EFFECT OF STRESS ON ULTRASONIC PULSES IN FIBER REINFORCED COMPOSITES

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An Acoustical-Ultrasonic Technique was used to demonstrate that relationships exist between changes in attenuation of stress waves and tensile stress for an 8-ply "0" degree graphite-epoxy fiber reinforced composite. All tests were conducted in the linear range of the material for which no mechanical or macroscopic damage was evident. Changes in attenuation were measured as a function of tensile stress in the frequency domain and in the time domain. Stress wave propagation in these specimens was dispersive, i.e., the wave speed depends on frequency. Wave speeds varied from 2700 m/sec to 6800 m/sec as the frequency of the signal was varied from 150 KHZ to 1.9 MHZ which strongly suggests that flexural/Lamb wave modes of propagation exist. The magnitude of the attenuation changes depended strongly on tensile stress. It was further observed that the wave speeds increased slightly for all tested frequencies as the stress was increased.

INTRODUCTION

Non-Destructive Evaluation (NDE) techniques are being widely used today to characterize the physical state of solid materials. Vary, et.al., (refs. 1-6) have demonstrated that correlations do exist between ultrasonic measures and mechanical properties of metals, ceramics, and fiber composites. Williams, et.al., (refs. 7,8) have shown that ultrasonic attenuation is an indicator of fatigue life for graphite-epoxy composites. Ultrasonic measurements in the area of composite materials have provided a nondestructive means for measuring variations in strength related properties, predicting interlaminar shear strength of fiber composite laminates, and ranking composite structures according to strength.

This research presents evidence on how well (NDE) techniques describe stress related effects. An ultrasonic attenuation study of a stress wave propagating through a "0" degree graphite-epoxy fiber reinforced composite specimen subjected to tensile loads was performed. This paper will provide not only qualitative data, but also quantitative data, showing the relationships that exist between changes in attenuation of stress waves and tensile stress for the 8-ply "0" degree specimen under consideration. Tensile testing was done in the linear range of the material, where linearity is defined by constant slope of the stress-strain curve in the range of the test conducted. Wave speeds were also measured showing that stress wave propagation is dispersive.

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The demonstrated conclusions are:

1. Dispersion does occur, i.e., wave speeds are frequency dependent.
2. The attenuation is strongly dependent on tensile stress.
3. The wave speed is weakly dependent on tensile stress.

EXPERIMENTAL PROCEDURE

Material

The specimen used was an eight-ply "0" degree angle-ply graphite-epoxy fiber reinforced composite. An AS graphite fiber and a PR-288 exposy resin have been used to construct an AS/PR-288 preimpregnated fiber-resin ply. The fibers were coated with a polyvinyl alcohol to enhance fiber-matrix interface strength properties. A schematic of the unidirectional composite is shown in Figure 1. The physical properties of the specimen have been determined by Vary, et.al., (ref. 3).

Apparatus

A schematic of the specimen and transducers in ultrasonic through transmission testing was shown in Figure 2. Broadband transducers of various center frequencies were used to gather all of the data over the various frequencies.

Aluminum semicylindrical buffers of 3.157 mm (.125 in) diameter were attached to the transducers in order to:

a. Provide a line contact of length 12.7 mm (.5 in) which is the width of the specimen.
b. Prevent bending from occurring as pressure was applied to the transducer holders.
c. Place the sending and the receiving transducer at specified location.

Strain gages were mounted on the specimen on both faces to measure the axial and transverse strains. Strain gages were 0° and 90° orthogonal back-to-back. Also strain gages were installed onto the transducer holders to measure the pressure applied to the transducers. Williams, et.al., (ref. 8) defined and measured a "saturation pressure" which is required for reproducible coupling of transducer to specimen; this pressure was monitored by the strain-gaged transducer holders.

An Ultragel II ultrasonic couplant was used between the aluminum buffer and the specimen. A very thin coating of couplant was used where effects of thickness of the couplant were neglected. A felt material was used on the backside of the transducer holder to insure that energy did not enter the transducer holder from the specimen.

The ultrasonic equipment and the tensile testing system are schematically shown in Figure 3.

