POROSITY CHARACTERIZATION IN FIBER-REINFORCED COMPOSITES BY USE OF ULTRASONIC BACKSCATTER

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INTRODUCTION

The use of ultrasonic backscatter to characterize anomalous states in fiber-reinforced composites has received considerable attention in recent years. The ultrasonic backscatter from composites with oriented fiber reinforcement, unlike that from monolithic materials, displays a strong angular dependence. Hence, three independent variables are available over which to analyze the backscatter. These are the azimuthal angle ϕ (the rotation orientation of the composite plate about the perpendicular), the elevation angle θ (the angle between the ultrasonic beam and the perpendicular to the insonified composite plate), and time. Bar-Cohen and Crane [1] considered various ways of exploiting the angular dependence of backscatter to examine anomalies in composite laminates such as fiber misalignment, cracks, and porosity. Several other efforts employing similar approaches have followed [2-4]. This paper addresses specific questions concerning the angular dependence of backscatter and the use of this angular dependence to assess porosity levels. Additionally, problems inherent in the analysis of the temporal behavior of backscatter are discussed, and an approach to the spectral analysis of backscatter for porosity assessment is demonstrated.

EXPERIMENTAL METHOD

The terminology "ultrasonic backscatter" used herein refers to the signal received by a single ultrasonic transducer in a pulse-echo immersion configuration. In general, backscatter data are obtained by using nonperpendicular incidence. A diagram of the backscatter experiment is shown in Fig. 1. Measurements are made with a computerized scanning system which provides rotational movement for azimuthal and elevational scanning, as well as translational (x-y) movement for spatial averaging of backscattered data. Backscattered waveforms are digitized, averaged, and stored at each scan position. The data are then available for further analysis on one of several mainframe computers.

The composite specimens examined in this study are 16-ply laminates of epoxy-impregnated carbon fiber fabric into which porosity was introduced during processing at levels ranging from 0.2 to 6.5 vol. %.

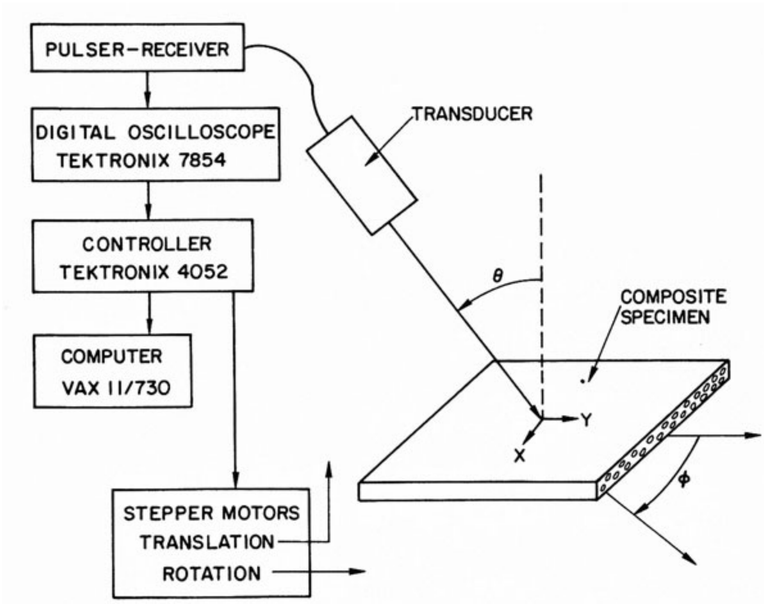

Fig. 1. Schematic of ultrasonic backscatter experiment.

Specimen series with both unidirectional and 0°, +45°, -45°, 90° multidirectional layups were manufactured. Attention is restricted in this paper, however, to unidirectionally reinforced specimens. Ply thickness is approximately 130 μm, and fiber diameter is 8 μm. The fibers constitute 60-65 vol. % of the composite. A more complete description of the test specimens and the techniques used to establish porosity levels is presented in Ref. 5.

