# ANALYSIS OF ULTRASONIC BACKSCATTER FOR POROSITY CHARACTERIZATION IN GRAPHITE-EPOXY COMPOSITES

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## INTRODUCTION

This paper summarizes recent work on the use of ultrasonic backscatter for the estimation of porosity levels in continuous-fiber-reinforced, layered graphite-epoxy composites. This work is a continuation of previous work described in Refs. 1-3, which addresses the effect of porosity on (1) azimuthal angle backscatter scans, and (2) the spectral characteristics of backscatter.

The impact of porosity on azimuthal-angle backscatter scans was addressed for unidirectionally reinforced composites in Ref. 2, and for nonwoven multidirectionally reinforced composites in Ref. 3. The present work addresses the impact of porosity on azimuthal-angle backscatter scans obtained in woven multidirectionally reinforced composites. An approach for obtaining intelligible frequency spectrum information from the random backscatter signals was first introduced in Ref. 2, where it was applied to backscatter from unidirectionally reinforced specimens. Results of an exploratory application of this spectral analysis to backscatter from nonwoven multidirectionally reinforced composites were presented in Ref. 3. In the present work, the results of a rigorous study of the spectral characteristics of backscatter from nonwoven, multidirectionally reinforced composites are given.

## AZIMUTHAL ANGULAR BACKSCATTER SCANNING OF WOVEN CROSS-PLY COMPOSITES

The experimental ultrasonic backscatter apparatus and azimuthal angular scanning technique used in this work have been described in Refs. 2 and 3. The specimens examined in this work consist of 14 plies of woven carbon-fiber fabric in which a horizontal fiber bundle crosses under every fifth vertical fiber bundle. Specimen characteristics are outlined in Table 1.

Table 1. Characteristics of Woven Cross-Ply Sample

General Properties

| | |
|---|---|
| Fiber content by volume | 60-65% |
| Fiber density | 1.78 g/cm$^3$ |
| Epoxy density | 1.26 g/cm$^3$ |
| Fiber diameter | 8 μm |
| Fiber bundle width | 2.35 mm |

Ply Lay-up

| | | | |
|---|---|---|---|
| 1: | 0 | 8: | 0 |
| 2: | 90 | 9: | 90 |
| 3: | +45 | 10: | -45 |
| 4: | -45 | 11: | +45 |
| 5: | +45 | 12: | -45 |
| 6: | 0 | 13: | 90 |
| 7: | 90 | 14: | 0 |

Total thickness = 3 mm

Azimuthal-angle backscatter scaning is performed by fixing the polar angle of incidence in a pulse-echo experiment and rotating the specimen azimuthally, i.e., about a perpendicular to the composite plate. To insure ultrasonic penetration, the polar angle chosen must not exceed the critical angles for propagating waves in the specimen. Through-transmission polar-angle scans were obtained to determine these critical angles. Plots showing the peak amplitude of the received through-transmitted broadband pulse as a function of polar angle for a fixed azimuthal angle are presented in Fig. 1 for frequencies of 2.25 and 10 MHz. These plots were obtained from a "porosity-free" (0.01 vol.%) woven cross-ply specimen with azimuthal incidence perpendicular to the top fiber bundle in the first ply. At 2.25 MHz (Fig. 1a), the critical angle for compressional waves is ~16°, and the critical angle for shear waves is well beyond 45°. Indeed, the shear wavefield is approximately at its maximum at 45°, which was the maximum excursion of the polar-angle scanning apparatus used. At 10 MHz (Fig. 1b), the critical angle for compressional waves is ~12°, and the critical angle for shear wavefields is ~25°. The amplitude of the transmitted shear wavefield is seen to be relatively small at 10 MHz.

The frequency-dependent transmission characteristics seen in the comparison of Fig. 1a and Fig. 1b are due to the layered ply structure of the specimen. At longer wavelengths (2.25 MHz), the elastic properties "experienced" by the wavefield are an average of the local constituent plies, whereas at shorter wavelengths (10 MHz), the wavefield "experiences" each ply and ply interface individually. Such a transition from "quasi-isotropic" to "layered anisotropic" propagation behavior was also seen for nonwoven cross-ply composites in the 2- to 10-MHz range [3]. Clearly, for effective penetration in backscatter scanning, polar angles must be kept below 12° at 10 MHz, whereas at 2.25 MHz, the optimum polar angle appears to be ~45°. On the basis of repeated measurements at various azimuthal angles, the polar angle transmission properties appeared to be approximately isotropic with respect to azimuthal angle, particularly at 2.25 MHz.