Experimental Loading

An ultrasonic wave was transmitted into the specimen by a sending transducer. Two inches away in the longitudinal direction, and on the same face, a receiving transducer was placed to sense the stress wave energy traversing the specimen. The receiving transducer output was displayed on the oscilloscope for real time analysis and on the spectrum analyser for frequency analysis.

The specimen, mounted in a tensile machine where care was taken to minimize off-axis loading or twisting, was pulled at an initial loading rate of approximately 17 μm/sec (.04 in/min) to set the grips. After this initial loading to about 445N (100 lbf) which was the reference load for attenuation measurements and change in attenuation measurements, further loading was done at mean rate of 4.2 μm/sec (.01 in/min).

The load was increased to 3560N (800 lbf), 6675N (1500 lbf), and in some experiments to 13350N (3000 lbf) successively. Then the load was decreased to 6675N, 3560N, and 445N. At the same time strain-load data was generated, photographs of the stress wave output and the frequency output were taken.

The loading-unloading cycle was repeated five to seven times for each setting of independent variables; the test usually was completed within a two-hour period. The number of cycles that were required was dictated by the reproducability and stability of the attenuation changes.

Typical output signals are shown in Figure 4 and Figure 5 for an entire loading-unloading cycle.

RESULTS

In this experimental research many observations were made concerning how various parameters effected the ultrasonic output; only a few were examined and are presented in this paper because of time, equipment, and experimental system limitations. This chapter will present the dispersion phenomenon and the wave type, the attenuation as related to tensile load, and the wave speed as related to tensile load; the specimen was "0" degree graphite-epoxy fiber reinforced composite.

Dispersion

Dispersion is understood to mean that wave speeds are frequency dependent. From the data collected and the measurements taken, a graph shown in Figure 6 was plotted showing speed versus frequency. The wave speed was determined by measuring the delay time between the output wave front and input wave front over a fixed distance. The graph shows that the wave velocity along the longitudinal direction is frequency dependent. Wave speeds varied from 2.7×10^5 cm/sec to 6.8×10^5 cm/sec as the frequency of the signal was varied from 150KHZ to 1.9 MHZ.

There are two types of dispersion. First is viscoelastic dispersion due to viscoelastic properties of the material. Second is a geometric dispersion due to the dimensions of the material. Williams (ref. 8) demonstrated that there is no viscoelastic dispersion in the graphite-epoxy composite for longitudinal and shear wave velocities in the range tested. Shear wave velocities were tested in the range of 0.48 to 3.0 MHZ and longitudinal wave velocities were tested in the range of 0.225 MHZ to 5 MHZ. The frequency range for the results presented in this paper is 0.15 to 1.9 MHZ, which is very close to the range of Williams' result.

For the wave propagating in the x_1 direction and having a particle motion in the x_1 direction, Williams (ref. 8) measured the longitudinal wave speed and found it to be 8.5 to 10^5 cm/sec. This wave speed C_L is plotted in Figure 6 and is used as a comparison since the material used in Williams' research is very similar to the material used in the research reported here.

By comparing C_L to the velocities obtained in this experiment as shown in Figure 6, one can see that the wave velocities measured were not longitudinal wave velocities. The sending transducer inputs a longitudinal wave perpendicular to specimen which, because of many reflections, becomes a wave propagating along the length of the specimen. During this propagation shear waves are formed due to the reflections and interact with longitudinal waves. This interaction of waves propagating along a thin specimen produces Lamb waves (ref. 9). Dispersion does occur in the propagation of flexural/Lamb waves (ref. 10).

Lamb wave propagation may exist in a multimode state at a given frequency producing a finite number of wave speeds to exist simultaneously. Because of experimental equipment limitations, this research could not define which mode (fig. 6) and how many modes were superimposed upon each other, but this paper recognized the possible existence of different modes simultaneously in the stress wave output.

