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(NASA-CR-158240) FURTHER DEVELOPMENT OF ULTRASONIC TECHNIQUES FOR NON-DESTRUCTIVE EVALUATION BASED ON FOURIER ANALYSIS OF SIGNALS FROM IRREGULAR AND INHOMOGENEOUS STRUCTURES Final Report (Washington Univ.) G3/38

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"Further Development of Ultrasonic Techniques for Non-Destructive Evaluation Based on Fourier Analysis of Signals from Irregular and Inhomogeneous Structures"

Final Technical Report

NASA Grant Number: NSG 1392

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Hampton, Virginia

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I. INTRODUCTION

This document is the Final Technical Report on a project that extended over an interval of 2 years and included both theoretical and experimental research on the ultrasonic properties of inhomogeneous materials. Because most of the research supported under this grant has been reported in the form of semi-annual progress reports, this report represents a summary of the central features of the work. Details not included in this report which are pertinent to any of the topics presented here can be found in the semi-annual progress reports.

II. OVERALL FEATURES OF THE RESEARCH PLAN

The goal of the research sponsored by NASA grant NSG 1392 has been the development of ultrasonic techniques for the non-destructive evaluation (NDE) of inhomogeneous materials. The work summarized in this report consists of investigations that were conducted at Washington University's Laboratory for Ultrasonics. Recently Dr. Matthew O'Donnell, Senior Research Associate in the Laboratory for Ultrasonics, visited NASA Langley Research Center to present a formal report on the progress of this work, and to interact with staff members in several groups involved in non-destructive evaluation. Through this visit the results of our work were broadly disseminated by direct interaction with staff members of NASA. The visit to Langley also served as an occasion to discuss the specific application of the ultrasonic methods developed during the funding period to the non-destructive evaluation of composite materials. Consequently, the principle accomplishment of the research sponsored by this grant may be the development of specific, quantitative ultrasonic indices for the non-destructive evaluation of composite structures.

III. SUMMARY OF RESEARCH

A. Development of Model Systems

To investigate the use of Fourier analysis techniques as structural probes of inhomogeneous materials, model systems had to be designed to test some of the general properties of the interaction of sound with an inhomogeneity. The first model systems investigated were suspensions of solid spheres in water. These systems were used primarily to test if the frequency dependence of the attenuation coefficient could be used to characterize structural inhomogeneities. The mechanisms responsible for the attenuation of ultrasound in suspensions are well understood. Consequently, these systems allowed comparison between theoretical computation of the frequency dependence of the attenuation coefficient and measurement of the attenuation coefficient over a range of frequencies. The results of theoretical computations of the attenuation coefficient in suspensions of polystyrene spheres in water are plotted as a function of the radius of the scatterer in Figure 1. The analysis used to obtain the results presented in Figure 1 was based on the partial wave expansion of all possible waves that could be generated at the surface of the inhomogeneity. The losses due to coupling to shear waves in the liquid are termed viscous losses, losses to thermal waves are termed thermal losses, and losses to longitudinal waves are termed scattering losses. In the limit where $k_\ell R \ll 1$ ($R < 1$ μm) we see that thermal losses are the dominate loss mechanism, whereas for $k_\ell R \approx 1$ ($R > 50$ μm) scattering losses are the dominate loss mechanism. For $k_\ell R \approx 1$ the attenuation coefficient should be a strong function of frequency. In Figure 2 we present the results of a measurement of the frequency dependence of the attenuation coefficient in a suspension of 50 μm polystrene spheres in water. As predicted, the measured attenuation is a strong function of frequency in this model system.

To test the potential applicability of the ultrasonic scattering coefficient to the NDE of inhomogeneous systems, we have investigated ultrasonic scattering processes in both suspensions of hard spheres in water, and suspensions of hard spheres in polyester resin. The second model system was constructed to test the applicability of partial

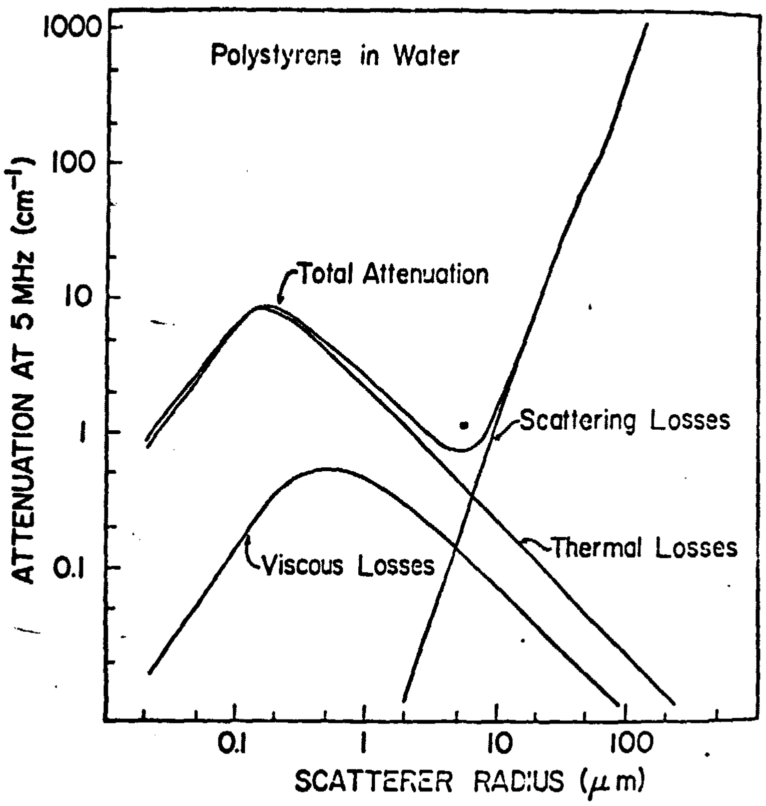

Figure 1. Attenuation vs scatterer radius in a suspension of polystyrene spheres in water.

