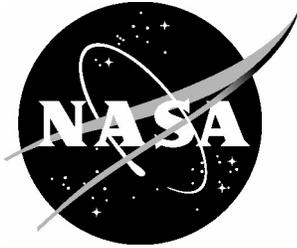


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Application of Ultrasonic Guided Waves for Evaluating Aging Wire Insulation

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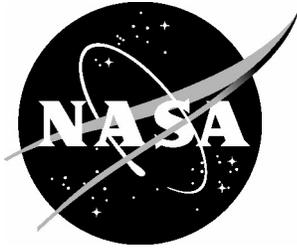
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ABSTRACT

Aging wiring has become a critical issue to the aerospace and aircraft industries due to Shuttle and aircraft incidents. The problem is that over time the insulation on wire becomes brittle and cracks. This exposes the underlying conductive wire to the potential for short circuits and fire. The development of methods to quantify and monitor aging wire insulation is highly warranted. Popular methods of monitoring aging wire problems focuses on applying electrical sensing techniques that are sensitive to the conductor's condition, but not very sensitive to the wire insulation's condition. Measurement of wire insulation stiffness and ultrasonic properties by ultrasonic guided waves is being examined. Initial laboratory tests were performed on a simple model consisting of a solid cylinder and then a solid cylinder with a polymer coating. Experimental measurements showed that the lowest order extensional mode could be sensitive to stiffness changes in the wire insulation. To test this theory conventional wire samples (typically found in aircraft) were heat-damaged in an oven, in a range of heating conditions. The samples were 12, 16, and 20 gauge and the heat damage introduced material changes in the wire insulation that made the originally flexible insulation brittle and darker in color. Extensional mode phase velocity increased for the samples that were exposed to heat for longer duration. The flexural mode was also examined as a means of measuring the insulation condition, but proved to be limited in application. Tensile tests were conducted on wire samples to measure stiffness changes. The trend of the tensile tests compared well to extensional mode measurements. Although the heat-damage conditions may be more extreme than environmental aging, indications are that this method has the potential to detect and quantify degradation in wire insulation.

INTRODUCTION

Electrical wiring is critical to the operation of most modern-day equipment. Wiring is subjected to heat, cold, moisture, stress, and vibrations, which can eventually cause the wire insulation and even the wire conductor to age and possibly fail. In most cases these environmental and operational conditions are modest and the wire conductor remains intact. Over time or when conditions are extreme, wire insulation may become brittle and crack or be damaged in such a manner to expose the wire conductor and become a potential source for instrumentation failure, short circuits, smoke, and fire. Generally, wire inspections are done visually and often after-the-fact in response to an instrument or system failure, the visual inspection may find cracks and burns, but offers little quantitative information about the condition of the wire insulation.

In attempts to measure the wire and wire insulation condition some efforts have been made to adapting electrical sensing systems such as Time Domain Reflectometry, Standing Wave Reflectometry, Frequency Domain Reflectometry, and resistance tests (Furse and Haupt, 2001). Other efforts are investigating the application of dielectric sensors, chemical sensors, thermographic methods, indentation methods (hardness testers), and reported on here, ultrasonic methods. All of these methods may have unique characteristics that could play a role in evaluating aging wire.

The ultrasonic method concept is to generate an ultrasonic guided wave that will travel down an insulated wire. Part of the wave will travel in the wire and part in the wire insulation. Assuming the wire condition remains constant, then the condition of the wire insulation and its stiffness will affect the overall wave speed and amplitude of the guided wave. Thus, a measurement of wave speed will, in part, be an indication of material stiffness or wire insulation condition. For experimental purposes, the insulated wire may be considered a cylindrical wave-guide or a clad rod, where the wire conductor is the core and the wire insulation is the cladding. A number of researchers have examined acoustic guided wave propagation in a cylindrical geometry (Meeker and Meitzler, 1964), (Thurston, 1978), (McNiven, et al., 1963), (Abramson, 1957), and (Rose, 1999) and for detailed analysis the reader is referred to these papers. In general the analysis focuses on deriving the nature of the elastic wave propagation. The core and cladding materials are assumed to be homogeneous, isotropic, and elastic and bonded at their interface. A solution for the displacements in the two materials is obtained, based on the linear elastic theory and the frequency equation is obtained from which dispersion curves are generated. In general many acoustic wave modes will propagate in an isotropic cylinder. The characteristics of the wave mode are a function of material property, geometry, frequency, propagation order, and circumferential order. Modes with circumferential order of zero are axisymmetric modes and are referred to as extensional modes. The first branch of the extensional mode is designated by the symbol $L(0,1)$, while higher branches are designated as $L(0,2)$, $L(0,3)$, etc. Modes of circumferential order one are antisymmetric, ordinarily called flexural modes. The first branch is designated by the symbol $F(1,1)$ and higher branches are designated as $F(1,2)$, $F(1,3)$ etc. (Thurston, 1978). The extensional mode extends to zero frequency where the limiting phase velocity is called the bar velocity. In the low frequency regime, the range where the extensional

mode phase velocity is relatively constant, this mode is nearly nondispersive. As frequency increases, the phase velocity drops to a value slightly below the Rayleigh wave velocity and then approaches the Rayleigh wave velocity at higher frequencies (Thurston, 1978). The flexural mode is highly dispersive in the low frequency regime. It approaches zero as the frequency approaches zero, and it approaches the Rayleigh wave velocity with increasing frequency. Some applications of ultrasonic guided waves include material testing or characterization of wire (Madaras, et al., 1992 and 1995) or fibers, and for use as ultrasonic delay lines.

In this report, the use of ultrasonic guided waves, both extensional and flexural modes, is examined for their use in detecting degradation in electrical wire insulation. Two ultrasonic transducers are used in a pitch-catch configuration to generate and receive ultrasonic guided waves. Tests were conducted on a wire model and then on wire samples that had been heated in an oven to cause insulation degradation. After ultrasonic testing, several heat-degraded wire samples were stressed in a small tabletop load frame to estimate their Young's modulus. Modulus values were then compared to ultrasonically measured values. Finally, an ultrasonic measurement tool was designed to simplify the ultrasonic measurement procedure. Such a tool could be used to assess insulation degradation and perform NDE on local areas of wire insulation.

SAMPLES

To gain an understanding of the ultrasonic modes generated in cylindrical geometry, the initial samples were rods of solid aluminum and rods of solid brass. These rods were then coated with heat shrink tubing to model a typical wire with insulation. Material properties and geometry of the brass rod and heat shrink tubing used in calculations are shown in Table I. The longitudinal velocity of the heat shrink tubing was measured using ultrasonic pulse echo methods and the density was measured through volume and mass measurements of a small sample. Other values were estimated using these measurements and tabulated textbook values for thermoplastic material (Gangal and Grot, 1989).

TABLE I. Some material properties and geometry of materials used in wire model.

<i>Material</i>	<i>Brass</i>	<i>Heat Shrink Tubing</i>
Young's Modulus (GPa)	108.94	0.72
Density (kg/m ³)	8500	958
Poission's Ratio	0.35	0.46
Long. Velocity (m/s)	4535	1868
Shear Velocity (m/s)	2178	510
Rayleigh Velocity (m/s)	2036	484
Radius (mm)	1.59	2.175

TABLE II. Specification of aircraft wires used in experiments.

<i>Wire Type</i>	<i>Gauge</i>	<i>Conductor</i>	<i>Insulation ID (mm)</i>	<i>Insulation OD (mm)</i>
MIL-W-81381/7 Polyimide (Kapton™)	20	Stranded Silver Coated Copper	0.942	1.286
MIL-W-81381/21 Polyimide (Kapton™)	16	Stranded Tin Coated Copper	1.326	1.628
MIL-W-81381/12 Polyimide (Kapton™)	12	Stranded Nickel Coated Copper	2.086	2.496
MIL-W-22759/34 E-EFTE (Tefzel™)	20	Stranded Tin Coated Copper	0.942	1.452
MIL-W-22759/34 E-EFTE (Tefzel™)	16	Stranded Tin Coated Copper	1.326	1.906
MIL-W-22759/34 E-EFTE (Tefzel™)	12	Stranded Tin Coated Copper	2.086	2.798
MIL-W-22759/87 Polyimide and FEP (Oasis™)	20	Stranded Nickel Coated Copper	0.942	1.346
MIL-W-22759/87 Polyimide and FEP (Oasis™)	16	Stranded Nickel Coated Copper	1.326	1.742
MIL-W-22759/87 Polyimide and FEP (Oasis™)	12	Stranded Nickel Coated Copper	2.086	2.578

Electrical wire samples were 12-, 16-, and 20-gauge aviation class wires with military specification. Three wire insulation types were used in testing: a MIL-W-81381 wire that has a polyimide (Kapton®) insulation, a MIL-W-22759/34 wire that has an ethylene-tetrafluoroethylene (Tefzel®) insulation, and a MIL-W-22759/87 wire that has a combination of polyimide and fluoroethylene polymer (PTFE) insulation. Some specifications for these wire types are given in Table II.