Attenuation vs. Tensile Stress

The relationship between attenuation and tensile stress was investigated by measuring the pulse amplitude change in the time domain and in the frequency domain. The tensile load applied to the specimen was in the linear range of the material where linearity is demonstrated by the constant slope of the stress-strain curve shown in Figure 7. Percent change in amplitude vs. tensile load in the frequency domain is shown in Fiugre 8 for each of the six frequencies used in the experiment. At 150, 180, 250, and 1900 KHZ, a negative attenuation with increasing load is observed whereas at 850 and 1700 KHZ the attenuation is positive. The slope of these lines remains constant with cycling, but a translation of the lines occurs in the first few cycles, after which the lines stabilize for subsequent cycles. The data needed to plot these lines come from direct measurements of amplitude changes from photographs of which Figure 4 is typical.

Figure 9 shows percent change in amplitude vs. tensile load in the time domain. At 150, 180, 250, and 1900 KHZ a negative attenuation with increasing load is observed whereas at 850 KHZ a positive attenuation occurs. The slopes and translation of these lines with cycling behaves similarly to the frequency lines. Theoretically Figures 8 and 9 should be identical, but as one can see from Figure 5 the energy response in the time domain is stretched out into many small immeasurable spikes. The data plotted in Figure 9 reflects only the main part of the pulse. The 1700 KHZ response could not be clearly separated from the 1900 KHZ response in the time domain and hence was not plotted.

The data shown in Figures 8 and 9 behave in a generally similar manner. The data clearly indicates that the attenuation, both positive and negative, of the ultrasonic pulse depends on tensile stress.

Wave Speed vs. Tensile Load

The data at all frequencies clearly shows that the wave speed increases with increasing stress. This can be clearly seen in Figure 5 where all pulses are translated to the left (decreasing arrival time) with increasing load. The data showed wave speed changes as large as 8% at stress levels 30% of the ultimate stress.

CONCLUSION

It has been shown that dispersion did occur, i.e., wave speeds were frequency dependent. Moreover, it was found that flexural/Lamb waves existed, and a superposition of different modes existed in the stress wave output of the signal.

It has been proven that attenuation depended strongly on tensile stress. Also it was observed that attenuation was frequency dependent.

Finally, it was demonstrated that wave speeds were weakly dependent on tensile load.

Further research is needed using a pulsing system producing narrow band frequencies since all effects measured were frequency dependent.

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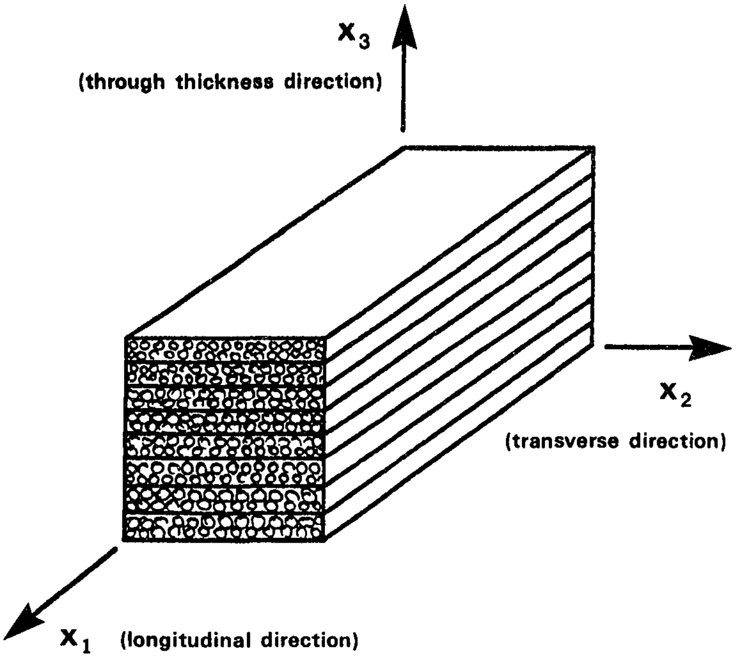


