ULTRASONIC VELOCITY CHANGE AND DISPERSION DUE TO POROSITY IN COMPOSITE LAMINATES

David K. Hsu and Hyunjo Jeong
Center for NDE
Iowa State University
Ames, Iowa 50011

INTRODUCTION

Voids or porosity in carbon fiber reinforced plastics (CFRP) caused by improper curing, moisture in the prepreg and other reasons can degrade the mechanical properties of the composite components [1-3]. Voids caused by trapped air in the layup process or volatile gas released in the curing process tend to occur at the interface between the plies of unidirectional prepregs and are usually elongated along the adjacent fiber directions [4]. On the other hand, voids in woven composites tend to be more spherical. Matrix dominated strengths such as transverse tensile and interlaminar shear strengths are affected the most by the presence of porosity. Quantitative nondestructive evaluation (QNE) methods for the detection and characterization of porosity in composites are therefore highly desirable.

Since voids are strong scatterers for elastic waves, ultrasound has been a useful probe for the detection and evaluation of porosity in CFRP. The correlation between ultrasonic attenuation and void content in CFRP is well known [5] and has become the basis for wide industrial quality assurance practices against porosity. At the Center for NDE at Iowa State University, measurement procedures were developed to obtain ultrasonic attenuation as a function of frequency using broadband pulses. Model-based quantitative relationship between the "attenuation slope", or \( \frac{da}{df} \), and the volume fraction of porosity has been established for both spherical voids and long cylindrical voids with elliptical cross section [6]. The porosity content estimation technique based on the ultrasonic attenuation has been experimentally tested on various CFRP systems with encouraging results [7,8].

In this paper we present an experimental study of using ultrasonic velocity for the NDE of porosity in CFRP. Compared to attenuation, velocity has been essentially undeveloped as a tool for the NDE of porosity in composites. A common concern with using velocity has been its dependence on other material properties such as variations of fiber volume fraction. One theoretical calculation [9] showed that the longitudinal velocity in graphite-epoxy changes only very slightly with fiber volume fraction in the range of interest. In this paper we use the terms graphite-epoxy and carbon-epoxy interchangeably. In this work longitudinal velocity was measured as a function of porosity content and frequency in both woven composite laminates and laminates made of unidirectional prepreg tapes. The velocity measurements were also made with broadband pulses; in fact, the same experimental data were used for
calculating both the attenuation and velocity. It was therefore natural to test the Kramers-Kronig relationship that relates attenuation and velocity changes.

EXPERIMENTAL METHOD

Ultrasonic velocity in CFRP laminates was measured in an immersion tank using a "substitution technique" in the through-transmission mode. The measurement configuration is shown in Fig. 1. Two unfocused broadband transducers were set up to face each other and separated by a distance of typically 15 cm.

The transducers used were 6.35 mm (1/4") diameter probes with a center frequency of 5 or 10 MHz. The transmitting transducer was driven by a spike voltage pulse. The pulse transmitted through water only was digitized and stored in the computer as the reference signal. The composite panel was then inserted perpendicular to the acoustic path. Because the speed of sound in the composite is greater than that in water, the pulse transmitted through the sample appeared earlier in time than the reference signal. This "sample signal" was also digitized and stored. Frequency dependent attenuation and velocity were then computed from the FFT of these signals.

When the lineshapes of the reference signal and the sample signal are similar, the velocity in the sample \( v_s \) may be computed from the time difference \( \Delta t \) between corresponding points of the waveforms using the following simple equation:

\[
v_s = \left[1 / v_w - \Delta t / d\right]^{-1}
\]  

where \( v_w \) is the speed of sound in water and \( d \) is the sample thickness. Equation (1) can be derived easily from time of flight consideration. This technique is quite convenient for measuring the sound velocity in thin composite laminates because the reference signal and the sample signal do not appear at the same time and the time difference between them can therefore be very small without the concern for overlapping.

\[
\Delta t = \frac{L}{v_w} - \left(\frac{L - d}{v_s} + \frac{d}{v_s}\right) = d \left(\frac{1}{v_s} - \frac{1}{v_w}\right)
\]

\[
v_s = \left[ \frac{1}{v_w} - \frac{\Delta t}{d} \right]^{-1}
\]

Fig. 1. Velocity measurement using the substituting method.
When the composite laminate is thicker or contains porosity, the through-sample signal will have a different lineshape than the reference signal. This is a result of the frequency dependence of the attenuation and velocity in the sample which changes the spectral content and hence lineshape of the pulses. In this case the measurement of $\Delta t$ becomes ambiguous and one should measure the velocity as a function of frequency using a phase spectroscopic technique [10].