A set of wire samples was heated in an oven to mimic aging. It was assumed that heating would degrade the insulation and eventually cause it to become brittle. This process may not accurately model thermal aging, but was used to generate a set of samples with mechanical property variations. Using “aged” as a sample descriptor may be somewhat misleading, thus the term “heat-damaged” is used.

This first heat-damaged set consisted of a baseline and two heating conditions for each wire type and wire gauge. These heating conditions, a short and long oven exposure time, are shown as a function of wire type in Table III. The heating duration and temperature were arbitrarily chosen to quickly induce heat damage in the wire insulation as indicated by a physical appearance or color change. It should be noted that the maximum continuous service temperature of Teflon® Film is 205°C (DuPont, 2003). Thus, the induced heat damage may include additional physical changes, such as geometrical variations, and changes in chemical and electrical characteristics. An example of one heat aged set is shown in Figure 1. This figure shows baseline and heat-damaged

MIL-W-22759/34 wire samples. The insulation on the baseline samples was smooth, flexible, and off-white in color. For the short exposure samples the insulation remained smooth and flexible, but its color changed to gray, and the insulation for the long exposure samples became brittle, cracked, and black in color. The appearance of the other wire sets was similar to the one shown. The insulation on the MIL-W-81381 baseline samples was smooth, flexible, and yellowish in color. For the short exposure samples the insulation remained flexible and darkened slightly, and for the long exposure samples the insulation became brittle and cracked. The insulation on the MIL-W-22759/87 baseline samples was smooth, flexible, and white. For the short exposure samples the insulation remained smooth and flexible, but darkened slightly. For the long exposure samples the insulation cracked and lost its original glossy shine, but remained white.

TABLE III. Oven exposure time and temperature.

<i>Wire Type</i>	<i>Baseline</i>	<i>Short Exposure</i>		<i>Long Exposure</i>	
		Time (hours) / Temp. (°C)		Time (hours) / Temp. (°C)	
MIL-W-22759/34	No heat damage	1	349	1	399
MIL-W-81381	No heat damage	1	399	49	399
MIL-W-22759/87	No heat damage	1	399	50	399



FIGURE 1. A close-up of the 16-gauge insulated wire (MIL-W-22759/34) that was heat-damaged. Top: Baseline, Middle: Short Exposure, Bottom: Long Exposure.

A second set of wire samples was heated in an oven at lower temperature and in smaller incremental steps to examine the heat-damage effect in more detail. Polyimide (MIL-W-81381) wire samples of each gauge were heated in an oven at 370°C for up to 200 hours. Samples of various gauges of MIL-W-22759/34 and MIL-W-22759/87 wire were heated in an oven at 270°C for up to 200 hours. The first samples were removed from the oven when the set temperature was reached. This group of wires did not remain or dwell at the set temperature; they only experienced the effects of heating up to the set temperature and then cooling down. This was different than the baseline that was not exposed to any heating conditions. Other wire samples of each gauge were removed from the oven, after dwelling at temperature, about every 3 hours up to 15 hours and then about every 20 hours.

EXPERIMENTS

The experimental system is schematically shown in Figure 2. This system consists of two piezoelectric transducers, ultrasonic pulse generator, a system of ultrasonic pre-amps, and a digital oscilloscope. The piezoelectric transducers have a bandwidth specified to be 50 kHz to 1.5 MHz. The signal from the ultrasonic receiver is first fed through an ultrasonic pre-amp with a 20-kHz to 2-MHz bandwidth and a 40- or 60-dB gain and then through another amplifier with a maximum gain of 42-dB and a bandwidth set at 10 kHz to 300 kHz. The output of the amplifier was recorded by an 8-bit/500-MHz digitizing oscilloscope. The signal was averaged 1000 times to improve signal to noise and then

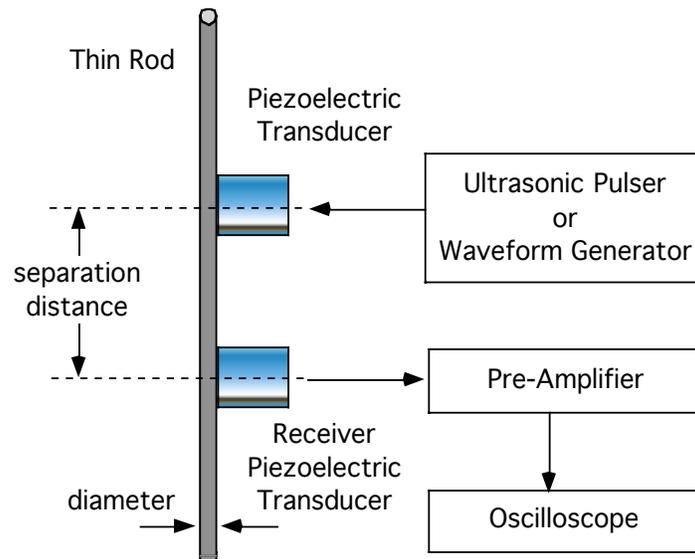


FIGURE 2. Schematic of experimental setup.

recorded for later analysis. The transducers were mechanically attached to the rod or wire as shown in Figure 3. The clamp face opposite the transducer had a groove machined in it, to hold the wire along the center of the transducer surface. The transmitting transducer was driven with an impulse excitation from a commercial ultrasonic pulser. During measurements, a wire sample, nominally 60 cm (24 inches) long was held horizontally. One end of the wire was held fixed and the other end was clamped to a metal rod weighing about 0.45 kg (1 pound). The resulting small tensile load held the wire straight and stationary while the transducer position along the wire was varied.

A typical ultrasonic signal in the bare aluminum rod is shown in Figure 4. The smaller amplitude wave at about 50 μ s is the first extensional wave mode and the larger amplitude wave initiating at about 75 μ s is the first flexural wave mode. The amplitude difference between the extensional and flexural wave modes is consistent with the geometry of the ultrasonic generation. Since the transmitting receiver is located on the side of the rod, a larger amplitude bending force is applied to the rod and thus it was assumed a larger amplitude flexural mode would be generated. This assumption was checked by examining the signal as a function of rotational angle between the transmitting and receiving transducers. The transmitting transducer was held stationary while the receiving transducer rotated around the aluminum rod in increments of 10°. A plot of the resulting extensional and flexural mode amplitudes is shown in Figure 5. The extensional mode amplitude is constant and the flexural mode amplitude follows a cosine-squared shape with a minimum at 90°. This is consistent with the assumption and the geometry of the loading.

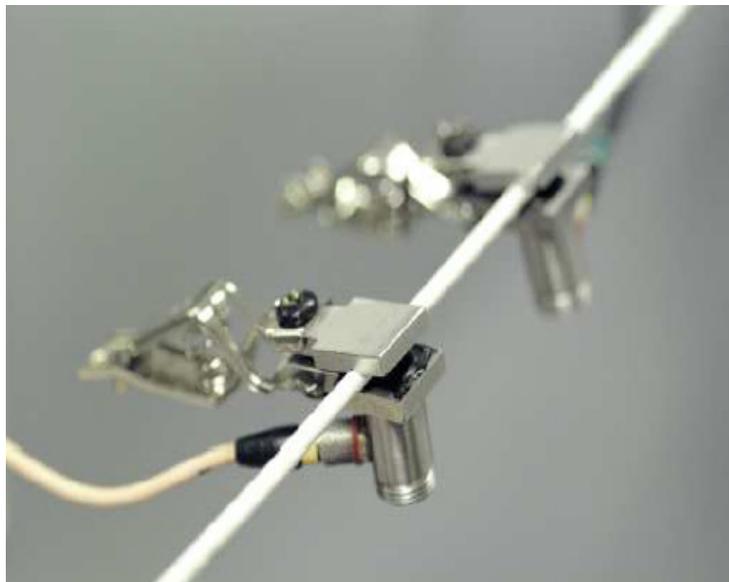


FIGURE 3. Ultrasonic transducers clipped to insulated wire.

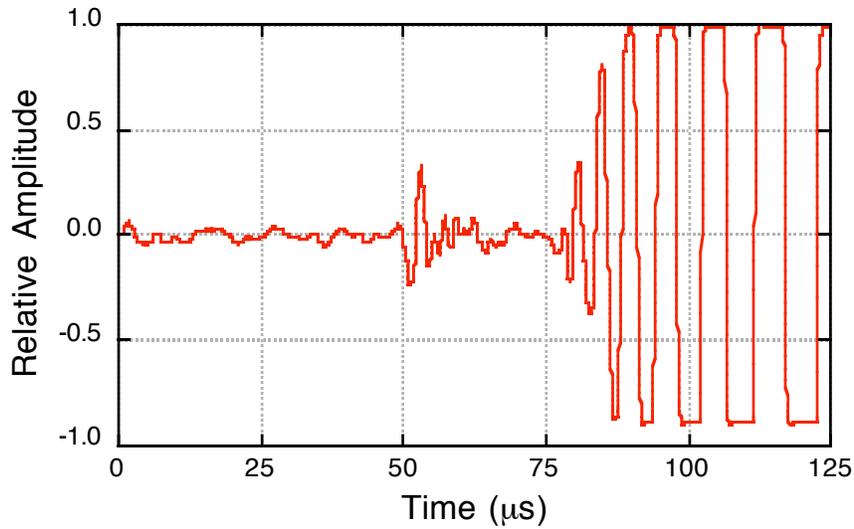


FIGURE 4. A typical ultrasonic signal in a bare aluminum rod is shown. The extensional wave mode initiates at about 50 μs and the flexural wave mode initiates at about 75 μs .

