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Ultrasonic and Electromagnetic Waves for Nondestructive Evaluation and Structural Health Monitoring

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Abstract

Use of ultrasonic and electromagnetic waves is continuously increasing for nondestructive evaluation (NDE) and structural health monitoring (SHM) in civil, aerospace, electrical, mechanical and bioengineering applications. Between bulk waves and guided waves, the latter is becoming more popular for NDE/SHM applications because the guided waves can propagate long distances and reach difficult to access regions. For inspecting porous and some non-porous materials in which the ultrasonic waves attenuate fast, electromagnetic waves such as THz (terahertz) radiations have been found to be very useful. Recent advances in ultrasonic and electromagnetic wave applications for NDE and SHM are discussed in this paper.

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1. Introduction

Guided ultrasonic waves are very useful for Nondestructive Testing (NDT) of materials. Their use for material inspection and structural health monitoring (SHM) is increasing continuously. The reasons behind its increasing popularity are: (1) compared to the bulk waves the guided waves can propagate longer distances before they lose their strengths, (2) both longitudinal and shear stresses are generated by guided waves and thus various types of defects can be detected by guided waves after properly combining normal and shear stress components, (3) guided waves have multiple modes and by tuning the appropriate mode it is possible to image various types of hidden defects.

Ultrasonic waves for NDT applications are often generated by ultrasonic piezoelectric transducers or piezoceramic patches mounted on the specimen. Piezoelectric transducers and patches are used both as transmitters to
generate, and as receivers to receive ultrasonic waves. Sometimes the specimen is immersed in a fluid medium for NDT inspection because the fluid serves as a good coupling medium for ultrasonic waves. When the specimen is immersed in a fluid, the ultrasonic waves can easily travel from the transducer to the specimen through the coupling fluid. However, ultrasonic waves encounter difficulty in propagating through porous and viscous materials because these waves attenuate very fast in such materials. For nondestructive inspection of such materials electromagnetic waves in the terahertz (10^{12} Hz) frequency range have been found to be quite useful. Those electromagnetic waves are called T-ray.

For better understanding of the experimental results and for correct interpretation of ultrasonic and electromagnetic wave generated images and scattered field patterns a good understanding of the interaction between these waves and the specimen geometry is needed. For this reason a good modeling tool for the analysis of wave propagation in specimens having various geometrical shapes and containing internal anomalies is necessary. These problems cannot be solved analytically. Numerical techniques such as the finite element method (FEM) and boundary element method (BEM) are not very efficient for modeling high frequency wave propagation problems because the required element size is very small for that case.

An efficient semi-analytical technique called DPSM (Distributed Point Source Method) has been recently developed for this purpose and is discussed here. This technique is very useful for modeling the stress/displacement fields (for ultrasonic waves) and electric/magnetic fields (for electromagnetic waves) in the vicinity of an anomaly – crack and inclusion – or a boundary. Thus DPSM can numerically simulate ultrasonic and electromagnetic experiments. In this new era of immense computational power, engineers and scientists are implementing different numerical and semi-analytical techniques to solve a variety of engineering and scientific problems using high speed computers to reduce the cost and time associated with conducting experiments.

The FEM has gained popularity for numerical simulation in almost all fields of engineering. However, the success of the finite element method in high frequency wave propagation problems has been limited due to the requirement of extremely small size elements. DPSM can avoid this difficulty and successfully model the wave fields in fluid and solid structures.

DPSM technique for ultrasonic field modeling was first developed by Placko and Kundu [1]. They successfully used this technique to model ultrasonic fields in a homogeneous fluid [2], non-homogeneous fluid with multiple interfaces [3], and fluid containing a cavity [4,5]. It was also extended to model phased array transducers [6]. It was then generalized to model stress and displacement fields near a fluid-solid interface [7], in plates with uniform and non-uniform thicknesses [8-10], and in the vicinity of cracks [11-14].

2. Experimental Investigation

Experimental results for a composite plate and a composite-concrete interface are presented in this section to show the superiority of the guided wave imaging technique over the conventional C-scan technique that uses bulk or body waves (often longitudinal or P-wave).

2.1 Composite Plate Inspection by Ultrasonic Technique

To compare guided wave and bulk wave generated ultrasonic images, a five-layered composite plate was fabricated with some internal defects [15]. Fibers in the top, bottom and middle layers run in the 0° direction while the second and fourth layer fibers run in the 90° direction. Top and bottom layers did not have any imperfection but the fibers in the middle layer were broken as shown in Fig. 1. Some fibers from the fourth layer were missing, see Fig. 1. There are no broken or missing fibers in the second layer; however during the fabrication process the left half of the second layer was not properly attached to its neighboring layer and it created a delamination defect. The objective was to detect these internal defects (broken fibers in the third layer, missing fibers in the fourth layer, and the delamination the the second and the first layers) in otherwise perfect looking composite plate specimen by scanning it with the bulk P-wave (Conventional C-scan technique) and different Lamb waves. Generated images are shown in Fig. 2. From this figure one can see that the bulk wave images can only show the delamination defect while
different Lamb mode generated images can clearly show all three types of defects. Readers are referred to reference 15 for more information on this composite plate inspection technique.

