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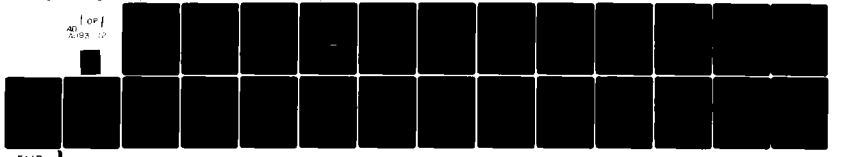

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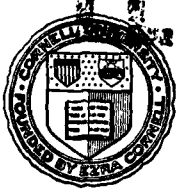

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technique and the other is based on the Kramers-Kronig relation to find the attenuation from measurement of the dispersion. The new techniques are expected to be especially useful for measurements in highly absorbent composite specimens. A firm basis for the technique has been established and measurements with graphite-epoxy specimens are described. Good agreement can be obtained between the various attenuation measurement techniques.

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This report describes broadband measurements of ultrasonic dispersion and atteniation in cross-plied specimens of graphite-epoxy. Quantitative comparisons of dispersion and attenuation data are made by means of least-square fit algorithms implemented into the ultrasonic signal processing system. Reproducible measurements in graphite-epoxy have been obtained. Two new frequency-dependent attenuation measurement techniques are described for measurements in composite materials. One is a continous-wave resonance

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ULTRASONIC NON-DESTRUCTIVE TESTING OF MATERIALS

Second Interim Report to

Air Force Office of Scientific Research

by

W. Sachse and Y.H. Pao

Contract No. [redacted] [F49620-78-C-0100]

August 1, 1979 - July 31, 1980

December 1980

Department of Theoretical and Applied Mechanics

Cornell University, Ithaca, New York - 14853

I. INTRODUCTION

This interim scientific report summarizes the progress made in the second year of the research project dealing with the ultrasonic non-destructive testing of composite materials. This was to be the final year of the project as originally scheduled (August 1, 1978 through July 31, 1980); however, the original contract has now been amended to continue for one more year, through July 31, 1981.

The overall objective of this program is to investigate experimentally and theoretically the dispersion and attenuation of ultrasonic waves in various composite materials. For the second year, the research has focused on:

1) Ultrasonic measurement of dispersion and attenuation in unreinforced epoxy resin and cross-plied graphite/epoxy.

2) a. Development and implementation of new techniques for frequency-dependent ultrasonic attenuation measurements in composite specimens.

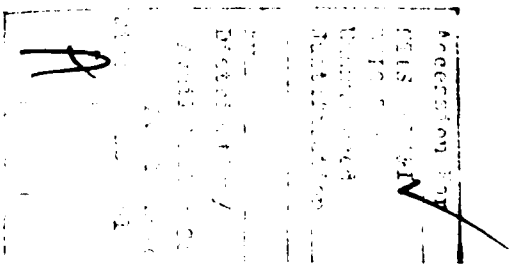
b. Critical comparison between the various techniques for measuring the frequency-dependent attenuation in composite specimens.

3) Detection of deformation-induced microstructure changes in cross-plied graphite/epoxy from ultrasonic dispersion and attenuation measurements.

4) Mathematical foundation of the Kramers-Krönig relation.

Details of these investigations, some already reported in the form of journal papers, are described in the next four sections.

Research personnel supported by this contract in the second year included the principal investigator (W. Sachse, 1 month), co-principal investigator (Y.H. Pao, 1 month), and the following associates and assistants:



Post doctoral associates:

R. Weaver (12 months)

A. Cerancglu (1 month)

Graduate Assistants:

C. Chang (1 month)

C. Chen (1 month)

D. Kishoni (1 month)

G.C. Ku (2 months)

II. DISPERSION AND ATTENUATION OF ULTRASONIC WAVES IN COMPOSITE MATERIALS

In the second year, the ultrasonic wave dispersion and attenuation measurements have been made principally in 32-ply 0/90° cross-plied specimens of graphite/epoxy (AS3501-5). The specimens were typically .175 in. (.4450 cm.) thick. While this restricted the testing geometry to ultrasonic measurements normal to the ply-layers, this is, in fact, typically how structures fabricated of such materials are inspected.

1. Measurements of Dispersion

The phase and group velocities were measured in the frequency interval from approximately 1 to 10 MHz using the method of ultrasonic phase spectroscopy, a technique which had been developed, in part, under earlier AFOSR sponsorship. The basis of technique and its implementation have been reported in References 1 and 2 (see footnotes) and in the Scientific Report of 1979. The basic formula for the frequency dependent wave number, $k(f)$, of the composite is determined from the Fourier phase spectrum, $\phi(f)$, of a broadband ultrasonic pulse which has propagated through a specimen of thickness ℓ. The dispersion is given by

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[1] W. Sachse and Y.H. Pao, J. Appl. Physics, 49, 852-857 (1978).

[2] W. Sachse, C.S. Ting and A. Hemenway, in Composite Materials: Testing and Design, ASTM STP 674, ed. S.W. Tsai, pp. 165-183 (1979).

$$k(f) = [\phi_o - \phi(f)]/z + 2\pi f\tau_g \qquad (2.1)$$

where ϕ_o is an initial phase constant and τ_g is a time-delay constant, both are known in a particular testing situation. From the dispersion relation, follow the phase velocity, $c = 2\pi f/k(f)$, and group velocity $v(f) = 2\pi(df/dk)$.

As mentioned in last year's report, the dispersion relation for various specimens of graphite/epoxy - both uni-directional and cross-plied - is nearly linear. The additional measurements completed in the second year are in agreement with those obtained previously. An example is shown in Figures 1(a) - (d). It is noted that the graphite fiber diameter in these specimens is approximately 15μ and this is about 6 times smaller than that of the boron fibers in the specimens for which the dispersion was extensive, particularly when the wave propagation direction coincided with the fiber direction, as reported in our previous publications [1-2].