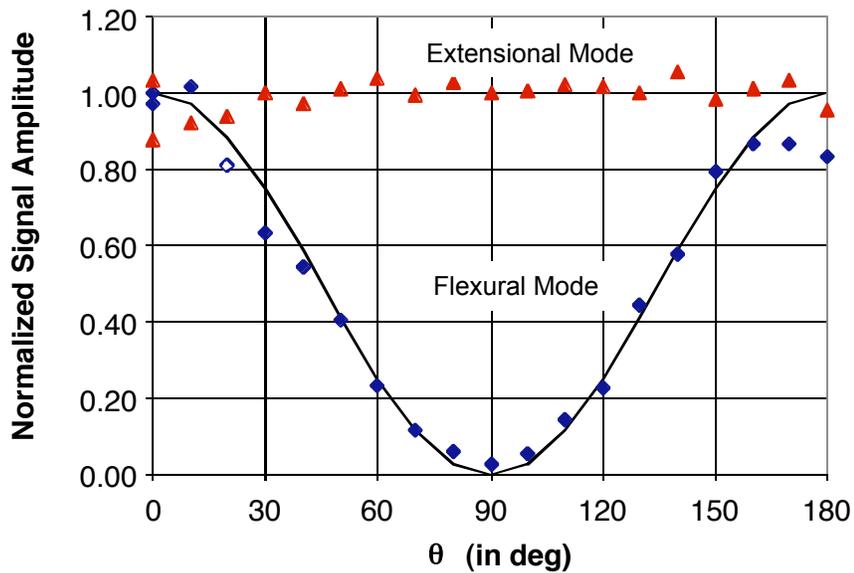


FIGURE 5. Plot showing the extensional and flexural mode amplitudes as a function of angle between the transmitting and receiving transducers. The solid curve is $\sin(2\theta)$, added to emphasize the flexural mode behavior.

Signals similar to the one shown in Figure 4 were observed when the distance between the ultrasonic transmitter and receiver was varied. Analyzing these signals as a function of distance showed that the frequency content of the extensional mode remained constant while the frequency content of the flexural mode varied and contained some higher order modes. These higher order modes were evident in the signal as small changes or variation in the sinusoidal shape of the wave and changed as the distance between the transducers varied.

Extensional Mode Experiments

The extensional mode phase velocity was determined by taking a series of 10 to 12 measurements of a constant phase point as a function of transducer separation range of about 50 to 250 mm (2 to 10 inches). The location of a constant phase point was plotted against the transducer separation and a linear curve fit was applied to the data. The slope of the linear fit was the measure of the phase velocity and the standard deviation of the fit was the error for the measurement. This extensional mode phase velocity measurement was essentially a traditional time-of-flight measurement.

Flexural Mode Experiments

Examination of the flexural mode was not a simple time-of-flight type measurement because this mode is dispersive. To extract the phase velocity in this case a Fourier phase method was used. This method was described and demonstrated by Sachse (Sachse and Pao, 1978), and used by a number of other authors, (Schumacher, et. al., 1993), (Prosser and Gorman, 1994), (Veidt and Sayir, 1990), and (Alleyne and Cawley, 1991), to investigate flexural mode dispersion of Lamb wave signals in metallic and laminated composite materials.

In the Fourier phase method an elastic wave is generated and detected at two different distances along the rod or wire. For each signal the flexural mode wave is windowed and then the phase (ϕ) of this windowed portion of the signal is obtained by performing a Fourier transform. The phases were unwrapped to remove any $2\pi n$ uncertainties and then the phase difference ($\Delta\phi$) was obtained. The phase velocity (v_{ph}) as a function of frequency (f) can be found to be

$$v_{ph}(f) = \frac{2\pi fd}{\Delta\phi} \quad (1)$$

where d is the distance between the two receiver locations.

Surface Wave Measurements

The extensional and flexural mode waves travel in both the wire insulation and wire conductor. For previous measurements it was assumed that the condition of the wire conductor is constant and thus would not be a factor in the extensional and flexural mode

measurements. If this assumption were wrong it would be beneficial to have a method to interrogate only the insulation. One possible method, examined here, is the application of Surface or Rayleigh waves. These waves propagate along the free surface of a semi-infinite elastic material, are nondispersive, and their displacement amplitude decays exponentially with distance from the free surface. Extensional and flexural modes at low frequencies have phase velocities that are very different. As frequency increases the phase velocity of these modes approaches the Rayleigh wave velocity and the distinct extensional and flexural modes merge. Efforts were made to identify this point by observing the extensional and flexural modes as a function of frequency and then use the wave mode at this frequency to infer the condition of the wire insulation.

Young's Modulus Measurements

Young's modulus was measured using a small computer controlled, electromechanically actuated table top load frame with a 450-kg (1000-pound) load cell. For displacement measurements an extensometer with a 2.54-cm (1.0-inch) gauge length was used. The general testing procedure involved applying a tensile load to a wire sample until the first detectable signs of yielding, where yielding was defined as a change of slope in the linear stress-strain curve. The typical load at this point was 9 to 45 kg (20 to 100 pounds) depending on wire gauge. This measurement was repeated after moving the extensometer to a new location in the central test region of each wire and away from the load frame grips. At each location, four measurements were taken around the wire's diameter using this procedure and the results averaged. For each measurement, efforts were made to avoid placing the extensometer at locations on the wire where evidence of bending existed. It was noted that residual stress in areas of bending was high and could cause the measurements to be inconsistent. When these results differed by greater than 20 percent, that group of measurements was ignored. This Young's modulus measurement represents a combined modulus from both the wire core and the insulation.

Other Measurements

Two other measurements were conducted using ultrasonic guided waves. One measurement examined the variation in the ultrasonic signal due to insulation damage. This was accomplished by using the clip-on transducers described above, generating an ultrasonic signal in the wire, and recording this signal before and after making a cut in the wire insulation. The second item examined was the use of a non-contact low-power laser diode as a method of generating ultrasound. This method was previously demonstrated (Madaras and Anastasi, 1999) and (Anastasi and Madaras, 1999) and was shown capable of generating ultrasound in aluminum and composite materials. The low-power and non-contact nature of this method makes it potentially attractive in some applications.

RESULTS

Extensional Mode Results

Initial measurements and dispersion curve calculations were carried out on a simple model of an insulated wire to identify the extensional and flexural wave modes. This model consisted of a solid aluminum rod with a polymer (heat shrink tubing) coating. The aluminum rod simulated the wire and the polymer coating simulated the wire insulation. It was assumed that there was a uniform bond at the interface of the aluminum and polymer coating. The calculations were performed using a commercially available software package that generated dispersion curves for plate and cylindrical geometry materials (Pavlakovic and Lowe, 2001).

Calculated dispersion curves for the extensional and flexural low-order modes are shown in Figure 6. This figure illustrates the significant effect of the coating that decreases the range of frequencies where dispersion is most noticeable and decreases the magnitude of the phase velocity. This effect was shown to be a function of the coating thickness (Reuter, 1969). The low frequency regime for the bare and coated aluminum rod is approximately 0-250 kHz and 0-50 kHz, respectively. In this frequency range the phase velocity of the extensional mode is 5119 m/s for the bare aluminum rod and 3200 m/s for the coated rod.