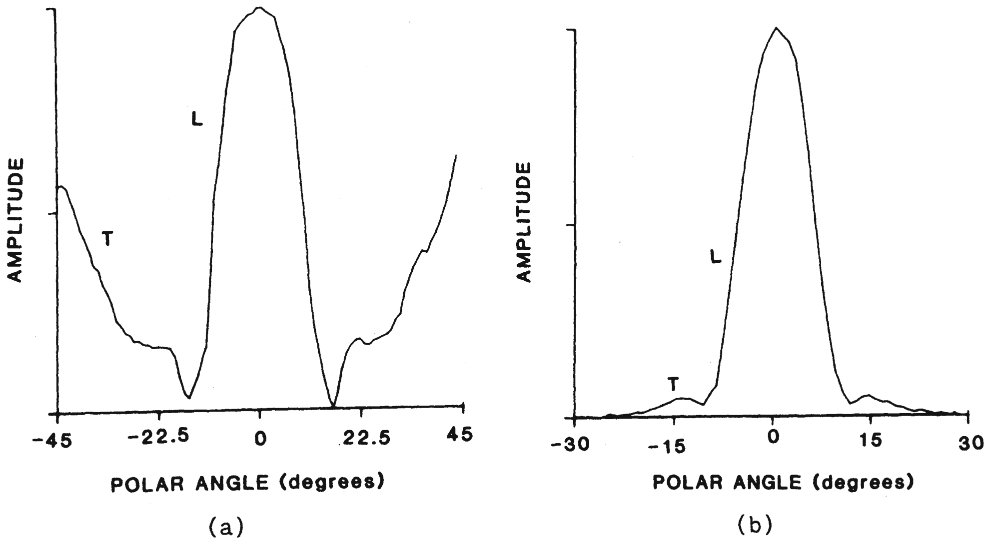


Fig. 1. Through-transmission polar-angle scans in woven cross-ply composites. (a) 2.25 MHz, (b) 10 MHz.

Azimuthal-angle backscatter scans were performed in woven cross-ply specimens containing 0.01, 1.58, and 3.41 vol.% porosity, as measured by acid digestion [1]. Figure 2 shows plots of

$$C(\phi,p) = 10 \log_{10} < \int_{-\infty}^{\infty} v(t,p)^2 \, dt > \quad , \tag{1}$$

where $\phi$ is azimuthal angle, p is porosity content, v(t,p) is the recorded time domain backscatter signal, and < > denotes a 6x6 spatial average [2,3]. Figure 2a was obtained with a 2.25-MHz broadband transducer at a 45° polar angle, whereas Fig. 2b was obtained with a 10-MHz broadband transducer at an 8° polar angle. Angular-scattering peaks typical of backscatter in fiber-reinforced composites are seen at 0°, 45°, 90°, 135°, and 180°, corresponding to azimuthal incidence perpendicular to the fiber direction in a constituent ply. It is observed that the scattering peaks at 45° and 135° are significantly smaller than the others, for reasons which are not clearly understood. It was observed in the nonwoven cross-ply composites[3] that scattering peaks originating at subsurface plies were somewhat smaller owing to the attenuation losses in the plies at a lesser depth. However, the drop in amplitude of the 45° and 135° peaks in Figs. 2a and 2b seems too extreme to be due solely to attenuation, and evidence supporting this conjecture is provided by the experiment to be discussed in reference to Figs. 2c and 2d. (Note: bleeder cloth-related roughness was removed by grinding.) The exact explanation of the origin of the fiber-related scattering peaks is of secondary importance for the purposes of this paper. Of primary importance is the assumption that the source of fiber-related scattering is the same in each specimen studied.

Figures 2a and 2b show that the introduction of porosity increases the overall level of backscatter, and that the additional backscatter due to porosity appears nondirectional with respect to azimuthal angle, particularly at 2.25 MHz. This is in contrast to results obtained for the nonwoven composites[3], for which porosity-related scattering displayed a directionality similar to that of the fiber-related scattering. The directionality of porosity-related scattering in the nonwoven composites was explained by the cylindrical morphology of the pores, which are free to grow parallel to the fibers [4]. The nondirectionality of scattering by porosity in the woven composites is consistent with a recent observation that pore growth occurs primarily at the intersection of fiber bundles, and that growth is constrained by the weave to a near-spherical morphology [5]. Indeed, the results of Fig. 2a closely resemble those of a model experiment which examined scattering by glass spheres in a fiber-reinforced matrix [6]. As previously observed in the nonwoven composites[3], discrimination between porosity levels is better at 2.25 MHz than at 10 MHz.

