# POROSITY MEASUREMENT IN COMPOSITES USING ULTRASONIC ATTENUATION METHODS

Francis A. Reed, Thomas J. Batzinger, and Robert W. Reed
United Technologies Research Center
411 Silver Lane
East Hartford, CT 06108

Staffan Jönsson
FFV Materialteknik AB
Box 13200
S-580 13 Linköping, Sweden

## INTRODUCTION

The measurement of porosity content in composites has been an area of interest to the NDE community. Theoretical and experimental work have related ultrasonic scattering to the amount of porosity in composites and metals [1]. By monitoring the frequency dependence of the ultrasonic scattering, information concerning the amount of porosity in the material can be determined. The scattering of ultrasonic waves can be measured by monitoring the attenuation of the waves as they travel through a material. To accurately measure the attenuation associated with material properties such as porosity scattering, corrections must be made to the ultrasonic amplitude data. These corrections concern other ultrasonic loss mechanisms that are attributed to the measurement process such as surface or boundary effects and transducer focus effects.

The surface or boundary effects on the ultrasonic signals can be separated into two mechanisms: the effects of impedance changes on the transmission of ultrasonic waves and the effects of surface roughness on the scattering of ultrasonic waves. Since the time for the ultrasonic waves to travel through the material is greater than the pulse width that was used, the impedance effects can be considered to be frequency independent. The attenuation caused by scattering due to surface roughness has been shown to be proportional to the square of the frequency of the ultrasonic waves [2]. Hence, the frequency dependent characteristics of the surface scatter, if not properly accounted for, can cause errors in porosity content determinations.

The transducer beam characteristics must also be considered when accurate attenuation information is required. Refraction at the surfaces of the composite sample will change the effective focal lengths of the ultrasonic beam in relation to the beam traveling through the coupling medium. When focused transducers are used to collect ultrasonic data, the spot size of the ultrasonic beam is dependent on the frequency of the transducer. This means that a transducer at a fixed position is radiating a different area of the sample when the frequency of the ultrasonic beam is changed. Since the porosity distribution in composites tends to be nonuniform, transducer beam spot size variations can cause associated changes in the attenuation data.

With the correction of the ultrasonic data for these different loss mechanisms, it is possible to quantitatively measure the porosity content in materials by using ultrasonic techniques. This paper will discuss the corrections to ultrasonic attenuation data that are needed to minimize the effect of these different loss mechanisms. The frequency dependence of the ultrasonic attenuation will be related to defect types. Experimental data will also be presented to demonstrate the capabilities of these evaluation methods.

## ULTRASONIC METHODS

Ultrasonic transmission measurement methods have been used extensively to evaluate composite materials [3,4]. With through-transmission measurement techniques, the sample is usually immersed in a coupling medium between a pulsing transducer and a separate receiving transducer as is shown in Figure 1. The amplitude of the ultrasonic pulse is then measured. The attenuation is determined by comparing the amplitude with the sample in place to the amplitude of ultrasound transmission through the coupling medium alone. The two transducers can be positioned using computer-controlled robotic manipulators. This allows ultrasonic attenuation images of the sample to be collected by scanning the transducers over the sample in a raster pattern.

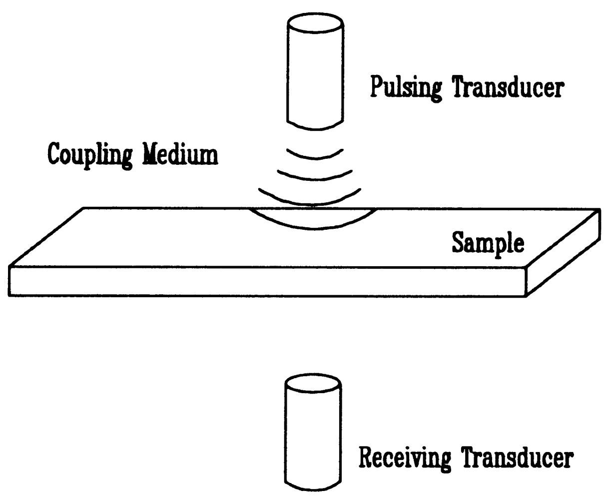


Figure 1. Through-transmission Ultrasonic Attenuation Measurement

By collecting the ultrasonic attenuation data at different frequencies, the frequency dependence of the scattering the defects within the material can be determined. Previous work has shown that defects such as delaminations which are much larger than the wavelength of the ultrasonic beam will have frequency independent attenuation characteristics[5]. Porosity with dimensions much smaller than a wavelength will display a power law relationship between frequency and attenuation. When the porosity is on the order of the wavelength in size, frequency and attenuation are directly dependent[1].

