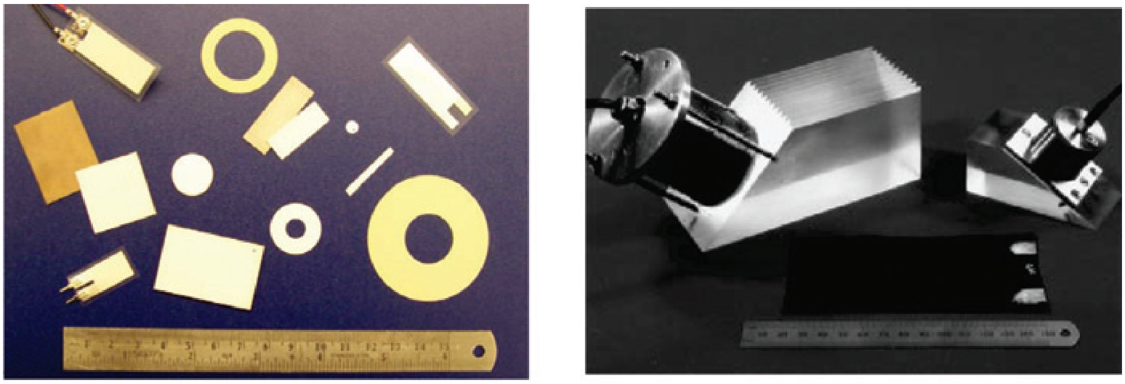
where the positive exponent corresponds to the symmetric Lamb modes, while the negative exponent corresponds to the antisymmetric Lamb modes. The Rayleigh–Lamb equations yield relations between the excitation angular frequency $\omega$ and the phase velocity $c_p$ (= $\omega/\xi$) of the GW in the plate. This is called the phase-velocity dispersion curve. It is plotted in Figure 3(a) for an aluminum alloy plate. Thus, at any excitation frequency, there are at least two modes possible for this structure: the fundamental symmetric ($S_0$) and antisymmetric ($A_0$) modes. Then, as one moves higher up along the frequency axis, higher Lamb modes are possible. The equations for SH-waves in a plate can be derived by relaxing the constraint of zero displacements along the 3-axis. Another important characteristic is the group velocity curve (see Figure 3b). The group velocity (denoted $c_g$) is defined as the derivative of the angular frequency with respect to the wavenumber $\xi$. For an isotropic medium, it gives a very good approximation to the speed of the peak of the modulation envelope of a narrow frequency bandwidth pulse. This approximation improves in accuracy as the pulse moves further away from the source or if the GW mode becomes less dispersive. The procedure above, although for a simple structure, can be generalized to complex structures. Further details on the fundamentals of GW propagation can be found in textbooks such as Auld (1990) and Graff (1991).

## 3. Transducer Technology

As mentioned in the introductory section, GW testing is quite common in the NDE industry. The most commonly used transducers are angled piezoelectric wedge transducers (Zhu et al., 1998; Wilcox et al., 2001), comb transducers (Pelts et al., 1996) and electromagnetic acoustic transducers (EMATs; Alers and Burns, 1987). Other options that have been explored in recent years for NDE are Hertzian contact transducers (Degerketin and Khuri-Yakub, 1996) and lasers (Pierce and Culshaw, 1998). However, while these types of transducers function well for maintenance checks when the structure is offline for service, they are not compact enough to be permanently onboard the structure during its operation as required for SHM. This is particularly true in aerospace structures, where the mass and space penalties associated with the additional transducers on the structure should be minimal.

### *3.1. Piezoelectric Transducers*

The most commonly used transducers for SHM are embedded or surface-bonded piezoelectric wafer transducers (hereafter referred to as “piezos”). Piezos are inexpensive, and are available in very fine thicknesses (0.1 mm for ceramics and 9 µm for polymer film), making them very unobtrusive and conducive for integration into structures.



(a) (b)

Figure 4. (a) Piezos (PZT and PVDF) of various shapes and sizes. (b) The LPAS developed by Culshaw et al. (1998) (right) with a conventional angled wedge ultrasonic transducer (left). [This material has been reproduced from Culshaw, B., Pierce, S. G., and Staszekski, W. J. (1998). *Proceedings of the Institution of Mechanical Engineers, Part I, Journal of Systems and Control Engineering*, **212**(3): 189–201.]

Piezos operate on the piezoelectric and inverse piezoelectric principles that couple the electrical and mechanical behavior of the material. An electric charge is collected on the surface of the piezoelectric material when it is strained. The converse effect also occurs, that is, the generation of mechanical strain in response to an applied electric field. Hence, they can be used as both actuators and sensors. The most commonly available materials are lead zirconium titanate ceramics (known as PZT) and polyvinylidene fluoride (PVDF), which is a polymer film (see Figure 4a). Both of these are usually poled through the thickness (normally designated the 3-direction), which is also the direction in which the voltage is applied or sensed. When used as an actuator, the high-frequency voltage signal causes waves to be excited in the structure. In the sensor configuration, the in-plane strain over the sensor area causes a voltage signal across the piezo. Piezoceramics are quite brittle and need to be handled with care. In contrast, polymer films are very flexible and easy to handle. Monkhouse et al. (1997, 2000) designed PVDF films with copper backing layers to improve its response characteristics. An interdigitated electrode pattern was deposited using printed circuit board (PCB) techniques for modal selectivity, and the transducers were able to detect simulated defects. However, because of their weaker inverse piezoelectric properties and high compliance, the performance of PVDF-based transducers as actuators and sensors is poorer. In addition, PVDF films cannot be embedded into composite structures because of the loss of piezoelectric properties under typical composite curing conditions. Therefore, PZT is the more popular choice for the transducer material among GW SHM researchers (see, for example, Keilers and Chang, 1995; Diaz Valdes and Soutis, 2000; Osmont et al., 2001; Kehlenbach and Das, 2002; Kessler and Spearing, 2002). Some researchers have examined the design of arrays of actuators to enable inspection of a structure from a central point. The idea is to have each sector scanned by the actuator within that sector. Wilcox et al. (1999) investigated the use of circular and linear arrays using piezoceramic-disk actuators and linear arrays using square shear piezoceramics for long-range GW SHM in isotropic plate structures. The field of vision for the linear arrays was restricted to about 36° on either side of the array because of the interference of side lobes. Interestingly, the ratio of the area of the plate inspected to the area of the circular transducer array was about 3000:1. This gives an indication of the long-range scanning capabilities achievable with actuator arrays. Wilcox (1998) proposed the idea of a circular array of six PVDF curved finger interdigitated transducers (IDTs), so that each element would generate a divergent beam, which enables the inspection of a pie-slice shaped area of the plate. Thus, the six IDTs together would have a 360° field of vision about themselves.

### *3.2. Piezocomposite Transducers*

In order to overcome the disadvantage of PZT in terms of brittleness, and also to allow for easier surface conformability in curved shell structures, different types of piezocomposite transducers have been investigated. Badcock and Birt (2000) used PZT powder incorporated into an epoxy resin (base material) to form poled film sheets, which were used as transducer elements for GW generation and sensing. These were shown to be much superior to PVDF piezo elements of same dimensions tested on the same host plate under similar conditions, but inferior to a pure PZT piezo element of the same dimensions. Egusa and Iwasawa (1998) developed a piezoelectric paint using PZT powder as pigment and epoxy resin as binder. They successfully tested its ability to function as a vibration sensor up to 1 MHz. This makes it an attractive candidate as a structurally integrated GW sensor. Hayward et al. (2001) designed IDTs with 1–3 coupling piezocomposite layers, consisting of modified lead titanate ceramic platelets held together by a passive soft-set epoxy polymer, and sandwiched between two PCBs for wavenumber and modal selectivity. However, these also compared unfavorably to pure PZT piezos in tests. Culshaw et al. (1998) developed an acoustic/ultrasonic based structural monitoring system for composite structures, and used a low profile acoustic

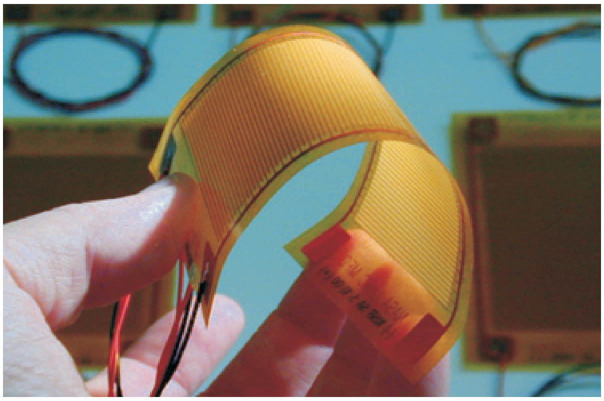


Figure 5. The MFC transducer (see http://www.smart-material.com)

transducer (LPAS), on the lines of traditional angled wedge ultrasonic transducers, to generate the GWs. An appreciable reduction in size was achieved over traditional ultrasonic transducers, raising the possibility of their use as SHM transducers (see Figure 4b). The LPAS used a "1–3" actuation mode piezocomposite layer as the active phase and two flexible PCBs with interdigitated electrode patterns as the upper and lower electrodes. A key advantage in such an angled wedge configuration is modal selectivity, which can be achieved by correct choice of the wedge angle. A similar low-profile wedge transducer (using an array of piezos) was developed by Gordon and Braunling (2005) for on-line corrosion monitoring. Active fiber composite (AFC) transducers were developed by Bent and Hagood (1997). AFCs are constructed using extruded piezoceramic fibers or ribbons embedded in an epoxy matrix with interdigitated electrodes that are symmetric on the top and bottom surfaces of the matrix. Kapton sheets on the outer surfaces electrically insulate the sensor/actuator and make it rugged. These fiber-based piezocomposite transducers also bring in the possibility of unidirectional actuation and sensing. AFCs have been investigated for use in GW-based SHM applications by Schulz et al. (2000). Wilkie et al. (2000) developed a similar piezoceramic fiber-matrix transducer, called the macro fiber composite (MFC; see Figure 5). This uses rectangular piezoceramic fibers, which are cut from piezoceramic wafers using a computer-controlled dicing saw, and hence significantly reducing the small-batch manufacturing costs compared to AFCs. Raghavan and Cesnik (2004, 2007a) have successfully used surface-bonded MFCs for GW unidirectional excitation and sensing in beam and plate structures. In both piezoceramic fiber-based transducers, because the piezoelectric "3–3" mode of actuation along the fiber direction is used (instead of the transverse direction, as in the piezoelectric wafer), the actuation authority can be theoretically as high as three times that of a wafer of similar dimensions.