Figure 1. Principal directions of the "0" degree angle-ply specimen

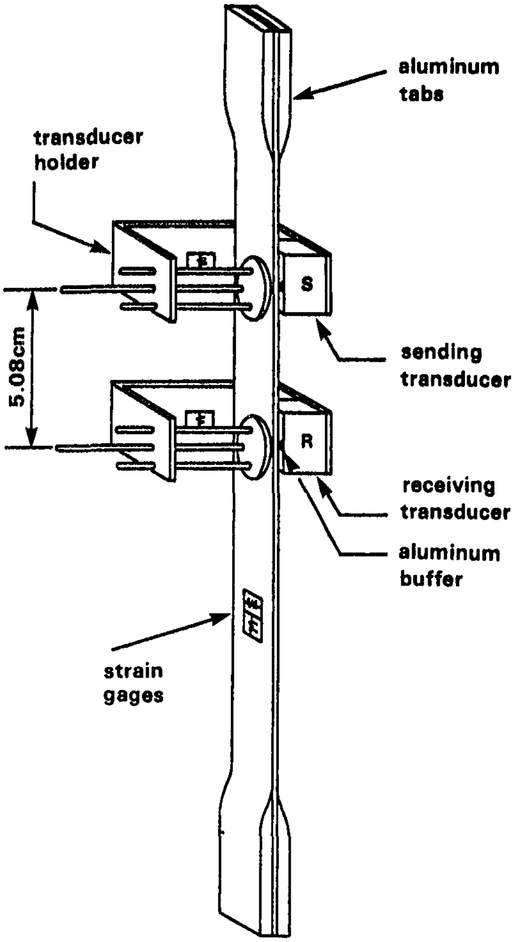