Before defect characterization can be performed, the raw attenuation data must first be corrected for the ultrasonic loss mechanisms previously described. The following section contains a collection of correction methods for through-transmission measurements.

## ATTENUATION MEASUREMENT CORRECTIONS

### Surface Effects

The surface of the sample can affect the propagation of ultrasound in many ways. By analyzing flat composite samples where the surface of the sample is perpendicular to the ultrasonic beam, geometric effects associated with refraction can be minimized. Since the samples have only unidirectional or isotropic lay-ups, beam energy deviations that are caused by elastic property anisotropy will be small and be considered negligible. This would most likely not be the case for three-dimensional weaves. The main effects that will require corrections are impedance losses and surface scatter losses.

The impedance losses associated with a through-transmission measurement system are due the reflections of the ultrasonic waves. The ultrasonic amplitude that is transmitted across an interface can be described as follows:

$$\frac{\text{Ampl}_{\text{transmitted}}}{\text{Ampl}_{\text{incident}}} = \frac{2z_{\text{composite}}}{z_{\text{couplant}} + z_{\text{composite}}} \tag{1}$$

where Ampl refers to the transmitted and incident ultrasonic amplitude, and z refers to the acoustic impedance of the coupling medium and composite sample. For both surfaces of the composite plate, the attenuation due to reflection losses is:

$$\alpha_{\text{impedance}} = -20\log_{10}\left(\frac{4z_{\text{couplant}}z_{\text{composite}}}{\left(z_{\text{couplant}} + z_{\text{composite}}\right)^2}\right) \tag{2}$$

where $\alpha_{\text{impedance}}$ is the attenuation in dB The value for the attenuation correction for graphite-epoxy plates immersed in water is typically 2.5 dB The acoustic impedance for the composite plates was determined experimentally by comparing the reflection amplitude from a smooth composite plate to the reflection amplitude of a smooth material of known acoustic impedance.

Corrections can also be made for the losses associated with scattering caused by surface roughness. Assuming that the surface roughness was a small perturbation on the ultrasonic beam, Nagy and Adler determined that the reflection and transmission coefficients from the following equations:

$$R = R_0 e^{-2h^2 k^2_{couplant}} \tag{3}$$

$$T = T_0 e^{-\frac{1}{2}h^2\left(k_{couplant} - k_{composite}\right)^2} \tag{4}$$

where R is the modified amplitude reflection coefficient, $R_0$ is the reflection coefficient for a smooth surface, T is the modified amplitude transmission coefficient, $T_0$ is the transmission coefficient for a smooth surface, k is the wave number of the couplant and composite, and h is the root mean square value of the surface roughness[2]. The surface roughness was determined by experimentally measuring the reflection coefficient and comparing that value to the coefficient calculated using acoustic impedance data. Substituting $2\pi f/v$ for the wave number and reordering the expression yields:

$$\alpha_{roughness} = 40\pi^2 h^2 f^2 \left( \frac{1}{v_{couplant}} - \frac{1}{v_{composite}} \right)^2 \log_{10}(e) \tag{5}$$

where $\alpha_{roughness}$ is the attenuation in dB associated with losses due to surface roughness, f is the frequency of the ultrasound, and v is the longitudinal velocity of ultrasound in the couplant and composite respectively. This correction must be calculated separately for each side of the plate. On the composite samples that were used for the experimental analysis, the spatial frequency of the surface roughness was smaller than the spot size of the ultrasonic beams. Since the reflections from the samples was relatively constant, the attenuation correction was calculated at one location on each side of the sample for use in correcting the entire data set for the plate. This correction was repeated for each frequency.

Ultrasonic Beam Property Effects

The attenuation effects associated with the ultrasonic beam can be separated into two main areas: refraction effects and spot size variation effects. Refraction effects make the effective distance the ultrasonic beam must travel between the two transducers seem longer. Spot size variations caused by frequency changes will effect the pressure distributions associated with the beam.