To illustrate the complexity of the backscatter phenomenon, Fig. 2 presents the backscattered signal received in response to a 1.5-cycle broadband pulse incident upon a nonporous composite at θ = 35°. The phase information in such backscattered signals undergoes severe and apparently

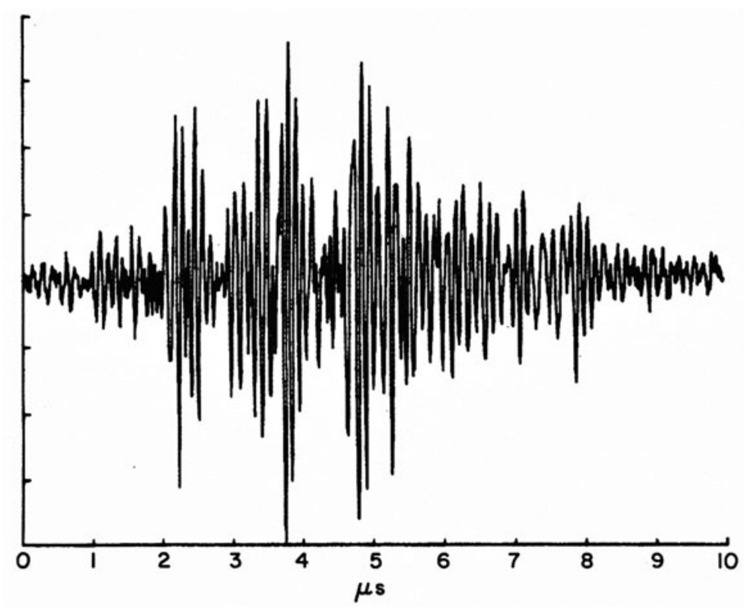

Fig. 2. Ultrasonic backscatter from composite with 0.2 vol. % porosity. 10-MHz transducer at Θ = 35°.

random fluctuations as small changes are made in translational and angular orientation, as is typical of scattering from randomly distributed scatterers. Indeed, the internal structures observed in optical micrographs of composite laminates are aptly described as random perturbations of uniform layers of fibers. Therefore, all scattering data are collected in the form of statistical means obtained through translational (x-y) spatial averaging. Unless otherwise stated, backscattered measurements presented here were obtained by averaging the measured parameter over a 6x6 rectangular grid covering a 2.4-cm x 2.4-cm region of the composite specimen. The spatial average of a parameter p is denoted $\langle p \rangle$.

ANGULAR DEPENDENCE OF BACKSCATTER

In the study discussed here, the maximum achievable separation of the angular and temporal dependence of backscatter is desired. The influence of temporal (or, equivalently, frequency-related) information is significantly reduced by measuring the parameter $\langle E(\theta, \phi) \rangle$ proportional to the total energy of the received broadband wavetrain $v(\theta, \phi, t)$, where

$$E(\theta, \phi) = \int_{-\infty}^{\infty} v^2 (\theta, \phi, t) \, dt. \tag{1}$$

The quantity $E(\theta, \phi)$ was chosen as the measured parameter to simplify comparison with time-harmonic theoretical calculations [5], since it is easily verified that

$$\int_{-\infty}^{\infty} v^2(\theta, \phi, t) \, dt = \int_{-\infty}^{\infty} \left| \hat{v} (\theta, \phi, \omega) \right|^2 d\omega, \tag{2}$$

where $\hat{v}$ represents the Fourier transform of v.

Azimuthal scans of four unidirectionally reinforced composite specimens containing porosity ranging from 0.2 to 6.5 vol. % are presented in Fig. 3. The scan of Fig. 3 was obtained with a 0.5-in. dia., 5-MHz broadband transducer. As noted previously [1-4], maxima occur when the azimuthal orientation of the reinforcing fibers in a constituent ply is perpendicular to the incident ultrasonic beam. This azimuthal dependence of backscatter is, of course, ultimately related to the angular scattering behavior of the individual reinforcing fiber. However, it is proposed that it is more appropriate to view the observed backscatter phenomenon as resulting from oriented inhomogeneities in elastic properties and density due to a nonuniform distribution of reinforcing fibers on the scale of the ultrasonic wavelength. Preliminary digital image analysis of optical micrographs of composite structures reinforces this intuitive notion, and a quantitative correlation will be forthcoming.

