論 文

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Ultrasonic Nondestructive Evaluation(NDE) of Composite Materials

— A Review —

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Synopsis This essay is a general review of the application of ultrasonic NDE techniques to the performance assessment and characterization of composite materials. A brief review of ultrasonic input-output characterization of a composite plate by shear waves is presented. A theoretical development of ultrasonic wave propagation in isotropic and anisotropic media excited, respectively, by a circular transducer and an oscillatory point source is summarized. Some experimental results are described in which ultrasonic velocity and attenuation measurements give insight into material degradation of fatigued composite laminates. Ultrasonic determination of the elastic constants of a composite plate and an experimental attempt at ultrasonic testing of an isotropic plate containing a crack are also included. A recent effort for the characterization of viscoelastic materials using the ultrasonic NDE technique is outlined. Finally, the reliability of ultrasonic NDE is briefly touched upon.

1. Introduction

Ultrasonic nondestructive evaluation techniques have been widely utilized in many engineering problems such as flaw detection, material processing controls, material property characterizations and degradation judgements of engineering structures for both isotropic and anisotropic materials. However, the accomplishments in ultrasonic nondestructive evaluation(NDE) studies for engineering applications seem to be far from completeness, although abundant research reports in this area have been published. There has been only partial success in the application of ultrasonic NDE techniques to many materials characterization problems and the need for further intensive research efforts on the problems can not be emphasized too much. Among other newly developed materials, fiber reinforced

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composite materials are most attractive materials for aerospace applications because of their high specific mechanical properties. It has been shown that many composites, such as the unidirectional fiber glass epoxy composites or fiber glass reinforced ceramics, as shown in Fig. 1, may be modelled

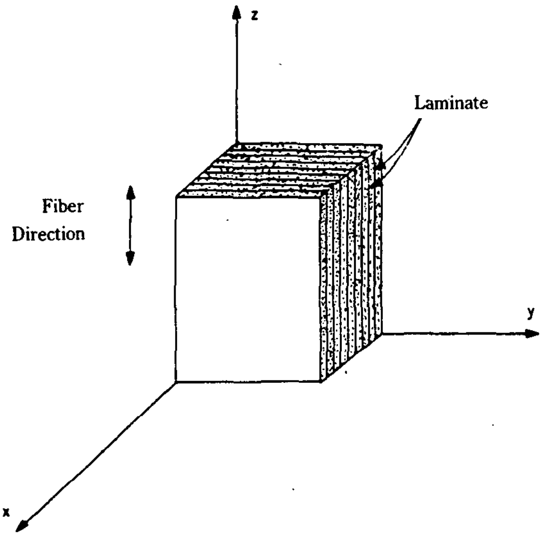

Fig. 1 Unidirectional fiber reinforced composite modelled as transversely isotropic medium.