As described in the next section, the frequency dependent phase velocity of a material is required in both of the new broadband attenuation measurement techniques developed under this contract. Algorithms were developed for a least-square curve fitting of the measured phase velocity, $c(f)$, in any frequency sub-interval of the original measured data. The results obtained from thirteen measurements on eight graphite/epoxy specimens are shown in Figures 2(a) - (b). The coefficients of the phase velocity polynomial obtained for these tests are in Table I. These results show the reproduceability of the dispersion measurements which can be achieved.

2. Conventional Measurements of Attenuation

This program began by utilizing the conventioanl measurement techniques to determine the frequency-dependent attenuation in composite specimens. In the second year, such measurements were made in the 32 ply-0/90° cross-plied specimens of graphite/epoxy. The techniques which have been used for

Table I - Longitudinal Phase Velocity in 32-ply Graphite/Epoxy (AS3501-5) 0/90° cross-plied

Phase velocity polynomial, $c(f)$:

$$c(f) = c_0 + c_1 f + c_2 f^2$$

Specimen Number	c_0	c_1	c_2
1P	0.2850643	0.0035786	-0.0001167
1P1	0.2970861	0.0025584	-0.0000792
2P	0.2957520	0.0026031	-0.0000832
2P1	0.2934446	0.0027297	-0.0000864
3P1	0.2918476	0.0030310	-0.0000959
4P	0.2941632	0.0025928	-0.0000801
5P1	0.2895339	0.0032158	-0.0001156
5P2	0.2937272	0.0030645	-0.0001072
5P3	0.2950088	0.0029550	-0.0001027
7P1	0.2882639	0.0032913	-0.0001114
7P2	0.2886748	0.0031782	-0.0001087
8P1	0.2888710	0.0035110	-0.0001218
4P1	0.2937630	0.0027102	-0.0000845

attenuation measurements include: resonance techniques, the r.f. burst method, the broadband pulse-echo method, pulse reflection measurements and the new Hilbert-transform technique. The first listed technique was [illegible] it especially suitable for frequency-dependent attenuation measurements in highly absorptive materials such as composites. Also, the last-mentioned technique was implemented in this year. Details of these two techniques are described more fully in Section III.

Conventional attenuation measurement techniques were described in the last annual report, and are contained in the following paper which was invited by the Canadian National Research Council at a recent seminar:

W. Sachse, "Dispersion of Ultrasonic Waves: Acoustic Emission Measurements and Ultrasonic Composite Materials Characterization", Proceedings of the First Seminar on Advanced Ultrasonic Technology, G. Bégin, ed., National Research Council (Canada), Montreal (1980, in press). (Reference 3)

The results obtained with the r.f. burst and broadband attenuation measurements (as with the other techniques) are difficult to compare quantitatively unless the frequency-dependent attenuation curve is fit to a polynomial function. For our comparisons, we fit a second-order polynomial in the least squares sense to the data in a selected frequency interval and compare the resulting polynomial coefficients. It should be also possible to compute the specimen's resonance spectrum, and with the inverse Fourier-transform, the time signals expected for a one-dimensional specimen and testing geometry, which approximates our testing configuration. These results can then be adjusted interactively for a best fit to the original spectrum or time waveform. This new test procedure has not yet been implemented but we shall do so in the third year of this program. Quantitative comparisons with the polynomial coefficients between the above-mentioned attenuation measurement techniques and the newly-developed techniques is given in the next Section.