It is noted in Fig. 3 that increases in backscatter due to porosity occur in all azimuthal directions. Differences in backscatter between the maximum ($\phi \sim 90°$) and minimum ($\phi \sim 45°$) azimuthal orientations are approximately 22.5, 21.8, 20.4 and 17.4 dB, ±0.6 dB, for the specimens with 0.2, 1.1, 2.0, and 6.5% porosity, respectively. This represents a far more uniform percentage increase in backscatter over azimuthal angle than was previously reported in work which considered the effects of introducing spherical inclusions (glass spheres) into a fiber-reinforced matrix [3]. The explanation for this more uniform percentage increase is possibly provided by the cylindrical morphology of porosity observed in the specimens of this study [6]. It is conceivable that scattering from cylindrical porosity displays an angular dependence quite similar to scattering by the fiber-related internal structures. Thus, the use of maximum-to-minimum backscatter ratios to gauge the percent volume of

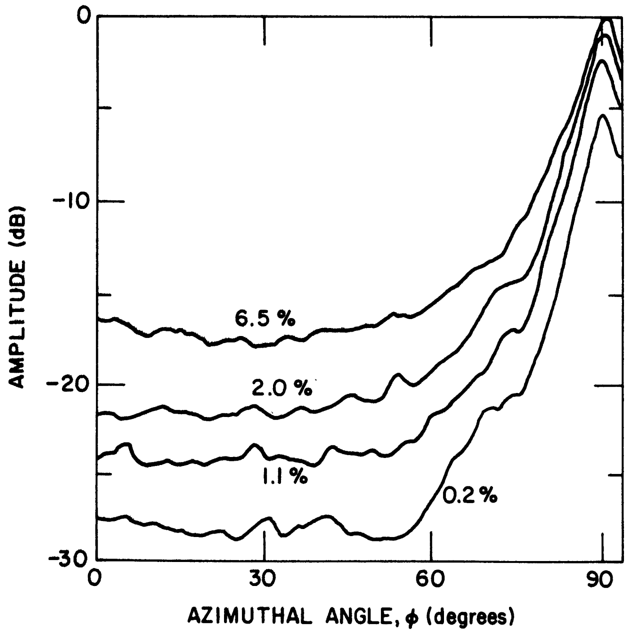

Fig. 3. Backscatter vs. azimuthal angle for unidirectinally reinforced composites with 0.2-6.5 vol. % porosity at $\theta = 35°$.

porosity appears to be less than straightforward. Indeed, such angular scan data may be a better indicator of the morphology than of the volume percent of porosity. It is seen in Fig. 3 that the absolute increase in backscatter at $\phi \sim 45°$ is a more reliable indicator of porosity.

An experiment was performed to investigate the effect of depth on the detection of porosity. The experiment examined backscatter from a stack of five uniformly aligned unidirectionally reinforced specimens having a total thickness of 11 mm. The top four specimens contained 0.2 vol. % porosity, whereas the porosity level of the bottom-most (deepest) specimen was varied. Results of azimuthal scans with a 10-MHz, 0.5-in.-dia. broadband transducer at $\theta = 35°$ are presented in Fig. 4. Although discrimination is not as good, differences between bottom-most specimens with different porosity levels are detected in Fig. 4b. It is noted that scattering at the boundaries between specimens is considerable; hence, porosity discrimination in an actual 11-mm-thick laminate would probably be better. Figure 4 illustrates an additional problem in porosity estimation, i.e., the difficulty of distinguishing a lower level of porosity at smaller depths from a higher level at greater depths.

To further understand the ultrasonic penetration displayed in Fig. 4, angular through-transmission measurements were performed placing a second receiving transducer behind the composite plate shown in Fig. 1. Pulsed through-transmission measurements were performed with highly-damped 10 MHz transducers, which allowed the isolation of the through-transmitted quasi-longitudinal and two quasi-shear pulses. These through-transmission measurements revealed that the scans of Fig. 4 represent primarily the scattering of the two quasi-shear modes. Results of these measurements are presented elsewhere [5]. It was observed in performing the 10-MHz scans of Fig. 4 that maximum discrimination of porosity levels (i.e., maximum separation between curves in Fig. 4) was obtained at elevation