as a homogeneous transversely isotropic continuum without noticeable error for engineering applications.[1] The incident SH wave was recently used by Williams et al.[2] for the investigation of ultrasonic noncontact input-output characterization of a homogeneous transversely isotropic elastic plate to enhance the quantitative understanding of the ultrasonic NDE parameter such as stress wave factor (SWF). Furthermore, it also provides the potential for assisting in the development of better NDE schemes utilizing the SWF. The SWF has been generally used to characterize microstructural defect states of materials since Vary et al.[3] introduced this factor for nondestructive evaluation for materials. Unlike conventional pulse-echo testing[1] where nonoverlapping reflected wave echoes are analyzed, the SWF is also valid for the analysis of overlapping echoes. An important step in any quantitative ultrasonic NDE procedure is the analysis of the stress wave transmission characteristics of the test structure through which the transmitting and receiving transducers communicate. The ultrasonic input-output characteristics of the SWF configuration in isotropic plates of any thickness; in particular, to plates whose thickness are smaller than the far field distance of the transmitting transducer was investigated by Karagulle et al.[5] The stress wave field generated by a point source in an infinite anisotropic medium can be described in analogy with the problem of magnetohydrodynamic waves discussed by Lighthill.[6] The particular case of transversely isotropic media has been studied by Williams et al.[7] with utilization of an asymptotic approximation. The theoretical prediction of the stress wave fields under a point source excitation can give information regarding the proper use of NDE techniques. This may also provide improved precision of a material's diagnosis by establishing more quantitative standards. It is common to model fiber reinforced composites as homogeneous materials. However, fiber reinforced composites are inherently nonhomogeneous materials in which fabrication procedures can affect their service reliability without effect on their visual appearance. Williams et al.[8] observed in an unidirectional graphite fiber epoxy composite that a small change(14℃) in the precure temperature resulted in significant changes in transfiber compressive fracture strength and the transfiber compression-compression fatigue life. The ultrasonic attenuation of the composite in the as-fabricated state was considered as an indicator of the composite fatigue life in Ref.8. The relationship between ultrasonic attenuation and fatigue survivability of graphite fiber epoxy composites fabricated under various processing temperatures and pressures were made. Ultrasonic NDE techniques have been used to measure elastic material properties such as elastic constants for both isotropic and anisotropic materials. The through transmission ultrasonic technique was used to measure the phase velocities of longitudinal and shear stress waves for the determination of the elastic constants of a fiberglass epoxy unidirectional composite.[9] The pulse-echo configuration of conventional ultrasonic testing techniques(in which the transmitting and receiving transducers are coupled to the same face of the test structure) utilized the reflected wave field(echo) from the defect. The echo from a defect is affected by the defect type, shape, size, orientation and diffraction of the incident ultrasonic wave. The received-signal gives an accurate measure of the defect size only in a limited number of cases. The SWF analysis has shown encouraging results in several NDE applications, for example, Ref. see10. The experimental SWF output signals generated in isotropic plates containing cracks perpendicular to their faces are analyzed by Williams et al.[11] Ultrasonic NDE techniques have been reconsidered as a useful tool to characterize polymeric materials even though the high attenuation causes some problems regarding experimental accuracies. Characterizing some polymers(namely, polypropylene and polycarbonate), Lee at al.[12] recently used the ultrasonic NDE technique. The effect of nonlinear viscoelasticity on ultrasonic output signals was investigated. Two theoretical models for the study of nonlinear viscoelasticity via ultrasonic NDE techniques were proposed and ultrasonic NDE experimental results obtained during material creep tests were given. A direction of further ultrasonic NDE studies in the nonlinear viscoelasticity was suggested. After the importance of nondestructive testing came to be recognized in the 1930s and 1940s, NDE techniques, together with a better understanding of the characteristics and failure modes of materials, have become realized as important ingredients for producing reliable structures and materials. However, many large and small failure accidents of various structures are still occurring thoughout the world. This may remind us of a old phrase saying, "It is impossible to make anything foolproof, for fools are always ingenious". Recently, the reliability of nondestructive inspection has been of concern to Silk et al.[13] In the following a critical review on the arguments mentioned in this chapter will be given. It is not attempted, however, to complete the existing various problems in the area of ultrasonic NDE techniques for composite materials. Nevertheless, it is hoped to render physical insight and intuition in dealing with ultrasonic NDE techniques to various composite materials.

2. Basic Theory

Plane Wave Solution of the Homogeneous Problem

The solution of the equations of motion for transversely isotropic medium are solved under the following assumption: (1) The medium is homogeneous and has constant density. (2) The medium obeys Hooke's law. The equations of motion can be expressed in the compact form as shown below.

$$
\begin{aligned}
Sxx,x + Sxy,y + Sxz,z &= Ro \cdot U,tt \\
Sxy,x + Syy,y + Syz,z &= Ro \cdot V,tt \quad \cdot (2-1) \\
Sxz,x + Szy,y + Szz,z &= Ro \cdot W,tt
\end{aligned}
$$

where Srs(r, s = x, y, z) are the normal(r = s) and shear(r = s) stresses with respect to coordinate system oxyz. U, V and W are the displacement components of a point in the medium along the directions x, y and z, respectively. Ro is the average density of composite material. The index following commas and t denote derivatives and time, respectively. Assuming a general orthotropic medium in which the principal axes coincide with the reference system oxyz, the generalized Hooke's law can be obtained as listed below.

$$Sxx = C_{11} \cdot U,x + C_{12} \cdot V,y + C_{13} \cdot W,z$$
$$Syy = C_{12} \cdot U,x + C_{22} \cdot V,y + C_{23} \cdot W,z$$
$$Szz = C_{13} \cdot U,x + C_{23} \cdot V,y + C_{33} \cdot W,z$$
$$Sxz = C_{44} \cdot (V,z + W,x)$$
$$Syz = C_{55} \cdot (V,z + W,y)$$
$$Sxy = C_{66} \cdot (U,y + V,x) \quad \cdots\cdots (2-2)$$

where the C_{ij} are the nine independent elastic constants of the stiffness matrix. The number of independent constants C_{ij} for transversely isotropic media is reduced to five by the following constraints:

$$C_{11}=C_{22},\ C_{13}=C_{23},\ C_{44}=C_{55},\ C_{66}=(C_{11}-C_{12})/2 \quad \cdots\cdots (2-3)$$

