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FINAL REPORT

SIMULATION IN THE ULTRASONIC SUBMERSION TEST FOR LAYERED ANISOTROPIC PLATES

GRANT AFOSR-89-0399

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Simulation in the Ultrasonic Submersion Test

for Layered Anisotropic Plates

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Abstract

This is a report describing the research performed during the past two years. The project has been funded for two years, and additional funding for a third year is requested. The contents of this report includes the following: (I) a description of the typical ultrasonic submersion test set-up, (II) a brief summary concerning the research achievements for the past two years. A renewal of one year was requested to complete work already brought to a high level during the past two years and is currently being funded.

I. Typical ultrasonic submersion test set-up

The ultrasonic submersion test is a useful technique for the inspection of material properties. The present research topic concerns the use of the ultrasonic submersion test as a means to inspect multilayered fiber reinforced composite plates. Each layer of the composite is a transversely isotropic solid characterized by five elastic constants.

The significance of an ultrasonic test relies on its ability to interpret the acoustical signals picked up by the transducer. Figure (1) illustrates the ultrasonic submersion test set-up given by Wu & Ho (1990). A transducer sends a pressure wave, which propagates through the coupling fluid, penetrates through a sample plate and reaches the receiver transducer located on the opposite side of the coupling fluid.

The goal of this research is ultimately to determine the structural properties of a sample composite plate, such as its layer configuration and stiffness. This goal can be achieved by understanding well the physical principles of the test so that the acoustical signals picked up by the receiver transducer are correctly evaluated. For example, the interpretation of the arrival time of acoustical signals is related to the path of a wave package and its speed, both of which depend on the sample stiffness. The interpretation of the pressure level in the receiver transducer is related to the transmission coefficient, attenuation and geometrical decay of the propagating waves. The transmission coefficient depends on the mechanical properties of the sample, such as its impedance and other factors. The geometrical decay is related to the propagating distance from the pitcher transducer to the receiver transducer. A successful interpretation of an ultrasonic test means that such structural properties of the sample as its layer configuration or stiffness may be precisely extracted.

Because of its close relation with the stiffness of the sample and its easy interpretation from the picked up signals (wavefront), the determination of the wavespeed is one of the major concerns in an ultrasonic test . Two types of wavespeeds, body-wave and guided-wave, are the main concern in a test.

When a *high frequency* wave package penetrates through a composite plate, the wavespeed of major concern is the body wave type. The first distinctive feature of waves in anisotropic media is the difference between the direction of power flow and the direction of phase flow. In figure 2 (Auld, 1973), the direction of phase velocity is horizontal while the direction of power flow is not. In anisotropic media, the path of a wave train is interpreted to mean the path of power flow. The ray path in the composite plate, figure 1, is the direction of power flow, not the direction of the phase velocity. The path and the velocity of power flow can be easily measured from the location of the receiver transducer and the arrival time of the wavefront of a wave package. Wu and Ho (1990) successfully interpreted the location of the transducer and the arrival time of the acoustical signals to obtain the five elastic constants of a single layered composite. However, they did not study multilayered plates and did not study the propagating (decay) feature of waves in the composite.

When a *low frequency* wave package is incident from certain special angle and excites a guided wave mode, the wavespeed of concern is a guided-wave type (Lamb or leaky Lamb wave). The guided wavespeed is obtained from solving a frequency equation, which is an equation giving the relationship between wavenumbers and excited frequency. For multilayered media, the frequency equation can be found from the propagator matrix of the system. Many recent articles published in Journal of the Acoustical Society of America fall into the category of investigating the guided wavespeed, see Chimenti & Nayfeh (1988,1989,1990), Dayal & Kinra (1989), Karim, Mal & Bar-Cohen (1990).

The main difficulty involved with interpreting the pressure level picked up by a receiver transducer is taking into account the effect of attenuation due to imperfection and geometrical decay. As the slowness surface for waves in anisotropic media may not be in a convex shape, a focussing effect may be induced in the wavefront surface. Thus, the second distinct feature of waves in anisotropic media is that the geometrical decay of waves may not be $1/R$ in a three-dimensional space and $1/R^{1/2}$ in a two dimensional space. Without excluding the effect of geometrical decay from the measured signals, a wrong conclusion may be reached concerning the attenuation caused by the imperfection.