### 3.3. Other Transducers

Some non-piezoelectric transducers have also been explored for GW SHM. Fiber optic sensors have been explored for a wide variety of smart structures applications, including GW SHM. The advantages of fiber optic sensors are their size (diameter as fine as 0.2 mm), flexible structural integration (embedding/surface bonding), and the possibility of vast networks of multiplexed sensors. Culshaw et al. (1998) used an embedded fiber optic sensor in the Mach Zehnder configuration to sense the GWs, and the characteristics of such fiber optic sensors were compared to those of conventional piezo sensors. An important advantage highlighted by Culshaw et al. was the higher bandwidth capability of fiber optic sensors (which can go up to 25 MHz) due to the absence of mechanical resonances. Betz et al. (2003) used fiber Bragg gratings in a strain rosette configuration to sense Lamb waves as well as to extract the direction from which they emanate. However, one major drawback with fiber optic sensors is the high cost involved in acquiring the associated support equipment.

Another non-piezoelectric transducer is a flat magnetostrictive sensor for surface bonding or embedding into structures, which has been developed for GW SHM by Kwun et al. (2002). The transducer consists of a thin nickel foil with a coil placed over it, and can be permanently bonded to the surface of a structure. It is rugged and inexpensive, and can be used as both a GW sensor and actuator. However, little work has been done to characterize this new type of transducer. Developments in microelectromechanical systems (MEMS) and nanotechnology have affected many engineering disciplines in the world today, and GW SHM is no exception; some researchers have initiated involving these technologies for GW SHM transducer development. Varadan (2003) developed MEMS technology based micro-IDTs for GW SHM, which were either micromachined, etched or printed on specially cut piezoelectric wafers or on certain piezoelectric film deposited on silicon using standard microelectronics fabrication techniques and microstereolithography. Neumann et al. (2004) fabricated capacitive and piezoresistive MEMS sensors for use as strain sensors for GW applications. Their performances were compared and it was concluded that piezoresistive sensors were far superior. The size of these transducers was of the order of 100 μm (see Figure 6). Schulz et al. (2002) discussed the potential of nanotubes as transducers for SHM. A key advantage of using carbon and boron nanotubes for actuation is that they are also load bearing because of their property of superelasticity. In this sense, the use of nanotubes provides great potential for health monitoring of structures because the structure is also the sensor. However, various problems, including high cost, must be solved before smart nanocomposites can become practical.

## 4. Developments in Theory and Modeling

### 4.1. Developments Motivated by NDE

The theory of free GW propagation in isotropic, anisotropic, and layered plates and shells is fairly established. A short primer on elastic waves theory leading up to GW theory in isotropic plates can be found in Raghavan and Cesnik (2005a). Lowe (1995) has reviewed various techniques for obtaining dispersion curves in generic multilayered

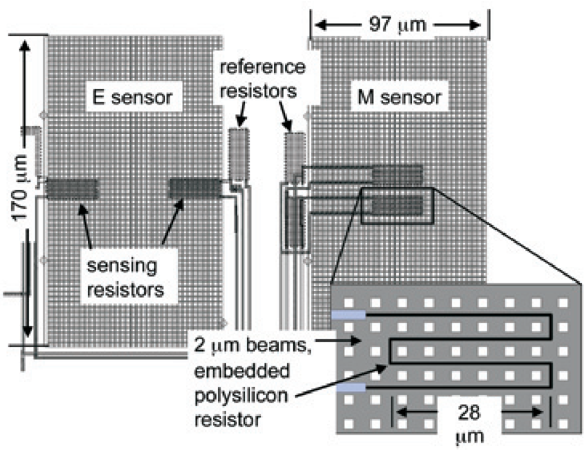



Figure 6. Layout of piezoresistive MEMS sensors presented in Neumann et al. (2004)

plates and cylinders. As pointed out in Lowe (1995), the two major approaches for computing dispersion curves for multilayered structures are the transfer matrix and the global matrix. The former is computationally efficient, but suffers from precision problems at high frequencies. However, the latter is robust even at high frequencies, but can be slower computationally. Several computationally efficient numerical routines have been implemented in *Disperse* (Pavlakovic and Lowe, 2003), which is commercial software, to generate analytical dispersion curves (plots of wavespeed versus frequency) and mode shapes for various configurations with or without damping. More recently, Adamou and Craster (2004) presented an interesting alternative to root finding of the dispersion equations obtained by solving the underlying differential equations. Their approach uses a numerical scheme based on spectral elements, which is computationally more efficient for complex structural configurations. However, while a large body of literature exists for plates and shells, relatively less work has addressed GW propagation in beam-like structures. This is because analytical solutions of the GW propagation problem using three-dimensional (3D) elasticity in beams are very difficult, if not impossible. In fact, in the literature, 3D elasticity solutions exist only for cylindrical (Gazis, 1958, 1959) and rectangular (Kastrzhitskaya and Meleshko, 1991) cross sections. Wilcox et al. (2002) used a finite element based technique for computing the properties of GWs that can exist in an isotropic straight or curved beam of arbitrary cross section. It uses a 2D finite element mesh to represent a cross section through the beam and cyclic axial symmetry conditions to prescribe the displacement field perpendicular to the mesh. Mukdadi et al. (2002) used a similar semi-analytical approach – with finite element method (FEM) elements in the cross section and an analytical representation along the beam axis – to compute dispersion curves in multilayered beams with a rectangular cross section. Bartoli et al. (2006) extended this approach for arbitrary cross-sectional waveguides to account for viscoelastic damping.

Complications can arise in GW testing because of the dispersive nature of many classes of these waves. For example, in plate structures, at any given frequency, there are at least three GW modes. Hence, it is essential to have a fundamental understanding of GW theory and modeling, and characterization of the nature of GWs generated and sensed by the transducers typically used. This will be crucial in effectively designing transducers and algorithms for damage detection. Several researchers have examined the generation of GWs in plates and shells with conventional ultrasonic transducers used in NDE. The work by Viktorov (1967) was an early milestone in this field, covering models for excitation of Lamb and Rayleigh waves in isotropic plates by NDE transducers in various configurations. The book by Rose (1999), for example, is a more recent work, which reviews various aspects of free and forced GW theory in different structural configurations for NDE. However, a majority of these works use the assumption that the structure and transducer are infinitely wide in one direction, making the problem 2D. Santosa and Pao (1989) solved the generic 3D problem of GW excitation in an isotropic plate by an "impulse point body force", also using the normal mode expansion technique. Wilcox (2004) presented a 3D elasticity model describing the harmonic GW field by "generic surface point sources" in isotropic plates; however, the model was not rigorously developed, and some intuitive reasoning was used to extend 2D model results to three dimensions. Mal (1988) and Lih and Mal (1995) developed a theoretical formulation to solve for the problem of forced GW excitation by finite-dimensional sources using a global matrix formulation in multilayered composite plates. The 2D Fourier spatial integrals were inverted using a numerical scheme. Viscoelastic damping was addressed, and, specifically, the cases of excitation by NDT transducers and acoustic emission were solved based on the developed formulation.

GW SHM researchers can also benefit from several mode sensitivity studies conducted for various defect types by NDE researchers to decide the mode and frequency for GW testing. The choice of the GW mode and operating frequency will depend on the type of defect to be detected. GWs are multimodal, with each mode having unique through-plate-thickness stress profiles. This makes it possible to concentrate power close to the anticipated location of the specific defect of interest through the plate thickness. For example, by exciting a mode with a through thickness stress profile such that the maximum power is transmitted close to a particular interface in a composite plate, the plate can be scanned for defects along that interface, as suggested by Rose et al. (1993). They predicted, through analysis of Rose et al. (1993) predicted, through analysis of displacement and power profiles across the structural thickness, that in metallic plates the $S_0$ mode would be more sensitive to detect big cracks or cracks localized in the middle of the plate. However, the $S_1$ mode would be better suited for finding smaller cracks or cracks closer to the surface. This idea was also proven experimentally. Kundu et al. (2001) proposed the idea that, often, the presence of a specific defect type at a certain location through the plate thickness reduces the ability of the plate to support a specific component of stress at that thickness location. In such cases, the GW mode with maximum level of that stress component at that through thickness location should be most sensitive to that defect. This concept can be used, for instance, to scan for broken fibers in a composite, as that reduces the normal stress carrying capacity along the fiber direction. Similarly, Guo and Cawley (1993) proved that, in composite plates, delaminations located at ply interfaces where the shear stress for a particular guided mode falls to zero cannot be detected by that mode. Alleyne and Cawley (1992) used similar ideas to propose procedures for notch characterization in steel plates. In applications where the structure is in a non-gaseous environment (e.g. fuel tanks), the mode selection depends on the level of GW attenuation due to leakage into the surrounding media (Maslov and Kundu, 1997). There have also been several studies to investigate scattering and mode conversion of GWs from various defects (see, for example, Al-Nassar et al., 1991; Veksler, 1991; Chang and Mal, 1999; McKeon and Hinders, 1999; Meguid and Wang, 1999), which would be useful in identifying the defect type using GW signals.

### *4.2. Models for SHM Transducers*

While the body of literature in NDE is significant, relatively few studies have addressed the issue of GW excitation for SHM. There is a crucial difference between GW excitation/sensing in SHM applications and in NDE applications: as mentioned in Section 3, SHM transducers are typically permanently mounted on the structure, unlike in NDE. Therefore, it would be desirable to use coupled models involving the dynamics of both the transducer and the underlying structure for excitation models in SHM. Such models, however, can be very complex and possibly intractable for analytical solution if no simplifying assumptions are employed. This is because no generic 3D elasticity/piezoelectricity standing wave solutions for solids bounded in all dimensions (in this case, the actuator) exist. The majority of efforts initiated to examine GW excitation using SHM transducers address piezos bonded on plates. These efforts can be classified as semi-analytical/numerical and analytical approaches.

#### *4.2.1 Numerical and Semi-analytical Approaches*

Lee and Staszewski (2003) have provided a good review of several numerical approaches to GW modeling. The examined methods were the FEM, the finite difference method (FDM), the boundary element method (BEM), the finite strip element method (FSM), the spectral element method (SEM), and the mass spring lattice method (MSLM). The merits and demerits of each are discussed. It should be noted that conventional approaches can be computationally intensive and are unsuitable for media with boundaries or discontinuities between different media, such as multiply composites. In response to this, a simulation and visualization tool, Local Interaction Simulation Approach (LISA), was developed and implemented to model GW propagation for damage detection applications in metallic structures. However, in that work, coupled models were not addressed, and it is assumed that the actuator causes uniform normal traction over its surface. Wilcox (1998) developed a modeling software tool to predict the acoustic fields excited in isotropic plates by PVDF IDTs. Each electrode finger of the IDT was modeled as causing normal traction over its area. By using an axisymmetric 3D elasticity solution for a single point normal traction force and superimposition of the individual solutions due to the point sources over the IDT, the software then finds the GW field due to the IDT by numerically integrating over all sources.