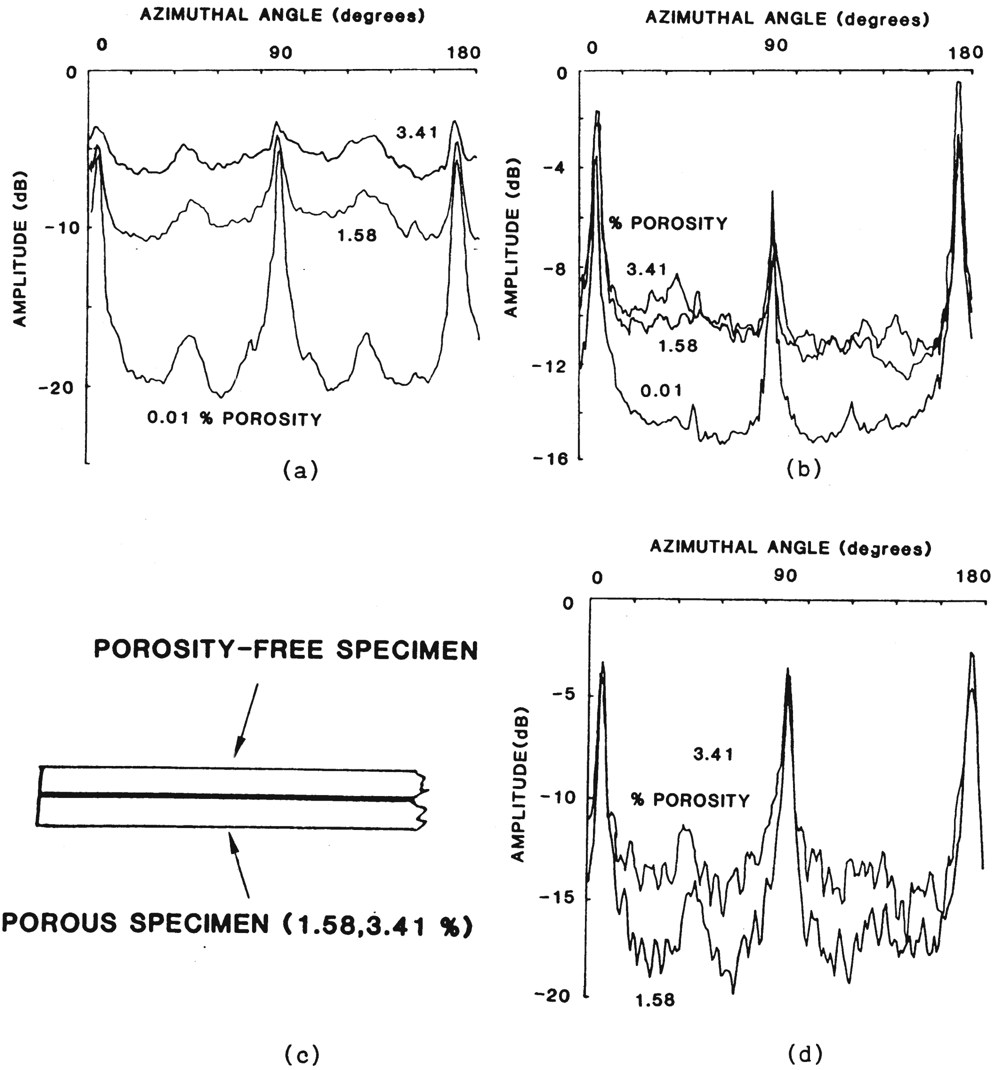


Fig. 2. Azimuthal-angle backscatter scans in woven cross-ply composites. (a) 2.25-MHz, 45° polar angle; (b) 10-MHz, 8° polar angle; (c) experimental configuration for two-specimen test; (d) detection of porosity in bottom specimen of (c) at 2.25 MHz.