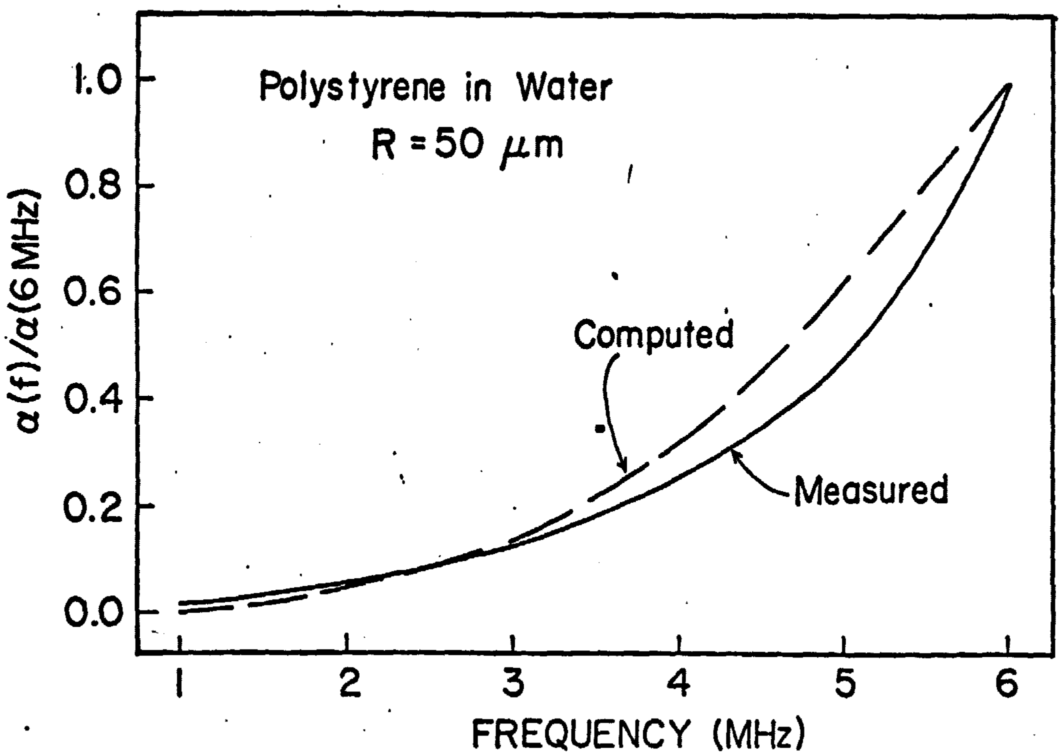

Figure 2. Comparison between theoretical predictions and measurements of the frequency dependence of the attenuation coefficient in a suspension of 50 μm diameter polystyrene spheres in water.

wave analysis to the description of an inhomogeneity in a solid, and to test the range of material properties over which the measurement systems were valid. Three suspensions of crown glass spheres in resin were constructed, including a 4% by volume suspension of 450 μm spheres in resin, which is illustrated in Figure 3. Measurement of the frequency dependence of the backscatter coefficient and angular dependence of the scattering coefficient on these system are presented in Section III.C of this report. A description of the measurement systems used to conduct these scattering experimentsis given in the next section of this report.

B. Scattering Measurement Systems

The ultrasonic scattering coefficient is measured over a range of frequencies using a broadband generalized substitution techhique. A highly damped focused piezoelectric transducer is driven to provide a broadband pulse. For backscatter measurements, the backscattered signal is detected by the same transducer, amplified, and appropriately gated to eliminate any echoes which may arise from specular reflections at the surfaces of the sample. In the system originally used to obtain backscatter measurements, the gated signal is fed into an analog spectrum analyzer. The output of the spectrum analyzer, comprising the logarithim of the Fourier transform, is then integrated, peak detected, and sampled as illustrated in Figure 4. Due to the logarithmic character of the output of the spectrum analyzer, the processing described above is not strictly linear if the gate length is significantly longer than the inverse of the bandwidth of the spectrum analyzer. Although the gate length has been chosen such that linear processing is approximated, an alternate scheme has been developed to ensure strictly linear processing. The new processing scheme is illustrated in Figure 5. Using this system the gated output of the transducer is fed into a sampler. The sampling point is positioned at a specific time delay, determined by an applied dc voltage, after the master clock pulse. Using the software capabilities of the HP9825A calculator and a digital to analog converter (DAC), the sampling point can be moved through the gated output of the transducer. The output of the sampler is monitored by the calculator through the use of an analog to digital converter (ADC). Consequently, as the sampling point is scanned under computer control, a digital representation of the gated, time domain signal from the transducer is stored in the calculator.

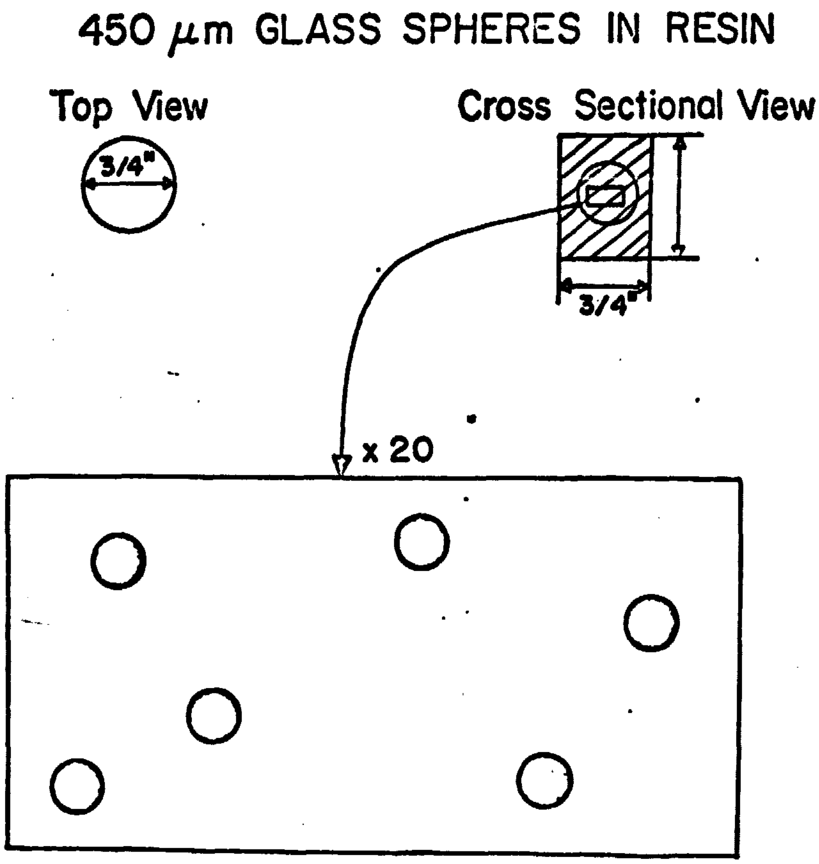

Figure 3. Representation of a 4% by volume suspension of crown glass spheres in polyester resin.

