

Applications of Advanced, Waveform Based AE Techniques for Testing Composite Materials

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ABSTRACT

Advanced, waveform based acoustic emission (AE) techniques have been previously used to evaluate damage progression in laboratory tests of composite coupons. In these tests, broad band, high fidelity acoustic sensors were used to detect signals which were then digitized and stored for analysis. Analysis techniques were based on plate mode wave propagation characteristics. This approach, more recently referred to as Modal AE, provides an enhanced capability to discriminate and eliminate noise signals from those generated by damage mechanisms. This technique also allows much more precise source location than conventional, threshold crossing arrival time determination techniques. To apply Modal AE concepts to the interpretation of AE on larger composite structures, the effects of wave propagation over larger distances and through structural complexities must be well characterized and understood. In this research, measurements were made of the attenuation of the extensional and flexural plate mode components of broad band simulated AE signals in large composite panels. As these materials have applications in a cryogenic environment, the effects of cryogenic insulation on the attenuation of plate mode AE signals were also documented.

Keywords: Acoustic Emission, Composite Materials, Nondestructive Evaluation, Plate Waves, Attenuation, Modal Analysis

1. INTRODUCTION

The interpretation and analysis of AE signals generated in laboratory testing has been significantly improved by a number of recent advances. These include the development of digital, waveform based, acquisition instrumentation with sufficient memory and acquisition rates for AE testing. Another important development has been the improvements in high fidelity, high sensitivity, broadband sensors. However, most important has been the increased understanding of the nature of AE signal propagation as guided acoustic modes in many practical testing geometries such as plates, shells, pipes, tubes, and rods. Analysis of guided mode AE signals is known as Modal AE. It has led to significantly improved AE source location accuracy. Modal AE also has provided the capability to differentiate signals from different source mechanisms (including extraneous noise) in laboratory testing of coupons and small scale structures with closely spaced sensors. However, to apply these concepts to the testing of large structures, careful consideration must be given to the different propagation behavior of the different guided modes over longer distances of propagation. In particular, differences in attenuation for the different modes must be characterized and corrections in amplitude measurements made to account for signal losses of the different modes. This includes signal loss in both the virgin material and that due to structural elements such as joints, stiffeners, or coatings. As an example, measurements of far field, peak amplitude attenuation are presented for the extensional and flexural plate modes propagating in two different thicknesses of a composite material. The input signals for these measurements was a broad band, simulated AE source (pencil lead fracture or Hsu-Neilsen source). Even though the flexural mode contains much lower frequency components, its signal loss is much larger than that of the extensional mode. This is due to the significant dispersion of the flexural mode which causes a spreading of the signal in time over increasing propagation distances. The material studied is a candidate for cryogenic hydrogen propellant tanks on the prototype of a Reusable Launch Vehicle (X-33). As such, the effects on the attenuation of the plate modes due to bonded cryogenic foam insulation, which will be used on these tanks, were also evaluated. The presence of this cryogenic foam insulation had no measurable effect on the propagation of the extensional plate mode. However, it caused further severe attenuation of the flexural plate mode.

2. MODAL AE

A number of early AE studies, including those by Pollock¹, Stephens and Pollock², Egle and Tatro³, and Egle and Brown⁴, made passing mention of the propagation of AE waves as guided acoustic modes in confined geometries such as plates and rods. However, these works offered little as to the importance of these modes on the interpretation and analysis of AE with respect to source location accuracy and identification of source mechanisms. In fact, Pollock⁵, as recently as 1990, raised these same questions in a review paper on critical problems for research in AE. At about this same time, Gorman⁶ published work on the

effects of guided wave AE propagation in plates. This research demonstrated the relationship between source motion direction and the relative amplitudes of the extensional and flexural plate modes in an AE signal. It also discussed the importance of making arrival time measurements on the nondispersive portion of the extensional mode to calculate accurate source location. These concepts have led to the development a new technique, known as Modal AE, in which signals are analyzed for location, noise discrimination, and source identification based on their guided acoustic mode content.