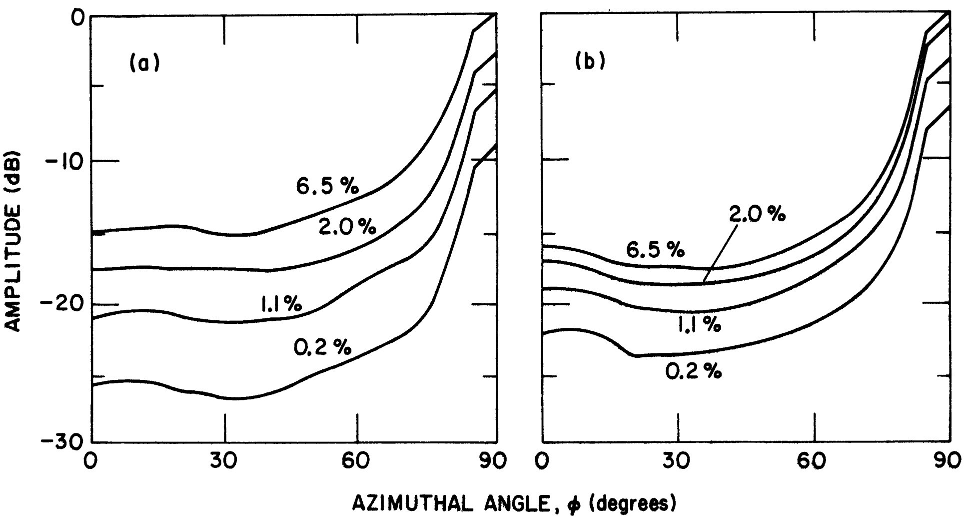

Fig. 4. Detection of porosity in (a) single specimens, and (b) same specimens placed at bottom of 11-mm-thick stack of composite plates. 10-MHz transducer at $\Theta = 35°$.

angles of $35° < \theta < 40°$. This phenomenon was likewise seen in the 5-MHz scans of Fig. 3, although to a lesser extent. However, according to the pulse velocities observed in through-transmission with azimuthal orientation parallel to the fibers, the transmitted quasi-shear wave is near the critical angle for $\theta = 35\text{-}40°$. This phenomenon was examined analytically by computing the transmitted fields from ultrasonically measured elastic constants for a transversely isotropic model. A detailed discussion of this analysis will be forthcoming. As an indicator of both the appropriateness of the transverse isotropy assumption and the accuracy of the elastic coefficient measurements, Fig. 5 compares the calculated and measured transmission through the composite laminate for azimuthal orientation parallel to the reinforcing fibers. Agreement is seen to be good. It is well known that the energy and the plane of constant phase do not necessarily propagate in the same direction in anisotropic materials. The wavevectors k_i^a , a = L, SH, SV, which defined the directions of phase propagation, and the corresponding energy flux vectors which define the directions of energy propagation, were obtained in the calculation of the transmitted fields. The propagation angles of these vectors (measured from the perpendicular) for the shear wave transmission of Fig. 5 are plotted as a function of θ in Fig. 6. It is seen that the transmitted shear-wave energy undergoes little refraction for $\theta = 35\text{-}40°$; thus, the penetration demonstrated in Fig. 4 is consistent with theory. Indeed, in further experiments which measured the lateral displacement of the ultrasonic beam transmitted through the composite plate at $\theta = 35°$, little refraction was observed.

FREQUENCY DEPENDENCE OF BACKSCATTER

Backscattered signals such as those of Fig. 2 can be viewed as originating in the random perturbations of a layered anisotropic medium. The corresponding frequency spectra therefore contain information regarding both random and ordered structures in the composite. The goal of signal processing discussed here is to minimize spectral information regarding fiber-related structures in the composite (both random and ordered), while retaining information regarding the distributed porosity. Spatial averaging of amplitude spectra (devoid of phase information) will reduce