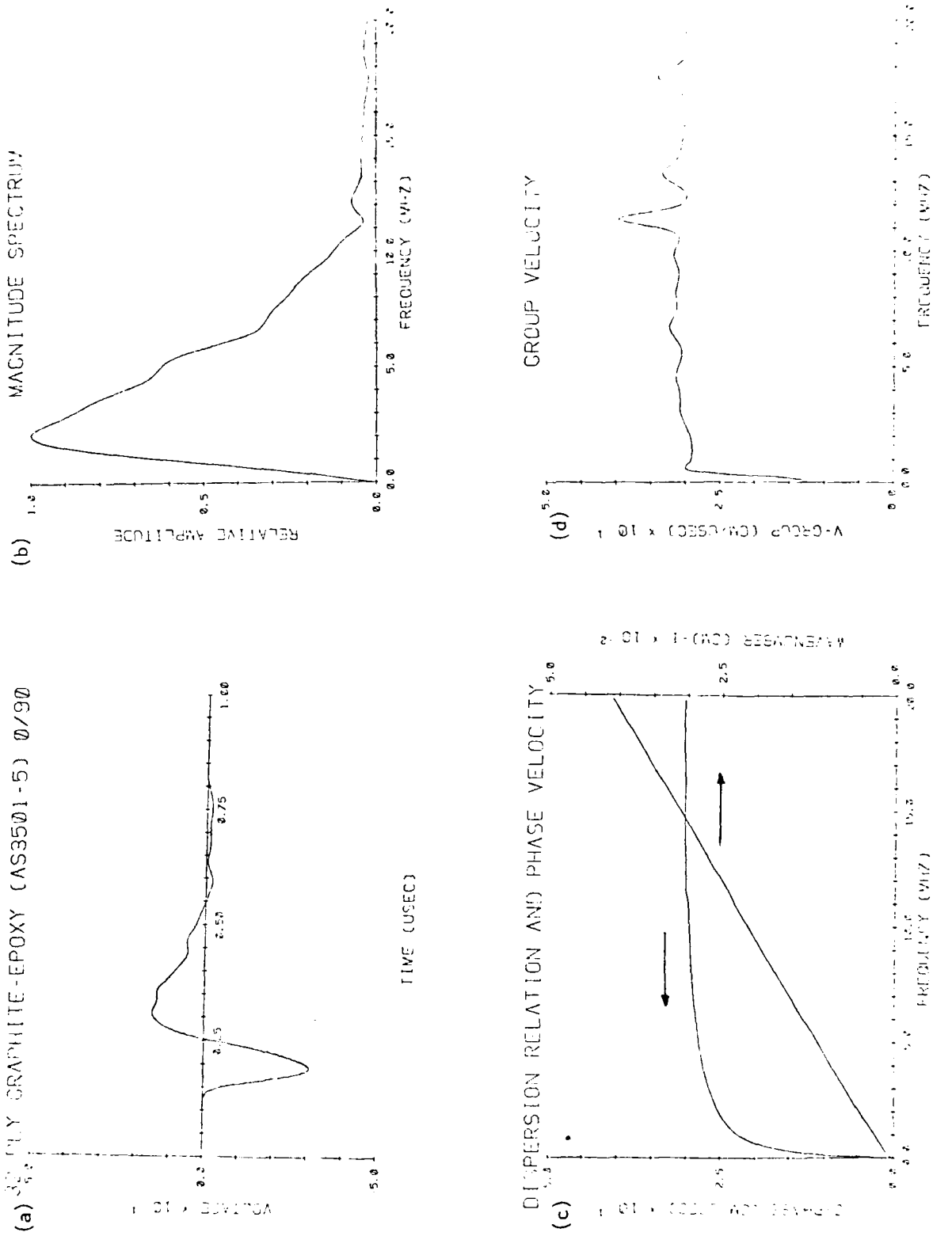

Figure 1 - Ultrasonic phase velocity measurements in 32-ply graphite-epoxy. (a) Longitudinal broadband pulse, (b) Magnitude spectrum, (c) Dispersion relation and phase velocity, and (d) group velocity.

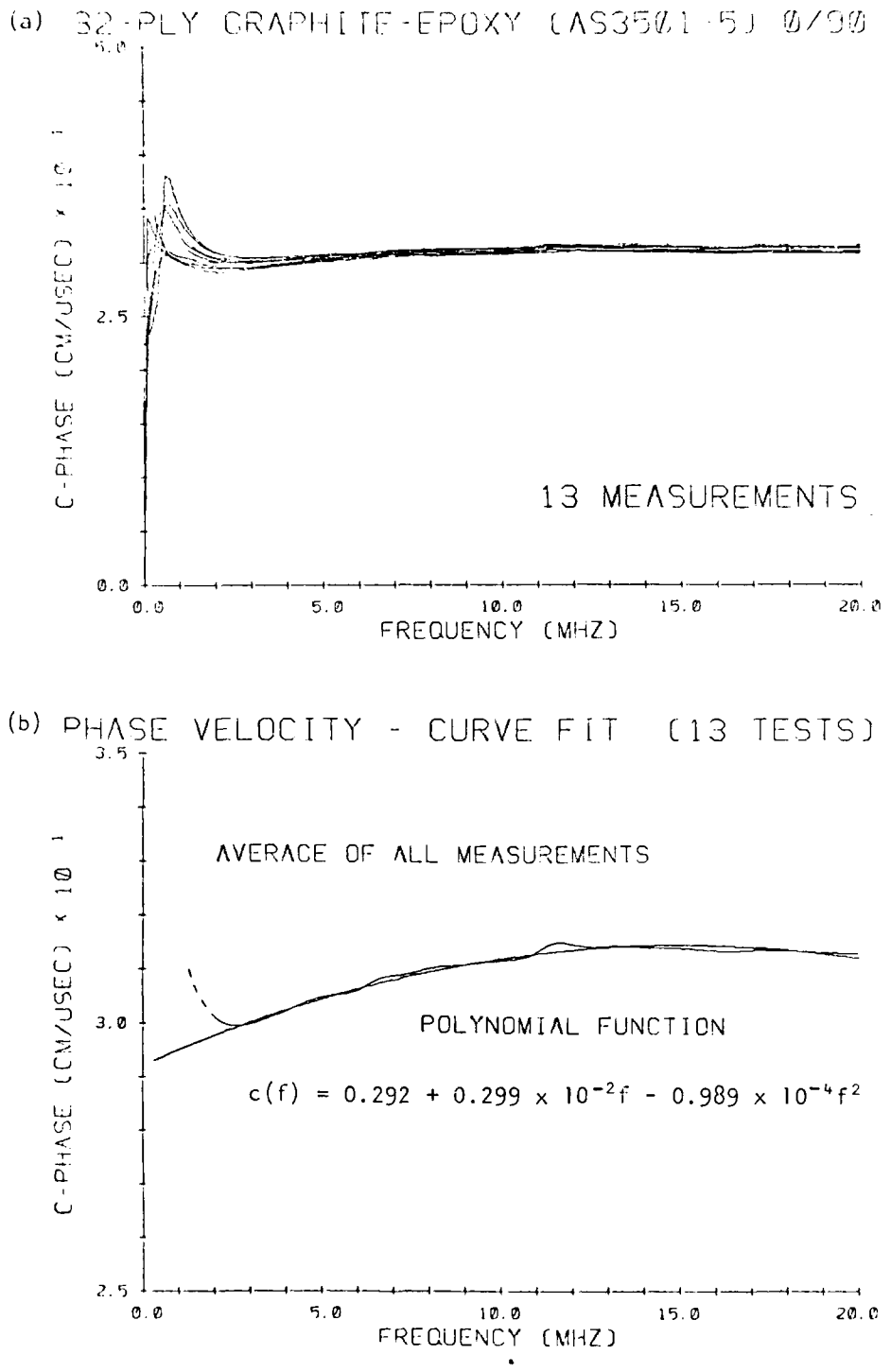

Figure 2 - Phase velocity determination in graphite-epoxy. (a) Results obtained from measurements of 8 specimens (13 tests). (b) Average of all measurements shown in (a) and the least-squares fit polynomial function to the phase velocity data between 1 and 20 MHz. Note the expanded vertical, phase velocity scale in (b).