The main purpose of the corrections for refraction effects is to maintain the effective ultrasonic beam lengths that were used in the calibration process. Typically, the ultrasonic test equipment is first calibrated by propagating ultrasonic pulses through the coupling medium, in this case water, to determine the ultrasonic amplitude associated with 0 dB of attenuation. For matched focused transducers, the distance between the transducers is usually set to twice the focal length. This will cause the spots of the two transducers to overlap one another. To avoid defocusing effects, the two spots should also overlap when the composite samples are being evaluated. The distance that the two transducers must be moved to maintain the focal properties can be determined from the following:

$$d_{composite} = d_{calibration} - \text{thickness}_{composite} * \left( \frac{v_{composite}}{v_{couplant}} - 1 \right) \tag{6}$$

where d is the distance between the transducers during the composite evaluation and system calibration, and thickness is the thickness of the composite sample. With this positioning correction during the ultrasonic evaluation of the composite plate, no further correction is needed to the attenuation images.

When the defects causing scattering in the samples tend to be isolated such as with porosity conditions, the frequency dependence of the scatter will be distorted by the beam size. The lower frequency ultrasonic beams will have larger focal points than the higher frequency beams due to diffraction effects[6]. This means that the different frequencies will image defects differently due to these focal effects. These effects can be seen in the graphs shown in Figure 2. By modeling the focal spot of a transducer by using a Bessel function, the attenuation by the shadow of a small defect can be illustrated. For this example, a 0.5 inch diameter, 3 inch focal length transducer was modeled to approximate the pressure field at the focal spot of the transducer. The attenuation data was generated by removing the energy that would strike a 0.0015 inch defect from the total energy in the beam as it traversed across the focal point of the beam. The ultrasonic data was simulated for 3 typical frequencies: 10, 20, and 30 MHz. When the defect is aligned with the center of the beam defined as 0 inches in the graphs, the highest frequency shows the greatest attenuation. This is because a greater portion of the beam is being blocked by the defect. The coefficient data graph shows the frequency dependence of the attenuation data. The coefficients were calculated from the following equation:

$$\alpha(f) = C_0 + C_1 f + C_2 f^2 \tag{7}$$

where $\alpha(f)$ is the attenuation associated with a defect blocking part of the ultrasonic beam, f is the frequency of the ultrasonic beam, $C_0$ is frequency independent part of the attenuation, $C_1$ is the portion that varies directly with frequency, and $C_2$ is the portion the varies with frequency squared. The values for the three coefficients were determined for each position by solving the equations at the three frequencies simultaneously. For plotting purposes, $C_1$ and $C_2$ were multiplied by the middle frequency and the middle frequency squared respectively to redefine the quantities in terms of decibels.

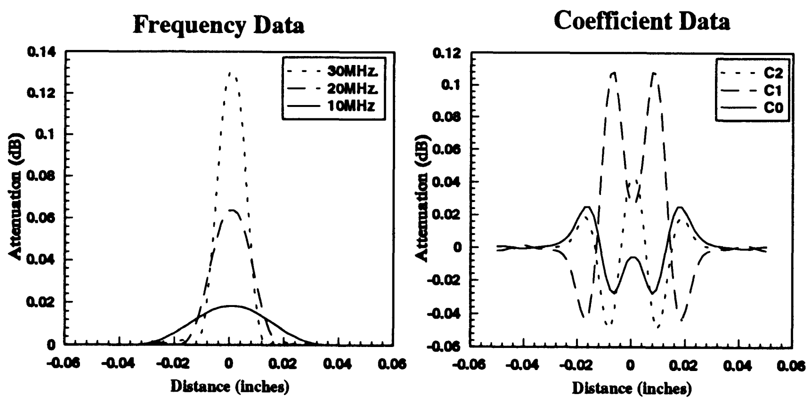


Figure 2. Attenuation and frequency coefficient data for a defect passing through the the ultrasonic beam of a 3 inch focal length, 0.5 inch dia. transducer.