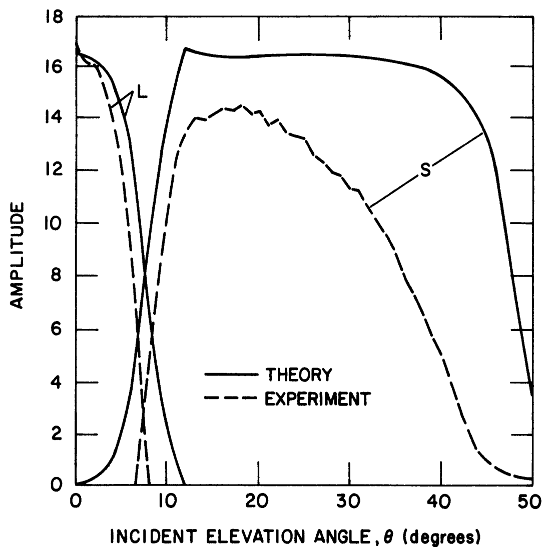

Fig. 5. Transmission of shear (S) and longitudinal (L) waves through unidirectionally reinforced composite with azimuthal orientation parallel to fibers. Solid curves were calculated from measured elastic constants; dashed curves were obtained experimentally with a 10-MHz transducer and a specimen with 0.2 vol. % porosity.

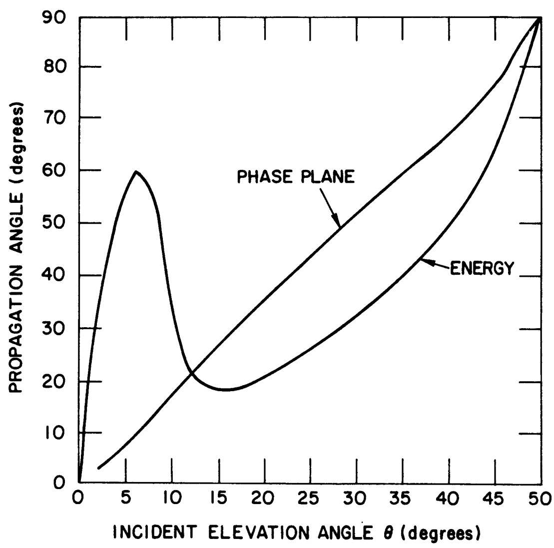

Fig. 6. Propagation direction of shear wave shown in Fig. 5. Elevation angles of phase plane propagation and energy propagation are shown vs. incident elevation angle in water.

information regarding specific configurations of randomly distributed scatterers, and, in general, a "smoothing" of the spectral data will be observed. However, spectral information regarding ordered structures (most notably the internal ply structure and overall thickness of the composite) will not be "smoothed out" by spatial averaging. The example presented in Fig. 7 shows the effect of spatial averaging on the energy spectrum (modulus squared of Fourier transform) of backscatter from a unidirectionally reinforced composite. Backscatter was recorded at θ = 22° with azimuthal orientation parallel to the fibers. A 0.5-in.-dia., 10-MHz broadband transducer was used in the far field. The energy spectrum of a single backscatter measurement is compared with the spatial average of 100 energy spectra obtained on a 10x10 grid covering a 3-cm x 3-cm area. Although a considerable reduction in fine structure is observed, the spectra after averaging still appear unintelligible because of the presence of information regarding the laminate structure and thickness of the composite.

It was noted that information regarding the total thickness of the specimen is necessarily contained in relatively long time records, corresponding to the transit times of multiple pulse reflections between the specimen boundaries. However, information regarding long-wavelength scattering from a single pore is, for practical purposes, contained in a time record approximately equal in length to the incident pulse. In an attempt to exploit this observation, the following signal processing algorithm was applied:

$$\langle F(\omega, \theta, \phi)\rangle = \langle \int_{-\infty}^{\infty} \left| \int_{-\infty}^{\infty} v(t, x, y, \theta, \phi)\, g(t - s) \exp(i\omega t)\, dt \right| ds \rangle, \quad (3)$$

where g(t) is a gating function. The gate function g(t) is defined to be just long enough to have a negligible effect on the backscattered spectrum from a single pore in the ka ~ 1 regime when the gate g(t) is centered on