Some researchers have worked around the intractability of coupled models by using semi-analytical approaches. In those works, a non-analytical model is used for the actuator dynamics in conjunction with an analytical model for the dynamics of the underlying structure. Liu et al. (2002) developed an analytical–numerical approach based on dynamic piezoelectricity theory, a discrete layer thin plate theory and a multiple integral transform method to evaluate the input impedance characteristics of an IDT and the surface velocity response of the composite plate onto which the IDT is surface-bonded. Moulin et al. (2000) used a plane-strain coupled finite element-normal mode expansion method to determine the amplitudes of the GW modes excited in a composite plate with surface-bonded/embedded piezos. The FEM was used in the area of the plate near the piezo, enabling the computation of the mechanical excitation field caused by the transducer, which was then introduced as a forcing function into the normal mode equations. Duquenne et al. (2004) extended this technique, initially developed for harmonic excitation in non-lossy materials, in order to describe transient excitation in viscoelastic materials. Glushkov et al. (2006) also examined the coupled 2D problem of Lamb waves excited in an isotropic plate by piezoelectric actuators (wherein variations were neglected along one direction normal to the direction of wave propagation). A theory of elasticity solution for the isotropic plate was coupled with a reduced-order model for the actuator (incorporating the piezoelectric effect). The resulting system of integral and differential equations was tackled by reducing the problem to an algebraic system and then solving it numerically. Veidt et al. (2000, 2001) used a hybrid theoretical–experimental approach for solving the excitation field due to surface-bonded rectangular and circular actuators. In the theoretical development, the piezo actuator was modeled as causing normal surface stresses, and Mindlin plate theory was used for the underlying structure. The magnitude of the normal stress exerted for a certain frequency was estimated experimentally using a laser Doppler vibrometer, which was used to characterize the electromechanical transfer properties of the piezos. This hybrid approach was used to predict experimental surface out-of-plane velocity signals with limited success.

#### *4.2.2 Analytical Approaches*

If the SHM transducer is compliant enough compared to the substrate structure (for example, if the transducer's thickness and elastic modulus are small compared to the host structure), it might be reasonable to assume uncoupled dynamics between the transducer and substrate. This allows the possibility of purely analytical solutions. This approach has been explored by some researchers using reduced structural theories or 3D elasticity models to model excitation and sensing by piezoelectric wafer transducers. Lin and Yuan (2001a) modeled the transient GWs in an infinite isotropic plate generated by a pair of surface-

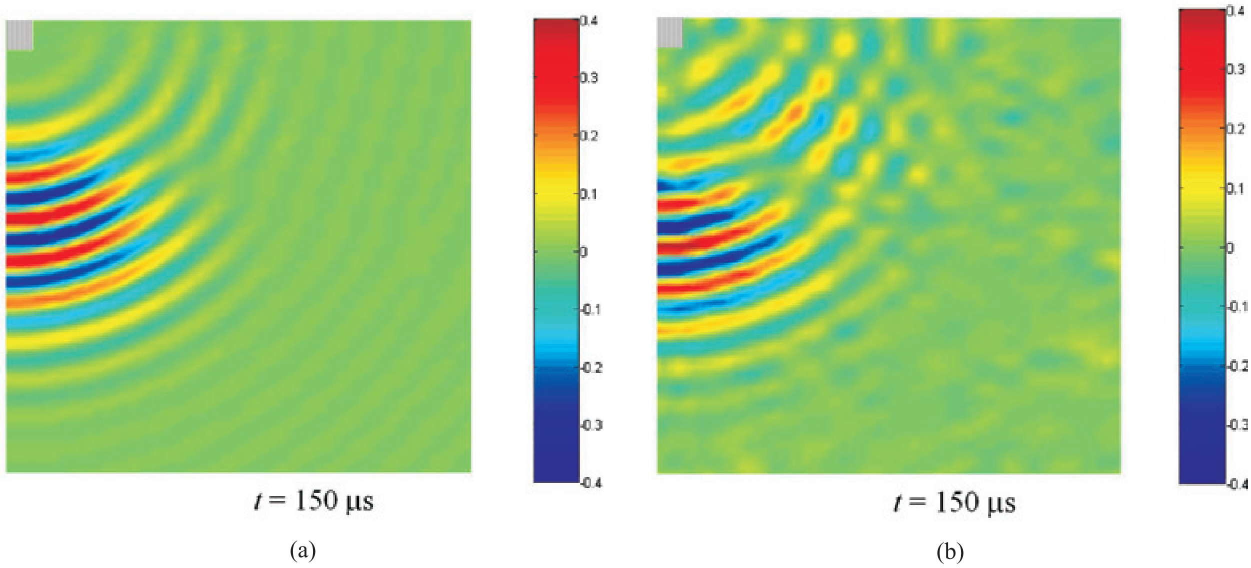



Figure 7. Normalized surface plots showing out-of-plane velocity signals over a quarter section of the plate spanning 20 × 20 $cm^2$. The MFCs (bonded on either surface, actuated in the $A_0$ mode) are at the upper-left corner, shown using a striped rectangle, and their fiber direction is along the vertical direction. The excitation signal was a 3.5-cycle Hann-windowed sinusoidal toneburst with center frequency of 30 kHz. (a) Theoretical plot obtained using the model developed in Raghavan and Cesnik (2006a). (b) Experimental plot obtained using laser vibrometry (scales normalized to peak over surface for all times)

bonded circular actuators (on either free surface at the same surface location) excited out-of-phase with respect to each other. Mindlin plate theory incorporating transverse shear and rotary inertia effects was used, and the actuators were modeled as causing bending moments along their edge. A simplified equation to describe the sensor response of a surface-bonded piezo sensor was derived, also using an uncoupled dynamics model. This assumed that the sensor was small enough so that it could be assumed a single point. Some experimental verification for the model was provided. Rose and Wang (2004) conducted a systematic theoretical study of source solutions in isotropic plates using Mindlin plate theory, deriving expressions for the response to a point moment, point vertical force and various doublet combinations. These solutions were used to generate equations describing the displacement field patterns for circular and narrow rectangular piezo actuators, which were modeled as causing bending moments and moment doublets, respectively, along their edges. However, the disadvantage of using Mindlin plate theory is that it can only approximately model the lowest antisymmetric ($A_0$) Lamb mode, and it can only be used when the excitation frequency-plate thickness product is low enough so that higher antisymmetric modes are not excited. In addition, it cannot model symmetric GW modes. Giurgiutiu (2003) studied the harmonic excitation of Lamb waves in an isotropic plate to model the case of plane waves excited by infinitely wide surface-bonded piezos. These were treated as causing shear forces along their edges. The Fourier integral transform was applied to the 3D linear elasticity based Lamb wave equations, after they were simplified for the 2D nature of this problem. Raghavan and Cesnik (2004, 2005b, 2005c, 2007a) presented an approach to solve for the GW fields generated by surface-bonded arbitrary shape piezo actuators in isotropic plates based on the 3D linear elasticity equations. Specific expressions were derived for the cases of ring-shaped/rectangular piezos and rectangular MFCs. A formulation was proposed to find the sensor response of piezos in transient GW fields, based on the assumption that their response is proportional to the average in-plane extensional strain over their contact surface. Numerical and experimental results were presented that validated the formulation. Figure 7 shows a sample result from the experimental tests for model validation of out-of-plane surface velocity in a 1 mm thick aluminum plate, with a rectangular MFC surface-bonded at the center. These models were used to deduce optimal dimensions for the actuator and sensor in various configurations.

In modeling the effect of surface-bonded piezo actuators, there has been a difference of opinion among researchers. A few works have suggested that these act similar to NDE transducers and operate by “tapping” the structure (i.e. causing uniform normal traction over their contact area). However, the majority of the works reviewed (including our own work) suggest that piezos are more effectively modeled as “pinching” the structure, or causing shear traction at the edge of the actuator, normal to it. This idea was inspired by the work of Crawley and de Luis (1987), who proposed such a model for quasi-static induced strain actuation of piezo actuators surface-bonded onto beams. For reduced structural models, this is equivalent to uniform bending moments along the actuator edge. In our opinion, support for the model from experimental results seems to be stronger from the latter school of thought.

## 5. Signal Processing and Pattern Recognition

Signal processing is a crucial aspect in any GW-based SHM algorithm. The objective of this step is to extract information from the sensed signal to decide if damage has developed in the structure. Information about damage type and severity is also desirable from the signal for further prognosis. Therefore, a signal-processing technique should be able to isolate from the sensed signal the time and frequency centers associated with scattered waves from the damage and identify their modes. The signal-processing approach should also be robust to noise in the GW signals. Deeper insights into the requirements of a GW signal-processing algorithm can be found in Raghavan and Cesnik (2007b). One can borrow from work carried out on signal processing for GW-based NDE testing and from other SHM algorithms, as many elements and goals of signal processing remain the same for most avenues of damage detection. There are, however, a couple of differences between GW signal processing for NDE and for SHM. In the latter, the algorithm should be capable of running in near real time or at frequent intervals, possibly during operation of the structure. Therefore, first, technician involvement should be minimal, and the process should be automated. Secondly, it would be highly desirable to have a computationally efficient algorithm for SHM. Staszewski and Worden (2004) have reviewed various signal-processing approaches that can be exploited for damage detection algorithms. Signal-processing approaches that have been used for GW testing can be grouped into data cleansing, feature extraction and selection, pattern recognition, and optimal excitation signal construction.

### *5.1. Data Cleansing*

Preprocessing or data cleansing may be needed to clean the signals, as any sensor, in general, is susceptible to noise from a variety of sources. This is particularly necessary if the feature extraction mechanism (which is discussed in Section 5.2) is not robust to noise. This group includes normalization procedures, detrending, global averaging and outlier reduction, which are all standard statistical techniques. Yu et al. (2004) used the techniques of statistical averaging to reduce global noise and discrete wavelet denoising using a Daubechies wavelet to remove local high-frequency disturbances. Rizzo and di Scalea (2004) achieved denoising and compression of GW sensor signals by using a combined discrete wavelet transform and filtering process, wherein only a few wavelet coefficients representative of the signal were retained and the signal reconstructed with low-pass and high-pass frequency filters (see Figure 8). Kercel et al. (2000a) used the Donoho principle to cleanse GW signals obtained from laser ultrasonics, wherein the biggest wavelet coefficients on decomposing with Daubechies wavelets (that contained 90% of the total signal energy) were retained and the rest of the coefficients were assumed as noise. A review of the various low-pass filters available for data smoothing is presented in the book by Hamming (1989).