A number of additional studies have advanced the Modal AE technique and demonstrated its validity, particularly for laboratory testing of coupons and small structures. Gorman and Prosser⁷ further documented the effect of source direction on plate mode amplitudes. Ziola and Gorman⁸ developed a new, threshold independent, method for source location applicable to guided mode AE signals using cross correlation techniques. Prosser et al.⁹ demonstrated guided wave AE propagation in other than flat plates by analyzing the propagation of AE signals in a thin graphite/epoxy composite tube. A method of accurately simulating plate mode AE signals was presented by Prosser and Gorman¹⁰. Examples of practical applications of Modal AE include monitoring fatigue crack growth in aluminum¹¹⁻¹⁶. Another successful application has been the detection of transverse matrix cracking in composite coupons¹⁷⁻¹⁹. A review of this new wavebased AE technology which contrasts it with conventional AE approaches was provided by Gorman²⁰.

In much of the previously described work, the specimens studied were of small lateral dimensions and/or the sensors were relatively spaced near the AE sources. Thus, propagation distances were short and effects of attenuation were minimized. Furthermore, the specimens consisted of coupons or other simple geometries with few structural elements such as stiffeners, bondlines, fasteners, etc. Under these conditions, analysis of the relative amplitudes of the easily discernible plate modes, either in the time or frequency domain, has allowed discrimination of noise signals from those caused by cracks. In fact, it has been more recently proposed by Dunegan²¹ that such an analysis can be used to not only discriminate and reject noise, but also to determine the depth of a crack in thicker specimens. Prosser and Gorman²² proposed a similar simplistic analysis to determine the angle of incidence for hypervelocity impacts of micrometeoroids and space debris on a spacecraft.

However, for testing larger structures with correspondingly longer distances of propagation, or structures with more structural complexity, simple relative amplitude measurements of guided modes will be insufficient. Corrections must be made to account for the significant differences in attenuation of the different guided modes. The following measurements show the large differences in far field attenuation for the extensional and flexural plate modes in composite materials, both for the case of a simple flat plate and for a plate with the structural complexity of a bonded layer of cryogenic foam insulation.

3. EXTENSIONAL AND FLEXURAL MODE ATTENUATION IN COMPOSITE PLATES

Measurements of the attenuation of acoustic waves propagating in thin composite plates were made in this study. Acoustic waves in plates propagate as Lamb waves. Only the lowest order symmetric (S_0) and antisymmetric (A_0) modes are observed in AE measurements in plates which are thin as compared to the wavelength. From the terminology of plate theory, which can be used to adequately describe these two modes at low frequencies, the S_0 mode is often referred to as the extensional mode and the A_0 is referred to as the flexural plate mode. As an example of these plate modes, a typical signal generated by a simulated AE source (pencil lead fracture) is shown in figure 1a. This signal propagated a distance of 20.32 cm. along the 0 degree direction in a 8 ply quasi-isotropic IM7/977-2 graphite/epoxy composite plate. The extensional and flexural mode components of this signal are identified in the figure. Because the pencil was fractured on the surface of the plate which creates an out-of-plane source motion, the flexural mode amplitude is much larger than that of the extensional mode. For real AE sources, the amplitudes of the different modes depend on the direction of source motion and the location of the source with respect to the midplane of the plate. As seen in this waveform, the extensional mode arrives first having propagated at a higher velocity followed by the flexural mode. The Lamb wave phase velocity dispersion curves for this plate are shown in figure 1b. As these curves illustrate, and as seen in the waveform, the flexural mode is highly dispersive with higher frequencies travelling faster while the extensional mode suffers little dispersion until high frequencies.

3.1 Theory

Attenuation is the loss of amplitude of an acoustic wave with propagation distance. As discussed by Pollock¹, there are four contributing factors to attenuation. These are 1) geometric spreading of the wave, 2) internal friction, 3) dissipation of the wave into adjacent media, and 4) losses related to velocity dispersion. As discussed and demonstrated by Pollock⁵ and Downs and