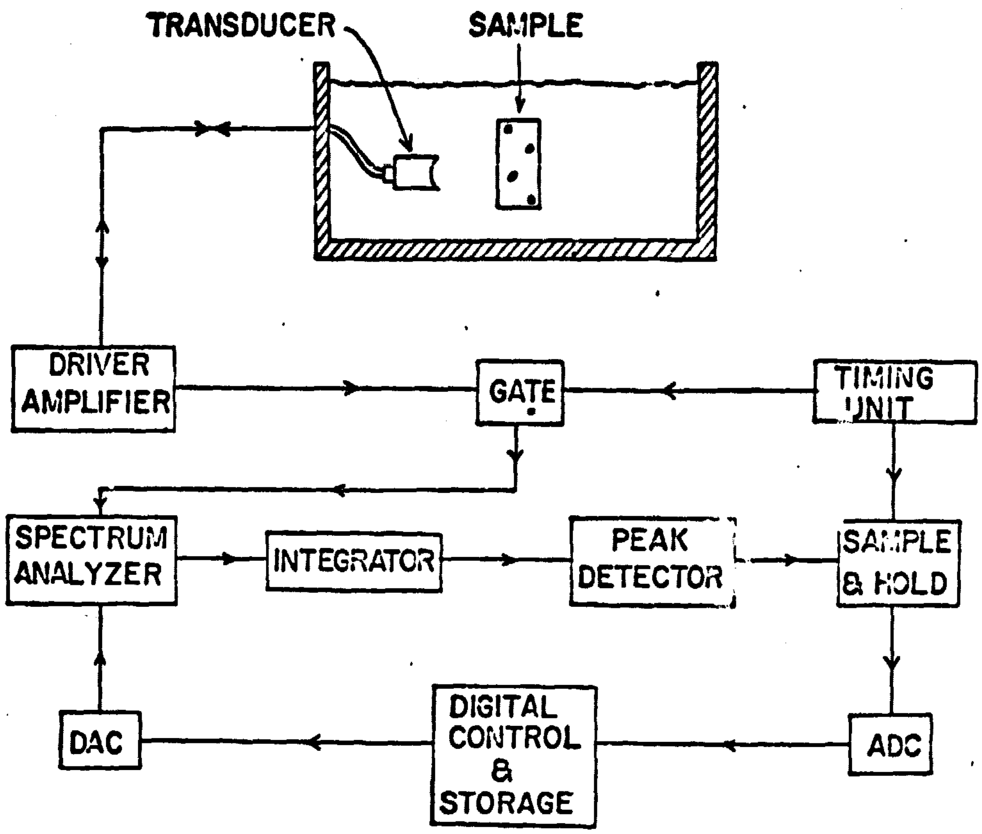

Figure 4. Block diagram of a spectrum analyzer based scattering system.

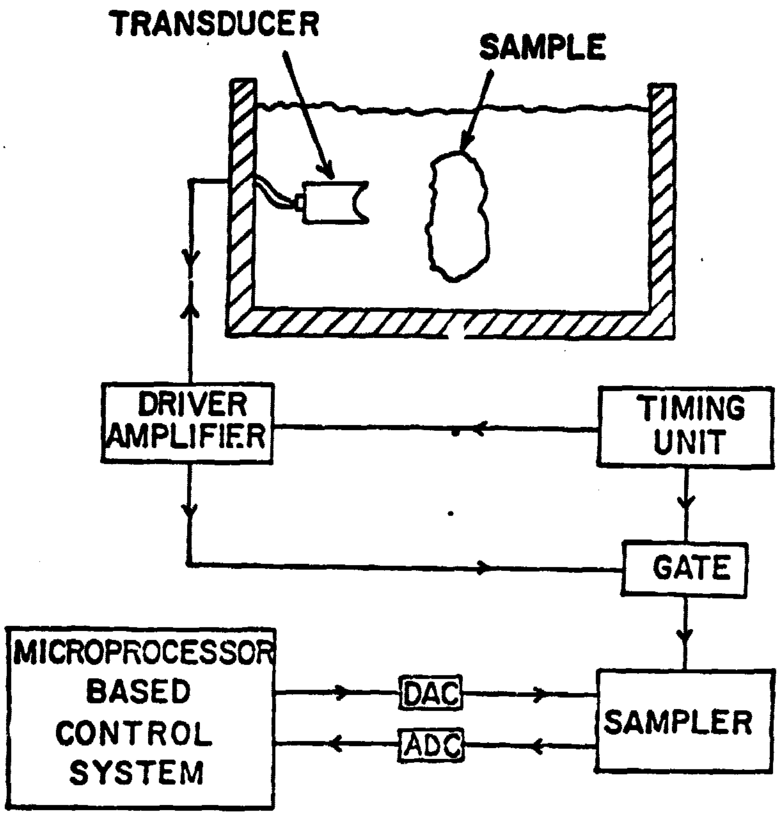

Figure 5. Block diagram of a sampler based scattering system.

The time domain signal is then Fourier transformed with a 512 point Fast Fourier Transform (FFT) algorithm. Using this system the magnitude of the Fourier transform of the backscatter transfer function can be obtained over the range of approximately 2 to 10 MHz.

The results of backscatter measurements obtained with this system are compared to results obtained with the spectrum analyzer based system in Figure 6. In Figure 6 the backscatter coefficient measured in a suspension of 35 μm diameter spheres in a polyester resin is illustrated as a function of frequency over the range 3 to 9 MHz. Results obtained with the spectrum analyzer based system (Log Processing) are represented by the dashed line, and results obtained with the sampler based system (Linear Processing) are represented by the solid line. As is clear from this figure the magnitude of the backscatter coefficient estimated by each system is similar at all frequencies (to within experimental errors). In contrast, the frequency dependence of the backscatter coefficient obtained by each system is different. The backscatter coefficient appears to vary as the third power of frequency based on measurements using the logarithmic processing scheme, whereas the backscatter coefficient appears to vary as the fourth power of frequency based on measurements using the linear processing scheme. Theoretical computations indicate that over this frequency range the backscatter coefficient should vary approximately as the fourth power of frequency in this suspension. Consequently, the sampler based system which utilizes strictly linear processing seems to yield a better estimate of the scattering coefficient than the spectrum analyzer based system which only approximates linear processing.

Recently, a new system designed to measure the angular dependence of the scattering coefficient has been constructed. This system permits automated measurements of both the frequency dependence and the angular dependence of the scattering coefficient. The mechanical apparatus for this system is illustrated in Figure 7. A stepping motor is used to rotate both the sample and the transmitting transducer while the receiving transducer is held fixed. By rotating the transmitter and the sample simultaneously, the same sample volume is interrogated at each angle. The stepping motor is driven under control of the 9825A calculator such that the motion of the mechanical apparatus can be regulated in software. The system has been