### *5.2. Feature Extraction and Selection*

Features are any parameters extracted from signal processing. Feature extraction and selection is necessary for improved damage characterization. Feature extraction can be defined as the process of finding the best parameters representing different structural state conditions, and feature selection is the process of selecting the inputs for damage identification by pattern recognition (Staszewski, 2000). In GW testing, the features of interest are typically time of flight, frequency centers, energies, time–frequency spread, and modes of individual scattered waves. The different approaches to feature extraction can be further classified into time–frequency analysis approaches and sensor array based approaches.

#### *5.2.1 Time–Frequency Analysis*

In this signal-processing group, a number of techniques using time–frequency representations (TFRs) have been explored for GW signal analysis. While Fourier analysis

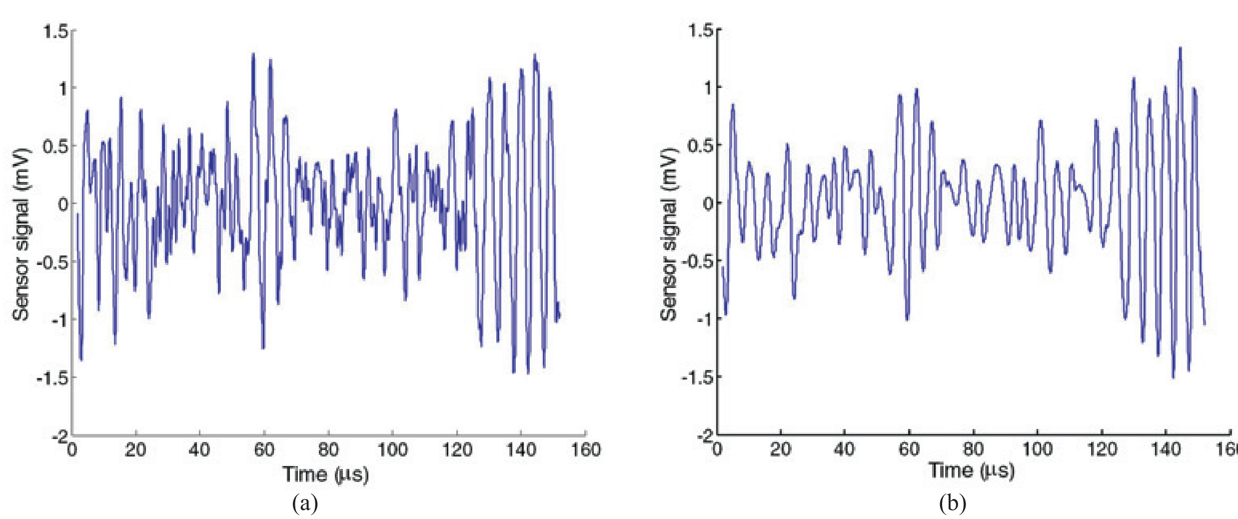



Figure 8. Denoising using discrete wavelet transform: Raw GW signal reflected from a dent in a metallic plate averaged over 64 samples (a) and signal denoised using a Daubechies wavelet (b)

gives a picture of the frequency spectrum of a signal, it does not provide visualization about what frequency component arrives at what instant of time in the signal. TFRs are designed to do exactly that, and yield an image in the time–frequency plane. They are well suited for analyzing non-stationary signals, such as GW signals. Once the image is generated in the time–frequency plane, post-processing is performed on these images to isolate individual reflections and identify their time–frequency centers. Their modes are identified using the time–frequency "ridges" (the loci of the frequency centers for each time instant within each reflection). Prasad et al. (2003) used the short time Fourier transform, which is one of the easiest conventional TFRs to compute, to extract a suitable parameter for a tomographic image reconstruction mapping the structural defects. This was also used by Ihn and Chang (2004) to process GW signals obtained from a network of piezoelectric wafer transducers mounted on a structure. Prosser et al. (1999) used a pseudo Wigner–Ville distribution to process GW signals for material characterization of composites. Niethammer et al. (2001) reviewed four different TFRs to gage their effectiveness in analyzing GW signals, namely, the reassigned spectrogram, the reassigned scalogram, the smoothed Wigner–Ville distribution, and the Hilbert spectrum. While each technique was found to have its strengths and weaknesses, the reassigned spectrogram emerged as the best candidate for resolving multiple, closely spaced GW modes in terms of time and frequency. Furthermore, the strength of TFRs to facilitate the identification of arrival times of different modes was established. Oseguda et al. (2003), Quek et al. (2003), and Salvino et al. (2005) used the Hilbert–Huang transform to process GW signals in plate structures. This technique allows for the separation of the GW signal into intrinsic mode functions (not to be confused with the GW modes) and a residue. This is followed by the Hilbert transform to determine the energy time signal of each mode, enabling the easy location and characterization of the notch. Kercel et al. (2000b) used Bayesian parameter estimates to separate the multiple modes in GW signals obtained from laser ultrasonics on a workpiece manufacturing assembly line. Once the dominant modes were separated by this method, the signals from flaws were isolated and could be easily characterized.

In the last two decades, the wavelet transform has emerged as a very important signal-processing technique for denoising, feature extraction and feature selection. The wavelet technique decomposes a signal in terms of "waveform packets" directly related to the basis used in the wavelet decomposition. The two types of wavelet transforms are the continuous and the discrete wavelet transforms. Staszewski (1998) presented a summary of recent developments in wavelet-based data analysis, which provides not only for effective data storage and transmission, but also for feature selection. As pointed out in that work, continuous wavelet transforms are useful for TFR generation while discrete wavelet transforms are better suited for decomposition, compression and feature selection (Staszewski and Worden, 2004). While a large number of wavelet bases are available in the literature (Strang and Nguyen, 1997; Mallat, 1998; Rao and Bopardikar, 1998), the Morlet (also referred to as "Gabor") and Daubechies wavelets seem to be the most commonly used bases for decomposing GW responses. Paget et al. (2003) constructed a new wavelet basis from a propagating GW signal. They proposed a new damage detection technique based on wavelet coefficients from the GW decomposition using the new basis. It was implemented for impact damage detection in cross ply laminates. Lefebvre and Lasaygues (1994) used a wavelet basis with a Meyer–Jaffard mother wavelet on a fractional scale for crack detection under a stainless steel coating on a steel plate, and were successfully able to distinguish between cracked and undamaged interfaces. Sohn et al. (2004) used the wavelet transform on GW signals obtained from a quasi-isotropic composite plate instrumented with a network of piezos. The Morlet wavelet was used as the "mother" wavelet, and the component corresponding to the excitation frequency was extracted from the transform, and correlated with the same feature for pristine condition Subsequently, extreme value statistics was used to decide whether the structure was damaged. Similarly, Lemistre and Balageas (2001) used continuous wavelet transform methods with a Morlet mother wavelet for delamination detection in composite structures, while Sun et al. (2000) used a similar methodology for notch characterization in pipes. Legendre et al. (2001) employed the Coifman wavelet for a wavelet transform based signal-processing scheme to analyze ultrasonic signals excited and received by EMATs in isotropic plates for defect location.

The matching pursuit approach to signal processing is a recent development introduced by Mallat and Zhang (1993). A similar algorithm was proposed independently by Qian and Chen (1994). This is a "greedy" algorithm that iteratively projects a signal onto a large and redundant dictionary of waveforms. At each step, it chooses the waveform from the dictionary that is best adapted to approximate part of the signal analyzed. Furthermore, it is robust to noise. This can be used to advantage for GW signal processing because, unlike in conventional TFRs, no post-processing has to be done to extract the time–frequency centers of the scattered waves after they are isolated. In the original paper on matching pursuits, Mallat and Zhang (1993) describe an efficient algorithm using a Gaussian-modulated time–frequency atoms (which have stationary time–frequency behavior) dictionary. Zhang et al. (2000) and Hong et al. (2005) have explored the matching pursuit algorithm with this dictionary for GW signal analysis. However, the implicit assumption in those works is that the signals are unimodal and non-dispersive. The atoms in the dictionary are ill suited for analyzing dispersive signals, which have non-stationary time–frequency behavior. Furthermore, those atoms would not help in GW mode classification, as different modes with the same energy at the same time–frequency center would yield similar atoms. Recently, Gribonval (2001) introduced a computationally efficient algorithm for matching pursuits using a dictionary consisting of Gaussian modulated *chirplet* atoms, which have linear time–frequency ridges. We have successfully used this (Raghavan and Cesnik, 2007b) for GW signal processing in isotropic structures with piezoceramic wafer transducers for pulse–echo based damage location and characterization. In Raghavan and Cesnik (2007b) we explain in detail its advantages over conventional TFR approaches, which include better computational efficiency, superior