In accordance with eqn. (2−3), the x-y plane is taken to be the isotropic plane for elastic properties. The equations of motion eqn. (2−1) can be written in terms of the displacements U, V and W using eqns. (2−2) and (2−3) for the transversely isotropic medium. Assuming a plane wave solution of the form

$$(U,\ V,\ W)=(Px,\ Py,\ Pz)\exp\{(6.28i/L)(x \cdot Nx+ y \cdot Ny+z \cdot Nz-Vn \cdot t)\} \quad \cdots\cdots (2-4)$$

where Px, Py, and Pz are the amplitude components of a particle displacement vector along the coordinate axes x, y, and z, respectively corresponding to a plane wave with unit normal N. Nx, Ny, and Nz are the direction cosine of the unit normal N along the coordinate axes x, y and z, respectively. Vn is the phase velocity defined for the direction N and L is the associated wavelength with the selected N and Vn. t denotes time. i is $\sqrt{-1}$. Substituting eqn. (2−4) into the equations of motion written in terms of the displacements U, V and W, the equations of motion can be obtained as shown below[1)]

$$C_{11} \cdot Nx^2+C_{66} \cdot Ny^2+C_{44} \cdot Nz^2-Ro \cdot Vn^2 \cdot P_x+(C_{12}+C_{66}) \cdot Nx \cdot Ny \cdot Py+(C_{13}+C_{14}) \cdot Nx \cdot Nz \cdot Pz=0 \quad \cdots\cdots (2-5a)$$

$$(C_{12}C_{66}) \cdot Nx \cdot Ny \cdot Px+(C_{66} \cdot Nx+C_{11} \cdot Ny+C_{44} \cdot Nz-Ro \cdot Vn^2) \cdot Py+(C_{13}+C_{44}) \cdot Ny \cdot Nz=0 \quad \cdots\cdots (2-5b)$$

$$(C_{13}+C_{44}) \cdot Nx \cdot Nz \cdot Px+(C_{13}+C_{44}) \cdot Ny \cdot Nz \cdot Py + C_{44} \cdot (Nx^2+Ny^2)+C_{33} \cdot Nz^2-Ro \cdot Vn^2 \cdot Pz=0 \quad \cdots\cdots (2-5c)$$

The condition for the existence of the plane wave solution can be expressed by setting the determinant of the matrix of the coefficients of Px, Py, and Pz in eqn. (2−5) equal to zero(This equation is known as Christoffel's equation and is not rewritten here). Noting the expression for the determinant is a cubic equation in Vn, three possible values of Vn for each selected set of Nx, Ny and Nz can be obtained. Moreover, the elastic properties are symmetric with respect to the z axis, so the direction cosines for the normal N can be expressed in terms of the angle between N and the z axis from which the velocities can be written in terms of a single variable. The expressions for the phase velocities associated with the possible plane wave solutions can be obtained easily. Furthermore, the amplitude of the particle displacement components associated with each of the phase velocity vectors can be found by using the computed values of the phase velocities.

3. Ultrasonic Input-Output Characterization by SH Waves

Assuming a plane progressive wave of the form similar to the eqn. (2−4) and substituting this into the eqn. (2−2), the stress components can be represented in terms of particle displacement and the slowness vector, which is in the same direction as the normal to the wavefront and whose magnitude is equal to the reciprocal of the magnitude of the phase velocity. Noting the required stress boundary conditions on the stress-free plane boundary, it can be confirmed that the frequency, w, of the reflected waves be equal to that of the incident wave and that

$$Sx^{(I)} = Sx^{(R)}, \quad Sy^{(I)} = Sy^{(R)} \quad \cdots\cdots (3-1)$$

where Sx and Sy are the components of the slowness vector along the x and y axes, respectively and I and R denote incident and reflect, respectively. As a result of eqn. (3−1), the slowness vectors of the incident and reflected waves lie in a plane called the plane of incidence. Locating the incident and reflected waves in the plane x=0, the analysis can be much simplified since

$$Sx^{(I)} = Sx^{(R)} = 0 \quad \cdots\cdots (3-2)$$

However, it should be noted that an SH wave with slowness vector in a plane containing the zonal axis of a transversely isotropic medium possesses a transverse displacement; that is, for the coordinates in Fig. 2, (Px, Py, Pz) = (1, 0, 0) where Px, Py, and Pz are the components of a unit vector of particle displacement along the x,yand z axes,respectively.[14)]

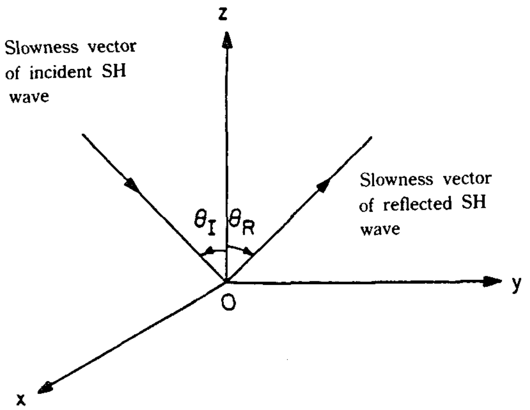

Fig. 2 Coordinate system (x, y, z) in analysis of single reflection problem at stress-free plane boundary of semi-infinite transversely isotropic medium.