Figure 2. Schematic diagram specimen and transducers

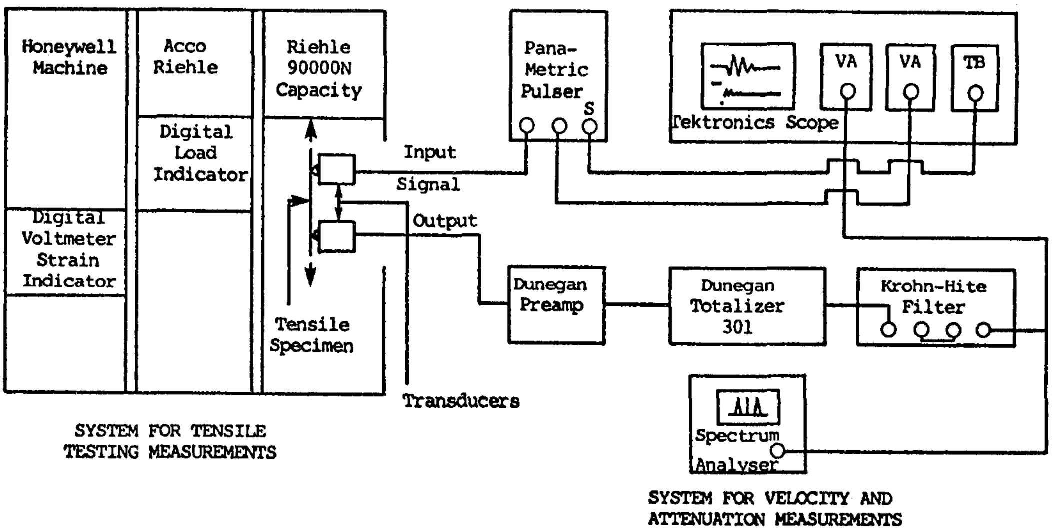
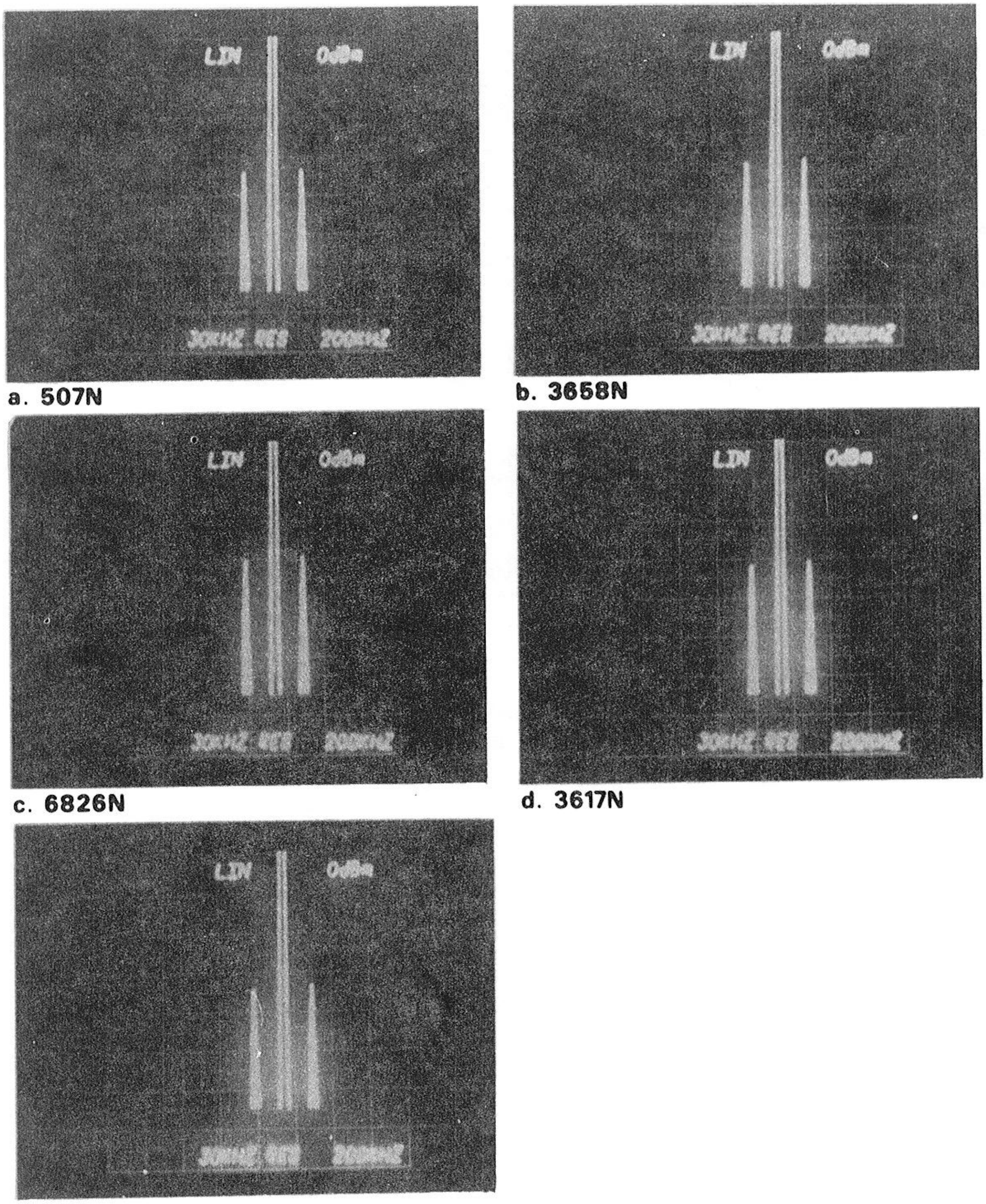