The through-transmission measurement of Fig. 1 suggests that the backscatter scan of Fig. 2 should detect porosity at relatively large depths in the specimen. However, the small amplitude of the 45° and 135° scattering peaks in Fig. 2 raises a concern that, to the contrary, backscatter originating at depths greater than the first or second ply is significantly reduced in amplitude. This important issue was examined directly by repeating the backscatter scan of Fig. 2a with a two-specimen stack, as depicted in Fig. 2c. The porosity-free (0.01 vol.%) specimen was placed on top. Successive scans were performed, first with the specimen of 1.58 vol.% porosity on the bottom, and then with the specimen of 3.41 vol.% porosity on the bottom. Results of this experiment are presented in Fig. 2d. The difference in porosity levels between the two porous specimens is clearly detected. Note that the separation between the curves for 1.58 vol.% and 3.41 vol.% porosity is approximately the same as in Fig. 2a (~4 dB). The effect of the 6x6 spatial average used in obtaining Fig. 2a is evident in the comparison of Figs. 2a and 2d, since spatial averaging was not employed in obtaining Fig. 2d.

The porosity dependence of the mean value and shape (i.e., peak-to-valley separation) of the backscatter curves of Figs. 2a and 2b were quantified by using the approach discussed in Ref. 3. The dependence of the mean value of the backscatter curves $C(\phi,p)$ is given by

$$\bar{C}(p) = \frac{1}{180} \int_0^{180} [C(\phi,p) - C(\phi, 0.01)] \, d\phi \quad , \qquad (2)$$

and the dependence of the shape of the backscatter curves is given by

$$\tilde{C}(p) = \frac{1}{180} \int_0^{180} [C(\phi,p) - C(\phi, 0.01) - \bar{C}(p)]^2 \, d\phi \quad . \qquad (3)$$

Plots showing $\bar{C}(p)$ and $\tilde{C}(p)$ for the curves of Figs. 2a and 2b are shown in Fig. 3. Of particular importance is the rapid initial increase in both $\bar{C}$ and $\tilde{C}$, which indicates high sensitivity to the onset of porosity.

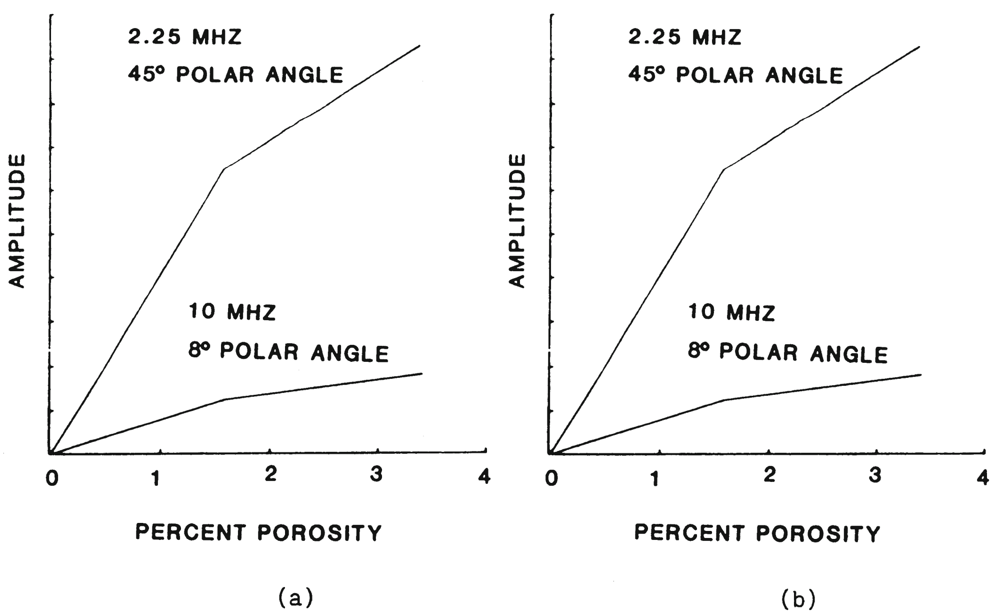


Fig. 3. Porosity dependence of (a) mean value and (b) shape of backscatter curves of Fig. 2.