The average measured phase velocity for the bare aluminum rod was 5128 ± 28 m/s. The measured value for the coated rod was 4597 ± 36 m/s and is approximately 40% more than the calculated dispersion curve value. This difference could be due in part to group

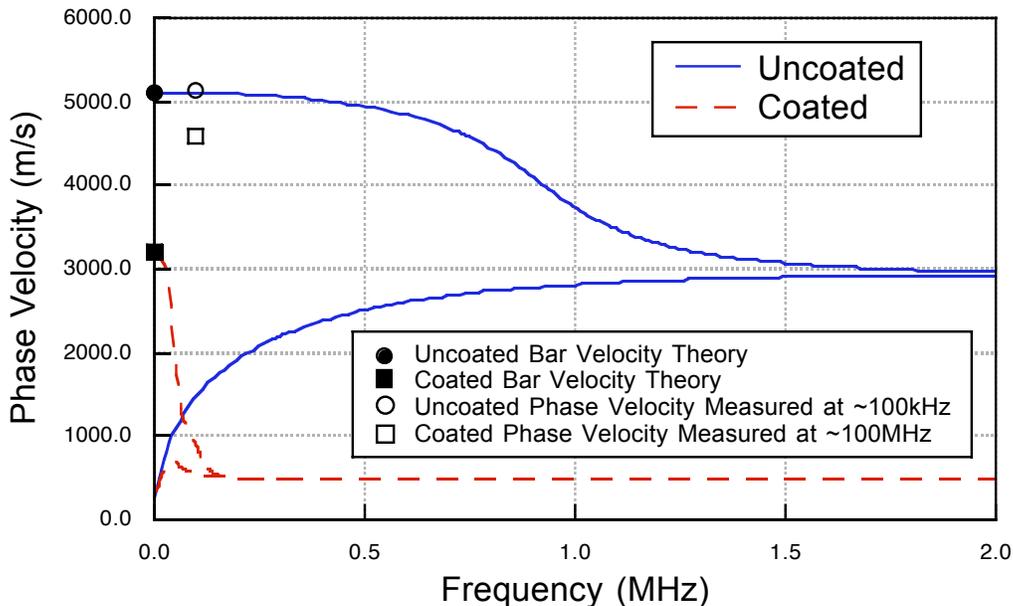


FIGURE 6. Theoretical extensional and flexural dispersion curves for uncoated and plastic coated brass rod.

velocity effects and to boundary conditions used in the numerical model. In the model a perfect coupling between the rod and plastic was assumed, but in the physical situation a weaker coupling may exist. More importantly, the result also indicates that some of the ultrasonic energy is traveling in the insulation and may be sensitive to insulator stiffness variations.

To test this theory measurements were conducted on the first set of heat-damaged wires. The phase velocity in these samples was measured following the same procedures described earlier and the results are shown in Figures 7, 8, and 9. These figures show a bar chart of phase velocity for each wire gauge and each heat-damage condition. In each gauge family the baseline samples showed the lowest phase velocity with phase velocity increasing for increasing heat damage. The 12-gauge wire in Figure 7 does not follow this trend and could be in part due to the poor condition of the wire; it was very brittle and some pieces of the insulation had detached from the wire. The phase velocity error varied from wire to wire, but in general was +/- 29 m/s or on the order of 1% of the measured values. Overall, this result shows that the extensional phase velocity measurement is able to distinguish between the baseline and heat-damage conditions.

To examine the effect of heat damage in more detail, measurements were made on the second set of wire samples. Results for the MIL-W-22759/34 wire samples in Figure 10 show the individual data points with an average phase velocity error for the 12-gauge and 20-gauge wire sets. The data for each gauge show a rapidly increasing phase velocity at small dwell times and a slower increasing phase velocity at longer dwell times. Results for the MIL-W-81381 wire set are shown in Figure 11 and show a similar behavior to the previous wire set. It appears as if the condition of the insulation is approaching a limiting phase velocity value. In general the phase velocity increases as a function of heat damage and is consistent with earlier results.

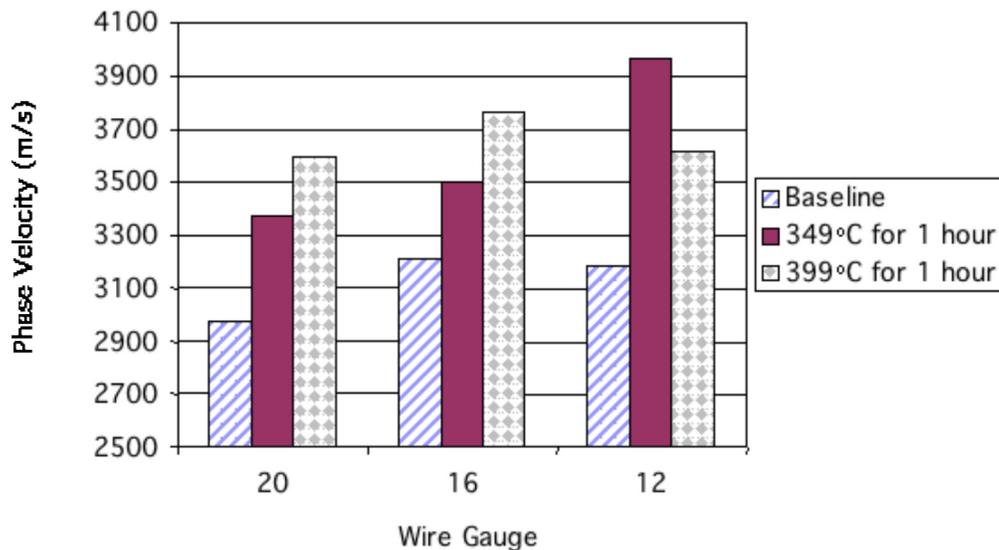


FIGURE 7. Ultrasonic wave velocity in heat-damaged MIL-W-22759/34 wire.

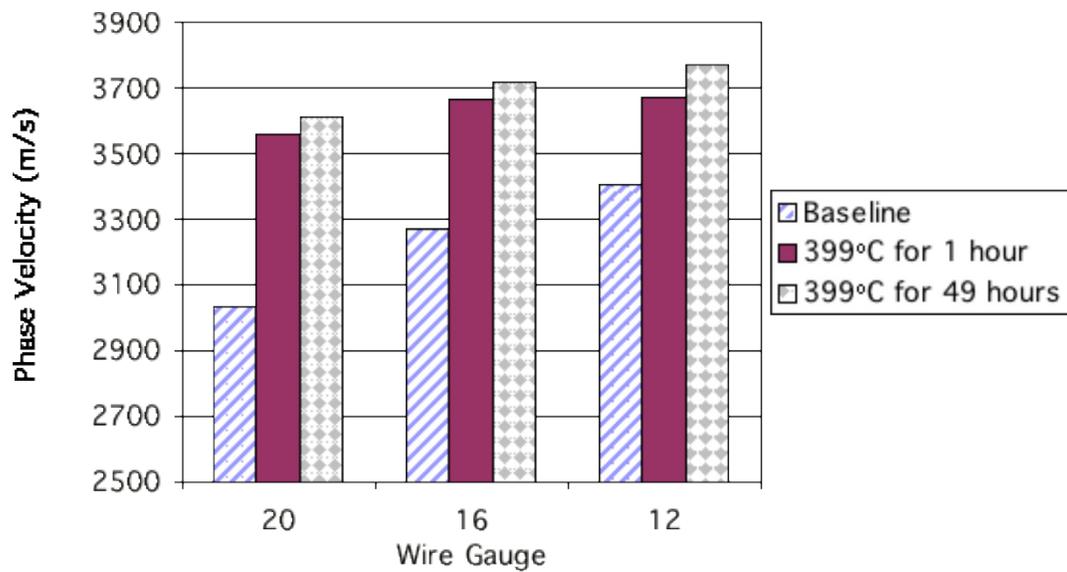


FIGURE 8. Ultrasonic wave velocity in heat-damaged MIL-W-81381 wire.

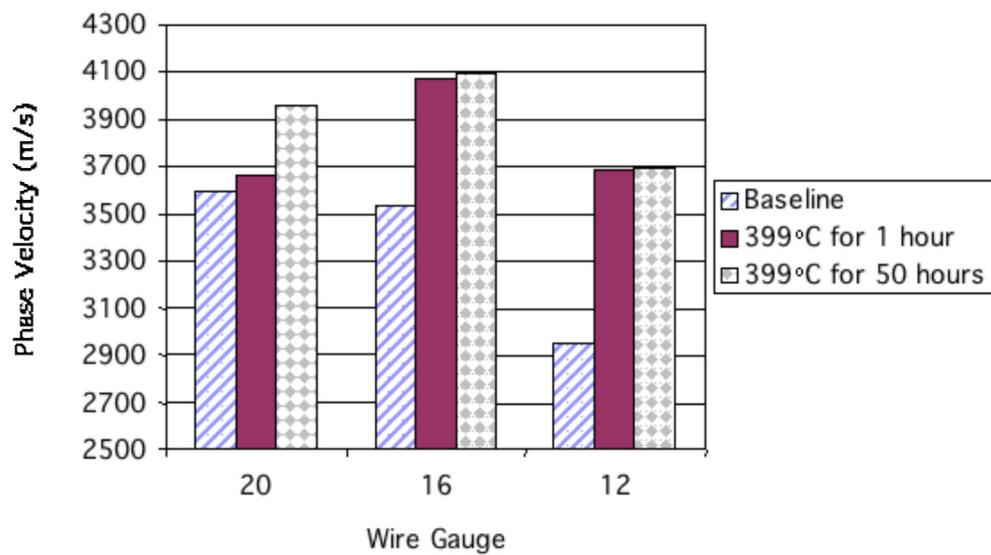


FIGURE 9. Ultrasonic wave velocity in heat-damaged MIL-W-22759/87 wire.