![Image 1: Left photo: third layer of the composite plate specimen showing broken fibers running in the 0° direction; right photo: fourth layer of the specimen showing some of the fibers running in the 90° direction are missing [15]](image1)

Figure 1: Left photo: third layer of the composite plate specimen showing broken fibers running in the 0° direction; right photo: fourth layer of the specimen showing some of the fibers running in the 90° direction are missing [15]

![Image 2: Left images are generated by bulk P-waves (conventional C-scan technique); right images are generated by different Lamb wave modes [15]](image2)

Figure 2: Left images are generated by bulk P-waves (conventional C-scan technique); right images are generated by different Lamb wave modes [15]

### 2.2 Composite-Concrete Interface Inspection by Ultrasonic Technique

A popular technique for strengthening old concrete structures is wrapping concrete beams and columns by flexible polymer composite layers. If the composite layer is properly attached to the concrete, then the strength of the composite wrapped structure is significantly increased. However, if there is any delamination or lack of attachment of the composite layer to the concrete substrate, the strength of the retrofitted structure is reduced significantly.

To compare the quality of images generated by bulk waves and guided waves, a specimen was fabricated with a debond or delamination between the composite layer and the concrete block and then scanned by C-scan and Lamb wave scanning techniques. In conventional C-scan technique an ultrasonic transducer working as a transmitter as well as a receiver scans the specimen with a normally incident P-wave or longitudinal wave beam, maintaining a fixed distance between the specimen and the transducer [16]. Time histories recorded over a perfectly bonded region and over the debonded or delaminated region are shown in Fig. 3. Note that the peak values for both signals are the same. This is because the signal reflected from the top surface of the composite plate is not affected by the presence of the debond. Signal arriving after the main peak is affected by the debond because the energy reflected from the composite-concrete interface arrives after the main peak. Ideally, the signals reflected from the top of the composite plate and from the composite-concrete interface should be clearly separated. However, since high frequency ultrasonic signals cannot penetrate deep inside thick composite layers that are used for civil structure rehabilitation, relatively lower frequency (500 kHz to 1 MHz) signals were used. At this frequency signals reflected from the top and the bottom of the composite layer are not clearly separated as shown in Fig. 3.
Figure 3: Reflected (A-Scan) signals from the perfect region (top) and debonded region (bottom) of a composite layer attached to a concrete block [16]

Images are generated by plotting the peak voltage in the time window where reflected signal from the interface arrives but the signal reflected from the top of the composite plate does not appear. Plotting this peak value as a function of the transducer position the C-scan image is generated. Right two images of Fig. 4 are obtained in this manner using 500 kHz (top) and 1 MHz (bottom) ultrasonic signals [16]. In both images the debonded region can be seen. However, one can see that the quality of the ultrasonic image is much better in the left image of Fig. 4. The left image is obtained by scanning the specimen by a guided wave mode instead of the bulk P-wave. For guided wave scanning two transducers are placed in pitch-catch arrangement. A specific guided wave mode is generated by inclining the transmitter at a critical angle corresponding to that mode and then fine tuning the frequency to produce a strong signal at the receiver position. The generated guided wave propagates through the specimen for a short distance and then it is detected by a receiver, placed in the fluid medium above the specimen surface. The transmitter-receiver pair then scans the surface of the specimen to generate the image of the interface [16].

Figure 4: Ultrasonic images of the delaminated region at the concrete-composite interface. The left image was generated by the Lamb wave scanning. The right two images were obtained by the conventional C-scan technique using 500 kHz (top image) and 1 MHz (bottom image) signals [16].

The Lamb wave inspection technique has been also used to inspect large metal plates [17, 18], metal pipes [19-21], concrete beams [22, 23] and reinforcing bars in concrete [24, 25].
2.3 Porous Material Inspection by Electromagnetic THz Radiation

Ultrasonic waves cannot detect cracks and voids inside very porous materials because such materials have high attenuation for ultrasonic energy; so it does not allow the ultrasonic energy to penetrate deep inside these materials. One example of such porous materials is silica foam TPS (thermal protection system) tiles used in space shuttle as heat insulators. Electromagnetic radiation in terahertz (THz) frequency range (also known as T-ray), can easily penetrate into such highly porous foam materials. T-ray has resolution needed to detect the internal defects.