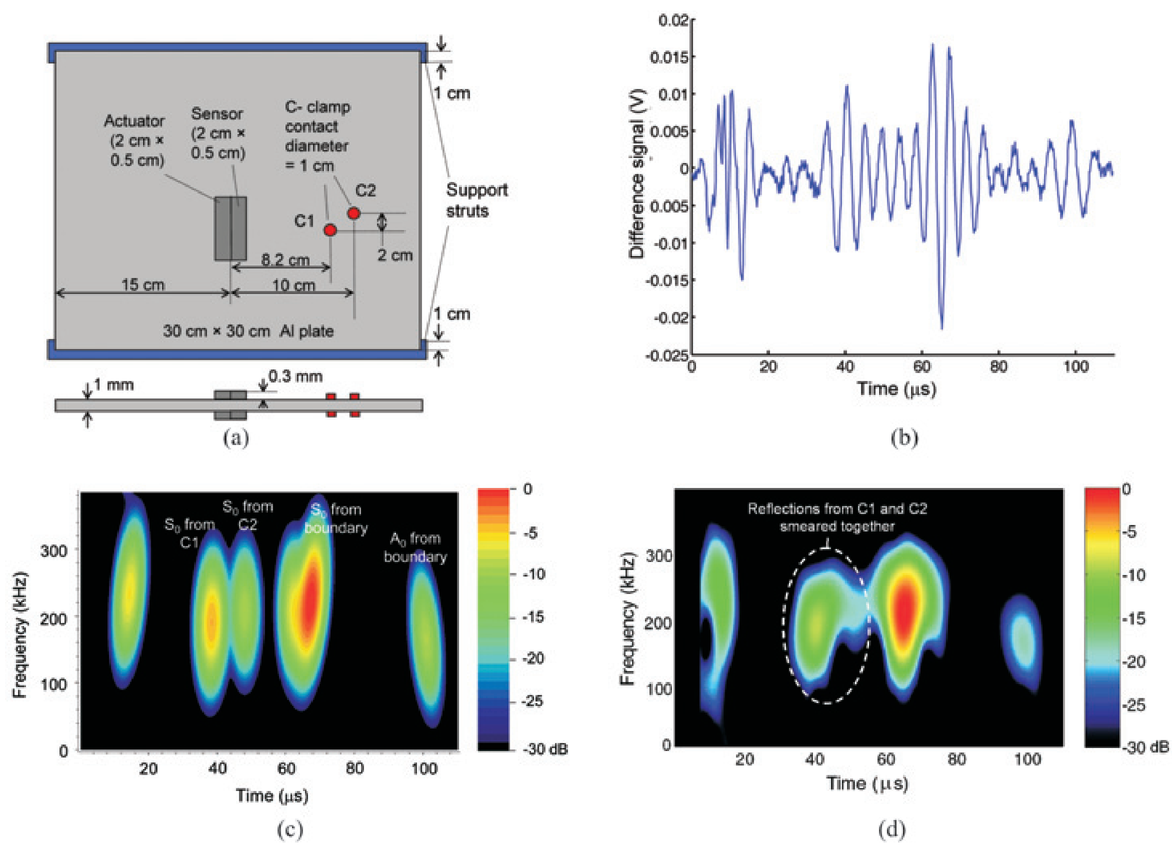



Figure 9. Illustration of the capabilities of the algorithm presented in Raghavan and Cesnik (2006b). (a) Schematic diagram of the experimental setup with two closely spaced artificial damage sites in the form of C-clamps. (b) Difference signal between pristine and "damaged" states. (c) Interference-free TFR generated from chirplet matching pursuit algorithm (implemented using the freeware *LastWave*; see http://www.cmap.polytechnique.fr/~bacry/LastWave), which was successfully used to isolate overlapping reflections. The mode correlation step was then able to correctly identify the GW modes (as labeled) and estimate the radial locations of the clamps. (d) Spectrogram for the same signal, which cannot resolve overlapped reflections

resolution leading to the ability to resolve multimodal overlapping GW reflections (see Figure 9), and ease of automated post-processing.

### *5.2.2 Sensor Array Based Approaches*

Another distinct approach that has been adopted for processing GW signals is the use of sensor arrays in conjunction with a multidimensional Fourier transform along both spatial and time dimensions. Alleyne and Cawley (1990) implemented a 2D Fourier transform method numerically, involving both spatial and time domain transforms for multi-element sensor arrays. The method allows for identifying individual GW modes and their respective amplitudes at any propagation distance even in the most dispersive regions. El Youbi et al. (2004) experimentally implemented this idea for SHM to detect holes drilled in a metallic plate. A surface-bonded 32-element piezo sensor array was used on an aluminum plate to obtain the 2D Fourier transform of the received Lamb signal, and thereby decompose it into its component modes. Because different modes are sensitive to different defects, the logic is that such a sensor array would be flexible enough to monitor a variety of defects. Martinez et al. (2004) used a new four-dimensional space–time/wavenumber-frequency representation for processing a 2D Lamb wave space–time signal in a one-dimensional medium to characterize transient aspects of wave generation and propagation in both space and time dimensions. This was used to investigate the generation, transmission and reflection of GWs in a cylindrical shell using an NDE transducer.

Some researchers have proposed algorithms using linear arrays of sensors for "directional tuning". With appropriate signal-processing techniques, these can be used to extract information about the direction of the incoming wave, and thereby enable virtual "scanning" of the structure without moving the transducers. Such approaches enable power-efficient coverage in structures, and keep the area occupied by the transducers to a minimum. It should be noted that such approaches are distinct from the actuator arrays discussed in Section 3.1. Lin and Yuan (2001b) presented an interesting approach to detect and image multiple damages sites in a plate-like structure. A migration technique (inspired by a similar technique in geophysical exploration) was adopted to interpret the backscattering wave

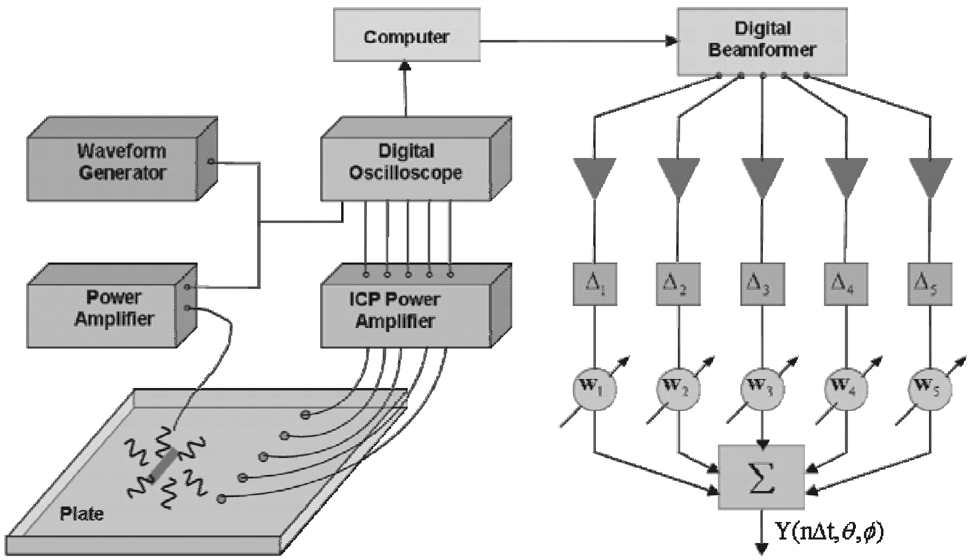



Figure 10. Schematic diagram of the array-based damage detection algorithm using beamforming, which was developed by Sundararaman et al. (2005)

field and to image flaws in the structure. The FDM was used to simulate the reflection waves and in implementing the pre-stack migration. This approach was proposed for a linear array of piezo actuators/sensors. Sundararaman et al. (2005) developed a signal-processing technique based on beamforming of diagnostic waves for damage detection and location, also using piezo linear phased arrays. Beamforming (illustrated in Figure 10) is the process of spatio-temporal filtering of propagating waveforms, done by combining waves from various directions in a weighted (with the weights $w_i$ in Figure 10) and phase-shifted (with the values $\Delta_i$ in Figure 10) summation to obtain higher signal-to-noise ratios in the final signal ($Y$ in Figure 10). Both damage, in the form of a local perturbation in mass by the addition of a small bolt, and artificial damage created by scoring the plate were successfully detected within certain confidence levels. Also, adaptive beamforming using the Frost constraint and one-mode pilot signal beamforming-based techniques using a least mean squares algorithm were implemented to produce better directivity patterns and reduce noise. Giurgiutiu and Bao (2002) developed an "embedded ultrasonic structural radar" (EUSR) algorithm using a 9-piezo element linear phased array. They were able to map artificially induced cracks in an aluminum plate specimen, even in the case where the crack was not in the direct field of view of the array (i.e. an offside crack). This was integrated with a graphical user interface. Interestingly, the developed algorithm finds its roots in a similar procedure used in biomedical imaging for human health diagnostics. Similarly, Purekar and Pines (2003) presented a surface-scanning methodology using piezo linear phased arrays for damage detection in isotropic plate structures. After individually exciting the array elements with a predefined phase delay (which depends on the direction in which scanning is performed), the other array elements were used to listen for echoes from defects and the boundaries. Once these signals were collected, signal processing and directional filtering were used to analyze the signals. From these results, the damage areas (simulated using C-clamps) were located within 1 inch for a 1-inch diameter contact area of the clamps. Moulin et al. (2003) discussed the conditions and limitations for the applicability and performance of linear phased arrays for angular steering of Lamb waves on a plate structure using a simple scalar diffraction model. Phased arrays were used in a pitch–catch configuration to detect impact damage in aluminum plates with sensors located close to the edge of the plate.

### 5.3. Pattern Recognition

Different conditions of the features extracted and selected represent different classes of "patterns" and indicate the state of structural health. Pattern recognition relates to the process of distinguishing between different patterns. Among pattern recognition strategies, the use of artificial neural networks (ANNs) is the most popular technique for GW-based damage detection strategies. For the fundamentals of ANNs, see, for example, Haykin (1994). Su and Ye (2004) extracted spectrographic features from Lamb wave signals in the time–frequency domain to construct a damage parameters database (DPD). The DPD was then used offline to train a multilayer feedforward ANN under supervision of an error back propagation algorithm. The proposed methodology was validated online by identifying delaminations in quasi-isotropic composite laminates with a built-in piezo network for SHM. Challis et al. (1996) applied ANNs to estimate the geometrical parameters of an adhered aluminum T-joint using ultrasonic Lamb waves. The frequency spectrum of received signals was applied as input to conventional feedforward networks, which were trained using the delta rule with momentum. Legendre et al. (2001) used a neural classifier to characterize ultrasonic Lamb wave signals to test metallic welds. This was based on a multilayered ANN, which was trained by selected feature sets chosen to be representative signals for each weld class. Zhao et al. (2004) used a new type of pattern classifier, the support vector machine (SVM), to classify defects such as porosity, surface notches, and subsurface cracks in metal matrix composite sheets. The SVM is a quadratic learning algorithm without overtraining problems, unlike ANNs and fuzzy logic.