Flexural Mode Results

To validate the Fourier method, experimental measurements were taken on an uncoated and coated brass rod and the flexural mode dispersion curves were obtained using the Fourier phase method. The results shown in Figure 12 are compared with calculated flexural mode dispersion curves. The calculations were performed using a commercially available software package that calculates dispersion curves in plate and cylindrical geometry. The experimental measurements follow the trend of the calculated curves and validate the Fourier method procedures. The difference between the calculated and experimental curves may be due to differences between actual and textbook material property values and between actual boundary conditions and the assumed perfect coupling of the core and cladding.

Next, measurements were performed on electrical wire samples. The samples were mil-spec MIL-W-22759/34 16-gauge wires. This electrical wire was examined in a baseline condition and in a heat-damaged condition. For numerical calculations the electrical wire

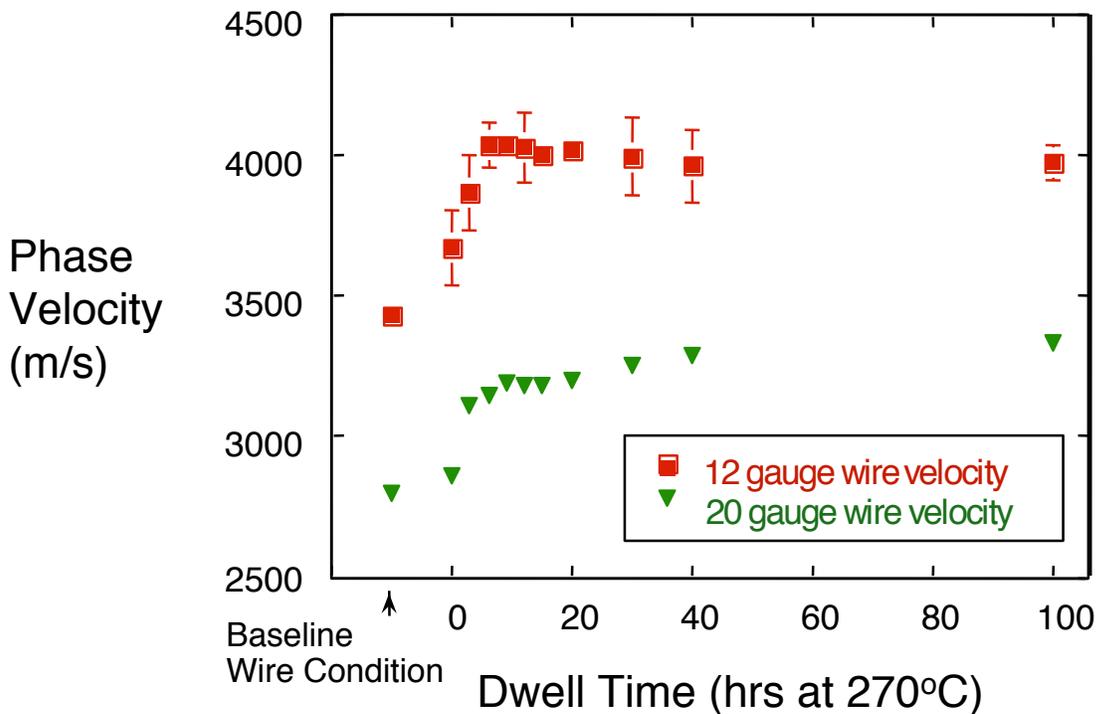


FIGURE 10. Phase velocity of MIL-W-22759/34 wire as a function of dwell time.

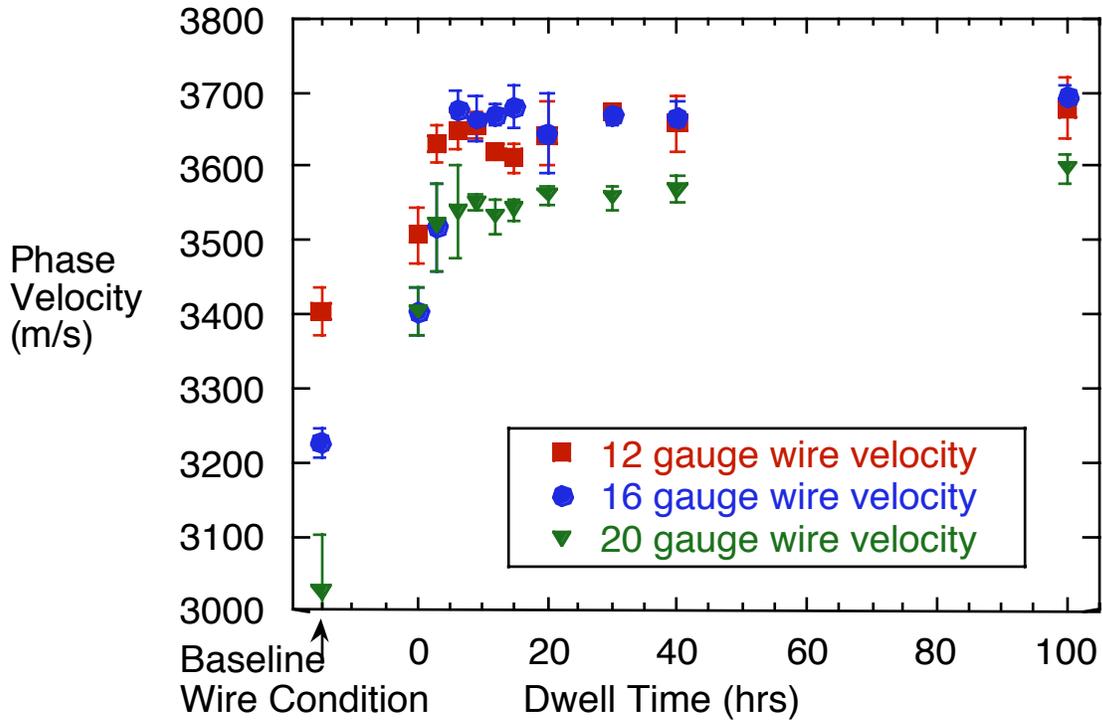


FIGURE 11. Phase velocity of MIL-W-81381 wire as a function of dwell time.

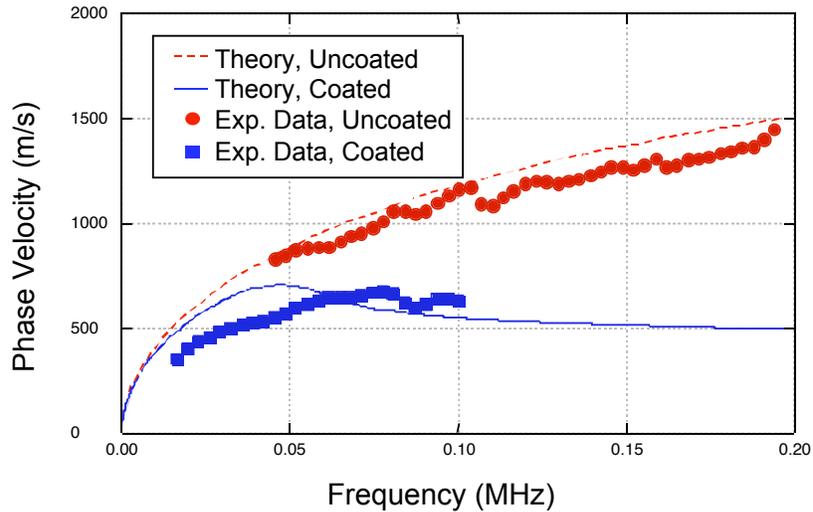


FIGURE 12. Comparison of theoretical and experimental flexural mode dispersion curves for uncoated and plastic coated brass rod.

TABLE IV. Material Properties and Radius used in numerical model of electrical wire.

<i>Material</i>	<i>Copper</i>	<i>Teflon[®]</i>
Young's Modulus (GPa)	122.70	1.864
Density (kg/m ³)	8900	2200
Poission's Ratio	0.35	0.40
Long. Velocity (m/s)	4700	1350
Shear Velocity (m/s)	2260	550
Radius (mm)	0.66	0.95

was modeled with a core of solid copper and a cladding of Teflon[®]. Properties, typical textbook values, and radius used in the calculations are shown in Table IV. Experimental and calculated flexural mode dispersion curves for the baseline and heat-damaged electrical wire are shown in Figure 13. For the heat-damaged sample a Young's Modulus value of 4.0 GPa was used. This value was chosen to make the calculated curve follow the experimental data and illustrate stiffening of the wire insulation. Although the experimental curves do not follow the calculations exactly the result does show a difference that may be associated with material stiffness. The difference between experimental and calculations may in part be due to the boundary condition between the cladding and core and that the model used a solid core while the actual wire core consisted of a bundle of small diameter wire strands.