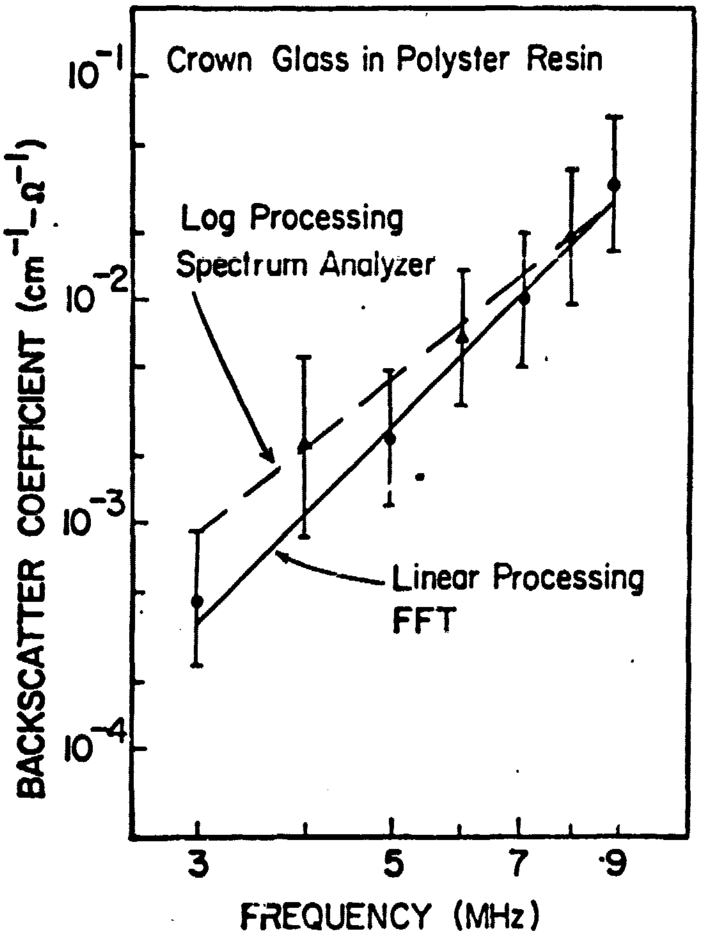

Figure 6. Comparison of the backscatter measured with the system of Figure 4 (dashed line) and the system of Figure 5 (solid line) in a suspension of crown glass spheres in polyester resin.

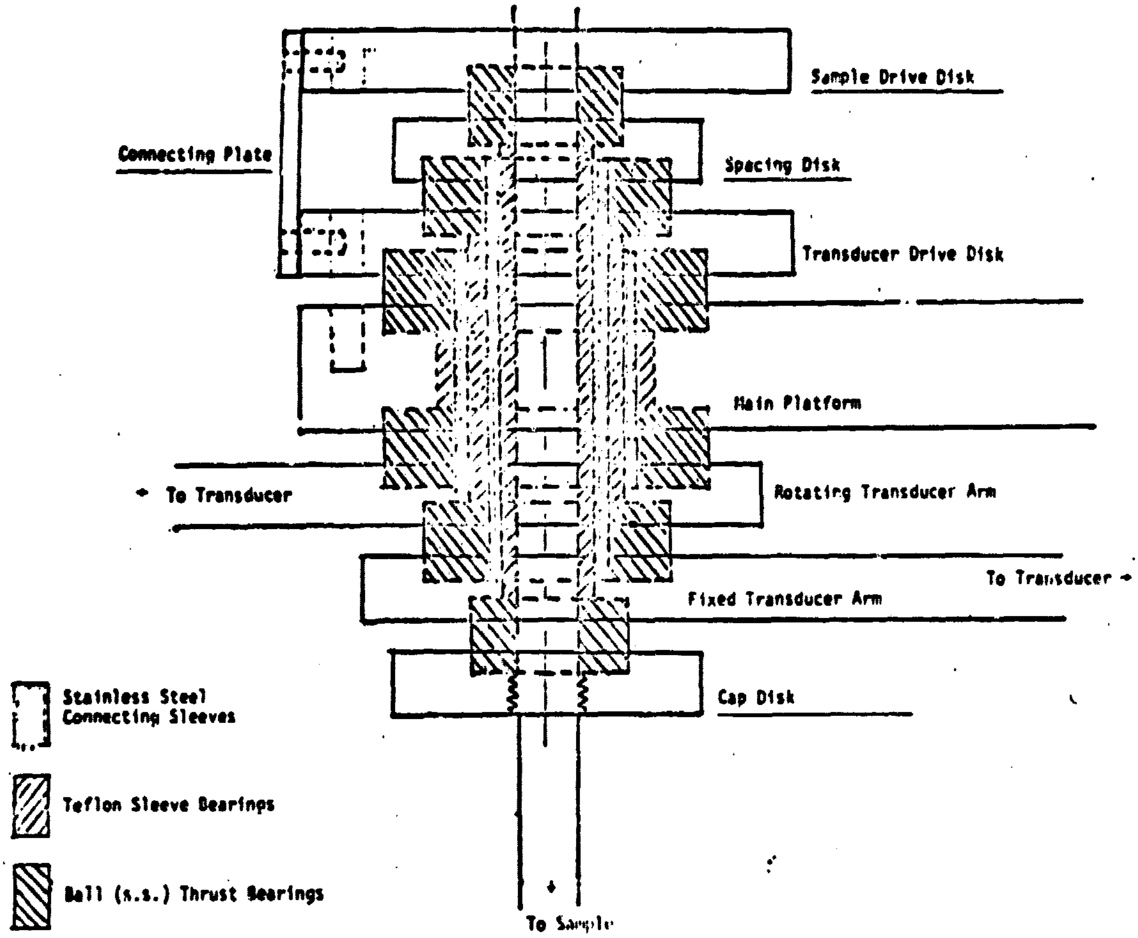

Figure 7. Schematic of the mechanical scanning apparatus of the system used to measure the angular dependence of scattering.

designed to provide a minimum rotation of 1/50 of a degree. The scattering coefficient is measured at each angle using the same system as that illustrated in Figure 5, except that the output of the separate receiving transducer is gated into the sampler.

C. Scattering Measurements on Model Systems

The ultrasonic backscatter coefficient has been measured in suspensions of crown glass spheres in polyester resin using the system illustrated in Figure 5. Data obtained with this system were analyzed using a generalized substitution technique, whereby the integrated backscatter from some volume of the sample is normalized to the signal obtained from a perfect reflector. The result of this normalization procedure is labeled the backscatter transfer function. The backscatter coefficient is obtained by modifying the backscatter transfer function to account for the length of the cylindrical volume of the sample being interrogated, the attenuation within the length of the cylinder, the cross section of the ultrasonic beam, and the distance from the transducer to the measurement site. In Figure 8 the backscatter coefficient obtained in a 4% by volume suspension of 35 μm diameter crown glass spheres in polyester resin is illustrated over the range 3 to 9 MHz. The dashed curve is the backscatter coefficient predicted from theoretical considerations. As is clear from this figure, the correspondence between theoretical predictions and measurements using the system illustrated in Figure 5 is quite good. The combined results of backscatter measurements on a suspension of 35 μm spheres in resin over the range 3 to 9 MHz and on a suspension of 450 μm spheres in resin over the range 2 to 5 MHz are illustrated in Figure 9. The ordinate in Figure 9 is the normalized backscatter coefficient, defined as the equivalent single particle backscatter coefficient normalized to the cross section of the inhomogeneity (see pp. 18 of the semiannual progress report submitted September 15, 1978). The abscissa in Figure 9 is the product ka, where k is the magnitude of the ultrasonic wavevector and a is the radius of the inhomogeneity. The solid curve in Figure 9 is the normalized backscatter coefficient obtained from theoretical computations. As is evident from an inspection of Figure 9, the measured backscatter closely parallels the results of theoretical predictions over a wide range of ka in this model system. Thus the scattering system of Figure 5 appears to provide accurate measurements