III. [illegible]

1. [illegible]

By analyzing the forced vibration of [illegible] it is possible to derive an equation relating the material [illegible] to the resonance peak width at any power level. If the material is [illegible] a Voigt solid, the equation of motion of the material for longitudinal displacement is given by

$$(K + \frac{4}{3} G) \frac{\partial^2 u}{\partial x^2} + \frac{4}{3} \eta \frac{\partial^3 u}{\partial x^2 \partial t} = \rho \frac{\partial^2 u}{\partial t^2} \qquad (3.1)$$

where K is the material's bulk modulus, G shear modulus, η the coefficient of viscosity, and ρ the mass density. The stress-strain relation of this material is

$$\tau = (K+4G/3)\varepsilon + (4\eta/3)\dot{\varepsilon} \quad ; \quad \varepsilon = \partial u/\partial x \qquad (3.2)$$

When such a specimen is driven by a harmonic force with frequency ω,

$$f(t) = F_o e^{i\omega t} \qquad (3.3)$$

the steady-state motion is given by

$$u(x,t) = \sum_n \frac{-i(2/\ell)F_o \cos k_n x}{(4\eta/3)\omega k_n^2 + i[\rho\omega^2 - (K+4G/3)]k_n^2} e^{i\omega t} \qquad (3.4)$$

where ℓ is the thickness of the specimen, and z_n, θ_n are constants. From this solution one can calculate the power resonance curves for each normal mode, corresponding to each k_n, and from these curves, one finds for the attenuation coefficient ($\omega=2\pi f$),

$$\alpha(f_n) = \frac{\pi(f_2-f_1)}{c(f_n)} \sqrt{\frac{p}{1-p}} \quad \text{[nepers/inch]} \tag{3.5}$$

In this equation, p is the power level ratio, which is defined as

$$p = \frac{W}{W_{max}} \tag{3.6}$$

where W represents the power level at which the bandwidth specified by frequencies f_1 and f_2 is measured, and W_{max} is the peak power level (see Fig. 3). The quantity $c(f)$ represents the measured phase velocity value at the resonant frequency.

Figure 3 shows schemetically a resonance curve with multiple modes. By analyzing different resonances, the material damping is determined as a function of frequency.

The application of this technique to make attenuation measurements in AS3501-5 0/90° cross-plied specimens is shown in Figure 4. In Figure 4(a) is the specimen resonance curve from which the transducer and electronics effects have been deconvolved. In Figure 4(b) are the attenuation values determined from a detailed analysis of the peak width as a function of fractional peak height for three of the resonance peaks indicated in (a). The results show that for each resonance peak a distinct attenuation value can be found regardless of the power level at which the peak width is measured. When each of the resonance peaks in (a) is analyzed in this way, the attenuation is found as a function of frequency, as shown in Figure 4(c). Details of this investigation will be given in the report:

P. Chen, W. Sachse and Y.H. Pao, "Analysis of Continuous-wave Resonance Spectra for Attenuation Measurements" (In preparation).

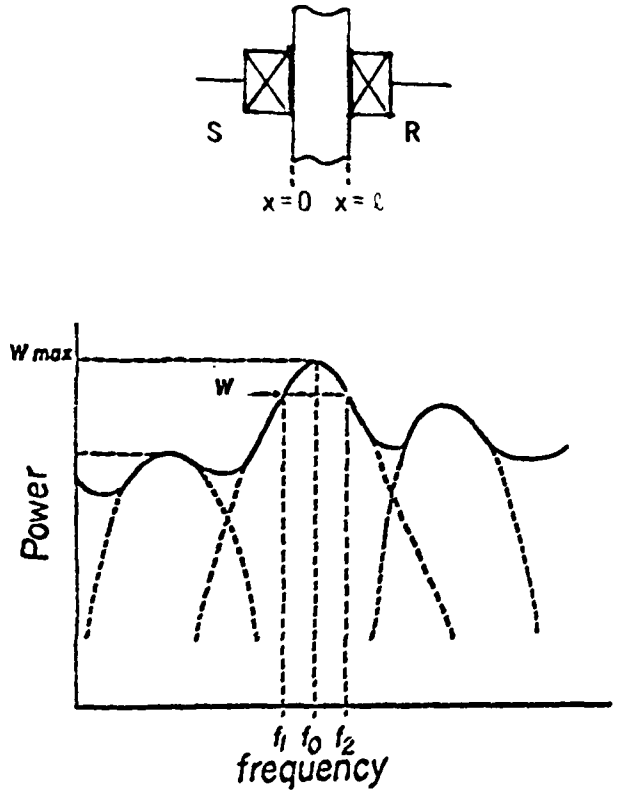

Figure 3 - Implementation of the new continuous-wave resonance method for attenuation measurements in highly absorptive composite materials. (a) Testing configuration; S - source, R - receiver; (b) Data reduction from the measured resonance curve.