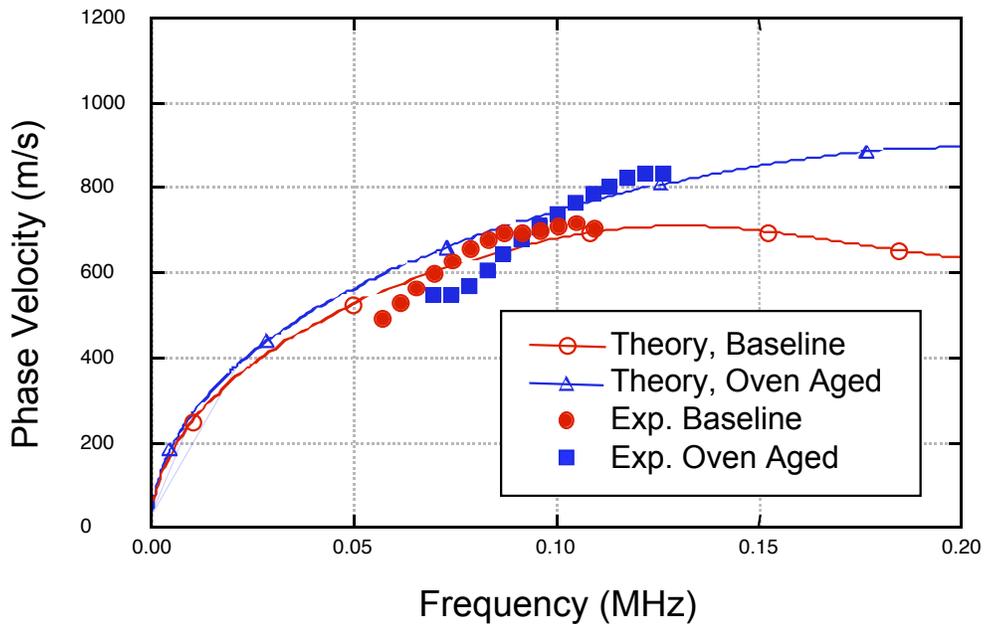


FIGURE. 13. Theoretical and experimental flexural mode dispersion curves for baseline and oven aged electrical wire.

In general, the phase spectrum method was easy to apply, but isolating and obtaining a clean flexural mode in wire samples was more difficult than in the solid wire rod. This difficulty could in part be due to the propagation of higher wave modes, boundary conditions, and the fact that the wire core was not solid but was made of stranded, coated wires.

Young's Modulus Results

Tensile tests were performed on a baseline set of MIL-W-81381 wires. A picture of a wire in the testing machine is shown in Figure 14. This set consisted of six 12-gauge wires, six 16-gauge wires, and six 20-gauge wires. The modulus measurement results, shown in the bar chart of Figure 15(a), were 8767 ± 292 KSI, 7714 ± 505 , and 5636 ± 486 for the 12-, 16-, and 20-gauge wires, respectively. Figure 15(b) shows the modulus calculation result based on the extensional mode phase velocity measurements. It was anticipated that the modulus derived from the extensional mode phase velocity would be similar to the tensile test values. However, the ultrasonic modulus measurements were



FIGURE 14. Wire in tensile testing machine with extensometer attached.

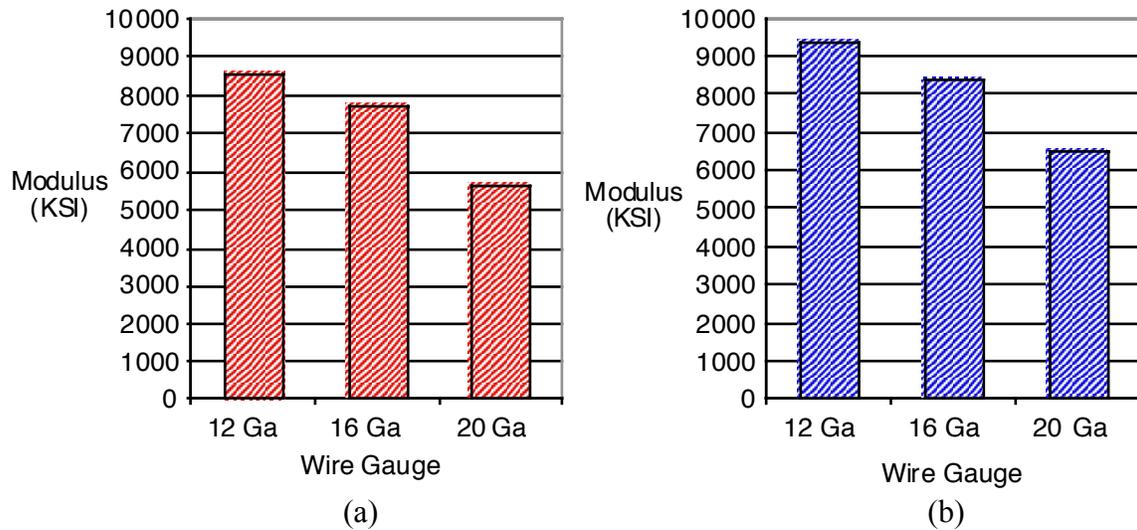


FIGURE 15. Modulus measurements in MIL-W-81381 baseline wires 12, 16, and 20 gauge, (a) modulus derived from tensile measurements and (b) modulus derived from velocity measurements.

consistently higher by about 10%. This ultrasonic modulus measurement and the tensile test modulus measurement were thus not identical, but showed a strong correlation.

In addition to the baseline measurements, tensile testes were performed on the second set of 12-gauge heat-damaged wires. Modulus measurements were made on the wires with dwell times of 0 hours, 3 hours, and 20 hours. The resulting modulus measurements were 9363 ± 716 KSI, 10248 ± 374 KSI, and 9456 ± 390 KSI, respectively. These results are shown in Figure 16 along with the modulus derived from the velocity measurements. Again, the results are not identical, but show a strong correlation. The inconsistency here and in the baseline measurements could be due, in part, to an unwinding of the wrapped wire core bundle during the tensile test.

Surface Wave Results

To identify the point where the extensional and flexural modes converge, measurements were performed on a sheet of Tefzel[®] material as a function of frequency. A sheet of material was chosen for initial measurements because it is easier to work with than the small cylindrical wires. Sheet thickness was 0.508 mm (0.02 inch) and the longitudinal wave velocity was 1690 m/s measured by an ultrasonic pulse echo method. It was assumed that knowing the Rayleigh wave velocity (V_R) and examining the ultrasonic signals that the correct mode could be identified. To this end, V_R was calculated using a mathematical approximation to the Rayleigh wave equation (Achenbach, 1999).

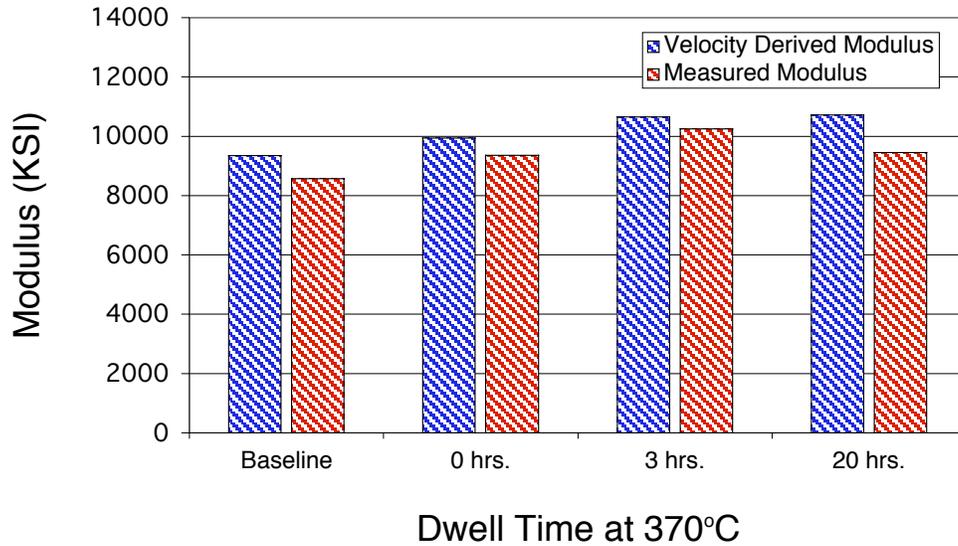


FIGURE 16. Modulus measurements: velocity derived modulus in heat-damaged MIL-W-81381 12-gauge wire.

$$v_R = \frac{0.862 + 1.14 \nu}{1 + \nu} v_T \quad (2)$$

In this calculation a Poission’s ratio (ν) value of 0.40 and a shear wave (v_T) velocity of 670 m/s were used. The Rayleigh wave velocity of 630 m/s was obtained in this calculation.