Figure 3. Experimental system



a. 507N

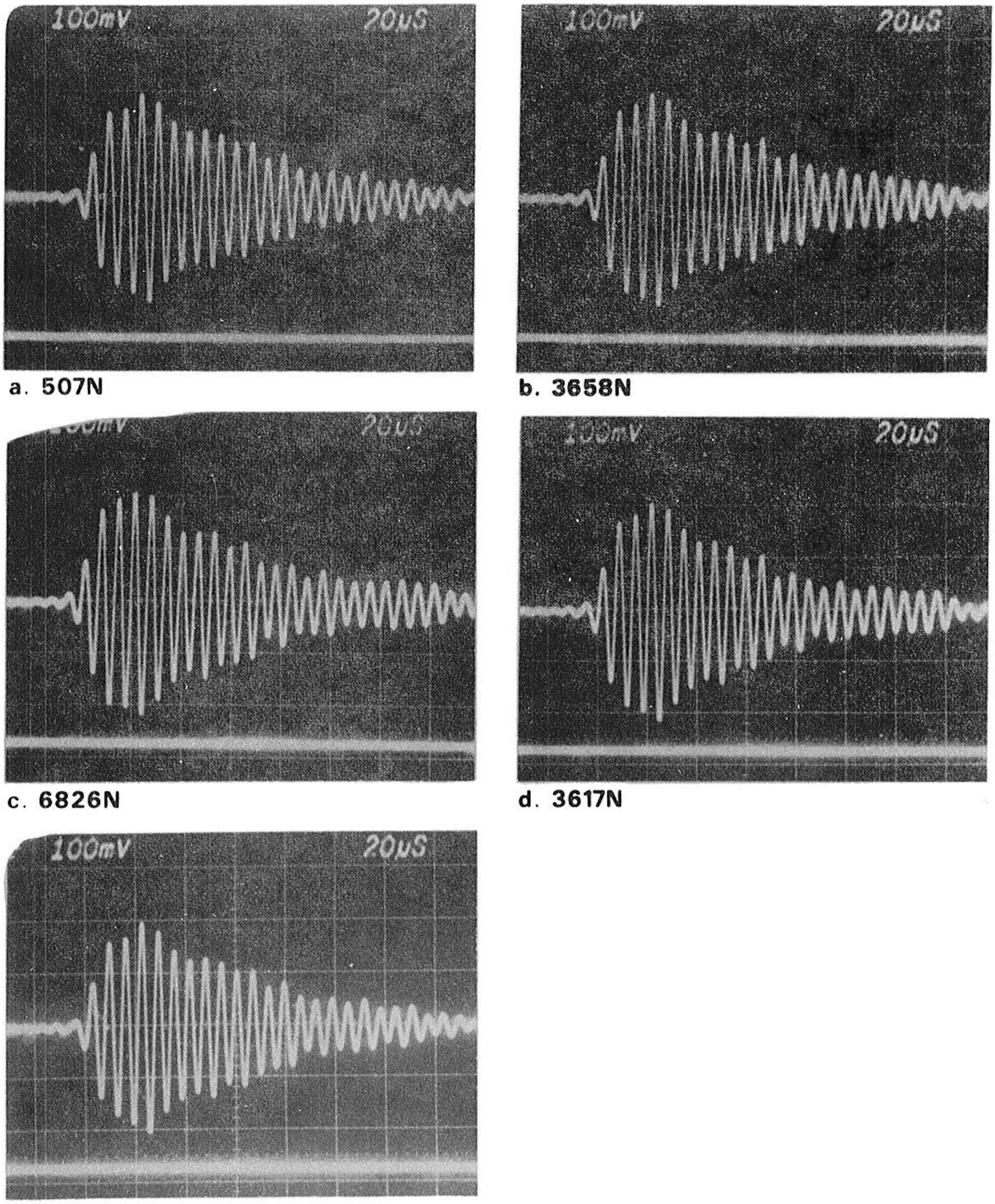
b. 3658N

c. 6826N

d. 3617N

e. 525N

Figure 4. - Ultrasonic pulse attenuation versus load of 150 kHz in frequency domai



a. 507N

b. 3658N

c. 6826N

d. 3617N

e. 525N

Figure 5. - Ultrasonic pulse attenuation versus load of 150 kHz in time domain.