Experiments were conducted on porous polymer tiles to see if mechanical damages (such as cylindrical holes) in the tile can be detected by passing T-ray through it. One can see in Fig. 5 that the strength of the transmitted THz beam at frequency 500 GHz and higher was altered due to the presence of a 3 mm diameter cylindrical hole oriented perpendicular to the beam path (left figure) while the same hole, when oriented parallel to the beam path (right figure), affected THz beam with frequency as low as 200 GHz [26,27].

![Figure 5: Transmitted T-ray strength as a function of the signal frequency in presence and absence of a cylindrical hole oriented perpendicular (left) and parallel (right) to the beam path [26,27]](image)

After successfully detecting the mechanical damage, it was investigated if the heat induced damage could be detected by THz beams. Extremely porous artificial pumice stone blocks (see Fig. 6) made of polymers were subjected to long term heat exposures at temperatures ranging from room temperature to close to the material’s melting point. It was found that effective dielectric properties were changed as the heat exposure temperatures were raised. A consistent trend with the heat exposure temperature variation was observed in sub-THz frequency. It was observed (see Fig. 6) that the material went through significant changes in its dielectric properties (permittivity index and loss tangent) between 200°C and 400°C, well below its melting point which was near 900°C [26,28].

![Figure 6: Variations of the electromagnetic properties of a porous tile (shown in the middle) as a function of the signal frequency for different heat exposure temperatures – the left figure shows the real part of the permittivity index variation and the right figure shows the loss tangent variations[28]](image)
3. Modeling

In the preceding section it is shown how ultrasonic and electromagnetic waves can detect internal defects. For proper interpretation of these results it is necessary to understand the interaction between elastic and electromagnetic waves with internal anomalies in the material. Unfortunately, only for some simple defect geometries the analytical solution is available. For complex problem geometries one has to depend on the numerical or semi-analytical solutions. Finite element method (FEM) is the most popular numerical technique in engineering and science. However, for wave propagation applications the advancement of FEM has been relatively slow for the reasons stated in the Introduction. With the advancement of computation power and development of more sophisticated finite element codes, such as PZFLEX and COMSOL, the FEM is becoming more popular for solving wave propagation problems. However, it should be noted that the FEM based wave propagation analyses available in the literature today are mostly confined to 2D problems [29-31]. For plane-stress, plane-strain and axisymmetric problems FEM works very well. However, it is difficult to solve a true 3D wave propagation problem at high frequencies by FEM even today [5].

3.1 Semi-Analytical DPSM Technique for Ultrasonic Problems

The semi-analytical technique called Distributed Point Source Method (DPSM) for solving different ultrasonic problems has been discussed in various publications [1-14]. In DPSM modeling a number of point sources are placed inside the solid transducer slightly behind the transducer face as shown in Fig. 7 to generate the acoustic field in the fluid medium in front of the transducer face. This figure shows M spheres of radius \( r_m \) placed behind the transducer face. At the centers of these spheres \( M \) source points are placed. Therefore, the point sources are located at a distance \( r_m \) behind the transducer face.

The pressure field in the fluid at point \( x \) at a distance \( r_m \) from the \( m \)-th point source of strength \( A_m \) is given by [5],

\[
p_m(x) = \frac{A_m \exp(ik_m r_m)}{r_m}
\]

(1)

By placing the point sources slightly behind the transducer face the need to compute the pressure at \( r_m = 0 \) is avoided. If \( M \) point sources model the transducer, as shown in Fig. 7, then the total pressure at point \( x \) is obtained from

\[
p(x) = \sum_{m=1}^{M} p_m(r_m) = \sum_{m=1}^{M} A_m \frac{\exp(ik_m r_m)}{r_m}
\]

(2)

Figure 7: \( M \) point sources, placed at the centers of small spheres located behind the transducer face, model the transducer. Field values (pressure, velocity etc.) are computed at \( N \) target points in front of the transducer [5].

If there is an interface in front of the transducer then additional point sources should be placed on two sides of the interface. Point source strengths are obtained by satisfying the boundary and continuity conditions on the transducer surface and at the interface. Readers are referred to references [5] and [32] for detailed discussion on DPSM formulation. DPSM generated results for various ultrasonic problems are given below.
Figure 8: Fluid-solid interface problem - an ultrasonic transducer generating 2.25 MHz beam strikes water-aluminum interface at 15.4° (left), 30.4° (middle) and 45.4° (right). Note leaky Rayleigh wave generation for Rayleigh critical angle in the middle image [7].

Figure 9: Plate immersed in a fluid - a solid plate is excited by two identical ultrasonic transducers placed on the two sides of the plate (not shown in the figure). Signal frequency and inclination angle of the transducers are adjusted to generate anti-symmetric (left) and symmetric (right) Lamb modes. Difference between two normal stresses ($\sigma_{11} - \sigma_{33}$) is plotted in this figure [8].