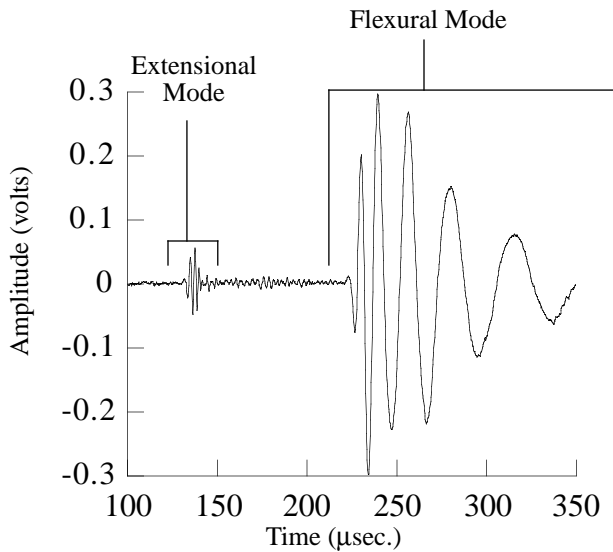


Fig. 1a. - Extensional and flexural plate modes identified in simulated AE signal propagating in 8 ply quasi-isotropic composite plate.

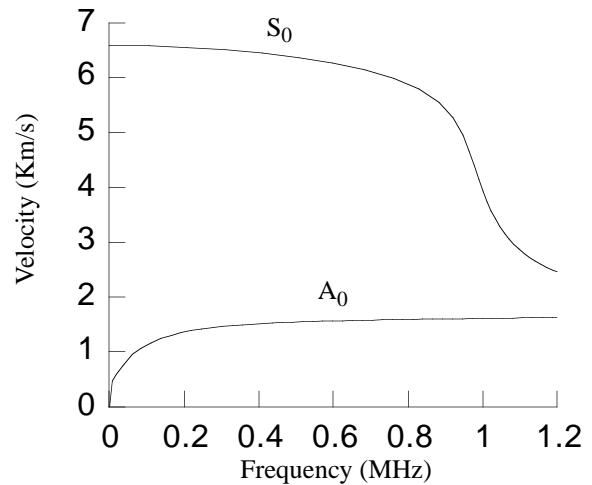


Fig. 1b. - 0 Degree dispersion curves for A_0 and S_0 Lamb modes in 8 ply quasi-isotropic gr/ep composite plate.

Hamstad²³, geometric spreading is the dominant source of attenuation in the near field close to the source. For two dimensional wave propagation in geometries such as plates, the amplitude decreases inversely as the square root of the distance of propagation. This can lead to significant attenuation greater than 40 dB over the first few centimeters of propagation. For plate waves, the attenuation over this region should be even greater as the signal begins to separate into the distinct modes and suffer from velocity dispersion. Geometric spreading losses explains why AE signals of significant amplitude at one sensor are not always detected by adjacent sensors. These signals are most likely small amplitude sources which are located very near, or under, the sensor on which they are detected.

In the far field, attenuation is typically dominated by absorption or conversion of sound energy into heat. Absorption usually has an exponential relationship of attenuation with distance. An attenuation coefficient, A , with units of dB/unit distance can be measured. For plate waves, the transition distance at which exponential attenuation begins to dominate geometric spreading is given by $4.34/A$.

Another mechanism of attenuation is amplitude loss due to dissipation into adjacent media. This can be caused by inhomogeneities in the medium which scatter the sound wave within the same material. Examples are grain structure within metals and fiber reinforcement in composites. It can also be caused by a medium in contact with the material or structure under test. A classic example relevant to AE testing is where acoustic waves propagate out of a pipe or pressure vessel into the contained fluid. Another instance is that of amplitude losses due to structural elements such as ribs and stiffeners. Amplitude losses of this type can be considerable and must be carefully evaluated when applying AE to practical structures. As an example, the considerable attenuation effects on flexural mode propagation in a composite plate due to the application of cryogenic insulation are presented later.

The final attenuation mechanism is that of signal loss due to velocity dispersion. Because of the different velocities for different frequency components, an initially short, broad band, pulse, begins to spread in time at increased distances of propagation. This causes a loss in amplitude. The magnitude of amplitude loss depends on the steepness of the dispersion curves and the bandwidth of the signal. Previously, in most AE research and testing, narrow band resonant acoustic sensors have been used. Likewise, most ultrasonic measurements are made with narrow band tone burst input signals, and bulk wave propagation with little or no dispersion is studied. Thus, dispersion induced attenuation is seldom observed and has been little studied. However, as demonstrated by the following measurements, this mechanism of signal loss is of considerable importance for analysis of broad band Modal AE signals. Flexural mode attenuation, as measured by far field peak amplitude signal loss with propagation distance, was significantly larger than that of the extensional mode. This was true even though the extensional mode peak

contained much higher frequencies which are typically more severely attenuated by absorption and scattering mechanisms.