In the phase spectroscopic method the phase velocity of the longitudinal wave propagating perpendicular to the composite laminate plate is obtained by calculating the phase difference $\Phi_s(\omega)-\Phi_r(\omega)$ between the sample signal and the reference signal. This phase difference, to within an uncertainty of $\pm 2\pi m$, $m$ being an integer, is obtained by performing a deconvolution of the two signals. The phase uncertainty of an integer multiple of $2\pi$ arises because the spectral contents of the pulses do not extend all the way to zero frequency. The phase velocity $v(\omega)$ is given by

$$v(\omega) = \frac{1}{\omega} \left[ \frac{1}{v_u} - (\Phi_s(\omega) - \Phi_r(\omega) \pm 2\pi m) / \omega d \right]$$

where $\omega$ is the angular frequency and the subscripts $s$ and $r$ refer respectively to the sample signal and the reference signal. The correct value of $m$ can usually be determined by comparing the phase spectral velocity $v(\omega)$ and the approximate velocity obtained from a simple time-of-flight measurement. Figure 2 shows the effects of errors of $2\pi$ on the phase velocity in a void-free graphite laminate. The center curve is the velocity with no error in the integer $m$ in Eq. (2) and the upper and lower curves are respectively the results with an error of $+2\pi$ and $-2\pi$ in the phase. The solid dots are the time-of-flight results using three different transducers. It is clear that any error in the phase can be eliminated by comparing with the time-of-flight result.
RESULTS

To study the effects of porosity on ultrasonic velocity, measurements were made on four composite systems: woven graphite-epoxy with 0 - 5% voids, woven graphite-polyimide with 0-11% voids, quasi-isotropic graphite-epoxy with 0-4% voids and unidirectional graphite-epoxy with 0-6.5% voids. Figure 3 shows the phase velocity of longitudinal waves propagating normal to woven graphite-epoxy laminates containing up to 5% voids. To demonstrate that the measured velocity results do not depend on the particular type of transducers used, Fig. 3 shows the measurement results obtained with both 10 MHz transducers and 5 MHz transducers. As can be seen, the agreement is good. Results in Fig. 3 show that the velocity decreases with increasing void content and the velocity dispersion is greater for laminates with more voids. The velocity data obtained with the phase spectral technique were compared with point-by-point toneburst measurements made at different frequencies. The agreements were very good.

Measurements were also made in quasi-isotropic graphite-epoxy laminates containing 0.2-3.4% voids, the results are similar to that in Fig. 3. The correlation of decreasing velocity with increasing porosity was also observed in a set of 10 woven graphite-polyimide laminates. To make a quantitative correlation between the velocity change and void content, the fractional velocity decrease $\Delta V/V$ (expressed in percents) with respect to the velocity in a void-free sample was plotted against the void content. Figure 4(a) shows the results for three composite systems at a frequency of 8 MHz. As a comparison, the same plot was also made for a frequency of 4 MHz, as shown in Fig. 4(b). A review of the results at different frequencies revealed that at higher frequencies the different systems followed almost the same slope; at lower frequencies, however, each material system seemed to follow a different slope. The explanation of the porosity-induced velocity changes in composites still awaits more theoretical modeling. Although theories are available for ultrasonic velocity dispersion in otherwise homogeneous solids containing porosity [11], the same has not been developed for composites.

![Graph showing ultrasonic phase velocity in woven carbon/epoxy laminates](image-url)

**Fig. 3.** Phase velocity of longitudinal waves propagating perpendicular to woven graphite-epoxy laminates as a function of frequency and void content.
Fig. 4. Velocity change versus void content of composites at 8 MHz (a) and at 4 MHz (b).
Comparison of measured velocity in graphite-polyimide composites with porosity and calculated velocity using Kramers-Kronig relation and $\omega_s = 5$ MHz.

**THE RELATIONSHIP BETWEEN ATTENUATION AND VELOCITY CHANGE**

--- **THE KRAMERS-KRONIG RELATION**

It is well known that ultrasonic attenuation and velocity are related by the Kramers-Kronig relation. In the general Kramers-Kronig relation the velocity change is proportional to an integration over frequency from zero to infinity of $\alpha(\omega)/\omega^2$. A simpler form of the Kramer-Kronig relation, known as the local approximation, relates the velocity change and the attenuation over a finite frequency range [12].

\[
\frac{1}{C(\omega_0)} - \frac{1}{C(\omega)} = \frac{2}{\pi} \int_{\omega_0}^{\omega} \frac{\alpha(\omega')}{\omega'^2} \, d\omega'
\]

where $C(\omega_0)$ and $C(\omega)$ are respectively the velocities at frequencies $\omega_0$ and $\omega$. In this work the local approximation is applied to the attenuation and velocity of composites containing porosity. Figure 5 shows the phase velocity in woven graphite-polyimide composites with 0-9.7% voids as measured by 5 MHz transducers. Also shown in Fig. 5 are the calculated velocity using the Kramers-Kronig relation and a reference frequency $\omega_s$ of 5 MHz. This calculation used frequency dependent attenuation data obtained previously [8] and the comparison is "normalized" at $\omega_s = 5$ MHz. These results show that the local approximation of the Kramers-Kronig relation holds in porous composites where the velocity dispersion is quite large.

**CONCLUSION**

Phase spectroscopic method is applied to broadband through-transmission ultrasonic measurements in composites containing porosity. The measurements yield frequency dependent velocity over the effective band of the transducers used. The void contents in CFRP are found to correlate with changes in the ultrasonic phase velocity. With increasing void content, the velocity decreases substantially. In addition, the velocity in CFRP containing voids is found to be more...
dispersive than that in void-free composites. Finally, the relationship between the ultrasonic attenuation and the velocity change is compared to that described by the local approximation of the Kramers-Kronig relation.

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