### *5.4. Excitation Signal Tailoring*

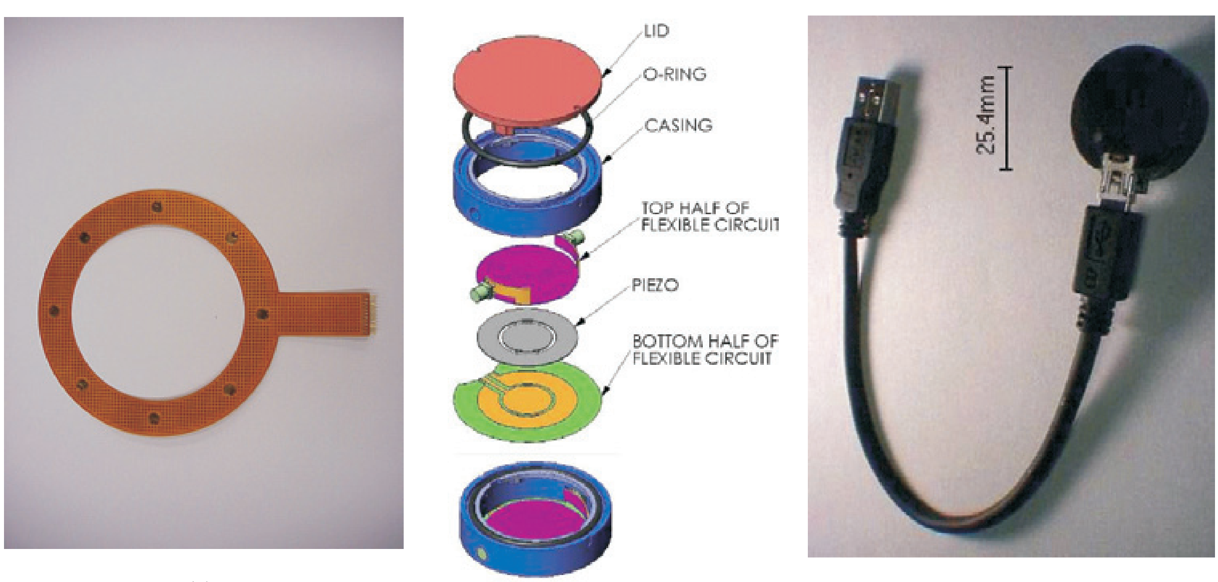
In order to overcome the dispersive nature of GW propagation, special excitation signals have been explored. Among these, time reversal techniques have been used by some researchers. The idea here is to apply a simple toneburst excitation to one piezo transducer in a pitch–catch arrangement, and record the signal at the receiving transducer. The newly recorded GW signal, which is distorted as a result of dispersion, is reversed in the time domain and applied to the original sensor (now acting as an actuator). The received signal at the original actuator (now acting as a sensor) will be very similar to the original simple excitation toneburst if the structure is undamaged (valid for linear homogeneous media). The presence of damage in the path between the transducers will induce changes to the signal that are non-reversible and easily identified. However, this approach does not differentiate between built-in structural features (e.g. rivets) and defects. Wang et al. (2003) used this technique to achieve spatial and temporal focusing in their piezoelectric transducer network designed for GW SHM. Ing and Fink (1996) used a similar strategy for a GW testing system using laser excitation and a multi-element sensor array. Sohn et al. (2005) used a combination of a time reversal technique and a consecutive outlier analysis to identify delaminations in composite plates using a piezo transducer network without baseline signals (on the premise that there are no structural features such as rivets in the actuator–sensor path). Alleyne and Cawley (1993) designed a signal, which, by superposition of its frequency components, recombined to form a signal with a simple shape (a pulse or tone burst) at the measurement position. Kehlenbach and Hanselka (2003) used chirp signals combined with matched filtering to ease time-of-flight determination in Lamb wave based SHM for composite plates.

## 6. Guided-Wave SHM System Development

For field deployment of GW-based SHM systems, several practical issues need to be addressed. The latest developments in this direction are covered in this section and are subdivided as packaging, integrated solutions, and robustness issues.

### *6.1. Packaging*

Packaging of the transducers, as well as ensuring reliable mechanical and electrical connections for them, is an important element of the SHM system design. The packaging design should account for the demands of harsh environments, load conditions and cycling fatigue experienced by the structure. Lin et al. (2001) have developed the "SMART Layer" (as shown in Figure 11a), which is a thin dielectric film with an embedded network of distributed piezoelectric actuators and sensors, and includes the wiring for the transducers. The layer can also incorporate other types of sensors, including fiber optic sensor net-




(a) (b)

Figure 11. Packaged piezos for GW SHM: (a) the SMART layer developed by Lin et al. (2001) (courtesy of Acellent Technologies, Inc., http://www.acellent.com); (b) packaging developed by Kessler et al. (2004) and Chambers et al. (2006) – components and assembled form

works, to monitor properties such as strain and moisture. The monitoring layer can be either surface-mounted on existing structures or integrated into composite structures during fabrication, thereby enabling GW SHM. Kessler et al. (2004) have presented a list of SHM system design requirements based on a survey of aerospace corporations and government agencies. In response to these requirements, fabrication techniques and packaging strategies were developed Chambers et al. (2006) for surface-mounted piezo transducers to address electrode design, encapsulation, mounting schemes and connectors for wired transducers (as shown in Figure 11b). Yang et al. (2003) embedded rod-shaped piezo transducers in washer-like packages to use for SHM in reusable launch vehicle thermal panel bolts. These transducers were able to survive unscathed in simulated re-entry environment tests in an acoustic chamber. Piezos are also available in a variety of commercially available standard packaged forms, such as Moonies (Lalande et al., 1995), Rainbow (Haertling, 1997), Crescent (Kugel et al., 1997), Thunder (Mossi and Bishop, 1999), Quick-Pack and PowerAct (Pretorius et al., 2004), designed for various applications. Other packaging strategies include the AFC and MFC described in Section 3.2. These packages improve their flexibility, reliability, resistance to harsh environments and/or mechanical and electrical connectivity characteristics. An overview of various piezoelectric materials and architectures is provided in Niezrecki et al. (2001).

### 6.2. Integrated Solutions

Some researchers have looked at efficient designs of the overall GW SHM system. This includes the packaged transducers, power source, wiring (for wired systems) and data logging/processing/transmission. These works are categorized as “integrated solutions” in this paper. Among the wired systems, Acellent Technologies Inc. (Lin et al., 2001) developed a “SMART Suitcase”, which essentially integrates the different GW SHM components (a high-frequency signal generator, data acquisition, amplifier and processing software) into a compact suitcase that can be used for field applications involving wired sensors. It was designed to support their developed “SMART Layer” described above Gorinevsky et al. (2005) described how a GW SHM system based on the above “SMART Suitcase” would link to a Central Maintenance Computer (CMC, developed by Honeywell Aerospace) for Integrated Vehicle Health Management (IVHM) in aircraft. Kim and Lee (2005) developed a hybrid coin-sized transducer that incorporates multilayer piezoelectric disks and fiber optic sensors. A portable microprocessor-based data logger and server are integrated with the transducer and can be used as an excitation source for the piezo actuator. Their system, called the “diagnostic network patch”, incorporates all signal processing, analysis and interpretation in these two modules, which can be performed in real time for up to 30-sensor channels.

A desirable scenario for certain applications is an SHM system consisting of self-contained transducer patches and networked to a central processor wirelessly. Such a self-contained patch would consist of the following elements: transducer, local power source, telemetry device, and some local data processing capability. The local power source and telemetry abilities are crucial to avoid wires being used to instrument an entire structure, then reducing the complexity of the SHM system. In addition, as pointed out in Kim et al. (2002), wires are susceptible to breakage and vandalism, and they present reliability and maintenance issues. Connecting moving/oscillating and fixed subsystems is another case when hard wiring is difficult or sometimes impossible. The local computing capability is essential to limit the volume of raw data that need to be transmitted to the central processor. As pointed out by Hay and Rose (2004), interfacing active sensors with wireless technology for GW SHM has lagged behind passive sensor technology mainly because of the power requirements and the electronic accessories that must be added to the active sensors in order to actuate the device. The power required for passive sensors in comparison is much less (in the mW range) and standard communication electronics technology suffices to interface with these. There have been several impressive achievements made in passive (or very low power) wireless sensing, such as in the “Motes” program (Glaser, 2004). “Motes”, also called “smart dust”, are devices that incorporate communications, processing, sensors, and power source into a package currently about two cubic inches in size. It has been tested for passive strain and load monitoring based SHM, with encouraging results. Ihler et al. (2000) presented a trade-off study of various wireless piezoelectric sensor network concepts, including a ranking of different possibilities for power supply, frequency selection, signal modulation and basic prerequisites for embedding of the sensor pad in a carbon fiber composite structure. Kim et al. (2002) fabricated a wireless active piezo sensor with fingers etched to form an interdigitated pattern using MEMS technology, and incorporated the required microelectronics and conformal antennas onboard chip-sized transducers. Small amplitude GWs were excited for health monitoring, using energy from radio frequency electromagnetic waves transmitted wirelessly to the transducer, thereby eliminating the need for a local power source. The data collected can be processed locally with the onboard chip to extract feature vectors, which can then be transmitted wirelessly to a central processor. To enable flush mounting onto structures with rain and erosion protection, the MEMS transducer was covered with a thin ultraviolet curable polymer coating. Lynch et al. (2004) used commercially available components to design and fabricate a low-cost wireless sensing unit for deployment as the building block of wireless SHM systems for civil structures (see Figure 12). The unit was about $10 \times 10 \times 3.3$ cm$^3$ in dimensions, had a transmitting range of about 150 m, and a power source that lasted about 50 hours. A GW-based scheme, with some time-series statistical pattern recognition algorithms incorporated into the onboard computing chip, was tested in a bridge structure with encouraging results. Lynch and Koh (2006) have also presented an excellent review of various works examining wireless sensors (both passive and active) for SHM. Another avenue that has been explored for local power sources is power harvesting, which is the process of acquiring the energy from the surrounding environment and converting it into usable electrical energy. This captured energy could then be used to prolong the life of the power supply or, in the

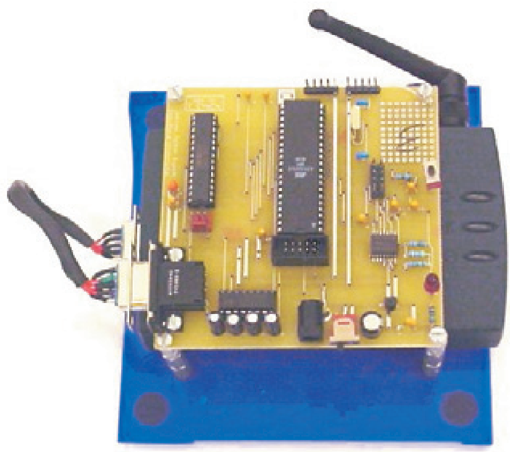



Figure 12. Wireless unit for civil structures developed by Lynch et al. (2004) using an onboard battery

ideal case, provide endless energy for the transducer's lifespan. Sodano et al. (2004) have reviewed the developments in this emerging technology, and have pointed out that this field is not yet mature. Innovations in power storage, such as the use of rechargeable batteries with piezoelectric materials, must be made before power-harvesting technology will see widespread use.