3.2 Measurements

Measurements were made of the loss in peak amplitude as a function of propagation distance in the far field for both the extensional and flexural plate modes in two graphite/epoxy plates. Measurements were made along the 0, 45, and 90 degree propagation directions. The two plates were different thicknesses of quasi-isotropic laminates of IM7/977-2 graphite/epoxy. This material is a candidate for the liquid hydrogen propellant tanks on the X-33 prototype of a Reusable Launch Vehicle being built by Lockheed-Martin. Both plates had nominal lateral dimensions of 0.99 X 0.99 m. The first plate was 0.12 cm. thick (8 plies) and the second was 0.37 cm. (24 plies). These are the currently designed minimum and maximum wall thicknesses of the tank. Both plates were C-scanned with conventional ultrasonics prior to testing and determined to be of good quality.

For these measurements, a simulated AE source (pencil lead fracture on the plate surface - also known as Hsu-Neilsen source) was used. For each propagation direction, the source was positioned 0.127 m from the plate edge. A sensor (Physical Acoustics Corporation R15) was placed next to the lead break source to provide a trigger source for the digital waveform recording system (Digital Wave Corporation F4000). This system digitized the signals with 12 bit vertical resolution and recorded 4096 points at a sampling frequency of 5 MHz. The preamplifier and system gain was individually adjusted for each channel to provide a measurable, unsaturated signal. A linear array of five, broad band, high fidelity AE sensors (DWC B1025) along the propagation direction was used to detect the simulated AE signals. The sensor nearest the source was at a distance of 10.16 cm. with the other sensors spaced at equal distances of 10.16 cm. apart along the propagation direction.

The peak amplitudes of both the extensional and flexural mode components of the signals were measured at all sensor positions. The measured amplitude values (in dB) were corrected for differences in preamp and system gain and plotted as a function of propagation distance. A linear least squares fit was then used to determine the attenuation. As expected in a quasi-isotropic laminate, the attenuation was nominally the same for the three measured propagation directions (0, 45 and 90 degrees). Typical plots of peak amplitude versus distance for both the 8 and 24 ply plates are shown in figures 2a and b. The scatter in the data

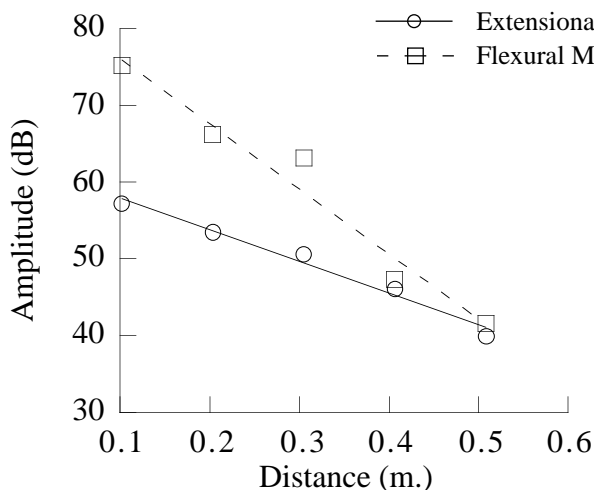


Fig. 2a. - Peak amplitude versus propagation distance for extensional and flexural modes in 8 ply composite plate.