Furtheremore, it is also noted that the shear stresses on the plane (which is perpendicular to x-axis) are not zeros; that is, Sxz ≠ 0 and Sxy ≠ 0. Assuming that an SH wave incidenting on the plane boundary (the x-y plane in Fig. 2) and applying the boundary conditions, it can be shown that the only nonzero stress is

$$Sxz^{(I)} \neq 0 \quad \cdots\cdots (3-3)$$

As a result of eqn. (3−3) and boundary conditions, it can be shown that Syz and Szz are equal to zero. This indicates that no P or SV waves will be reflected back into the medium because a reflected wave of either the P or SV type results in nonzero values of the stresses Syz and Szz. The nonzero boundary stress components are $Sxz^{(I)}$ and $Sxz^{(R)}$; that is

$$Sxz^{(I)} + Sxz^{(R)} = 0 \quad \cdots\cdots (3-4)$$

Since a reflected SH wave results in nonzero values of shear stresses Sxz and Sxy, it is therefore concluded that the only an SH wave will be reflected back into the medium. Expanding the Christoffel's equation consisted of coefficients of Px, Py, and Pz in eqn. (2−5) and nothing the slowness surface only for SH waves which are confined to the y-z plane, as shown in Fig. 2, the intersection of the slowness surface with the plane x=0 is given as

$$(C_{66}/Ro) \cdot Sy^2 + (C_{44}/Ro) \cdot Sz^2 = 1 \quad \cdots\cdots (3-5)$$

Typical numerical values of the constants C_{44}, C_{66} and Ro for the fiber glass epoxy composite shown in Fig. 1 are $C_{44} = 4.422 \times 10^9$ N/m², $C_{66} = 3.243 \times 10^9$N/m² and Ro=1850kg/m³. One quadrant of the slowness surface for an SH wave travelling in the fiberglass epoxy composite is obtained by substituting the numerical values of the elastic constants and the density into eqn. (3−5), and is shown in Fig. 3. The amplitude ratio of the reflected SH wave to the incident SH wave can be computed from the boundary condition on the stresses. After some algebraic manipulations the amplitude of the reflected SH wave is obtained as

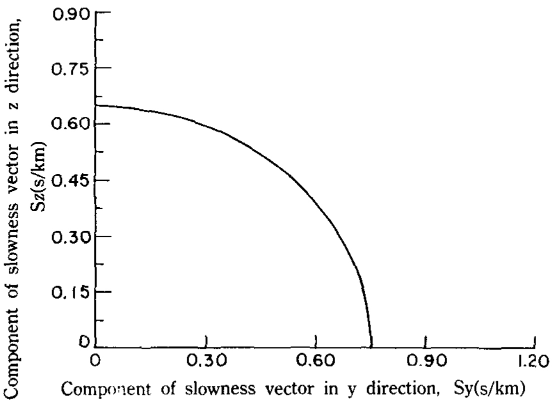

Fig. 3 Slowness surface for SH wave in unidirectional fiberglass epoxy composite for positive y-z quadrant.

$$A^{(R)} = -1 \quad \cdots\cdots \quad (3-6)$$

Therefore, the amplitude ratio of the reflected SH wave to the incident SH wave is negative one. Choosing a Cartesian coordinate system (x, y, z) so that the x-y plane is the isotropy plane (which lies in the midplane of the plate as shown in Fig. 1) and locating non-contact transmitting and receiving transducers on the same face of a fiberglass epoxy composite plate specimen as shown in Fig. 4, the ultrasonic amplitude gain percent (defined as (Vo'/Vo) X 100) (where Vo' is output electrical voltage, Vo is input electrical voltage) can be calulated. The properties of the equivalent continuum model (which are used for some computations in this study) of an unidirectional fiberglass epoxy composite plate are h=0.1m, $C_{11}=10.581\times10^9 N/m^2$, $C_{13}=4.679\times10^9 N/m^2$, $C_{33}=40.741\times10^9 N/m^2$, $C_{44}=4.422\times10^9 N/m^2$, $C_{66}=3.243\times10^9 N/m^2$, and Ro=1850 Kg/m³ where h is the plate thickness. The SH wave travelling from the input 0 to the output M may be considered as waves propagating in a semi-infinite transversely isotropic medium and travelling to point M' as if there were no bottom, as shown in Fig. 4(since the isotropic plane lies in the midplane and is parallel to both the top and the bottom faces where multiple reflections occur, the angle of reflection of the reflected SH wave is equal to the angle of incidence of an incident SH wave for each reflections at each face of the plate). The wave is reflected a total of (2n-1) times, as shown in Fig. 4. Thus, Um the amplitude of the displacement at point M, can be obtained by modifying Um' the amplitude of the hypothetical displacement at the point M' for the SH waves travelling in the y-z plane. Um' can be represented as shown in the following after some algebraic manipulations.