## SPECTRAL ANALYSIS OF BACKSCATTER FROM NONWOVEN CROSS-PLY COMPOSITES

Earlier work demonstrated the extraction of intelligible spectral features from random backscatter in nonwoven cross-ply composites [3]. Spectral resonances believed to be related to the layered ply structure were observed, and it was seen that the quality of these resonances was affected by the introduction of porosity. Motivated by these preliminary findings, a rigorous examination of these spectral resonances was undertaken for continuously varying azimuthal angle and several discrete polar angles. The experimental procedure was similar to the azimuthal angle backscatter scans discussed in the previous section of this paper. However, rather than applying Eq. (1), the signal processing applied to the backscattered signal at each angular position was

$$S(\omega,\Theta,\phi) = \langle \int_{-\infty}^{\infty} \left| \int_{-\infty}^{\infty} g(t-s)\, v(t,\Theta,\phi)\, \exp(i\omega t)\, dt \right| ds \rangle \quad , \qquad (4)$$

where $v(t,\Theta,\phi)$ is the time domain backscatter signal received at polar angle $\Theta$ and azimuthal angle $\phi$, and $g(t)$ is a Gaussian gate function. As before, $\langle\ \rangle$ denotes a 6x6 spatial average. Additionally, through-transmission signals were recorded at each scan position for the purpose of monitoring ultrasonic penetration. Data acquisition required storing 6x6, 1024 10-bit word waveforms collected at 2° azimuthal-angle increments over 180°, resulting in a 6.3-Mbyte data set per scan. Application of Eq. (4) to the data yields a two-dimensional data surface which is viewed as a function of frequency and azimuthal angle.

Data were collected on the nonwoven cross-ply specimens described in Ref. 3 (containing 0.34, 1.25, and 2.82 vol.% porosity) with a 5-MHz broadband transducer. The surface obtained for a fixed 18° polar angle, with a Gaussian gate ~2 µsec long, is shown in Fig. 4 for the specimen with 0.34 vol.% porosity. Similar surfaces were obtained for the specimens with 1.25 and 2.82 vol.% porosity. Resonant spectral characteristics (i.e., peaks and valleys) are seen at several azimuthal orientations. Furthermore, a comparison of surfaces for differing porosity levels revealed a significant dependence of these spectral characteristics on porosity content. Surfaces showing through-transmitted amplitude as a function of azimuthal angle and frequency were obtained from the through-transmission data acquired simultaneously with the backscattered data; similar surfaces are presented in Ref. 3. Pronounced spectral features in the backscatter data located at angular and frequency positions for which significant through-transmission (and therefore, penetration) are observed were chosen for study.

A particularly strong resonance observed in Fig. 4 at ~5 MHz and 0° azimuthal angle will be discussed here. A comparison of backscattered spectra for porosity levels of 0.34, 1.25, and 2.82 vol.% at a 0° azimuthal angle is presented in Fig. 5a. Note the lessening of the spectral minimum at 4.3 MHz with increasing porosity. The depth of this spectral minimum is seen to be very sensitive to the initial introduction of porosity. Similar results were reported in Ref. 3 at a different angular orientation. An effort was directed towards identifying the origin of the resonance noted in Fig. 5a, to determine whether it is related to either the layered ply structure or the total thickness of the specimen (e.g., a plate wave). To this end, a corner of the specimen with 0.34 vol.% porosity was ground from a thickness of 2 mm to a thickness of ~1.3 mm. Backscatter measurements were then made in both a 2-mm-thick region and the 1.3-mm-thick region of the specimen, keeping polar and azimuthal angles fixed at 18° and 0°, respectively. Backscattered spectra obtained with a 2-µsec gate are compared in Fig. 5b. Note that the spectrum from the 2-mm-thick region is slightly broader in bandwidth, but that the position of the spectral minima remain essentially fixed in frequency.

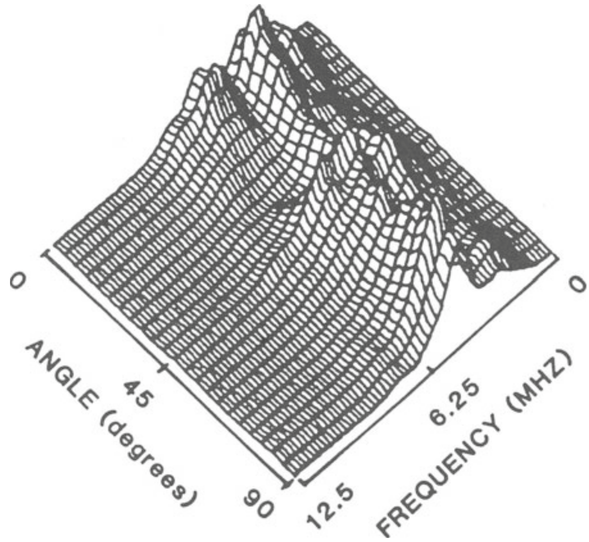


Fig. Processed backscatter spectra vs. azimuthal angle for nonwoven cross-ply composite containing 0.34 vol. porosity.