Ultrasonic signals were generated and examined as a function of transducer separation. The signals appeared similar to the extensional and flexural modes in the wire experiments. Signals were inspected at the Rayleigh wave mode arrival time, but distinct variations in the signal at this time were not observed. This measurement was repeated using transducers with center frequencies of 0.5 MHz, 1.0 MHz, and 2.25 MHz; the same results were obtained. The reason this mode was not observed could be in part due to attenuation of ultrasonic signal in plastic type material and that the Rayleigh wave mode may be of very small amplitude when compared to the lower frequency extensional and flexural modes.

Other Measurement Results

A baseline 12-gauge wire sample MIL-W-22759/34 was used in this measurement. The transducers were attached to the wire and an ultrasonic guide wave was generated and recorded before and after making a small cut in the wire insulation. Figure 17 shows the

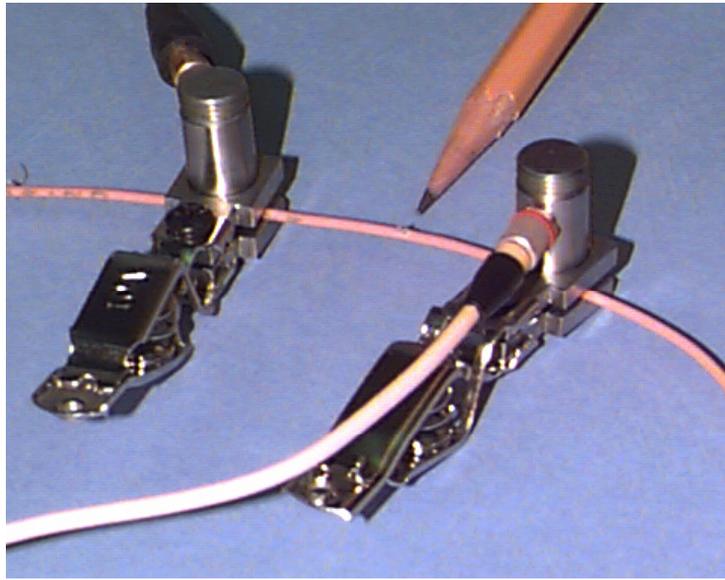


FIGURE 17. Transducers attached to a 12-gauge Mil-W-22759/34 wire with the pencil pointing to the insulation cut.

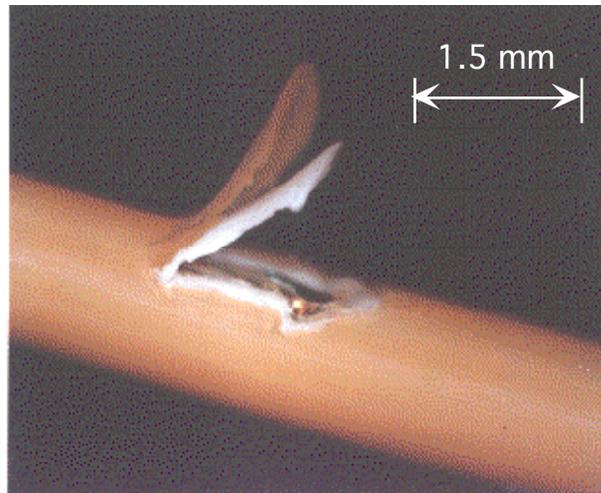


FIGURE 18. Close-up view of the insulation cut.

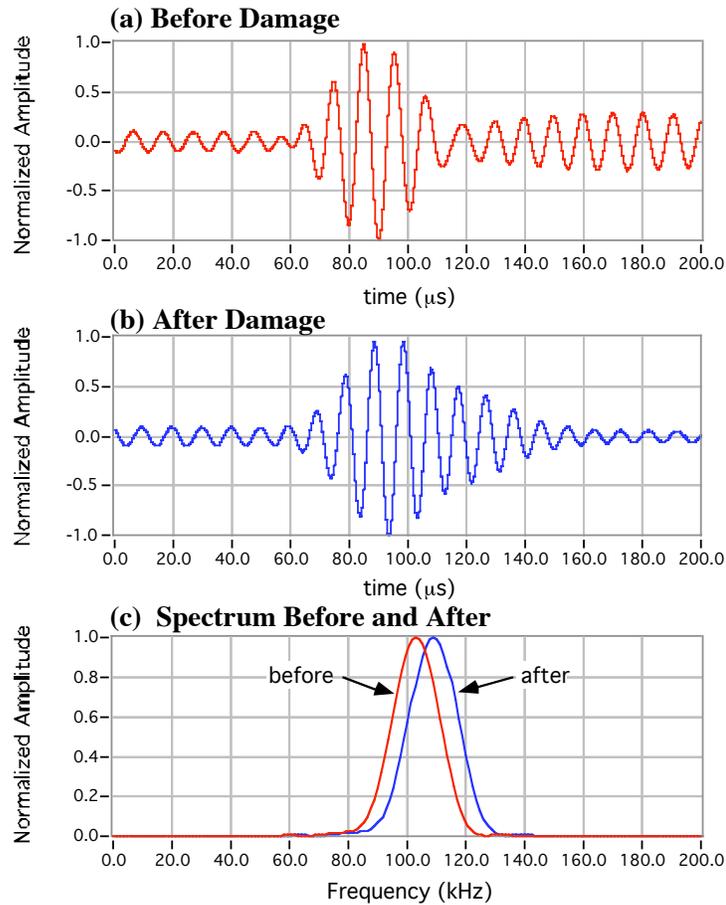


FIGURE 19. Signals and spectrum before and after damage are shown.

transducers attached to the wire and Figure 18 shows a close-up of the cut. A 100-kHz, 5-cycle Gaussian enveloped sine wave was used to drive the transmitting transducer. The output signals before and after damage and their spectra are shown in Figure 19. The signal before damage shows the modulated sine wave and the signal after damage shows the same signal that is slightly elongated. The spectrum of these signals shows a slight center frequency shift. These changes could in part be due to the cut and geometry change.

As in previous laser-diode ultrasound generation experiments a 150-mW modulated laser-diode was used as a transmitter to generate ultrasound. A conventional piezoelectric transducer was used as a receiver. A conventional ultrasonic signal was recovered by signal correlation. The laser-diode beam incident on the wire insulation was 2 mm in diameter and had a power density of 17.83 mW/mm^2 . A frequency generator modulated the laser-diode drive current, and thus the beam intensity, by using a frequency swept pattern from 1 kHz to 100 kHz. The insulation became damaged (slightly blackened) when the power density reached 20 mW/mm^2 , so these experiments stayed below this limit. Two wire samples were examined: a 12-gauge baseline sample and a 12-gauge sample that was heat-damaged at 349°C for 1 hour. A typical ultrasonic signal

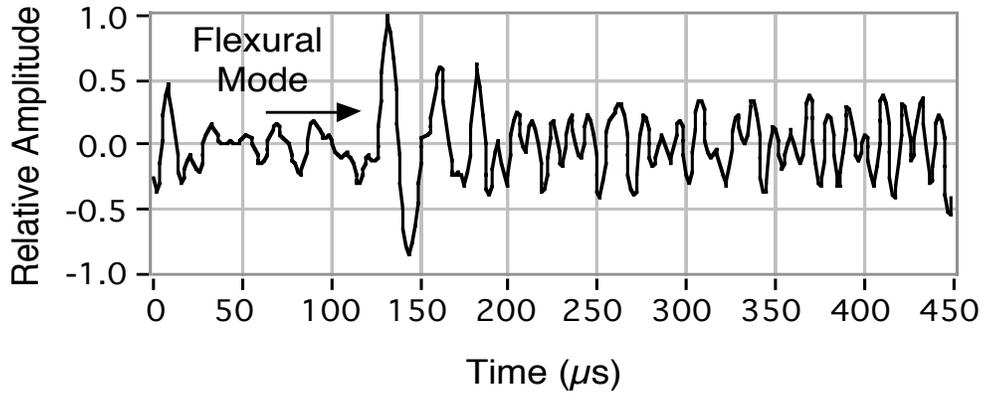


FIGURE 20. Laser-diode generated ultrasonic signal.

recovered from correlating the drive and received signals is shown in Figure 20. The first flexural mode, the larger amplitude signal, can be seen initiating at about 120 μs .

A fairly large amplitude signal can be seen at the beginning of the waveform and could be due in part to both signal processing and the electronics. The extensional mode that was shown to be generated with contact transducers in previous measurements could not be resolved. It is possible that the thermal generation mechanism lacked the energy to generate this mode.

The phase velocity of this flexural mode was measured by taking a series of measurements of a constant phase point as a function of generation point and receiver separation. The laser diode was translated in millimeter increments and the piezoelectric ultrasonic receiver was held in a fixed position. The location of a constant phase point in time was plotted against the translation stage displacement and a linear curve fit was applied. The slope of the linear fit was our measure of the flexural phase velocity. The baseline flexural phase velocity was 529 m/s while the heat-damaged sample had a phase velocity of 548 m/s. This measurement is consistent with previous measurements near 40 KHz that showed an increase in phase velocity for the heat-damaged samples.