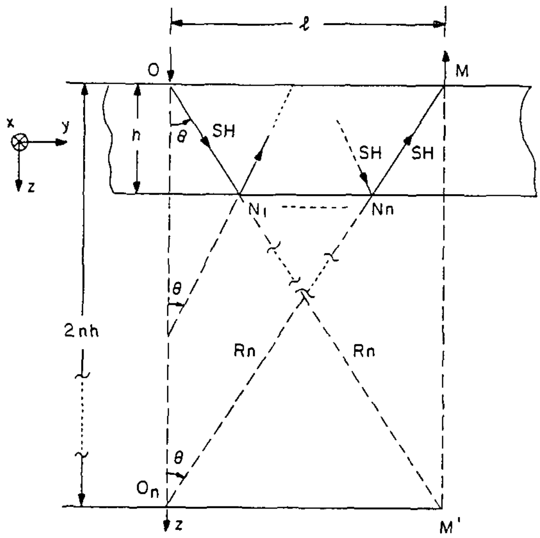

Fig. 4 Path of SH-SH-... wave which arrives at point M after n reflections from bottom boundary.

$$Um' = (C_{44}Ro)^{0.5} \cdot Sz^{*} Fl(w) \cdot Vo/\{6.28 \cdot Rn \cdot (C_{11} - C_{12}\} \quad \cdots\cdots \quad (3-7)$$

where Sz* represents the z coordinate of a point on the slowness surface (where the normal is parallel to the line which connects the origin of coordinate system and a point). Fl(w) is the transduction for the transmitting transducer in transforming a voltage to a stress, Vo is the amplitude of an input voltage and Rn is the total distance travelled by the wave. Um thus becomes

$$Um = Qshsh^{(2n-1)} \cdot Um' \quad \cdots\cdots (3-8)$$

where Qshsh is the reflection coefficient of the SH waves to SH waves, and its value is -1 as noted in eqn. (3-6). The gain percent defined as G% = (Vo'/Vo) X 100 can be represented as

$$G\% = K \cdot Fl(w) \cdot F2(w) \cdot Qshsh^{(2n-1)} \cdot (Ro \cdot C_{44})^{0.5} \cdot Sz^* \cdot \exp(-A\ell \cdot Rn)/\{6.28 \cdot Rn(C_{11}-C_{22})\} \quad \cdots\cdots (3-9)$$

where w is frequency, K is a possible electrical signal amplification factor, F2(w) is the transduction ratio for the non-contact receiving transducer in transforming a displacement to a voltage and Al is the SH wave attenuation constant of the fiberglass epoxy composite. Eqn. (3-9) may be useful in the ultrasonic material characterization of the unidirectional fiberglass epoxy composite plate. The directionally dependent phase velocity of the SH wave $C_\ell(\theta)$, for the unidirectional fiberglass epoxy composite plate is[1]

$$C_\ell(\theta) = [\{C_{66} \cdot \sin^2(\theta) + C_{44} \cdot \cos^2(\theta)\}/Ro]^{0.5} \quad \cdots\cdots (3-10)$$

where

$\theta = \tan^{-1}(\ell / 2nh)$

ℓ = the separation distance between the input 0 and the output M.

n = the number of reflection at the bottom face experienced by the SH wave in travelling from the input 0 to the output M

h = thickness of the composite plate

Then the delay time for the wave to reach the receiving transducer is

$$t_n = Rn/\{C_\ell(\theta)\} \quad \cdots\cdots (3-11)$$

Measuring delay time and gain percent, the material characterization can be carried out and the more rigorous development may be proceeded for investigation of various composite materials.