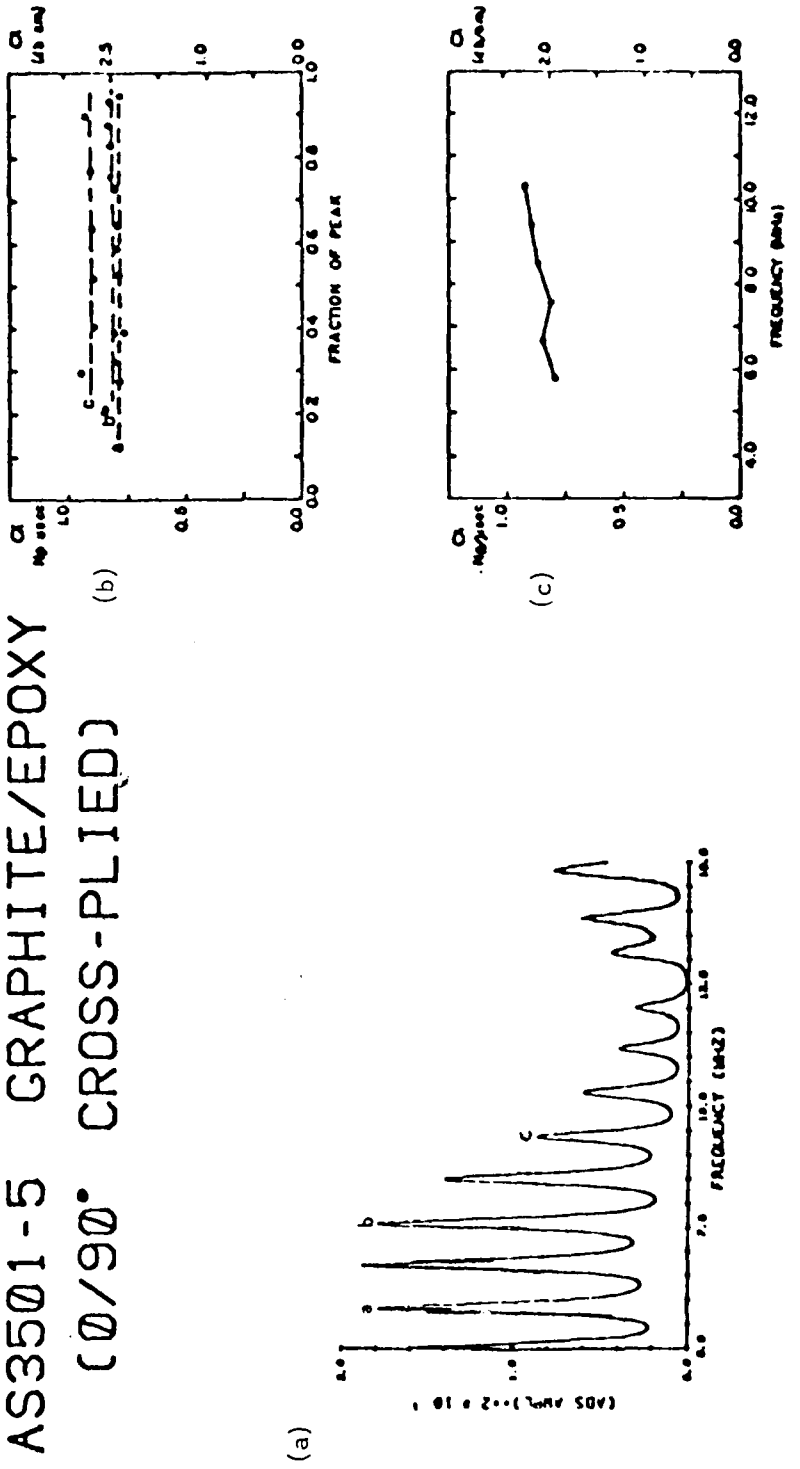

Figure 4 - Continuous-wave attenuation measurements in AS3501-5. (a) Power spectrum, (b) Attenuation versus peak height for the peaks indicated in (a), and (c) the derived frequency-dependent attenuation.

2. Attenuation from the Kramers-Krönig Formula

The Hilbert-transform technique for determining the frequency-dependent attenuation was developed in the first year of this research program. This year has seen its implementation to attenuation measurements in 3D-ply graphite/epoxy specimens. The technique is based on the Kramers-Krönig relation relating the real (phase velocity) and imaginary parts (attenuation) of the complex wave number of a material. That is, the frequency-dependent attenuation is related to the phase velocity by a pair of Hilbert transforms

$$\frac{\alpha(\omega)}{\omega} - \left(\frac{\alpha}{\omega}\right)_\infty = \frac{1}{\pi} \int_{-\infty}^{\infty} \left[\frac{1}{c(\xi)} - \frac{1}{c_\infty}\right] \frac{d\xi}{\xi-\omega} \tag{3.7}$$

which can be rewritten as

$$\alpha(\omega) = A\omega + \frac{2}{\pi}\omega^2 \int_0^{\infty} \left[\frac{1}{c(\xi)} - \frac{1}{c_\infty}\right] \frac{d\xi}{\xi^2-\omega^2} \tag{3.8}$$

where $A = (\alpha/\omega)_\infty$. Appearing in this equation is the phase velocity, $c(\omega)$, which is measured by the ultrasonic phase spectroscopy technique.

While applying this formula to the measurement of $\alpha(\omega)$ of real materials, we soon encountered difficulty. In the integral formula Eq. (3.8), the constant A can c_∞ are the asymptotic values of $\alpha(\omega)/\omega$ and $c(\omega)$ respectively as $\omega \to \infty$. They can presumably be estimated from a theoretical model, or data of other experiments. The function $c(\omega)$ in the integrand, however, must be supplied from the measurements of phase velocity over the entire range of frequencies $0 \leq \omega \leq \infty$. This can never be achieved in actual experiments.