Because a composite plate mainly serves the structure by its use as a plate or a membrane, it is also of interest to connect the guided (Lamb) wave modes to the structural vibration modes. The wavespeed in structural vibration modes can be analytically obtained and will provide the asymptotic solutions for the dispersion equation.

In summary, the essence of the ultrasonic testing is the ability to interpret the received acoustical signals. However, this ability relies on the understanding of the physical principles about waves passing through the testing sample. Thus, wavefront analysis, reflection and transmission coefficients, guided waves and geometrical decay are major topics in this research. The achievements made in understanding those topics during the past two years of research will be discussed next.

II. Summary of Current Achievements

(A) Guided waves.

The first part of the result relates to the understanding of guided waves. The far-field displacement expressed in terms of double Fourier integrals is:

$$u_k = \frac{1}{(2\pi)^2} \lim_{r \to \infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{f_k(\eta_1,\eta_2,\omega)}{g(\eta_1,\eta_2,\omega)} \exp[i\,(\eta_1 x_1+\eta_2 x_2-\omega t)]\, d\eta_1 d\eta_2 \tag{1}$$

The poles of the Fourier integrals are related to guided waves and $g(\eta_1,\eta_2,\omega) = 0$ is called the frequency equation. The functions f_k are due to excitations or loadings in a small region. The following represents the conclusions of the past two years:

(1) The dispersion function g can be constructed by propagator matrix method.

(2) For a single layer plate, there are several asymptotic solutions for the frequency equation $g = 0$. At low frequencies, three asymptotic solutions are constructed by membrane and Kirchhoff-plate models. At high frequencies, three asymptotic solutions are obtained from the plane-strain model and the SV wave model. A special solution is related to the common point of the slowness surfaces of quasi-SV-wave branch and SH-wave branch.

(3) The wave forms at the far field can be obtained by applying method of residues

and method of stationary phase, and the corresponding result is

$$u_k \approx \frac{f_k(\eta_1,\eta_2)\exp\{\, i\, [\eta_1 x_1+\eta_2 x_2- \omega t+\mathrm{sgn}(\kappa)\pi/4+\pi/2]\}}{(2\pi|\kappa| r)^{1/2}|\nabla g(\eta_1,\eta_2)|} \tag{2a}$$

where κ is the curvature of the slowness curve $g = 0$ for a specific frequency. Explicitly,

$$\kappa = -\Big[\frac{\partial^2 g}{\partial\eta_1^2}\Big(\frac{\partial g}{\partial\eta_2}\Big)^2 - 2\frac{\partial^2 g}{\partial\eta_1\partial\eta_2}\Big(\frac{\partial g}{\partial\eta_1}\Big)\Big(\frac{\partial g}{\partial\eta_2}\Big) + \frac{\partial^2 g}{\partial\eta_2^2}\Big(\frac{\partial g}{\partial\eta_1}\Big)^2\Big] / |\nabla g|^3 \tag{2b}$$

The expression for the far-field displacement field breaks down when $\kappa = 0$, which occurs when the slowness curve does not have a convex shape, and the corresponded guided wave decays slower than $r^{1/2}$.

(4) The wavefront curve of Lamb waves at time t due to a point source at $t = x_1 = x_2 = 0$ is the curve $x_k = V_k t$ where the velocity vector of the power flow (Lamb wave) is

$$V_k = \frac{-\,\partial g/\partial\eta_k}{\partial g/\partial\omega}$$

(5) One limiting case for which an analytical formula can be obtained is that of a layer sufficiently thin that the layer is essentially in a plane-stress state. For a thin plate that is subjected to a horizontal (in-plane) point force, the equation of motion is

$$q_{ijkl}G_{km,lj}+\delta_{im}=\rho\,\ddot{G}_{im}$$

where G_{km} is the displacement along the k direction due to a point load applied along the m direction at the origin, and $q_{ijkl}=c_{ijkl}-c_{ij33}c_{kl33}/c_{3333}$ is the reduced stiffness in the plane stress state. The steady-state displacement field written in the form of double Fourier integrals is