4. Input Source Dependence on Ultrasonics

The output signals caught on a receiving transducer are dependent on the behavior of the input signals. Steady-state harmonic stress waves in an isotropic elastic plate excited on one face by a circular transducer will affect the output monitored by a separate circular receiving transducer (which located at the same face of the plate). The radiation into a half-space introduces P and S waves into the plate, and they are successively reflected at the bottom and top faces of the plate. The frequency response at a receiving point due to a multiply reflected wave was formulated in integral form and its asymptotic behavior was given.[5] An example of parameterized plots which determine the particular field whose frequency response has the maximum magnitude compared with other reflected fields is shown in Fig. 5. It is very useful in the ultra-

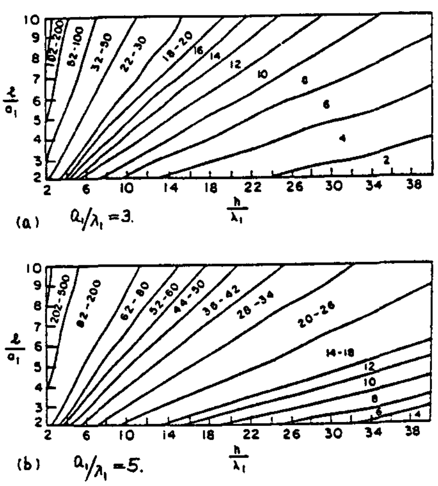

Fig. 5 Some Parameterized plots for a point receiver.

sonic NDE to identify the reflection with the maximum magnitude because it has the maximum signal to noise ratio in the ultrasonic NDE experiment. This also contributes to develop quantitative analyses of ultrasonic NDE parameters such as the stress wave factor (SWF). The spectral analysis of the SWF signal should benefit from this investigation. The knowledge of the far-field displacement pattern in an infinite transversely isotropic medium subjected to an oscillatory point source may be useful to allow a better choice to be made for the positioning of components of the measuring system.[7] Fig. 6, for an example, shows the polar diagram of the

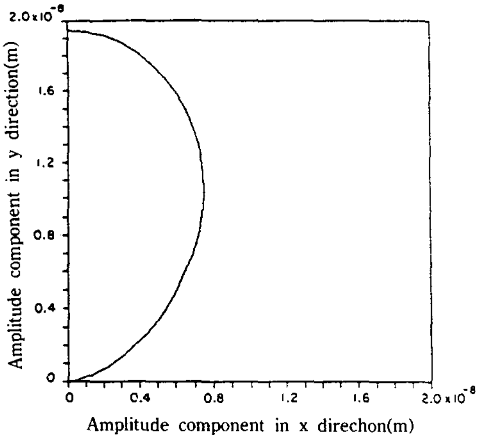

Fig. 6 Polar diagram for u displacement amplitudes for points along the line $x^2 + y^2 = 4m^2$, due to slowness surface SH only.

displacement amplitudes for the points 2 meters away from the origin on the x-y plane which is isotropic. The existence of preferential directions can be regarded as an important aspect to be considered when experimental tests are to be designed.

5. Ultrasonic Indicator of Fatigue Life

The tendency of graphite fiber composites to fail in a quasi-brittle mode (as defined by the absence of a substantial nonlinear region in the stress-strain curve) makes these composites more sensitive than many metals to microscopic imperfections, Macroscopic imperfections in various composites may be introduced during both fabrication and service. These imperfections may affect the ultrasonic wave propagation in terms of attenuation and phase velocity. The detailed ultrasonic NDE experimental data and their interpretation for monitoring fatigue damage or predicting fatigue behavior of various composites is likely to enhance their effective use. Alternate compression-compression fatigue tests for Hercules AS/3501-6 graphite fiber epoxy composites were carried out and ultrasonic longitudinal waves were monitored in Ref.8. A small change (14 ℃) in the precure temperature was found to be resulted in significant changes in the prefatigued static compression fracture stress Sf, the initial attenuation and the number of cycles to failure at Smax=0.8 Sf. During C-C fatigue when Smax=0.8 Sf, there is generally a 5% to 10% increase in attenuation. However, this increase does not appear to be a fracture precursor. The initial attenuation

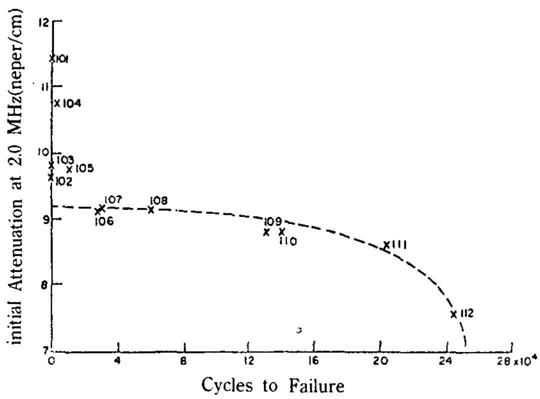

Fig. 7 Initial attenuation at 2.0MHz versus cycles to failure for transfiber compression-compression fatigue of laminate no. 1 specimens at $S_{max}=0.8$ Sf.

at 2.0MHz appears to be a good indicator of the relative survivability in the fatigue environment. There appear to be ultrasonic frequency-dependent "upper cut-off" attenuation values which define a minimal fatigue life and "lower cut-off" attenuation values which defines a fatigue life limit. Fig. 7 shows a typical "upper cut-off" values of approximately 9.4 neper/cm where the initial attenuation at 2.0MHz versus cycles to failure for specimens from laminate No. 1 only is plotted.