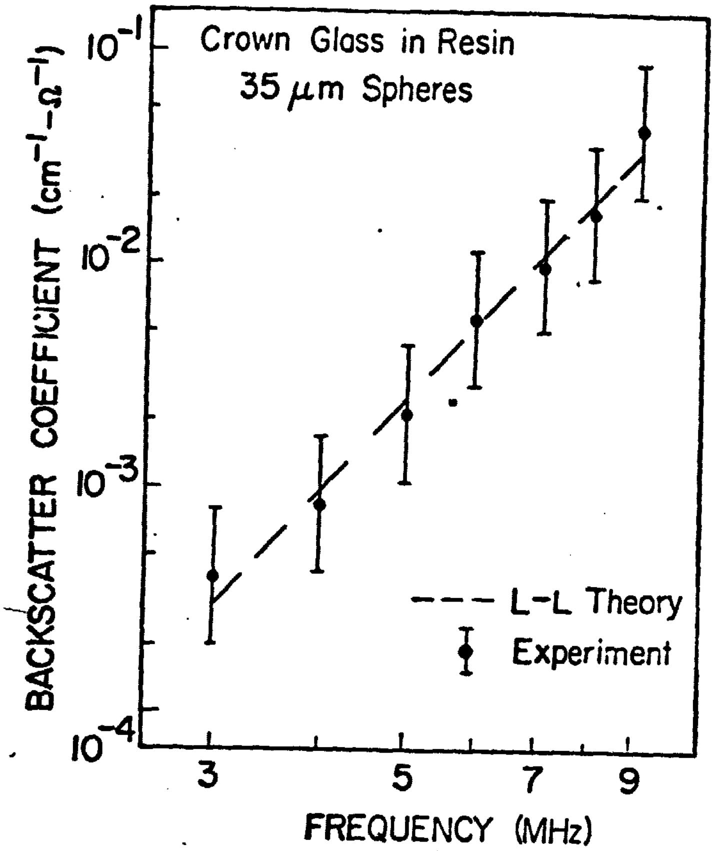

Figure 8. Frequency dependence of the backscatter coefficient in a suspension of crown glass spheres in polyester resin.

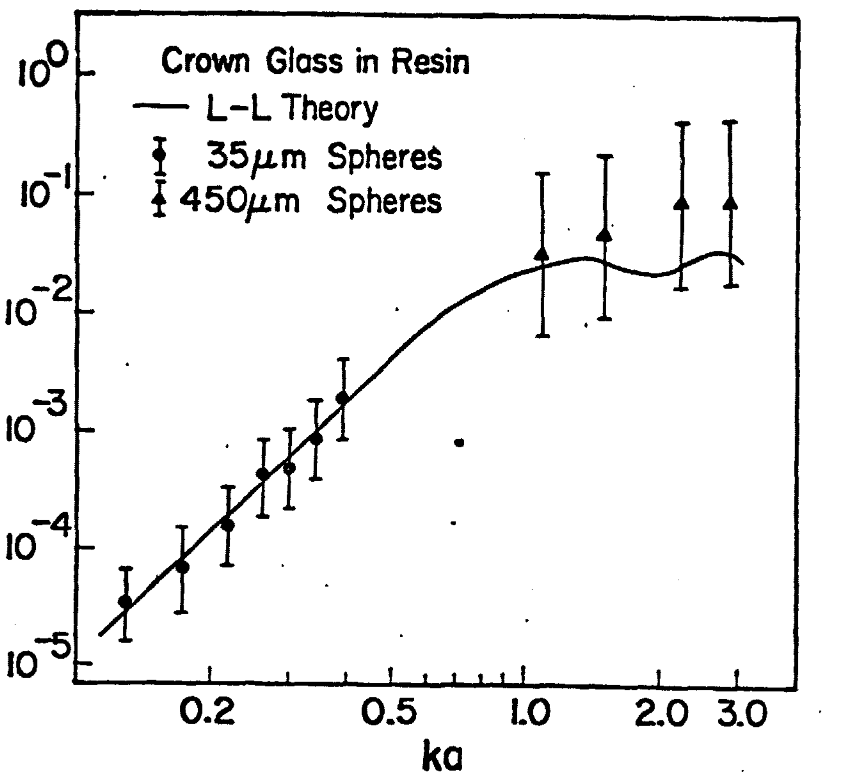

Figure 9. Acoustic Backscatter coefficient in suspensions of crown glass spheres in resin.

of the backscatter coefficient in materials exhibiting a collection of inhomogeneities. (We should note here that a slight error was detected in one of the computer programs used to compute the backscatter coefficient. When this error was corrected, experimental results obtained with the old scattering system illustrated in Figure 4 also matched theory much better than shown in Figure 9 of the semiannual progress report submitted September 15, 1978. However, the results obtained with the newer scattering system matched theoretical predictions better than the results obtained with the old scattering system.)

The results of measurements of the angular dependence of the scattering coefficient in a suspension of 35 μm crown glass spheres in resin are illustrated in Figure 10. The ordinate in Figure 10 is the normalized scattering coefficient at 5 MHz, defined as the scattering coefficient measured at some angle divided by the backscatter coefficient. The abscissa in Figure 10 is the angle between the transmitting and receiving transducer, where 0 degrees corresponds to backscatter. The dashed line in Figure 10 is the angular dependence computed from theory. As predicted, the measured scattering coefficient decreases with increasing angular excursion from 0 degrees. However, the scattering coefficient decreases at a rate that is much steeper than predicted. The diminished apparent scattering at angles other than 0 degrees may be a consequence of several methodological problems associated with measurements of the angular dependence which do not occur for backscatter measurements. First, when focused transducers are used the problem of beam alignment can become critical due to the narrow beamwidth. Second, transducer side lobes can reflect from sample surfaces and consequently compromise measurements at angles corresponding to specular reflections of the side lobes. And third, if there are any irregularities in the surface of the sample, then refractive effects and mode conversions can alter the apparent magnitude of the scattered signal. Based on the difficulty encountered in aligning focused transducers, it seems that the first difficulty listed above is the most serious when conducting automated measurements. Consequently, we have started to use transducers with more diffuse beams to conduct measurements of the angular dependence. In the next section we report on measurements of the angular dependence of the scattering coefficient in composite materials made with 1/2 inch diameter, planar transducers operating in the far field.