Figure 10: DPSM generated ultrasonic fields when a solid plate (middle image) containing a crack is struck by two inclined ultrasonic beams from two sides (top and bottom) of the plate [11, 12].
Figure 11: Pressure variation in the fluid generated by a 2.25 MHz transducer of diameter 6.35 mm (0.25 inch) striking a corrugated plate (left) and a flat plate (right) at 40° striking angle [10].

3.1 DPSM Technique for Electromagnetic Wave Modelling

The Electric and Magnetic fields in terms of Vector potentials using the Lorentz gauge are given by [33]:

\[\mathbf{E} = \nabla \left( \nabla \cdot \mathbf{A} \right) + i\omega \mathbf{A} \]  (3)

\[\mathbf{B} = \nabla \times \mathbf{A} \]  (4)

The Helmholtz equation in terms of vector potential is:

\[\nabla^2 \mathbf{A} + k^2 \mathbf{A} = -\mu \mathbf{J}_{f,s} \]  (5)

\[k^2 = \mu \omega^2 + i\sigma \omega \]  (6)

In which:
- \(\sigma\) = Permittivity of the Linear Medium, \(C^2/N.m^2\)
- \(\mu\) = Permeability of the Linear Medium, \(N/A^2\)
- \(\mathbf{J}_{f,s}\) = Currents due to free sources

Considering the potential equation due to a Dirac pulse excitation at source point \(\mathbf{x}_s\):

\[\nabla^2 \mathbf{A} + k^2 \mathbf{A} = 4\pi \delta(\mathbf{x}_s) \]  (7)

\[A_j = G = \frac{\exp(-ikr)}{r} \]  (8)

\(\mathbf{A} = (A_1, A_2, A_3)\) is the potential Green’s function vector and \(r\) is the distance of target point \(\mathbf{x}_t\) from the source point \(\mathbf{x}_s\).

In DPSM discrete point sources are distributed near boundaries and interfaces. It is assumed that every point source has three components of strength \(J_1, J_2, J_3\) that are computed in such a way that the boundary conditions and the compatibility conditions at interfaces are satisfied. The potential field vector due to a single point source using Eq.8 in terms of \(J_1, J_2, J_3\) and Green’s function \(G\) is defined as:
\[ A = [P]J \]  

(9)

In which:

\[ J = \begin{bmatrix} J_1 & J_2 & J_3 \end{bmatrix}^T \quad \text{and} \quad P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

Using Eqs. 3 and 9, the electric field due to a single point source can be expressed in terms of \( J_1, J_2, J_3 \) and the Green’s functions.

After some mathematical manipulation (see Refs. 26 and 34 for details) the electric field vector in terms of Green’s functions and three point source strength components \( J_1, J_2, J_3 \) is given as:

\[
E_m (\mathbf{r}) = \frac{J_1 G_{d1m}(\mathbf{r}) + J_2 G_{d2m}(\mathbf{r}) + J_3 G_{d3m}(\mathbf{r})}{(\mu \sigma - j \omega \mu_\sigma)} + j \omega J_m G(\mathbf{r})
\]

(10)

Rewriting Eq.10 in matrix form gives:

\[
E = [F]J
\]

(11)

In which

\[
F = \frac{1}{(\mu \sigma - j \omega \mu_\sigma)} \begin{bmatrix} G_{d11} & G_{d12} & G_{d13} \\ G_{d21} & G_{d22} & G_{d23} \\ G_{d31} & G_{d32} & G_{d33} \end{bmatrix} \begin{bmatrix} j \omega G & 0 & 0 \\ 0 & j \omega G & 0 \\ 0 & 0 & j \omega G \end{bmatrix}
\]

(12)

For solving a problem with two spherical scatterers (\( X_1 \) and \( X_2 \) in Fig. 12(a)) in front of an electric emitter the DPSM model should place point sources both behind the emitter surface and the scatterer interfaces as shown in Fig. 12(a). The DPSM generated electric field in front of the emitter in absence and presence of scatterers are shown in Figs. 12(b) to (d) [34].

![Figure 12: Interaction between Gaussian THz beam beam and dielectric scatterers generated by DPSM modeling - (a) Schematic of the DPSM model showing point source locations, (b) electric field withno scatterer, (c) electric field with oneoff-axis single scatterer, (d) electric field with oneon-axis single Scatterer, and (e) electric field in presence oftwo scatterers[34].](image-url)
Conclusions

In this paper some experimental results and semi-analytical DPSM generated results are presented for both ultrasonic and electromagnetic wave propagation problems in presence and absence of anomalies. Experimental results show the advantage of using ultrasonic guided waves for internal defect detection and advantage of using electromagnetic THz radiation for detecting mechanical and heat induced damage in highly porous materials. Different computed results demonstrate the flexibility of DPSM in modelling elastic and electromagnetic wave scattering problems. Interested readers are referred to a number of references provided in the text and in the figure captions for more detailed derivation of the theory and systematic presentation of the experimental results.

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