To alleviate this difficulty, we break the interval of integration into two parts by selecting an intermediate frequency, ω_N. Thus the formula (3.8) is changed to

$$\alpha(\omega) = A\omega + \frac{2}{\pi}\omega^2 \left(\int_0^{\omega_N} + \int_{\omega_N}^{\infty}\right)\left(\frac{1}{c(\xi)} - \frac{1}{c_\omega}\right)\frac{d\xi}{\xi^2-\omega^2} \qquad (3.9)$$

The first integral is evaluated numerically based on actual measurements of $c(\omega)$, $0 \leq \omega < \omega_n$; and the second integral for $\xi > \omega_N$ is evaluated analytically for an assumed function of $c(\omega)$.

As a first approximation, we assumed

$$c(\xi) = a\xi + b \quad , \quad \xi > \omega_N \qquad (3.10)$$

where a and b are two constants which can be determined by fitting a straight line to the experimental data in the range $\omega > \omega_N$. This procedure is tested against the theoretical model of the Voigt body for which exact expressions for both $\alpha(\omega)$ and $c(\omega)$ are known (see Interim Report, 1979). The results are shown in Figure 5 for $c_o = 0.25$ cm/μs, $\tau = 1$ sec.$^{-1}$, where $c_o^2 = (K + \frac{4}{3}G)/\rho$ and $\tau^2 = (3K/4+G)/\eta$.

Figure 5(a) shows the theoretical phase velocity curve $c(f)$ of a Voigt solid where the vertical scale for $c(f)$ is greatly amplified to exhibit the dispersion. We chose $f_N = \omega_N/2\pi = 20, 30, 40, 50$ MHz, and replace the $c(f)$ curve beyond f_N by a straight line according to Eq. (3.10). The curves for $\alpha(f)$ as calculated by formula (3.9) are shown in Figure 5(b). We find that even the curve labeled by $f_N = 50$ differs from the exact theoretical value. The curve labeled by $f_N = 20$ deviates from the $f_N = 50$ curve at high frequencies, but agrees closely when $f < f_N$.

As can be seen from this example, the accuracy of calculated $\alpha(\omega)$ depends on the range of measureable $c(\omega)$, the choice of ω_N, and the selection of a function representing the $c(\omega)$ for $\omega > \omega_N$. Details will be given in the following report:

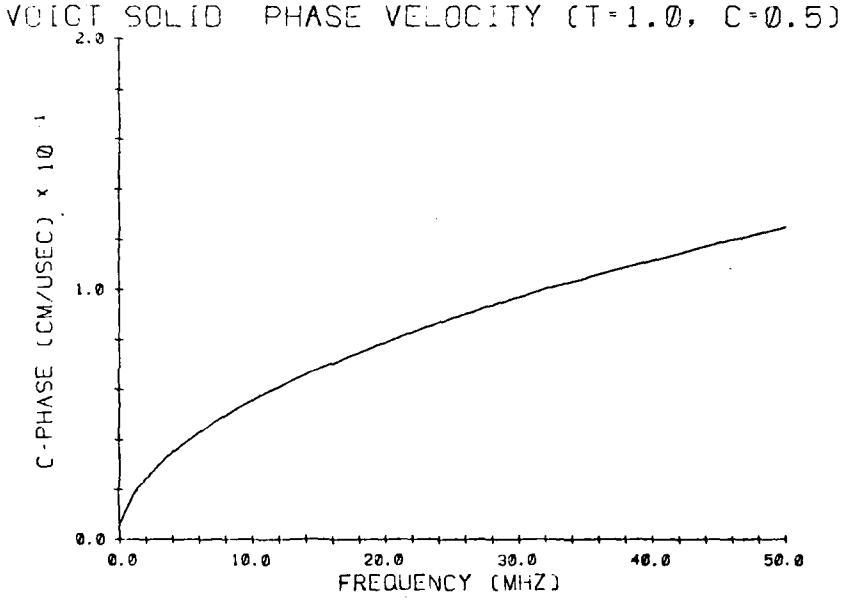

Figure 5(a) - Dispersion in a Voigt material. Phase velocity.

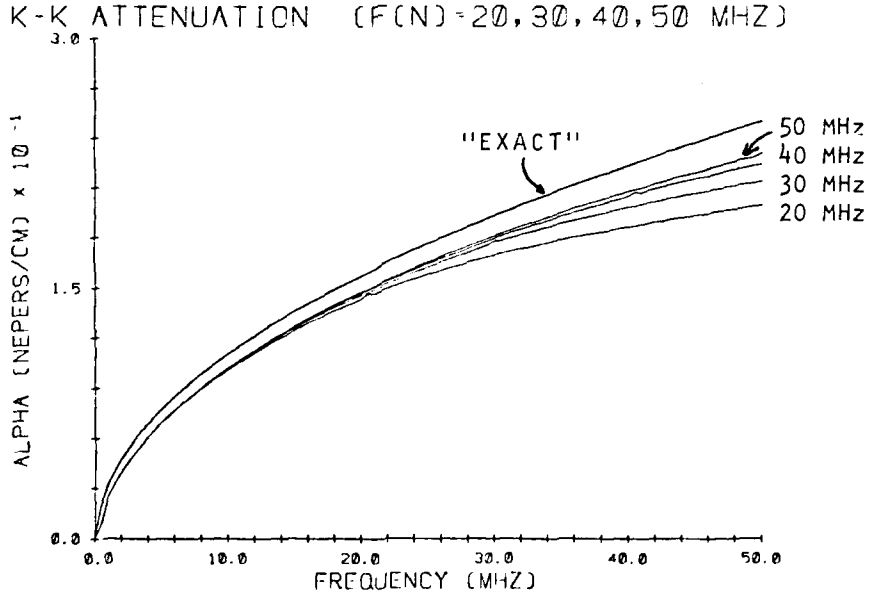

Figure 5(b) - Attenuation in a Voigt material. Exact value and Kramers-Krönig method determined ones with different data - analytic function transition frequencies.