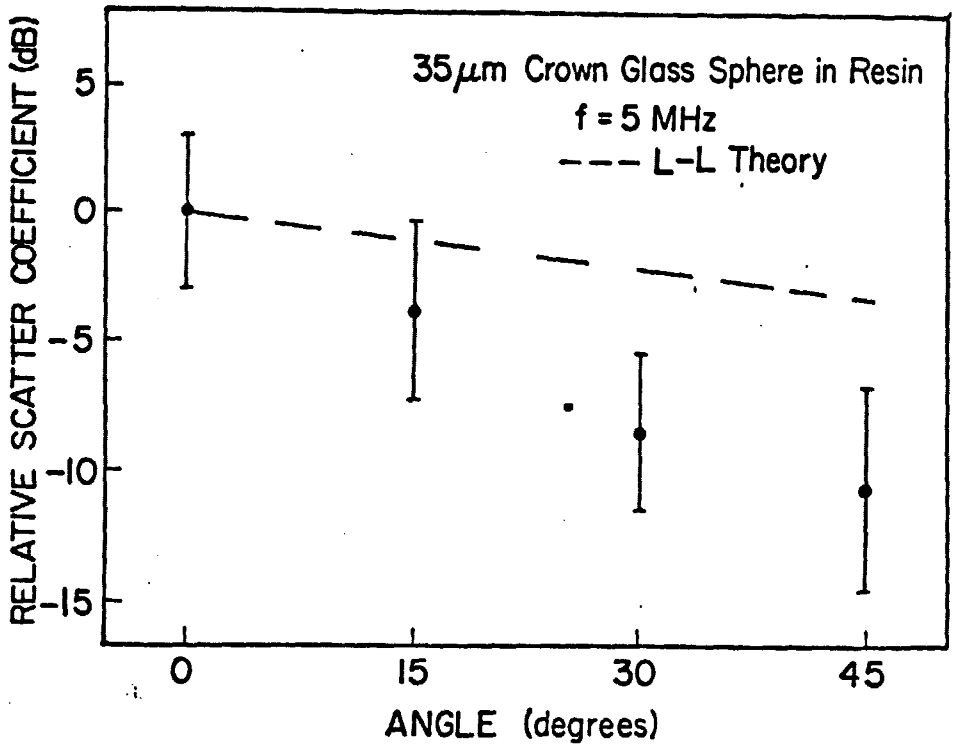

Figure 10. Angular dependence of the scattering coefficient in a suspension of 35 μm diameter glass spheres in resin.

D. Preliminary Measurement on Composites

During the final phase of research sponsored by NASA grant NSG 1392 we have undertaken a preliminary investigation of the frequency dependence of the attenuation coefficient and the angular dependence of the scattering coefficient in several composite structures. As detailed in previous proposals and progress reports, the attenuation coefficient can be measured using either reflected or transmitted ultrasound. At present, three basic systems developed at Washington University's Laboratory for Ultrasonics have been utilized for broadband attenuation measurements in the low MHz frequency range: i) a transmission system using piezoelectric detection, ii) a transmission system using acoustoelectric detection, and iii) a reflection system using piezoelectric detection. The results of a measurement of the attenuation coefficient in a 1 mm thick sheet of graphite composite with fiber bundles oriented in -45° and +45° planes over the range 3 to 9 MHz using the transmission piezoelectric system are illustrated in Figure 11. The dashed line depicted in Figure 11 represents the best fit straight line to the attenuation data. The results obtained on this same graphite composite using the transmission acoustoelectric system are presented in Figure 12. The apparent attenuation measured with this system is nearly identical to that obtained with the transmission piezoelectric system except for the periodic oscillations about the best fit straight line. These oscillations are the result of standing wave effects in the 1 mm thick composite sheet when interrogated by a 3 μsec long ultrasonic pulse used in the acoustoelectric system. To a good approximation these effects can be ignored by considering the best fit straight line to the data as the actual attenuation curve. A comparison of the dashed lines of Figures 11 and 12 indicates that both systems yield similar results for the frequency dependence of the attenuation coefficient in this graphite composite. The slope of the best fit straight line to the attenuation versus frequency curve (i.e., the slope of the attenuation) over the range 2-9 MHz for this composite is 0.255 cm^{-1}-MHz^{-1}. A similar result (slope = 0.250 cm^{-1}-MHz^{-1}) was obtained using the reflection piezoelectric system. In contrast, the slope of the attenuation is over six times larger in a boron composite, as illustrated in Figure 13. The slope of the attenuation over the range 2-9 MHz in the boron composite is 1.750 cm^{-1}-MHz^{-1}. These results indicate that the slope of the attenuation

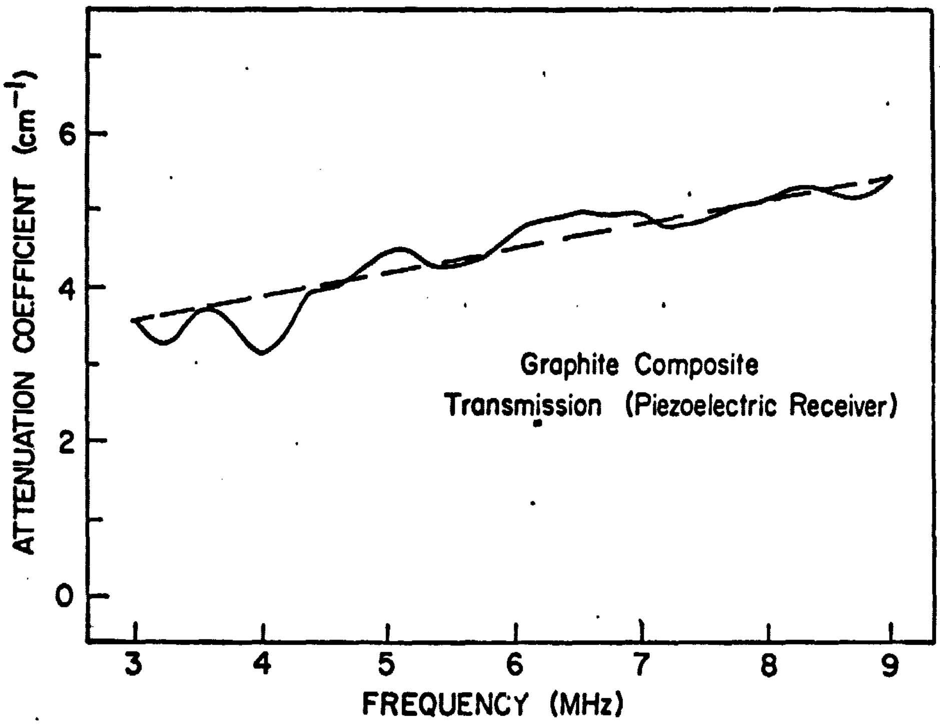

Figure 11. Attenuation in a ±45° graphite composite measured with a transmission attenuation system which uses piezoelectric detection.