### 6.3. Robustness to Different Service Conditions

In designing a SHM system for a real-world field application, ample consideration should be given to the robustness of the SHM transducer and algorithm to variable service conditions. The SHM system should be able to distinguish between signal changes due to damage events and changes in environmental conditions. It should also be able to compensate for these condition changes by the use of appropriate signal-processing methods. Furthermore, the physical SHM system components should be robust enough to these anticipated changes. Kessler et al. (2004) exposed their developed packaged piezo transducers, described in Section 6.1, to various environmental conditions in order to test the protective ability of the package. In separate tests, the transducer was exposed to temperatures of 180°F and saturation humidity levels (for a period of one day each), and artificial electrical noise from a brush-style electric drill. They observed that the packaging sufficiently protected the transducers against these simulated environmental effects. Schulz et al. (2003) explored various piezoelectric materials for high-temperature applications. While commercially available materials such as PZT-5A can be used to temperatures up to 170°C (which is half of its Curie limit), there are piezoelectric materials such as lithium niobate that retain their piezoelectric properties up to temperatures as high as 1200°C. However, their performance as piezoelectric materials is much poorer in comparison to that of more common ones (e.g. PZT-5A) at room temperature. Schulz et al. identified nanotubes as a potential transducer material for future high-temperature applications (up to 1000°C). Lee et al. (2003) studied the effect of temperature variation on the Lamb-wave response of a piezoceramic sensor in a pitch–catch configuration on a metallic plate from room temperature up to 70°C. They observed that the effect of temperature variation over this range was much more pronounced than the effect of damage (artificial hole), and they explored signal-processing options for retaining sensitivity to damage while eliminating sensitivity to temperature change. We have also done preliminary studies on the variation in the behavior of PZT-5A piezos as GW transducers with temperature over multiple thermal cycles from 20°C to 150°C (Raghavan and Cesnik, 2005a). We observed that there is some degradation in response magnitude after the first cycle (due to thermal pre-stabilization of the piezos), but the behavior became stable after that over the remaining cycles. Further investigations are ongoing towards an analytical characterization of such behavior and the effect of individual factors such as changing piezoelectric properties, variation in structural properties, and bond strength degradation. We observed that there is a significant degradation in response after the first thermal cycle, but the behavior seems to stabilize in subsequent cycles. Further investigations are ongoing towards an analytical characterization of such behavior and the effect of individual factors, such as loss in piezoelectric properties, variation in structural properties and bond strength degradation. Blaise and Chang (2001) investigated the performance of piezoelectric transducers (in a GW pitch–catch configuration) embedded into sandwich structures for cryogenic fuel tanks at low temperatures (to –90°C). An empirical model (linear) was fitted to experimentally obtained data points for damage detection under varying temperature. Both the reduction in signal amplitude and time of flight were compensated for. Reasonable agreement was obtained between the interpolated signals from the empirical model and experimental data for intermediate temperature values. Paget et al. (2000) studied the performance of a piezo actuator embedded in a graphite/epoxy composite for GW SHM under static and fatigue load tests. The embedded piezoceramic transducers revealed a large working range in the static tests at least up to 90% of the final failure and were insensitive to fatigue loading for generation of GWs. Changes only occurred after 50,000–100,000 of cycles at high stress levels (260 MPa, corresponding to 0.3% strain). For lower stress levels (130 MPa, corresponding to 0.15% strain), the piezoceramic transducer lasted more than 400,000 cycles. The changes were mainly associated with matrix cracks in the composite. Biemans et al. (2001) conducted a preliminary study into the application of GW-based SHM for fatigue crack monitoring in aluminum plates under static and dynamic load (6 Hz) conditions, and compared the results with the unloaded condition. Various options in signal processing were explored, and it was shown that, through appropriate choice of excitation signals and signal-processing technique, satisfactory damage detection results could be obtained for all load conditions. Manson et al. (2000) used the signal-processing method of novelty detection to build an internal representation of the system's normal condition for Lamb wave SHM in such a way that subsequent departures from this condition due to structural damage could be identified with confidence in a robust manner. The importance of obtaining a valid set of normal conditions, which could account for temperature and load variations, was highlighted. The effects of short-term and long-term temperature changes in a composite plate on the normal condition data were experimentally quantified, and similar tests were performed for environmental humidity changes (Manson et al., 2001). Giurgiutiu et al. (2004a) and Blackshire et al. (2005) studied the durability and survivability of commercially available piezos (PZT) under temperature cycling in an oven, weather exposure in outdoor environment (sun, rain, humidity, freeze–thaw, etc.), and exposure to water and maintenance fluids (hydraulic fluids and maintenance oils). The test results indicate that repeated thermal cycling and extended environmental conditions could potentially lead to piezo transducer failure. The importance of appropriate bonding agents for the sensor and protective coatings was highlighted. Doane and Giurgiutiu (2005) studied the behavior of piezos under large strain and fatigue cycling. The high strain tests indicated that the piezos remain operational up to at least 3000 microstrain and fail beyond 6000 microstrain. The fatigue tests, conducted up to millions of cycles, showed that the substrate always failed before the piezo.

## 7. Application Areas

The gamut of structures where GW-based SHM can be employed for damage prognosis is vast and ranges from ground vehicles, ships and aerospace structures to bridges, pipelines and offshore platforms. In this section we present some examples where GW SHM has been demonstrated in realistic structures.

### *7.1. Aerospace Structures*

Aerospace structures by themselves form a huge and very significant GW SHM application area. The Aloha Airlines fuselage separation (National Transport Safety Board, 1989) and the Columbia Space Shuttle tragedy (NASA, 2003) brought to the fore the critical need for effective SHM systems in aerospace structures. Derriso et al. (2001) outlined the importance of SHM in military aerospace vehicles to reduce maintenance downtime and to ensure high levels of reliability and safety, while Huang (2001) discussed the need for SHM in future reusable launch vehicles (RLVs) to achieve affordable and routine access to space with present-day aviation-like operations. Dalton et al. (2001) explored the potential of GW-based SHM for application in metallic aircraft fuselage structures. GW propagation was examined in a variety of typical structural configurations found in metallic monocoque fuselages, such as free skin, tapering skin, skin loaded with paint and sealant, stringer joints, etc. It was concluded that GW SHM is not the ideal candidate for complicated structural configurations or for skin coated with sealant due to damping. However, for the free and tapered skin configurations and lap joints, results were very promising, establishing it as an effective solution for these simpler configurations. Giurgiutiu et al. (2003) examined the feasibility of using piezo-based GW SHM on realistic aircraft panel specimens with rivets and splice joints, and were able to clearly distinguish between reflected signals from the structural discontinuities and simulated damage (cracks). Grondel et al. (2004) instrumented a single cell box composite specimen with construction and loading similar to that found in an aircraft wingbox using piezos to examine the ability of GW SHM. Their experimental results revealed a large sensitivity of GWs to disbond between the stiffener and composite skin and impact damage due to low velocity impact, major causes of in-service damage of aircraft structures. Koh et al. (2002) developed a simple algorithm based on GW power transmitted between two transducers in a pitch–catch configuration to detect disbond initiation and monitor its growth in a composite repair patch for aircraft panels. Matt et al. (2005) tested a piezo-wafer based GW system for monitoring the integrity of the bond between the composite wing skin and supporting spar for unmanned aerial vehicles (UAVs). Blaise and Chang (2002) demonstrated the feasibility of integrating piezo transducers within the cells of cores in honeycomb sandwich structures. The sensors were incorporated on the warmer side of the panels, which are similar to those in cryogenic fuel tank construction. The system showed good potential to detect damage in the form of disbond between the skin and the core. Yang et al. (2003) and Derriso et al. (2004) have worked on the use of GW SHM for RLV thermal protection panels. Damage in the form of base bracket loosening, panel loosening and impact damage could be detected. Lin et al. (2003) designed and manufactured special SMART layers (see Section 6.1) for filament-wound composite bottles, and embedded them during the filament winding process. A prototype of a filament-wound composite bottle with an embedded sensor network was fabricated (shown in Figure 13) and preliminary data analysis tools have been developed. This system exemplifies the application of GW SHM in rocket motor cases and fuel tanks for next-generation space vehicles. Lakshmanan and Pines (1997) studied the applicability of GW SHM using piezos to

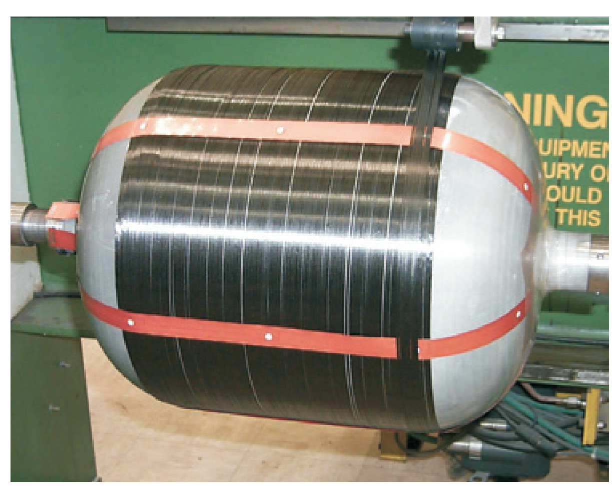



Figure 13. Photograph of an application area tested using GW SHM: Composite fuel tank instrumented with SMART layers by Lin et al. (2003) (courtesy of Acellent Technologies, Inc., http://www.acellent.com)

detect damage in rotorcraft blades in the form of transverse cracks and delaminations with encouraging results.

### 7.2. Civil Structures

As observed by Chong et al. (2003), the civil infrastructure in any country is among its most expensive assets (e.g. an estimated $20 trillion in the USA). These systems are deteriorating at an alarming rate, creating the need for new tools to provide feedback on the structure's health. Significant work has been carried out to investigate the use of embedded fiber optic sensor or strain gage networks in civil structures for SHM by strain monitoring and vibration mode testing (see, for example, Livingston and Jin, 2001; Shiba et al., 2001; Tennyson et al., 2001; Li et al. 2003). In comparison, relatively few activities have been carried out to develop GW-based SHM in civil infrastructure using *in situ* transducers for remote diagnostics. This is partly because civil structures are, in general, much thicker and larger in size in comparison to aerospace structures, implying that an *in situ* actuator would have to provide orders of magnitude higher actuation stresses to cover a reasonable area. While stress wave propagation methods are popular for assessing the condition of concrete structures for NDE, the greatest success in the practical application of stress wave NDE methods for testing concrete has been using mechanical impact to generate the stress pulse. Impact results in a high-energy pulse and high penetration of the stress waves, which is suitable for large-scale civil structures, such as bridge decks and building walls. However, some applications for smaller-scale civil structures have been tested for GW SHM with promising results. Rizzo and di Scalea (2004) investigated GW SHM for multiwire steel strands, used as pre-stressing tendons in pre-stressed concrete and as stay cables in cable-stayed and suspension bridges, with magnetostrictive transducers. Khazem et al. (2001) tested the applicability of a similar methodology on a real bridge structure, and they were able to scan the entire length of a suspender rope (about 100 m) for cable tension, cracks and corrosion damage. Wu and Chang (2001) showed that an embedded pair of piezos could be used for debond detection using GWs in steel-reinforced concrete columns. However, the methodology was unsuitable for crack detection. Lovell and Pines (1998) presented a simple GW propagation approach, which was capable of identifying characteristics of damage associated with loss of torque preload on a simple one-bolt lap joint. This was motivated by the idea of monitoring the dynamics of large buildings and bridges to assess the level of damage in bolted or riveted assemblies following a severe loading condition (e.g. earthquake).