The flexural mode phase velocity measured with the laser is much slower than the extensional mode phase velocity measured with the transducers. This is consistent with dispersion curve relations for cylindrical rods. These relations show that the flexural mode phase velocity approaches zero as frequency approaches zero while the extensional mode phase approaches the bar velocity as the frequency approaches zero.

Wire NDE Tool

The general procedure used to measure the extensional phase velocity was to record multiple ultrasonic signals as a function of transducer spacing and then calculate the extensional phase velocity from the signal arrival time and transducer separation. This

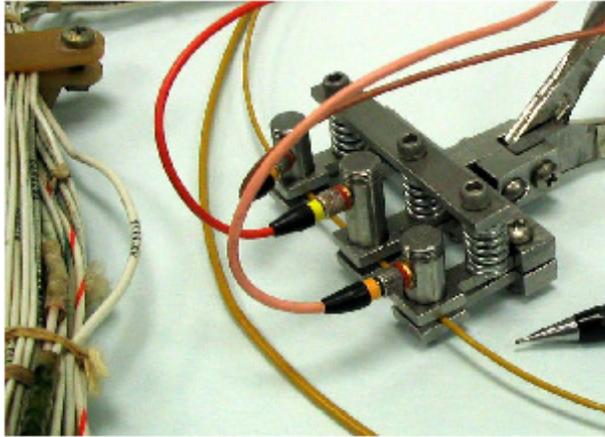


FIGURE 21. Wire Insulation NDE Tool clamped onto a 16-gauge wire.

procedure is adequate for laboratory based measurements, but would be impractical to perform on aircraft wires in small spaces. A more practical procedure is to use two measurements at two different distances from the transmitting transducer in a fixed tool. A compact arrangement is to locate the transmitter between two outer receivers. The different distances between the transmitter and two receivers divided by the difference between the separate signal arrival-times can be used to give the velocity. This arrangement eliminates the need to move the receiver or transmitter transducer multiple times to obtain various measurements from which the wave velocity is calculated. The disadvantage in this approach might be reduced accuracy, but the advantage is a simpler measurement procedure.

To facilitate this procedure a wire NDE tool was manufactured and is shown in Figure 21. A 16-gauge wire is shown attached in the tool in Figure 21. The tool consists of the transmitting transducer located between two receivers on a spring-loaded platform with a handgrip. The spacing between the transmitter and first receiver is 2.50 cm (0.98 inch) and the distance between the transmitter and second receiver is 3.50 cm (1.38 inches). Sample signals in a 16-gauge Kapton™ wire that were obtained with this tool are shown in Figure 22. The calculated phase velocity was 3269 m/s.

The laboratory-based instrumentation described previously was used with the wire NDE tool. This instrumentation is bulky and not suited for field type measurements. An initial attempt to reduce this bulk of instrumentation involved using smaller instrumentation in the form a field-portable laptop computer, an ultrasonic generator board, and an ultrasonic receiver board. Control and data acquisition software was written for these boards that included a graphical user interface that allowed the user to control the ultrasonic pulse energy and locate the extensional mode arrival from each ultrasonic receiver, and calculated the phase velocity based on the wire tool transducer separation. Tests were first conducted with this system on a solid wire rod and measurement results compared well to theoretical values. When tests were conducted on a sample wire it was generally difficult to isolate the extensional modes and calculate the velocity. Signal

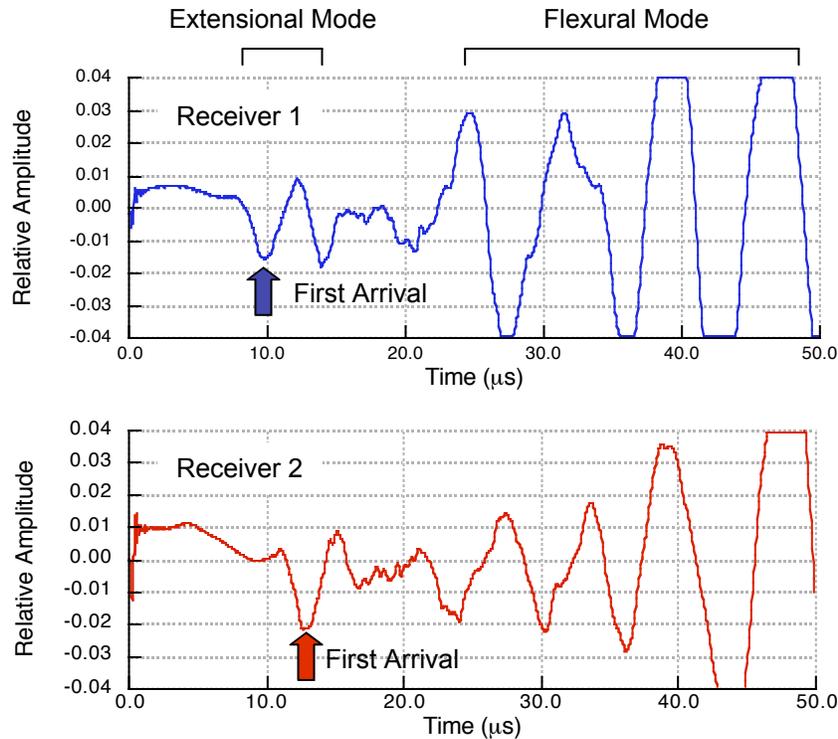


FIGURE 22. Sample singles in 16-gauge Kapton™ wire using the Wire Insulation NDE Tool shown above.

averaging improved signal identification, but identifying the extensional mode was still difficult. When the ultrasonic receiver board was replaced with a digital oscilloscope attached to the field-portable laptop via a GPIB interface, the extensional mode signals could be identified. Thus a new ultrasonic receiver board with better analog to digital resolution is needed for this field-portable system. A commercial manufacturer of field portable systems is being sought to build a practical high quality system

CONCLUSION

This work demonstrated the generation of ultrasonic extensional and flexural guided waves in a plastic coated solid aluminum rod and in insulated wire samples using a simple clip-on piezoelectric transducer for ultrasound generation. Guided wave measurements on the bare aluminum rod were used to distinguish between the extensional and flexural wave modes. Even though the flexural wave mode was larger in amplitude than the extensional mode, the extensional mode has a faster phase velocity and lower dispersion, making it easier to isolate constant phase points in a series of measurements. Thus, the extensional mode wave was the primary mode used for these measurements. However, the flexural mode is larger in amplitude than the extensional mode and some experiments were conducted to evaluate the flexural mode's usage.

The extensional wave mode measurements in the aluminum rod and polymer coated aluminum rod illustrated that the coating not only attenuated the wave amplitude, but decreased the phase velocity. Thus, ultrasonic energy propagated in both the polymer coating and aluminum rod and the concept of using guided waves to interrogate the wire insulation was shown to have potential. The aircraft wire measurements, in general, showed the extensional wave velocity increase for increasing heat damage or oven exposure. Thus, measurements of the extensional mode phase velocity may be sensitive to stiffness changes in the wire insulation and provide quantitative information about the insulation condition. Another aging effect of wire insulation on ultrasound would be attenuation effects, but these methods have not been investigated at length yet.

The flexural mode was more difficult to use because it is dispersive. To overcome this difficulty a Fourier phase method was used to directly obtain a plot of the phase velocity as a function of frequency. In the experiments with on the brass rod the theoretical measurements followed the trend of the experimental measurements. This was also the case for experiments on the wire samples, but the small bandwidth of the flexural mode signal limited the application of this method.

Young's modulus of wire samples was measured in a testing machine and compared to a modulus derived from the measured phase velocity. Results showed these values to have a strong correlation. This measurement illustrated that the material stiffness of the wire can be measured by extensional phase velocity.

An attempt was made to make the extensional mode measurement easier by designing a wire NDE tool and trying to reduce the weighty instrumentation. The instrumentation reduction needs more work, but the wire NDE tool had good test results. With instrumentation refinement and reductions this tool can potentially be used for measurements in aircraft.

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14. ABSTRACT Aging wiring has become a critical issue to the aerospace and aircraft industries due to Shuttle and aircraft incidents. The problem is that over time the insulation on wire becomes brittle and cracks. This exposes the underlying conductive wire to the potential for short circuits and fire. Popular methods of monitoring aging wire problems focuses on applying electrical sensing techniques that are sensitive to the conductor's condition, but not very sensitive to the wire insulation's condition. Measurement of wire insulation stiffness and ultrasonic properties by ultrasonic guided waves is being examined. Experimental measurements showed that the lowest order extensional mode could be sensitive to stiffness changes in the wire insulation. To test this theory conventional wire samples were heat damaged in an oven, in a range of heating conditions. The samples were 12, 16, and 20 gauge and the heat damage introduced material changes in the wire insulation that made the originally flexible insulation brittle and darker in color. Results showed that extensional mode phase velocity increased for the samples that were exposed to heat for longer duration.					
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