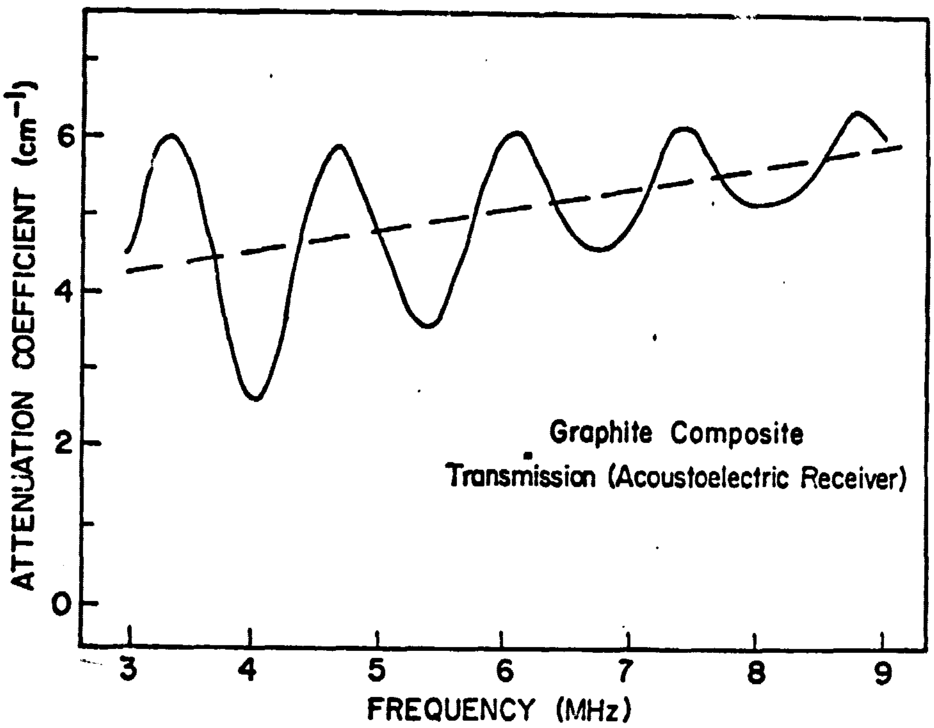

Figure 12. Attenuation in the same ±45° graphite composite as in Figure 11 measured with a transmission attenuation system which uses acoustoelectric detection.

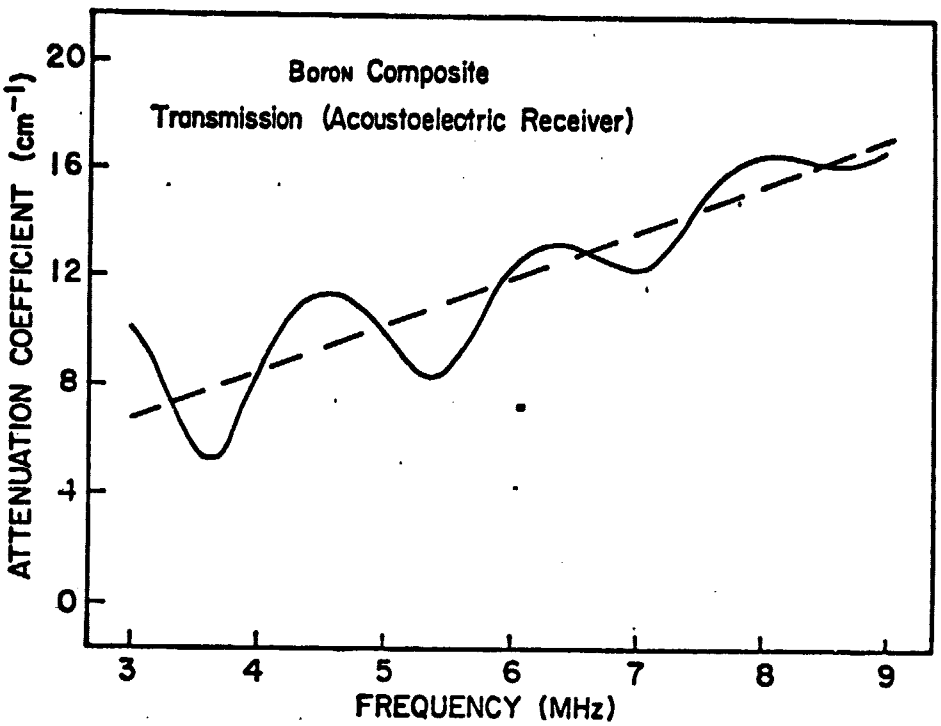

Figure 13. Attenuation in a boron composite measured with a transmission attenuation system which uses acoustoelectric detection.

is an index which can be obtained for composite materials using either transmitted or reflected ultrasound. In addition, this index is directly related to material composition and may potentially represent a sensitive probe of material integrity for composite structures.

Quantitative measurements of the angular dependence of the scattering coefficient may also represent a sensitive probe of material integrity. The scattering amplitude measured at 6 MHz in a ±45° graphite composite is presented as a function of angle between the receiving and transmitting transducer in Figure 14. The scattering amplitude measured at 6 MHz exhibits a sharp maximum near 35°. In Figure 15 we illustrate the scattering amplitude measured in the same composite material at 5 MHz (top panel) and at 7 MHz (bottom panel). The top panel of Figure 15 shows that the scattering amplitude measured at 5 MHz exhibits a sharp maximum near 45°, whereas the bottom panel of Figure 15 shows that the scattering amplitude measured at 7 MHz exhibits a sharp maximum near 30°. The general trend of sharp maxima in the angular dependence of the scattering amplitude was evident over a continuous range of frequencies from about 3 to 8 MHz, and over a continuous range of angles from about 25° to 60° in this particular composite. In addition, the angle at which each maxima occured was a continuously decreasing function of frequency, as illustrated in Figures 14 and 15. The existence of sharp maxima in the angular dependence which are highly frequency dependent is strongly suggestive of coherent scattering processes. Analysis of the time domain signal at any angle between 25° and 60° also strongly suggests that the composite material is acting as a highly selective frequency domain filter. Highly frequency dependent coherent scattering processes such as these are manifest when two conditions are met. First, the material must possess a periodic ordering of its structural components. And second, the insonifying beam must possess wavelengths that are comparable to or smaller than the appropriate distances which define the periodic order in the material. The wavelength of sound varies from about 900 μm to about 300 μm over the frequency range of 3 to 9 MHz in the ±45° graphite composite that has been analyzed. Thus the periodic ordering of fiber bundles in this composite material may give rise to coherent scattering processes. Measurements of the angular dependence of the scattering coefficient, therefore, may represent highly sensitive indices of the integrity of fiber bundles in composite materials.