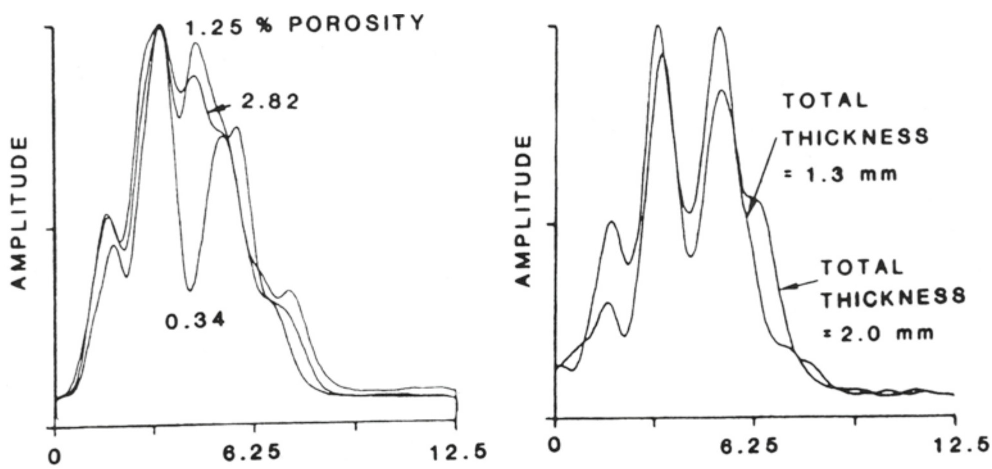


Fig. 5. Processed backscatter spectra at 18° polar angle and 0° azimuthal angle for (a) 2-mm sample thickness and varying porosity content, (b) 0.34 vol.% porosity and varying sample thickness.

This observation indicates that these spectral minima are not due to the generation of plate waves, but are rather associated with inter-ply resonances within the specimen. Such information is important if this technique is to be used for the inspection of composite components of varying thickness. An examination of the ply lay-up (+45°, -45°, 0°, 90°, +45°, -45°, 0°, 90°, 90°, 0°, -45°, +45°, 90°, 0°, -45°, +45°) reveals that the

0° plies are nearly periodically spaced in the specimen. It was seen in the azimuthal-angle backscatter scans of these specimens [3] that a constituent ply is a particularly strong scatterer when the azimuthal incidence is perpendicular to its fiber direction. Hence, in the experiment of Fig. 5, the composite specimen can be viewed as a volume containing nearly periodically spaced layers of a strong scatterer, the interaction of which produces the observed resonant spectral features. When porosity is introduced, it disrupts the periodicity of the scattering structures, resulting in the observed lessening of the spectral minimum.

## SUMMARY

Azimuthal-angle backscatter scans, which examine total backscattered energy as a function of porosity, were performed for woven cross-ply composites. Analyses which examined the overall level of backscatter and the angular dependence of backscatter revealed that both the mean value and shape (i.e., peak-to-valley separation) of the backscatter curves were very sensitive to the initial onset of porosity. The observed sensitivity of backscatter curve shape to porosity is believed to be the result of the constraint of pore growth to a near-spherical morphology by the fiber weave. This is in contrast to the lesser sensitivity of backscatter curve shape to porosity previously observed in nonwoven cross-ply composites, in which the pores displayed a cylindrical morphology.

Azimuthal-angle scans were also performed in nonwoven cross-ply composites to examine the spectral content of the backscatter with previously developed signal processing. Spectral features were observed which appear to be related to the layered ply structure of the composite, and a sensitivity to the introduction of porosity was observed. A particular spectral minimum, which is believed to be associated with the near-periodic spacing of the 0° ply in the ply lay-up, was studied in detail. Strong sensitivity to the onset of porosity was observed.

## ACKNOWLEDGEMENT

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