6. Ultrasonic SWF Signals of Perpendicular Edge Cracks

For the characterization of cracks perpendicular to the faces of a test structure, special separate transmitting and receiving transducers with an inclined beam angle may be used and the principles of conventional pulse-echo or through-transmission techniques may be applied. This is, however, limited to the analysis of nonoverlapping signals. Stress wave factor (SWF) configuration (in which separate transmitting and receiving transducers coupled to the same face of the test structure as shown in Fig. 8) is known to be valid for the analysis of the

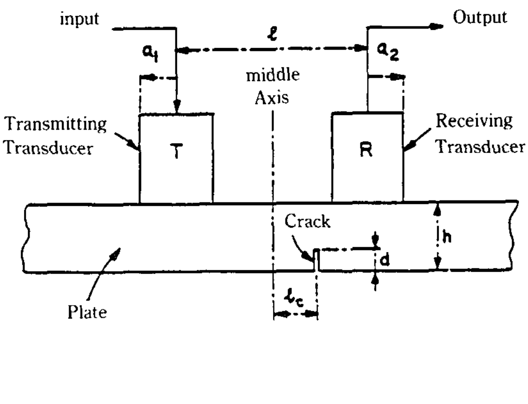

Fig. 8 Schematic of ultrasonic(stress wave factor) configuration showing geometry of plate, crack, and locations of transducers.

output signals with overlapping echoes. The SWF has been generally used to characterize microstructural defect state of materials since it has some characteristics which incorporate with ultrasonic NDE techniques. The existence, lateral location and depth of the crack(perpendicular to the faces of a test structure) affect the ultrasonic output signal characteristics in the frequency domain. The analysis of experimental SWF output signals generated in plates containing cracks perpendicular to its faces appears to be useful for the ultrasonic NDE technique. Fig. 9 shows the typical output, M(fo)

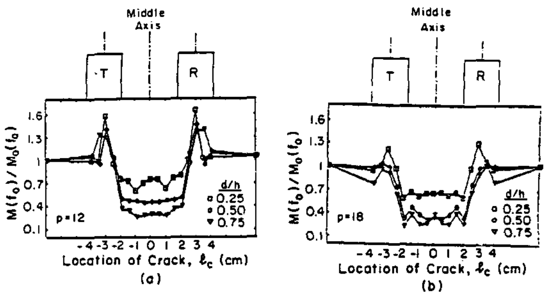

Fig. 9 Magnitude of reflections M(fo) and Mo(fo) with and without a crack, respectively.

/Mo(fo) where M and Mo are the magnitude of the Fourier transform of a reflection with and without a crack, respectively and fo its frequency which varies according to the change of the location of a crack. This result can be utilized to identify the crack more precisely.

7. Ultrasonic NDE of Nonlinear Viscoelasticity

The applicability of ultrasonic nondestructive techniques to experimental nonlinear viscoelastic material characterization was investigated by Lee et al[12]. Two theoretical nonlinear viscoelasticity models, a mechanical model and a phase velocity model(in which nondestructive parameters such as gain percent and phase velocity are distinguished) were proposed. Figs. 10 and 11 show typical relatio-

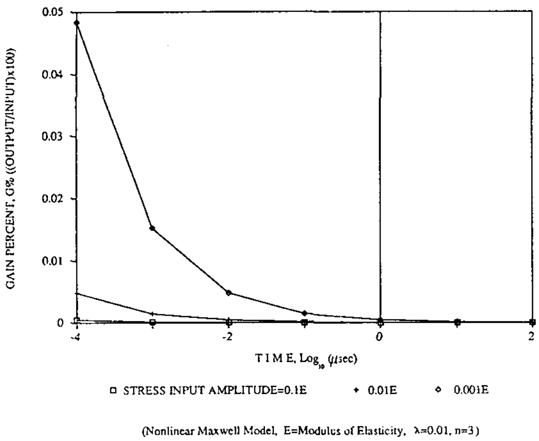

Fig. 10 Gain percent versus propagation time.