$$G_{km} = \frac{-1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{e_{3kp}e_{3mq}(q_{psqt}\eta_s\eta_t-\rho\,\omega^2\delta_{pq})}{g}\exp[i\,(\eta_1 x_1+\eta_2 x_2-\omega t)]\,d\eta_1 d\eta_2$$

where the explicit form of the dispersion function is

$$g=(q_{1111}\eta_1^2+q_{1212}\eta_2^2-\rho\omega^2)(q_{1212}\eta_1^2+q_{2222}\eta_2^2-\rho\omega^2)-(q_{1212}+q_{1122})^2\eta_1^2\eta_2^2$$

From g = 0, the explicit relationship between wavenumbers and frequency is

$$\left(\frac{\omega}{\eta}\right)^2=\frac{(q_{1111}+q_{1212})c^2+(q_{1212}+q_{2222})s^2\ \pm\sqrt{[(q_{1111}-q_{1212})c^2+(q_{1212}-q_{2222})s^2]^2+4(q_{1212}+q_{1122})^2c^2s}}{2\rho}$$

where $c^2=\cos^2\theta$, $s^2=\sin^2\theta$ and $\eta_1=\eta\cos\theta$, $\eta_2=\eta\sin\theta$. Also, $\partial g/\partial\eta_i$ and $\partial^2 g/\partial\eta_i\partial\eta_j$ are

$$\frac{\partial g}{\partial\eta_1}=2\eta_1[q_{1111}(2q_{1212}\eta_1^2+q_{2222}\eta_2^2-\rho\omega^2)+q_{1212}(q_{1212}\eta_2^2-\rho\omega^2)-(q_{1212}+q_{1122})^2\eta_2^2]$$

$$\frac{\partial g}{\partial\eta_2}=2\eta_2[q_{1212}(q_{1212}\eta_1^2+2q_{2222}\eta_2^2-\rho\omega^2)+q_{2222}(q_{1111}\eta_1^2-\rho\omega^2)-(q_{1212}+q_{1122})^2\eta_1^2]$$

$$\frac{\partial^2 g}{\partial\eta_1^2}=2[q_{1111}(6q_{1212}\eta_1^2+q_{2222}\eta_2^2-\rho\omega^2)+q_{1212}(q_{1212}\eta_2^2-\rho\omega^2)-(q_{1212}+q_{1122})^2\eta_2^2]$$

$$\frac{\partial^2 g}{\partial\eta_2^2}=2\{q_{1212}(q_{1212}\eta_1^2+6q_{2222}\eta_2^2-\rho\omega^2)+q_{2222}(q_{1111}\eta_1^2-\rho\omega^2)-(q_{1212}+q_{1122})^2\eta_1^2\}$$

$$\frac{\partial^2 g}{\partial\eta_1\partial\eta_2}=4\eta_1\eta_2[q_{1212}^2+q_{1111}q_{2222}-(q_{1212}+q_{1122})^2]$$

(B) Body Waves:

The far-field displacement expressed in terms of triple Fourier integrals is:

$$u_k^\alpha=\lim_{R\to\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{F_k^\alpha(\eta_1,\eta_2,\eta_3^\alpha)}{S^\alpha(\eta_1,\eta_2,\eta_3^\alpha)}\exp[i\,(\eta_1x_1+\eta_2x_2+\eta_3^\alpha x_3-\omega t)]\,d\eta_1d\eta_2d\eta_3^\alpha \tag{3}$$

For this case the major concern is to determine how the incident wave package propagates from the first fluid-solid interface to the second fluid-solid interface. The propagation of waves from the second fluid-solid interface to the receiver transducer is not of immediate concern as the waves are propagating in the coupling fluid. The function F_k^α is related to excitations or loadings in a small region. The function S^α has the property that $S^\alpha = 0$ is the equation for the slowness surfaces. The conclusions of the study are given next.