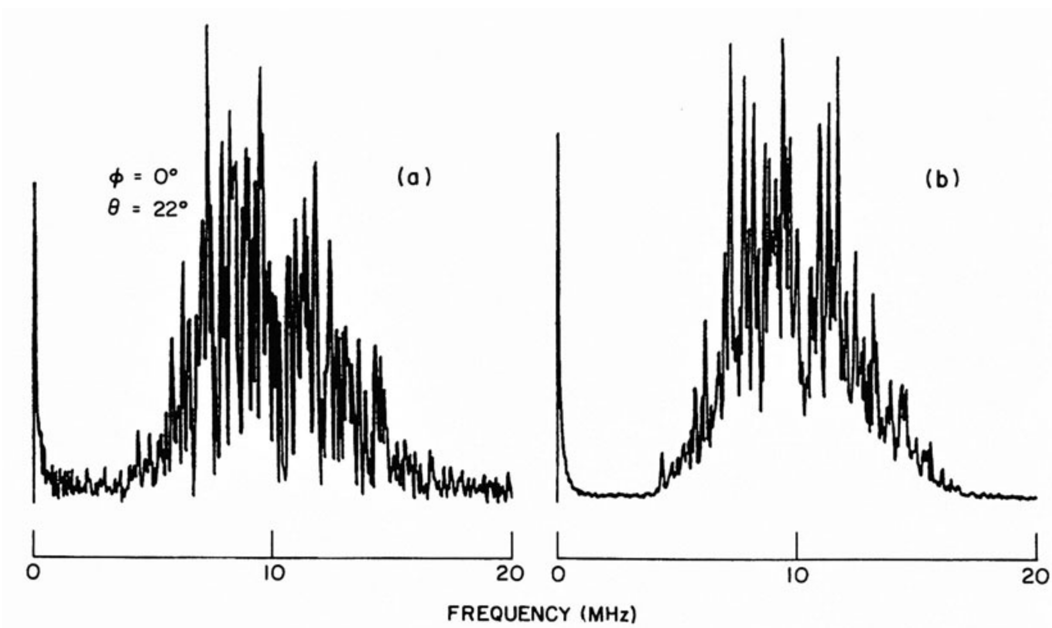

Fig. 7. Spatial averaging of backscattered energy spectra for specimen with 0.2 vol. % porosity. (a) one spectrum; (b) average of 100 spectra.

the backscattered time domain pulse. Numerical experiments to quantify the effect of this algorithm on backscattering from a single pore were conducted by convolving an experimentally measured incident pulse with the theoretically calculated backscatter from a spherical pore [7], and applying the algorithm to the resulting time domain pulse. The result of this procedure was then normalized (divided) by the output of the algorithm when applied to the incident pulse alone. The normalized output of such an experiment for a broadband pulse centered about ka = 0.5 is shown in Fig. 8. The monotonic increase with frequency of backscattered amplitude characteristic of small-ka scattering is retained, although the rate of increase is lessened by the algorithm. A gaussian gate function is used since it does not introduce oscillation into the resulting spectra.

The application of the algorithm to actual backscattered signals such as those shown in Fig. 2 results in a dramatic reduction of spectral structure. Furthermore, spectral information regarding porosity should, by definition of the gate function, be minimally affected. If the algorithm were successful in completely eliminating spectral information regarding the laminate structure, the resulting spectra could conceivably display a monotonic increase with frequency at a rate proportional to the volume fraction of porosity, as has been reported in related through-transmission attenuation measurements [8]. In practice, however, it is observed that spectral information believed attributable to the laminate structure is present even in relatively short (<200-nsec) time gates associated with >10-MHz broadband pulses. The observed spectral information is in the form of apparent resonances believed to be related to the resonant behavior of the layered ply structure.

Preliminary work has demonstrated that the spectral features observed in porosity-free composites are significantly altered by the introduction of porosity. An example is presented which demonstrates the impact of porosity on a particularly strong resonance observed in the unidirectionally reinforced specimens at approximately 2.3 MHz for $\theta = 35°$ and azimuthal orientation parallel to the reinforcing fibers. This resonance