Y.H. Pao, A.N. Gerannaris and P. Weaver, "Determination of Attenuation Coefficients From the Dispersion Relation" (in preparation).

It should be noted that although the afor mentioned method works well for an ideal Voigt viscoelastic material, our work with waveforms and dispersion relations measured in actual composite specimens has pointed to some inherent difficulties. The calculated attenuation coefficients varied widely as the result of the choice of the particular point, f_N, at which the high-frequency extrapolation begins. The final results are also sensitive to the number of points chosen as the basis for the straight line extrapolation.

An example of the results that can be obtained with the Kramers-Krönig relation is shown in Figure 6 for the frequency-dependent attenuation of longitudinal waves in 32-ply graphite/epoxy. In this example, the phase velocity data for frequencies above 6 MHz was extrapolated to fit a straight line. This result differs significantly from that measured by other techniques. Details will be given in the following report:

P. Chen and W. Sachse, "Broadband Ultrasonic Attenuation Measurements in Composite Materials" (in preparation).

IV. DETECTION OF DEFORMATION-INDUCED MICROSTRUCTURAL CHANGES

Experiments were begun this year to evaluate the various frequency-dependent velocity and attenuation measurement techniques for use as an early indicator of microstructural changes in composite specimens under applied load. Attenuation measurements using the broadband pulse technique were made in 32-ply specimens of AS3501 while loaded to failure. An example with longitudinal waves is shown in Figure 7.

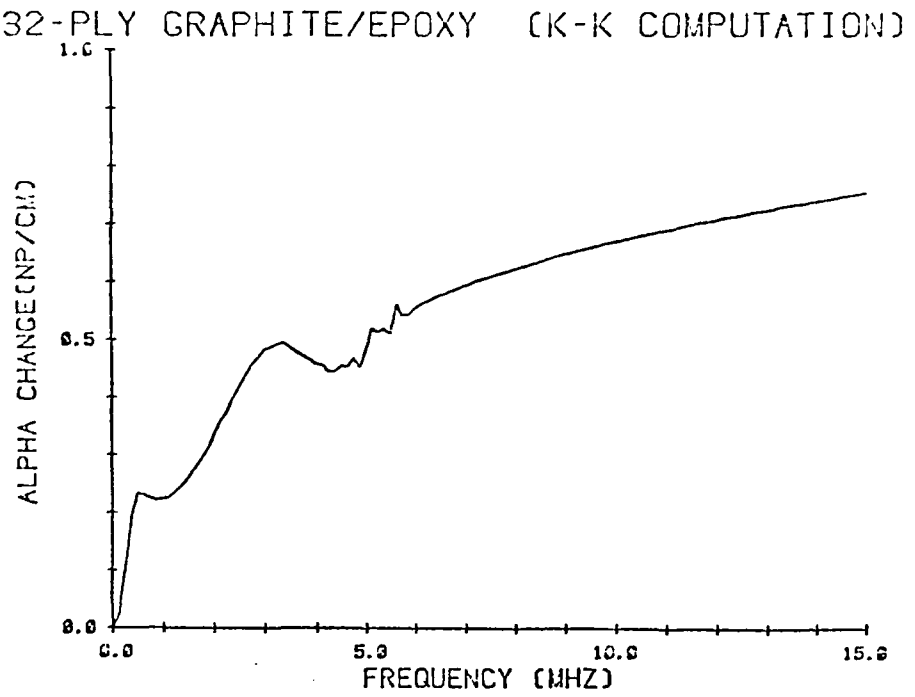

Figure 6 - Hilbert transform, Kramers-Krönig method application for attenuation measurement in 32-ply graphite-epoxy.

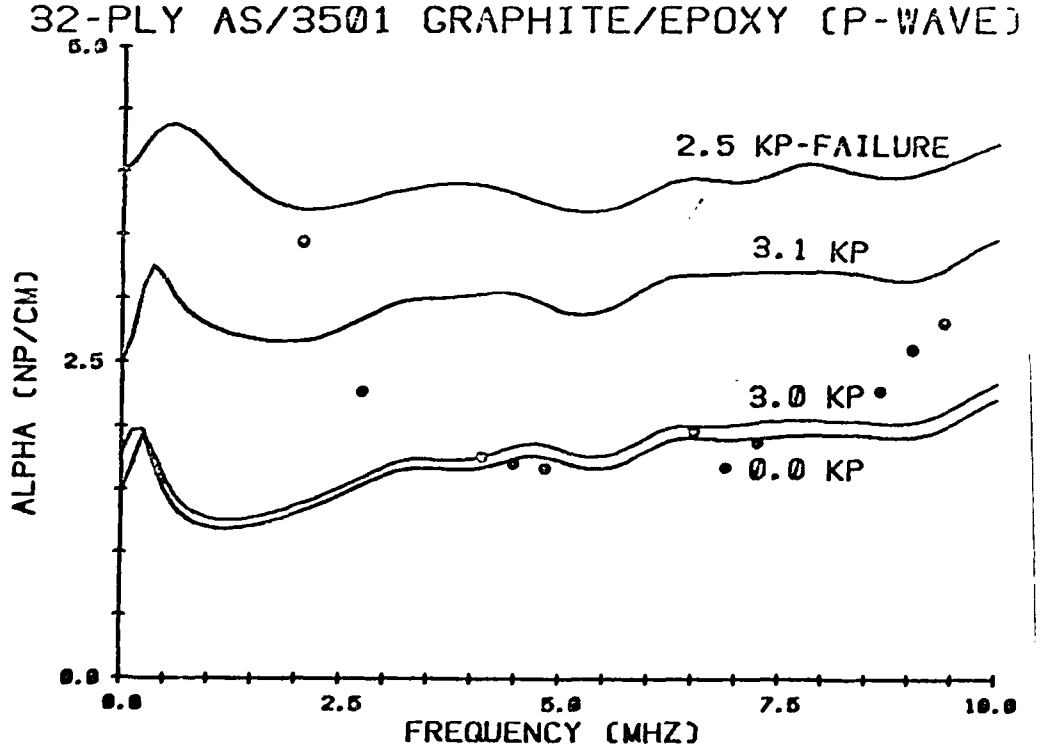

Figure 7 - Measurement of deformation-induced attenuation changes in graphite-epoxy. The solid lines represent data measured by the conventional broadband ultrasonic technique, the data points were obtained from the new continuous-wave resonance technique at zero load.