(1) The function F_k^α, related to the incident waves, can be obtained. Carrying out one Fourier integral by the method of residues, the displacement field of eq (3) becomes:

$$u_k^\alpha = \lim_{R\to\infty} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{2\pi i\, F_k^\alpha}{\dfrac{\partial S^\alpha}{\partial \eta_3^\alpha}} \exp[i\,(\eta_1 x_1+\eta_2 x_2+\eta_3^\alpha x_3-\omega t)]\, d\eta_1 d\eta_2 d\eta_3^\alpha$$

For an incident wave that originates from the fluid side and penetrates to an anisotropic half space, the incident wave can be viewed as a synthesis of plane waves with amplitude $A(\eta_1,\eta_2)$. Then,

$$\frac{2\pi i\, F_k^\alpha}{\partial S^\alpha/\partial \eta_3^\alpha} = A T^\alpha d_k^\alpha \quad \text{or} \quad F_k^\alpha = \frac{A T^\alpha d_k^\alpha}{2\pi i}\frac{\partial S^\alpha}{\partial \eta_3^\alpha}$$

where T^α is the transmission coefficient of a plane wave and d_k^α is its polarization vector.

(2) The wave forms of eq (3) at the far field are

$$u_k^\alpha = \frac{4\pi^2 F_k^\alpha}{|\kappa^\alpha|^{1/2} R\, |\nabla S^\alpha|} \exp[i(\gamma+\eta_1 x_1+\eta_2 x_2+\eta_3^\alpha x_3-\omega t)]$$

where the Gaussian curvature is

$$\kappa^\alpha = \frac{\left(\dfrac{\partial^2 \eta_3^\alpha}{\partial \eta_1^2}\right)\left(\dfrac{\partial^2 \eta_3^\alpha}{\partial \eta_2^2}\right) - \left(\dfrac{\partial^2 \eta_3^\alpha}{\partial \eta_1 \partial \eta_2}\right)^2}{\left[1+\left(\dfrac{\partial \eta_3^\alpha}{\partial \eta_1}\right)^2+\left(\dfrac{\partial \eta_3^\alpha}{\partial \eta_2}\right)^2\right]^2}$$

and $\gamma = \pi/2$, 0 or π, depending on the signs of the two principal curvatures. The point of stationary phase $(\eta_1,\eta_2,\eta_3^\alpha)$ satisfies

$$S^\alpha(\eta_1,\eta_2,\eta_3^\alpha)=0 \quad \text{and} \quad \frac{\dfrac{\partial S^\alpha}{\partial \eta_1}}{x_1} = \frac{\dfrac{\partial S^\alpha}{\partial \eta_2}}{x_2} = \frac{\dfrac{\partial S^\alpha}{\partial \eta_3^\alpha}}{x_3} \tag{5}$$

This result also means that when the phase velocity is along the direction $(\eta_1, \eta_2, \eta_3^\alpha)$, its corresponding direction of energy velocity, (x_1, x_2, x_3), is along the normal direction to the slowness surface, i.e., $(\partial S^\alpha/\partial\eta_1, \partial S^\alpha/\partial\eta_2, \partial S^\alpha/\partial\eta_3^\alpha)$.

The expression giving the far field displacement breaks down when curvature ($\kappa \rightarrow 0$). This case will occur when the shape of a slowness surface is not convex, and the decay of waves is slower than $1/R$. Two special cases are related to cuspidal edges, which decay as $1/R^{5/6}$, or conical points, which decay as $1/R^{1/2}$. Our study confirms that the quasi-SV slowness surface of a typical fiber reinforced composite does not have a convex shape.

(3) Explicit formulae have been given to evaluate the required flight time and the horizontal shift of the receiver transducer to pick up the rays for a multilayered composite plate.

(C) The reflection and transmission coefficients

The reflection and transmission coefficients for a plane wave incident from an arbitrary angle of a pitcher transducer to the receiver transducer were also studied. The reflection and transmission coefficients were obtained by the method of propagator matrix. The effect of interfacial debonding is also considered. Detailed information is given in the paper sent out to publication and included with this proposal.

Publications during project period

1. W. Lin and L. M. Keer, "A Study of Lamb Waves in Anisotropic plates", Journal of the Acoustical Society of American, in press.
2. W. Lin and L. M. Keer, "Propagation of Waves in Fibre-Reinforced Composite Plates", under review.

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Personnel

During the project period, a post-doctoral fellow, W. C. Lin, assisted L. M. Keer in the performance of the research.