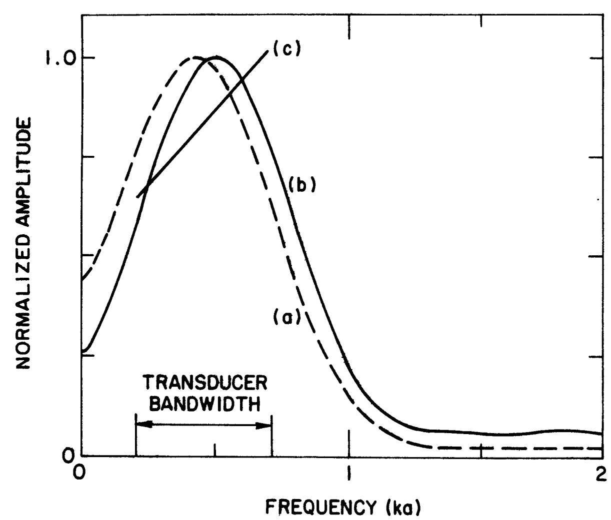

Fig. 8. Output of signal processing algorithm when applied to (a) incident longitudinal pulse and (b) longitudinal backscatter of incident pulse from a single spherical pore. Curve (c) is the ratio of (b) to (a), plotted over the usable bandwidth of the transducer. Each curve is normalized for a maximum value of unity.

is believed to arise from Lamb wave generation. Normalized backscattered spectra are presented in Fig. 9 for specimens containing 0.2, 1.1, 2.0, and 6.5 vol. % porosity. The data were collected with a 1.0-in.-dia., 2.25-MHz broadband transducer. A normalization spectrum was obtained by applying the algorithm of Eq. 3 to a 10x10 backscatter scan, made with the same 2.25-MHz transducer, of a large-ka spherical scatterer (1.25-in.-dia. Si_3N_4 ball). A resonance peak is seen at 2.3 MHz in the 0.2 vol. % porous sample. The introduction of 1.1% porosity lessens the sharpness of the resonance, and at 2.0 vol. % porosity the resonance peak is no longer observed. It is conceivable that such spectral information could be used to assess porosity levels. Further work is needed to understand the spectral response of these anisotropic laminate structures, as well as the consequent effects of porosity. However, the effectiveness of the signal processing algorithm in distilling the relevant spectral information from the backscattered signals is clearly demonstrated in Fig. 9.

SUMMARY AND CONCLUSIONS

Several questions have been addressed regarding the angular and frequency dependence of ultrasonic backscatter from composites. In the data obtained in this study, the relative maximum-to-minimum ratio of backscatter in azimuthal scans was found to be a less reliable indicator of porosity than the absolute magnitude of backscatter, presumably because of the cylindrical morphology of porosity in these specimens. Porosity at depths of 1 cm was successfully detected in unidirectionally reinforced materials, owing in part to interesting anisotropic propagation phenomena which result in minimal refraction of transmitted ultrasonic energy.

The frequency spectra of backscattered broadband pulses appear unintelligible owing to an overabundance of information regarding structures within the composite. A signal processing algorithm was introduced to enhance spectral information regarding scattering by porosity. An example was presented of the application of this signal processing algorithm to backscattering from composites of varying porosity. The introduction of porosity produced quantifiable changes in a prominent spectral feature chosen for study.

Ultrasonic backscatter from composites contains a wealth of information regarding the internal structure of the specimen. The problem to be solved is one of sorting relevant data from the complicated backscattered

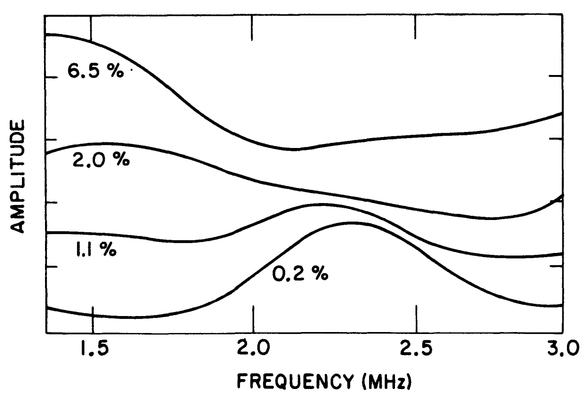

Fig. 9. Application of signal processing to backscattering from unidirectionally reinforced composites. Resonance peak is seen at 2.3 MHz in specimen with 0.2 vol. % porosity, and becomes pronounced as porosity increases.

signals. Future work will focus on identifying relevant information contained in the angular and temporal dependence of backscatter. A successful procedure for the assessment of porosity in composites by analysis of ultrasonic backscatter will likely exploit information received from a combination of angular and temporal scattering data.

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