### 7.3. Other Areas

The capability of GW SHM has been examined in a variety of other mechanical systems as well. Lin et al. (2002) have recently designed and fabricated custom SMART layers for automotive applications that conform to an automobile's complex shape. Their SMART suitcase (described in Section 6.2) was specially configured to perform *in situ* GW SHM in automobiles. Proof-of-concept tests were conducted using this system by the auto manufacturer BMW in carbon fiber samples for impact damage detection (Panajott, 2001). Na and Kundu (2002) designed a transducer holder device using commercially available NDT ultrasonic transducers for GW-based SHM in underwater pipelines. Encouraging laboratory demonstrations showed the potential of the transducer for online detection of damage in the form of dents and gouges. Some researchers have also examined the use of magnetostrictive transducers (Hegeon et al.,2003; Park et al., 2004) and PVDF film transducers (Hay and Rose,2002) for GW-based pipeline condition monitoring. Wang (1999) described the applications of GW-based damage detection in the petrochemical industry, including the testing of heater tubes, pipes, vessels, risers and heat exchanger tubing. Ghoshal et al. (2000) conducted preliminary investigations into the applicability of GW SHM for wind turbine blades made of fiberglass, and were able to detect artificial damage in the form of an added mass. Jones et al. (2004) illustrated the usefulness of GW SHM for crack detection and size estimation in dragline clusters used for the mining industry.

## 8. Integration With Other SHM Approaches

It is crucial to realize that while GW testing has several advantages, it may not be the best SHM solution in all scenarios. For example, in pulse–echo GW testing, a known shortcoming is the blind zone area close to the collocated actuator/sensor. This is a result of the finite duration of the emitting pulse as it is being generated. During this time, all reflection signals are masked by the outgoing excitation pulse. In such scenarios, however, the same network of transducers can be used for a different SHM methodology by simply changing the data processing and/or excitation signal. Passive strain sensors, such as fiber optics and foil strain gages, which can be used for GW sensing, can also be used for acoustic emission, strain and load monitoring, and for modal testing. Active transducers, such as piezos, magnetostrictive sensors and nanotubes, can be used for the above-listed passive SHM approaches as well as other active SHM schemes such as electromechanical (EM) impedance testing and active modal testing. This can be used to advantage, as other SHM algorithms may prove to be better solutions in certain scenarios. Thus, the overall SHM scheme could be designed to use a combination of two or more of these methods, capturing the benefits of each. For example, as proposed by Kessler and Spearing (2002), a passive system, such as acoustic emission or strain monitoring, could be used to monitor the structure in real time, and if this system detects a structural anomaly, then a dormant GW system could be triggered to localize and characterize the defect. This would be beneficial to minimize the power requirements of the SHM system. Such an approach was used by Mal et al. (2004), who implemented a combined vibration modal analysis method and GW-based method using a network of piezos, the idea being to use the former for global damage detection and the latter for localized damage characterization. Giurgiutiu et al. (2004b) discussed the complementary nature of the EM impedance and GW approaches in plate-like structures. The EM impedance method is suitable for damage detection in the near field, while the GW approach is better suited for far-field damage detection in the pulse–echo mode. Therefore, their simultaneous utilization will cover the structural area completely. The suitability of piezos for acoustic emission and impact wave detection was demonstrated by Osmont et al. (2000). The feasibility of using the same network of piezos as dual mode sensors for acoustic emission and GW SHM was also confirmed. Wait et al. (2004) also used a combined EM impedance and GW SHM strategy with a piezo wafer and MFC network in a metallic plate structure bolted to a base structure. GW testing was used to detect cracks in the plate, and the EM method, because of its high sensitivity to structural boundary conditions, was used to examine the torque level of the bolt connection to the base structure. Monnier et al. (2000) proposed a combined EM impedance and GW SHM strategy for comprehensive SHM in composites. The E-M impedance method was used for detection of degradation in the viscoelastic properties of the composite structure due to aging, and the GW method was used for detecting damage such as delaminations and matrix cracks. Blanas and Das-Gupta (1999) have reported on the capability of piezos for simultaneous use as GW transducers as well as load monitoring sensors for dynamic and impact loads in composite structures. The final architecture of any SHM system is determined by the type of application, structure and material combinations, and power available.

## 9. Summary and Path Forward

In this paper, we have reviewed the latest developments in the various facets of GW SHM. This emerging field has its roots in GW NDE, which is a well-established industrial technology. The transducers for GW SHM, particularly for aerospace structures, are typically smaller and more compact compared to those used in NDE. In this respect, ceramic piezoelectric wafer transducers appear to be the most popular option used by SHM researchers. In order to overcome the disadvantage of brittleness in piezoceramics, several piezocomposite transducers and some non-piezoelectric alternatives have also been explored. While the relevant GW theory for NDE is fairly developed, the SHM counterpart has lagged behind. However, there have been some efforts in this direction, and modeling tools and innovative numerical and semi-analytical approaches have been examined for SHM GW problems. Some analytical models for isotropic structures in simple configurations have been developed. Several signal-processing techniques have been explored for GW testing, most of which are time–frequency representations. For pattern recognition, neural networks have emerged as the popular option. There have also been several research efforts on array configurations and the associated signal processing to allow for scanning a structure from a central location with a minimum number of transducers. Several packaged versions of piezoelectric transducers are now available commercially, and some commercial entities are developing custom packaging and support electronics for GW SHM transducers (piezoelectric or hybrid). In terms of integrating the transducers with an onboard power source, computing chip and wireless telemetry, the major obstacle has been the high power requirements for exciting GWs with a reasonable scan range. In order to bring this technology closer to field deployment for commercial structures, a few works have examined the effect of environmental factors and noise on the transducers and their response characteristics. From the applications perspective, aerospace structures have been extensively examined. Their thin-walled constructions make them good candidates for this technology. However, there is no reason preventing their widespread applicability to other mechanical structures, and much potential exists in this class of structures. For civil structures, the development of GW SHM has lagged, perhaps because of the higher power requirement for the actuators to excite relatively bulky structures. Finally, while GW SHM has shown much potential and has several advantages, other schemes may be more applicable in certain scenarios. Researchers have looked at hybrid schemes involving GW testing and other methodologies for more comprehensive SHM solutions.

There are still several issues worthy of consideration to further advance the field of GW SHM. Transducers represent one crucial area where progress is required. As discussed earlier, the majority of the GW SHM reviewed works have employed piezoceramic wafer transducers. This is natural because, as pointed out in Niezrecki et al. (2001), for high-frequency actuation applications, piezoelectric transducers are most efficient and have high power density. There are two aspects in which these fall short. First, being brittle, they might be unsuitable for field application. In SHM, it is crucial that the transducers be able to survive events such as impact or collisions, so that they are in a position to decide the extent of damage to the structure from such events. Secondly, these have a limited temperature range of operation (e.g. PZT-5A is rated for up to 175°C), and their performance degrades significantly as the temperature crosses roughly half their Curie temperature. Furthermore, while the piezoelectric effect works at temperatures down to 0 K, the strength of the effect weakens at lower temperatures. To overcome the mechanical issue, piezocomposite transducers are a good start. These were originally developed for low-frequency structural actuation, and efforts should be invested into tailoring these for high-frequency GW transduction. Simultaneously, more detailed studies into other non-conventional transducer options, such as those discussed above, are desirable. Those might turn out to be superior to piezoelectric transducers. To address the second concern, high-performance active materials that do not significantly degrade at high or low temperatures need to be developed. The current piezoelectric materials developed for high temperatures are much weaker in terms of response compared to conventional piezoceramics at room temperature. Nanotechnology may provide new candidates in this regard. While some activities have been initiated into examining the non-obtrusiveness and robustness of GW SHM system packaging to environmental extremes, further efforts in this direction are also needed. Particularly, the effect of harsh environments in terms of temperature, load, humidity, etc., on packaging and the development of signal-processing algorithms to overcome these effects should be pursued. In addition, more research into reliable electrical and mechanical connections is desirable, including access to embedded transducers in composite structures. These may allow GW SHM to be used in extreme environment applications, such as in long-duration-mission spacecraft, aircraft engines, thermal protection system structures, cryogenic tanks, etc. In addition, transducer design should consider minimizing power and incorporating an onboard energy source for independent functioning. Significant advances in energy storage and/or harvesting devices are required to enable onboard power supply for GW excitation. Emerging alternatives in this regard are micro-engines (see, for example, Mehra et al., 2000) and fuel cells (Appleby, 1996; Fuller and Perry, 2002); however these are still far from commercialization. Another promising option is the wireless transmission of energy in the form of radio frequency waves, as was done in the work by Kim et al. (2002).

Theoretical work to model GW excitation by SHM transducers should be extended to more realistic structural configurations, such as curved shells, built-up structural constructions and composite structures. More investigation is required into different array configurations; these have better potential to monitor larger structural areas from a central location on the structure. In addition, coupled dynamics models of the transducer and the base structure are necessary and should be pursued. In many of the above scenarios, pure analytical models may not be possible and a combination of semi-analytical and numerical methodologies will be required. Modeling work carried out for piezos will need to be extended towards modeling other non-conventional transducers.

In the majority of the reviewed literature, GW testing was restricted to the lower GW modes. This might suffice if one is purely interested in locating the defect, and not in characterizing it. For the latter, higher modes would be very useful because of their higher selectivity and better defect sensitivity. The reluctance of researchers to use higher modes can be traced to two reasons: (i) the higher power requirements associated with exciting the necessary higher frequencies; (ii) most importantly, the inadequacy of the current signal-processing algorithms for higher mode testing. Advanced signal-processing methodologies that can accommodate such testing should be explored. These should be complemented by the development and use of defect sensitivity models for better theoretical foundations in defect characterization. While several signal-processing methodologies have been developed, most have not considered minimizing the computational complexity and processing power requirements. Future developments in this area should optimize the local processing requirements and minimize data to be transmitted to a central controller.

Finally, structural designers must take a holistic view of all SHM approaches and make use of the advantages of each in attacking SHM system problems. GW methods may certainly provide for the large-area coverage of more homogeneous structural layouts. There are several opportunities for retrofitting SHM systems in existing structures. However, it is our view that SHM systems will be much more effective if made an integral part of the structural design process, right from the planning stage. Much more work is required in this area.

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