As shown in this test, the attenuation of the ultrasonic waves remains relatively constant when loaded to near failure. Furthermore, the frequency dependence of the attenuation measured in an unloaded specimen is very similar to that under loads of up to 3.0 Kp (22.1 ksi; 152.3 MPa); that is, it increases only slightly between 1 and 10 MHz. The specimens in these tests were notched and began to fail at 3.1 Kp (18.4 ksi; 127.0 MPa). The attenuation as determined in a linear least squares sense is 0.088 np/cm. In addition, the attenuation values determined from analysis of the continuous-wave resonance curve of the unloaded specimen are shown as data points in the figure. These are in close agreement with the broadband attenuation measurement results between 3 and 8 MHz. The high values of attenuation determined for peaks above 8 MHz appear to be the result of ultrasonic signal-to-noise limitations. At these frequencies in this test, the resonance peaks are less than 3 db above the minima. The reason for the large attenuation values below 3 MHz is not clear

Additional measurements with other specimen materials and with other wave modes are still in progress. Results will be reported before the end of this project. A tentative title of the report will be:

W. Sachse and P. Chen, "Ultrasonic Measurement of Deformation-Induced Microstructural Changes in Composite Materials".

V. MATHEMATICAL FOUNDATION OF THE KRAMERS-KRÖNIG RELATION

It was mentioned in the Interim Report 1979 that the Kramer-Krönig relation, upon which the Eq. (3.9) was based, was a consequence of causality and homogeneity, and whether such a relation existed for inhomogeneous materials, such as fiber-composites, remained to be investigated. This investigation was completed and reported in the following paper:

B.L. Moyer and Y.H. Pao, "Dispersion Relations for Linear Wave Propagation in Homogeneous and Inhomogeneous Media", (to appear in J. Mathematical Physics, 1980).

This paper, which was completed in April, 1980, and sent to Dr. D. Ball of AFOSR, was reviewed and accepted for publication in a journal of the American Institute of Physics in July. A summary of the paper is given below.*

A plane harmonic wave propagating unidirectionally in + z axis is represented as

$$u(z,t) = A(\omega)e^{i[-\omega t - zK(\omega)]} \tag{5.1}$$

For a homogeneous medium, the wave number $K(\omega)$ is a well defined quantity, and the real part (Re K) and the imaginary part (Im K) of $K(\omega)$ define respectively the phase velocity $c(\omega)$ and attenuation constant $\alpha(\omega)$,

$$c(\omega) = \omega/[\text{Re } K(\omega)] \tag{5.2}$$

$$\alpha(\omega) = \text{Im } K(\omega) \tag{5.3}$$

For an inhomogeneous medium, the $K(\omega)$ is the wave number for the statistically average wave field in the medium, and $A(\omega)$ is the amplitude of the coherent part of the wave.

A theorem of the theory of complex variables states that if the function $K(\omega)$ is analytic in the upper half of the complex ω-plane and if $c_\infty = c(\omega)$ as $\omega \to \infty$ is bounded, the Im K and Re K are related by a pair of Hilbert transforms. The $\alpha(\omega)$ is then related to $c(\omega)$ as shown in Eq. (3.7), which is known as the Kramers-Krönig relation in solid state physics.

* Copy attached to this report.

In the aforementioned paper, a rigorous mathematical proof is given of the analyticity of $K(\omega)$ in the upper half ω-plane, and that the Kramers-Kronig relation exists without a priori knowledge of σ_{dc}. The proof is applicable for acoustic, electromagnetic, and stress waves in a homogeneous or inhomogeneous medium, so long as the medium is linear, causal, and passive.

The rigorous proof as given in this paper removes any doubt as to whether the Kramers-Krönig formula can be applied to composite materials. The difficulty of applying it to composite materials as mentioned in Section III-1 is then solely attributed to measurement uncertainty, and the band-limited measured values for $\sigma(\omega)$.

VI. SUMMARY

In the second year of the research program dealing with ultrasonic measurements of composite materials, additional wave dispersion and frequency-dependent attenuation measurements were made in graphite/epoxy materials. The results of the dispersion measurements are in agreement with earlier measurements made on similar materials. For quantitative comparisons of dispersion and attenuation data, least square-fit algorithms were implemented into the ultrasonic signal processing system for fitting polynomial velocity and attenuation functions to the measured data points. Reproducible measurements in graphite/epoxy have been obtained.

Two new frequency-dependent attenuation measurement techniques were developed for composite materials. One is a continuous-wave resonance measurement technique in which the resonance peaks of a specimen are analyzed at various power levels. The other utilizes the Kramers-Krönig relation to find the material attenuation from measurements or the dispersion, or vice versa,

[illegible] being required to make the measurements. This new technique is expected to be useful for measurements in highly absorbent composites. A flow theoretical basis for the technique has been established and measurements with graphite/epoxy specimens have been made. It is expected that when dispersion measurement technique is improved, good agreement can be obtained between the various attenuation measurement techniques.


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