The frequency dependence of the attenuation caused by the single defect is very complex. The positioning of the ultrasonic beam relative to the defect is critical. The easiest way to solve for these attenuation effects is to process the attenuation images of the composite samples after the images are collected. By spatially filtering the two higher frequency attenuation images, the effects of the smaller spot sizes can be removed. This will leave the three attenuation images with the spatial resolution properties of the lowest frequency image. When these filtering techniques are applied to the data shown in Figure 2, the attenuation data at all frequencies will be the same.

The weighting function for the filtering operation can be calculated as follows: 1) calculate the pressure fields of the transducer at the various frequencies, 2) perform a Fourier transform on the pressure fields, 3) divide the transformed low frequency image by the transformed higher frequency image, and 4) perform a inverse Fourier transform on the resultant data. This resultant function must then be convolved with the original amplitude data which is used to calculate the attenuation data.

This image processing simulates the appearance of the attenuation data as if the data had been collected using a constant ultrasonic beam profile. After filtering the middle and high frequency data, the attenuation images are then recalculated using the modified amplitude data.

All of these corrections were made on the following evaluations of composite samples.

## EXPERIMENTAL DATA

Experimental tests of the porosity measurement capability of the ultrasonic attenuation methods were performed on a group a well characterized composite samples. The samples were graphite/epoxy composites with either a unidirectional or an quasi-isotropic lay-up. The porosity in the samples had been previously characterized by destructively analyzing a portion of each sample. The samples were manufactured in three thicknesses: 2, 5, and 8 mm. The porosity content varied from 0.1 to 4 percent by volume among the various samples. The pore size among the samples varied from 0.1 to 1.0 mm.

The plates were evaluated using through-transmission ultrasonic techniques. The equipment that was used to inspect the samples has been described in detail previously[7]. The system has the capability to collect absolute attenuation data at three different frequencies during a single scan. Tone burst excitations were used to drive the pulsing transducer. The amplitude data was collected using peak detectors which have greater than 60 dB of dynamic range. This large dynamic range is very useful since one setup can be used to scan multiple samples without problems with sensitivity or signal saturation.

The test samples each were scanned at three different frequencies in the range: 5-12 MHz. for the 2 mm. thick plates, 3-7 MHz. for the 5 mm. thick plates, and 3-5 MHz. for the 8 mm. thick plates. Lower frequency ultrasound was used on the thicker plates to compensate for the higher attenuation values caused by the additional thickness. The corrected ultrasonic attenuation image collected for the 4 separate 2 mm. thick plates is shown in Figure 3.

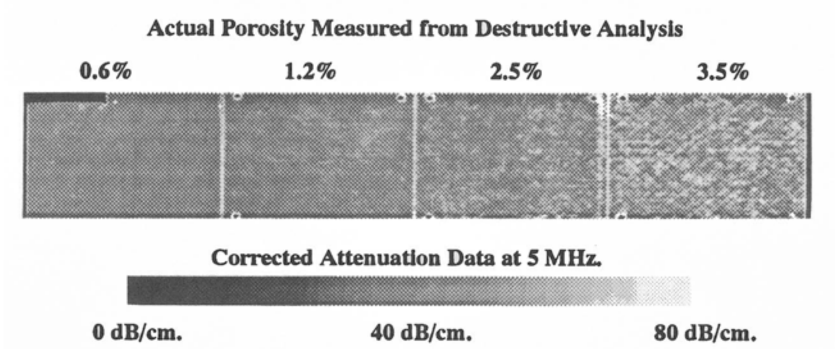


Figure 3. Attenuation data from 2mm. thick graphite/epoxy samples with various known amounts of porosity.

This attenuation image is typical of the attenuation images collected on the composite plates. The attenuation characteristically increases with the porosity content. The slope of attenuation vs. frequency was calculated using linear regression methods. Figure 4 shows the average value of the slope, determined for each sample, versus the actual porosity content. The linear regression fit of the experimental data can be described as follows:

$$\text{Porosity} = 0.45\frac{\%*\text{cm.}*\text{MHz.}}{\text{dB}}*\frac{d\alpha}{df}+0.41\% \tag{8}$$

where porosity is given in units of percent by volume, and the attenuation slope is in units of dB/(cm.-MHz.). This relation between porosity and attenuation slope was found experimentally to be valid over a wide range of pore sizes. The pore diameter varied from 0.3 to 5.0 wavelengths over the various frequency ranges. The upper limit for this linear correlation was the point at which the pore size was approximately equal to the spot size of the ultrasonic beam. At that dimension the pores would be imaged as descrete defects similar to disbonds. Porosity images of the composite samples can be formed using the ultrasonic attenuation data and the relation shown in Equation 8. Figure 5 shows the results of these calculations on the 2 mm. thick composite samples. The ultrasonic results agree with the porosity results obtained through destructive analysis. From the experimental results this correlation is estimated to have an uncertainty of $\pm 0.5\%$ volume porosity.