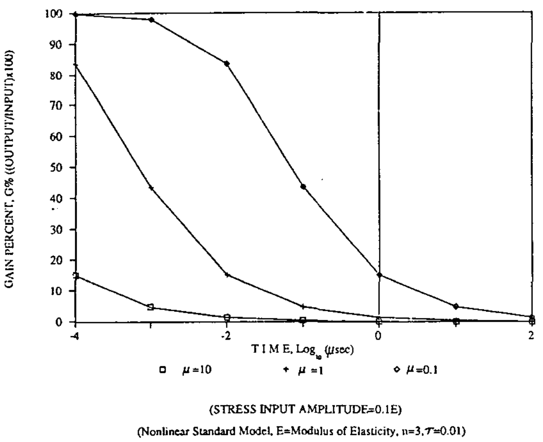

Fig. 11 Gain percent versus wave propagation time.

nships between ultrasonic parameter and nonlinear viscoelastic property. Nonlinear material creep tests were conducted and ultrasonic waves, namely, P waves and SH waves, propagating thorugh the thickness were monitored simultaneously during creep. The attenuation of SH waves was found to be sensitive to the material creep while the amplitude of P waves did not vary during material creep tests. Figs. 12 and 13 show typical experimental results.

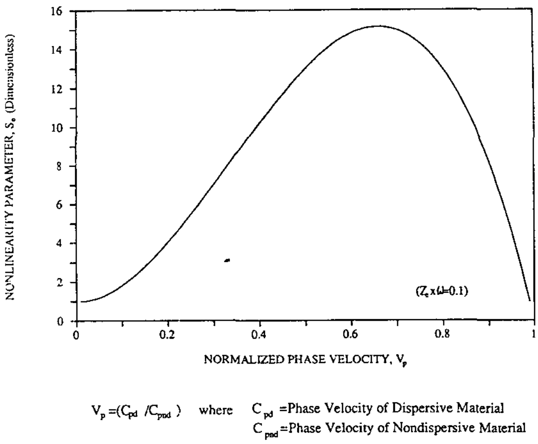

Fig. 12 Phase velocity versus nonlinear parameter.

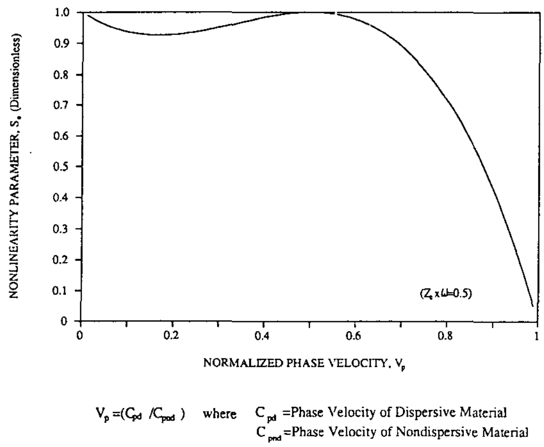

Fig. 13 Phase velocity versus nonlinear parameter.

Further studies via ultrasonic NDE techniques regarding nonlinear viscoelasticity parameters may be proceeded along the development described here.

8. Reliability of Ultrasonic NDE

The ultrasonic NDE technique consists of the following four main components

(1) the way in which the specimen is stimulated
(2) the nature and their interactions of the ultrasonic waves in the specimen
(3) the way of monitoring the response and of post-processing to extract information from received signals
(4) the way of arranging and selecting the sender and receiver to do the required job most efficiently

The following questions based on the above listed four main components in ultrasonic NDE techniques to enhance the reliability should be asked.

(1) Is the test procedure including the selection of couplant and pressure between transducers and specimen satisfactory to reduce the experimental errors ?
(2) Can the theoretical prediction be possible for the known defects in the specimen ?
(3) Is the experimental-data-analysis-tool appropriate for the interpretation of the recorded results ?
(4) Has enough consideration been given to the ways in which human error could affect the results ?

9. Concluding Remarks

A general review of the application of ultrasonic NDE techniques in composite materials is presented. The followings among others are emphasized in particular in this paper.

(1) Theoretical prediction of gain percent (defined as G%=(output electrical voltage/input electrical voltage)X100 and delay time for SH waves is given to enhance the quantitative understanding of the NDE.
(2) Ultrasonic wave propagations in both isotropic and anisotropic media excited, respectively, by a circular transducer and an oscillatory point source are summarized to render information regarding proper use of quantitative ultrasonic NDE technique to composite mateials.
(3) A methodology of the use of ultrasonic NDE techniques in the estimation of fatigue life and in the identification of cracks perpendicular to faces of the isotropic plates is summarized.
(4) An attempt to the characterization of nonlinear viscoelasicity via ultrasonic NDE techniques is introduced. Finally four questions which should be answered to enhance the reliability of ultrasonic NDE technique are provided.

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