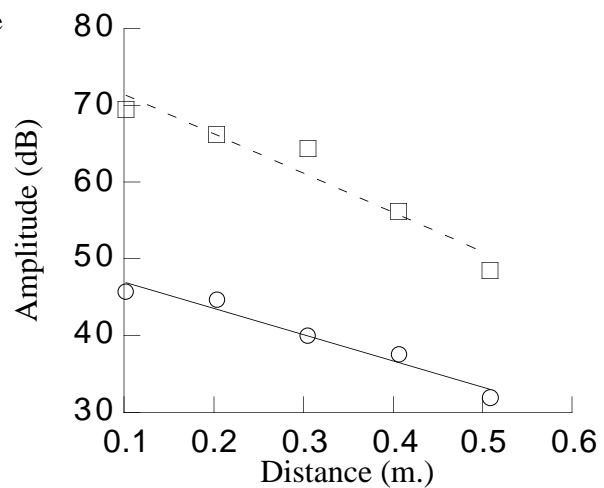


Fig. 2b. - Peak amplitude versus propagation distance for extensional and flexural modes in 24 ply composite plate.

along the linear fit in these plots is most likely due to variations in sensor coupling. This can affect amplitude measurements by several dB. To reduce the effect of coupling variations, amplitude measurements could be averaged for a number of signals with the sensor rebonded to the specimen before each leadbreak. Measurements of variations in the force required to break the lead and thus the input signal amplitude would then be required. This effect can also be quite large due to local variations in pencil lead composition, microscopic flaws, etc. The smaller initial amplitudes of the extensional and flexural modes in figure 2b as compared to 2a is most likely due to a weaker force required to fracture the lead. However, the accuracy of these single signal measurements was sufficient to illustrate the large attenuation differences between the two modes due to flexural mode

dispersion and provide useful input for calculating sensor spacings for structural monitoring.

The average attenuation of the extensional mode for the three propagation directions in the 8 ply plate was 42 dB/m. Variations in attenuation from the average along the different directions were no greater than ± 3 dB/m for all measurements to be discussed. For the flexural mode, the average attenuation was significantly larger at 83 dB/m. This large difference in attenuation between the two modes should have a great impact on sensor placement decisions on larger structures dependent on the mode of signal desired to be detected. Furthermore, if comparisons of the relative amplitudes of the modes are to be made to differentiate source mechanisms and noise, corrections for this different attenuation will be required. This large difference in attenuation between the extensional and flexural modes was measured even though the frequency content of the flexural mode near the peak was much lower than that of the extensional mode. An estimate of the peak frequency was made from the measurement of the half period of the cycle on which the peak amplitude was measured. The frequency of the extensional mode peak was 410 kHz while it was only 85 kHz for the flexural mode peak. Absorption and scattering losses, which are usually the dominant far field attenuation mechanisms, significantly increase with frequency in composite materials. Thus, based on the frequency content, one would expect the extensional mode attenuation to be larger. However, examination of the actual waveforms confirmed the large effect that dispersion has on reducing the amplitude of the flexural mode.

For the thicker, 24 ply plate, the average attenuation of the extensional mode was 35 dB/m. This is slightly less than that in the thin plate. This might be expected since the measured peak frequency was also less at 230 kHz. At 51 dB/m, the flexural mode attenuation was considerably less than in the 8 ply plate, although still larger than that of the extensional mode. The estimated peak frequency was 90 kHz which was comparable to that in the thin plate. In this thicker plate, the waveforms at different distances showed much less spreading in time due to dispersion than in the thinner plate. This observation is consistent with the smaller measured attenuation value.

4. ATTENUATION DUE TO CRYOGENIC INSULATION

In addition to attenuation of guided modes in a virgin material, attenuation due to signal loss into materials in contact with or bonded to the structure of interest may also be significant. The classic example mentioned earlier of attenuation due to a fluid in a pipe or pressure vessel has long been studied. However, measurements have been typically made with resonant sensors and not considering the effects on individual guided modes. The material tested in this research has applications for cryogenic propellant tanks for space vehicles. In this application, a foam material is bonded to the outer surface for insulation. Attenuation due to the foam insulation was measured for the extensional and flexural plate modes.