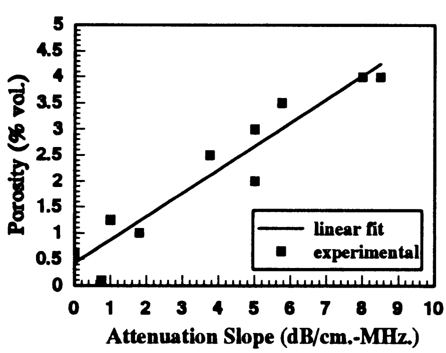


Figure 4. Attenuation slope versus porosity content in graphite/epoxy composite

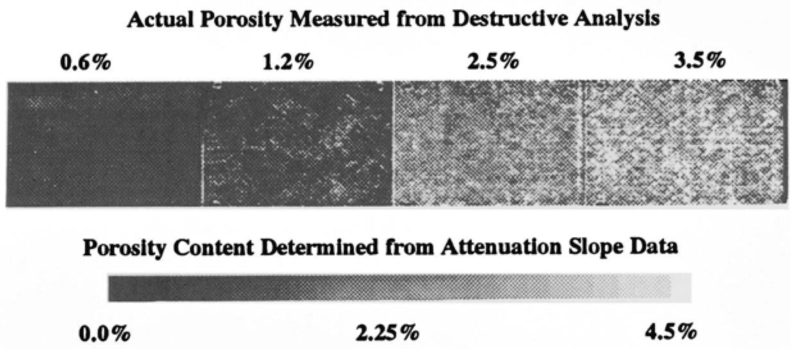


Figure 5. Estimated percentage by volume of porosity in 2mm thick composite plates as determined by using ultrasonic attenuation techniques.

## SUMMARY

Through-transmission ultrasonic attenuation measurements can be used to determine porosity content in materials. These measurements must be corrected for ultrasonic loss mechanisms that are associated with the measurement process itself. These methods have been demonstrated over a range of 0.1 to 4 % porosity contents and over a range of 0.1 to 1.0 mm. pore sizes.

## ACKNOWLEDGMENT

The composite samples that were evaluated in this paper were provided by S. Jönson and H. Ryden of FFV Materialteknik AB in Linköping, Sweden.

## REFERENCES

1. S. M. Nair, D. K. Hsu, and J. H. Rose, "Porosity Estimation Using the Frequency Dependence of the Ultrasonic Attenuation", Journal of Nondestructive Evaluation, Vol. 8, No. 1, 13 (1989)
2. P. B. Nagy and L. Adler, "Surface Roughness Induced Attenuation of Reflected and Transmitted Ultrasonic Waves", J. Acoust. Soc. Am., 82(1), 193 (1987)
3. R. F. Murphy, R. W. Reed, and R. S. Williams, Proceedings Nondestructive Testing and Evaluation of Advanced Materials and Composites Conference, Aug. 19-21, 1986 U. S. Air Force Academy, 135, NTIAC, NMCIAC, MCIC
4. R. F. Murphy and R. W. Reed, Proceedings 20th International SAMPE Technical Conference, Sept. 27-29, 1988, Minneapolis, MN., 481
5. H. J. Roth, Jl. of Appl. Phys., 19, 901 (1950)
6. J. Krautkrämer and H. Krautkrämer, "Ultrasonic Testing of Materials", Springer-Verlag, Berlin Heidelberg New York (1977)
7. R. F. Murphy, R. W. Reed, and T. J. Batzinger, "Multiparameter Ultrasonic Evaluation of Thick Composite Materials", Review of Progress in Quantitative Nondestructive Evaluation, 9B, 1473 (1990)