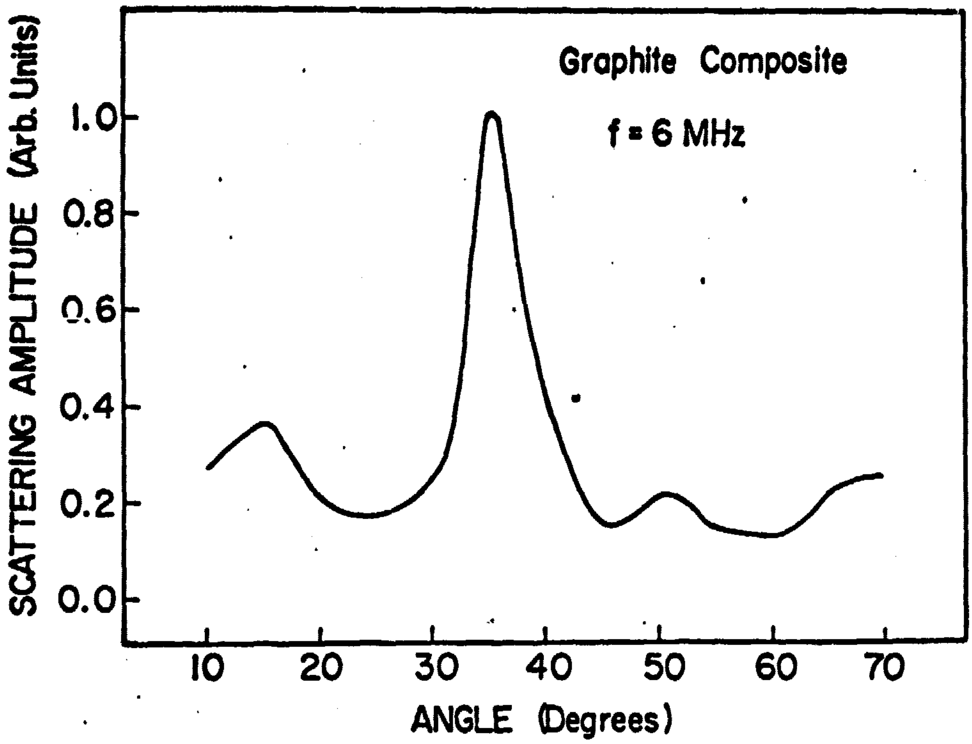

Figure 14. Angular dependence of the 6 MHz scattering coefficient in a ±45° graphite composite.

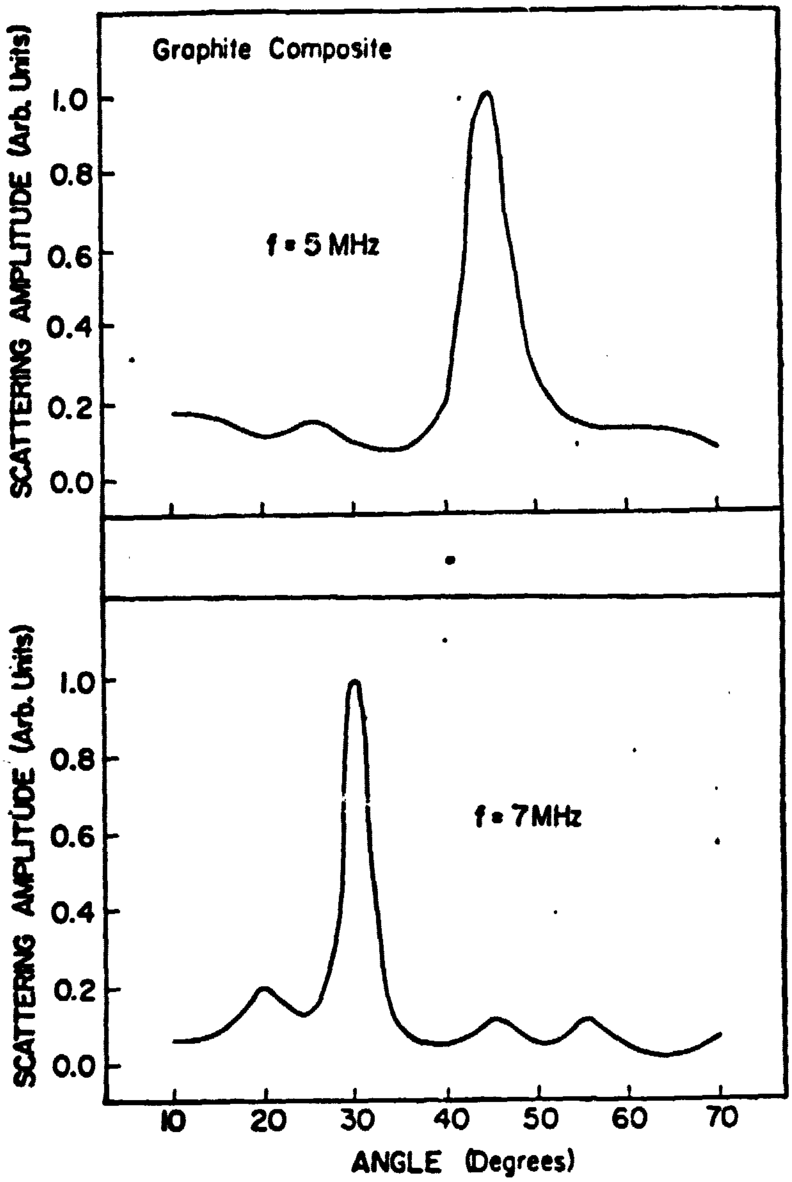

Figure 15. Angular dependence of the 5 MHz (top panel) and 7 MHz (bottom panel) scattering coefficient in the same ±45° graphite composite as in Figures 11, 12, and 14.

IV. PUBLICATIONS

Research that was carried out under support of this grant is related to the ultrasonic properties of inhomogeneous materials. The results of this research effort are currently being prepared for presentation at the next IEEE Ultrasonics Symposium, and will also be submitted for publication.

One article published during the funding period of NASA grant NSG 1392 describes research that was carried out under partial support of this grant.

"General Relationship Between Ultrasonic Attenuation and Dispersion", M. O'Donnell, E. T. Jaynes, and J. G. Miller, J. Acoust. Soc. Am. 63, 1935 (1978).

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