Smaller sections of nominal lateral dimensions of 41 X 41 cm. were cut from the 8 and 24 ply panels. Foam cryogenic insulation, of a thickness of 1.27 cm., was bonded to these panels in a stepped pattern as shown in figure 3a. Again, pencil lead breaks were used to simulate AE signals. However, for these measurements, breaks on the surface were used to generate signals with predominantly flexural mode components. Pencil breaks on the edge of the plate near its midplane were used to generate waveforms with large extensional mode components. The positions of the sensors and lead breaks relative to the specimen and insulation are illustrated in figure 3b. The leftmost surface and edge breaks allowed for signals to propagate through an uninsulated region. At the positions to the right, an increasing amount of insulated material covers the total distance of propagation. Measurements were made at these same locations prior to the application of insulation to insure that there was no variation in attenuation at different locations in the plate. No significant variations were observed. Two methods were used to account for variations in lead break signal input amplitudes. First, a second sensor was positioned near the lead break position. The measured amplitude from this sensor was used to correct all of the signals to a fixed input signal amplitude as measured near the source. In addition, five measurements were made at each sensor/lead break position and the amplitude corrected results averaged.

The resulting corrected and averaged peak amplitudes were then plotted for both the extensional and flexural modes, in both plates. For the extensional mode, no variations in amplitude were observed in either thickness of plate. Thus, the cryogenic insulation appears to have little or no effect on this mode of propagation. The flexural mode, however, suffers significant attenuation due to the presence of cryogenic insulation. This is not unexpected as this mode of propagation has a large out-of-plane displacement component and is known to be sensitive to surface conditions including the bonding of other materials. A plot of flexural mode amplitude in the 8 ply plate versus distance of insulated propagation is shown in figure 4a. A linear least squares fit which is also shown in this figure, yielded an attenuation coefficient of 89 dB/m due to the effects of insulation along. The flexural mode in the thicker plate suffered nominally the same attenuation due to insulation. This significant attenuation

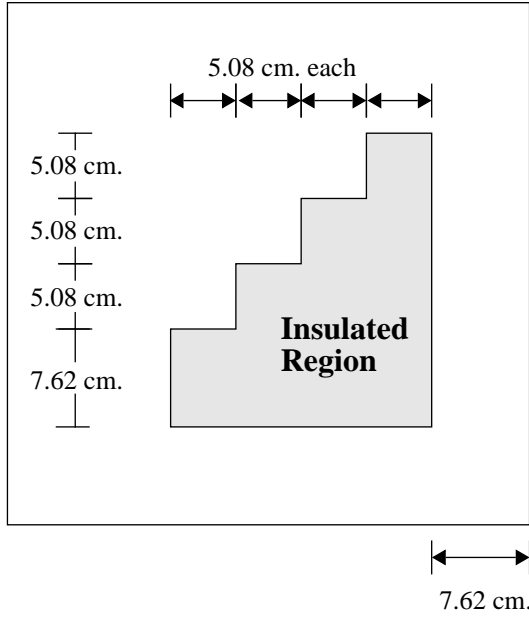


Fig. 3a - Dimensions of cryogenic insulation applied to composite panels.

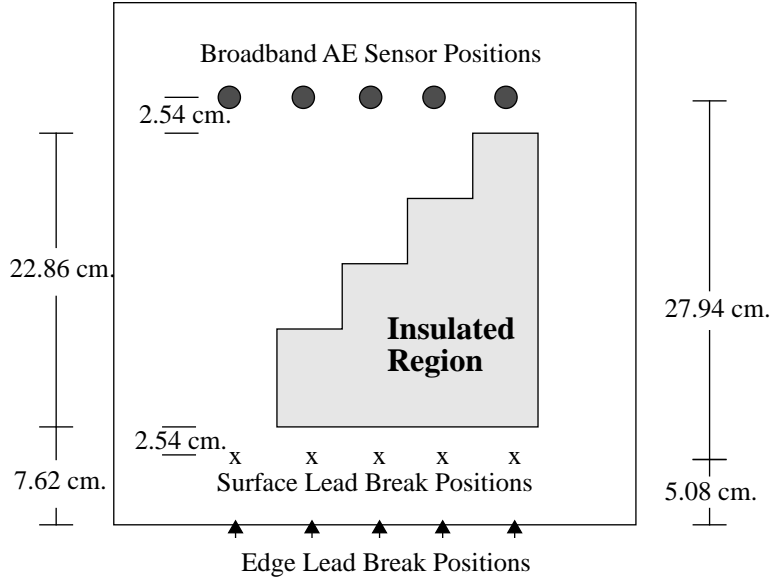


Fig. 3b - Sensor and lead break positions used to evaluate effect of insulation on attenuation of extensional and flexural modes. Surface lead breaks used to generate flexural mode signals and edge breaks used to generate extensional modes.