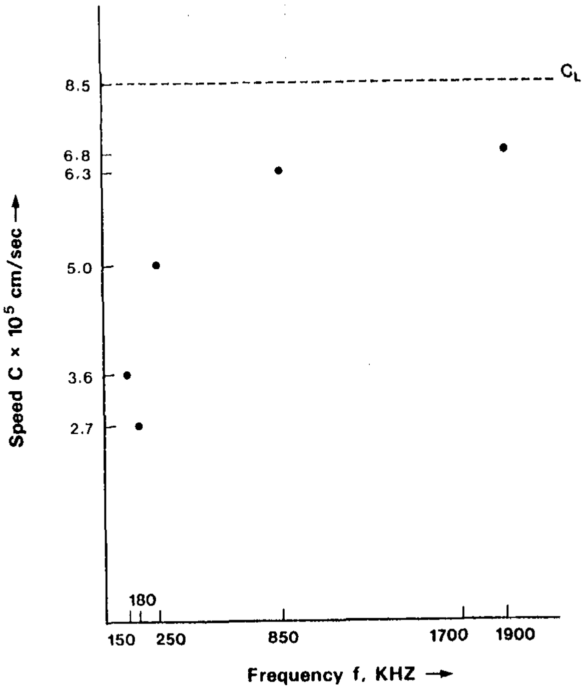


Figure 6. Wave speed vs. frequency

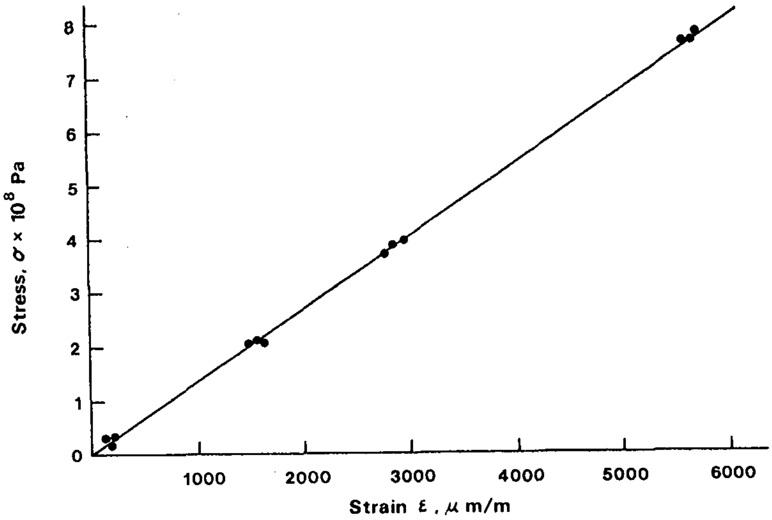


Figure 7. Axial stress vs. axial strain

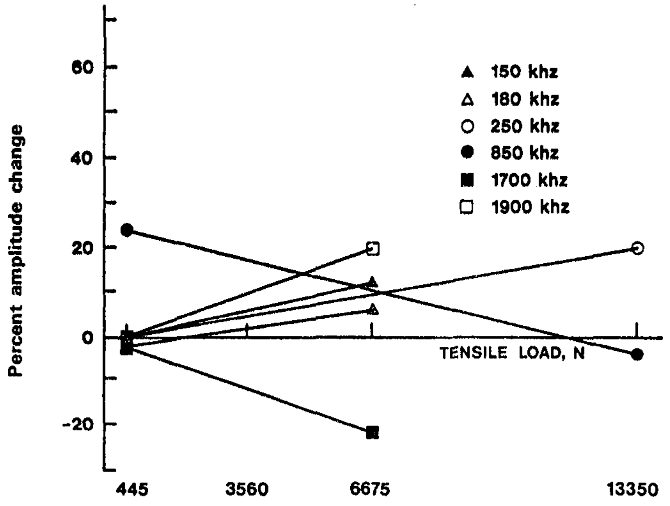


Figure 8. Percent change in amplitude vs. tensile load in the frequency domain

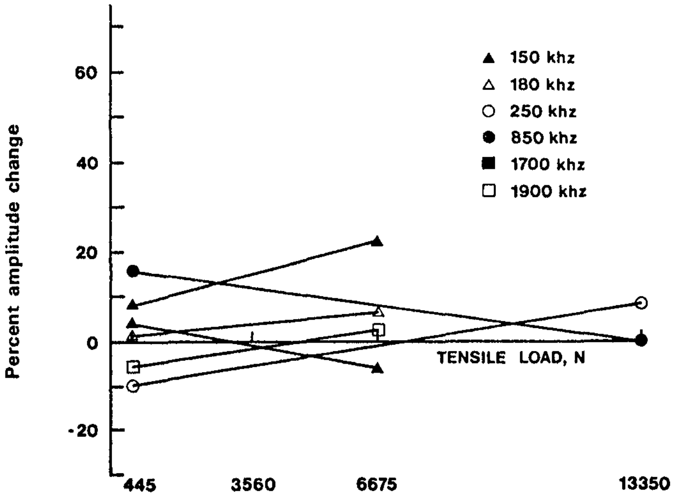


Figure 9. Percent change in amplitude vs. tensile load in the time domain