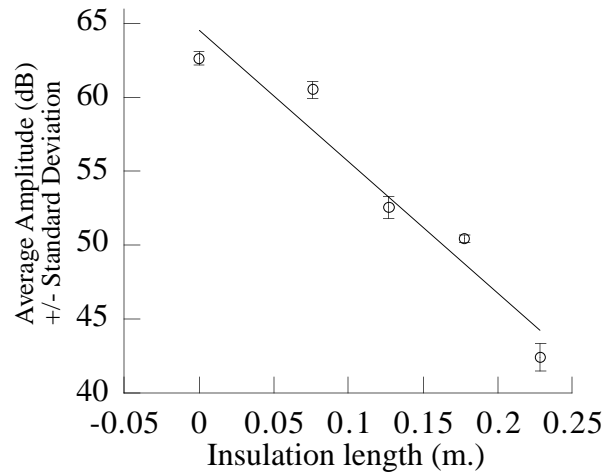


Fig. 4 - Effect of cryogenic insulation on signal amplitude for 8 ply composite laminate.

due to cryogenic insulation will have important consequences on the positioning of sensors and the type on analysis that can be used for AE monitoring of insulated tanks.

5. SUMMARY AND CONCLUSIONS

In this study, measurements were made of the far field attenuation of the extensional and flexural plate modes in two thicknesses (8 and 24 ply) of a quasi-isotropic composite. A broad band, simulated AE source (pencil lead fracture) was used to generate the plate modes. The peak amplitudes of the two modes were measured at different distances of propagation to determine the

attenuation. The attenuation of the extensional mode was less than that of the flexural mode and only a slight variation was observed between the two plate thicknesses. It was slightly less in the thicker plate in which the frequency content of the signal peak was lower. The flexural mode attenuation was greater than that of the extensional mode in both laminate thicknesses and was significantly higher in the thin 8 ply plate. This was the case even though the frequency content of the flexural mode peak was much lower than that of the extensional mode. Consideration of this difference in frequency content, along with analysis of the waveforms showed that spreading of the flexural mode in time due to velocity dispersion was the dominant mechanism for the increased flexural mode attenuation. In addition, the added attenuation effects due to bonding a cryogenic insulation foam on this composite material, which is a candidate for use on cryogenic propellant tanks, was documented. This insulation causes further severe attenuation of the flexural mode, while causing no noticeable signal loss for the extensional mode.

These measurements are of importance in the application of AE for health monitoring of structures made from this material. They will have significant impacts on decisions of the placement of sensors and the type of signal analysis that can be used. In addition, these measurements serve as an example of the importance that wave propagation effects can have on the application of waveform based, Modal AE analysis techniques to testing larger and more complex structures. Simple analysis of relative amplitudes of guided modes to differentiate source mechanisms and eliminate noise that are currently used for small coupons and laboratory specimen may be inadequate for longer distances of propagation. Corrections to amplitude measurements will be required based on location analysis of the signals combined with previously measured attenuation. In addition, structural variations such as thickness changes, attached stiffeners and coatings, and bonded joints, will affect the attenuation and dispersion of guided modes. These effects will also need to be characterized, understood, and accounted for in order to successfully apply Modal AE.

Future research will focus on characterization of the attenuation of these modes as a function of frequency. The added attenuation due to bonded insulation will also be analyzed as a function of frequency. Selection of sensors and bandwidths of filtering will be affected by these measurements. In addition, attenuation due to dispersion will be studied in more detail. Dispersion related attenuation of a broad band plate wave AE signal depends on the frequency content of the input signal, the frequency response of the detector, and the steepness or shape of the dispersion curve. Unlike the simple equations to predict the effect of geometrical spreading in the near field, no known analytical solutions currently exist to predict this effect. Thus, the development of analytical expressions or numerical techniques to predict effects of dispersion on attenuation for the flexural mode will be investigated.

6. ACKNOWLEDGEMENTS

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