Investigating the Use of Ultrasonic Guided Waves for Aging Wire Insulation Assessment

Robert F. Anastasi[a] and Eric I. Madaras[b]
[a]U.S. Army Research Laboratory, Vehicle Technology Directorate, AMSRL-VT-S, Nondestructive Evaluation Sciences Branch, NASA Langley Research Center, Hampton, VA 23681
[b]NASA Langley Research Center, Nondestructive Evaluation Sciences Branch, Hampton, VA 23681

ABSTRACT

Aging wiring has become a critical issue to DoD, NASA, FAA, and Industry. The problem is that insulation on environmentally aged wire becomes brittle and cracks. This exposes the underlying conductive wire to the potential for short circuits and fire. The difficulty is that techniques to monitor aging wire problems focus on applying electrical sensing techniques that are not very sensitive to the wire insulation. Thus, the development of methods to quantify and monitor aging wire insulation is highly warranted. Measurement of wire insulation stiffness 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 axisymmetric mode may be sensitive to stiffness changes in the wire insulation. To test this theory, mil-spec wire samples MIL-W-81381, MIL-W-22759/34, and MIL-W-22759/87 (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. Axisymmetric mode phase-velocity increased for the samples that were exposed to heat for longer duration. For example, the phase velocity in the 20-gauge MIL-W-22759/34 wire changed from a baseline value of 2790m/s to 3280m/s and 3530m/s for one-hour exposures to 349^0C and 399^0C, respectively. Although the heat-damage conditions are not the same as environmental aging, we believe that with further development and refinements, the ultrasonic guided waves can be used to inspect wire-insulation for detrimental environmental aging conditions.

Keywords: guided waves, wire insulation, cylindrical wave-guide, ultrasonic

1. INTRODUCTION

Electrical wiring is critical to the operation of most modern day equipment. Wiring is subjected to heat, cold, moisture, and vibrations, which can eventually cause the wire insulation and even the wire conductor to fail. In most cases these environmental and operational conditions are modest, but in some cases these conditions are extreme and can cause the insulation to become brittle and crack. The cracks expose the underlying wire conductor and become a potential source for short circuits and fire. Typical wire inspections are done visually and often after-the-fact, in response to an instrument or system failure. Visual inspection may find the cracks and burns, but offers little quantitative information about the condition of the wire insulation.

In its basic geometry the insulated wire may be considered a cylindrical wave-guide or more descriptively 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 [1-5] and for detailed analysis the reader is referred to these papers. Some applications of ultrasonic guided waves include material testing or characterization of wire [6, 7] or fibers, and for use as ultrasonic delay lines. In general many acoustic wave modes will propagate in an isotropic cylinder and in part, be a function of material property, geometry, frequency, propagation order, and circumferential order. Modes with circumferential order of zero are axisymmetric mode and can be divided into axial-radial and torsional. The first branch of the axisymmetric 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 anti-symmetric, 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., [2]. The axisymmetric mode extends to zero frequency where the limiting phase velocity is called the bar velocity. In the low frequency regime, this mode is nearly non-dispersive. As frequency increases, the phase velocity drops to a value slightly below the Rayleigh wave velocity and then approaches this wave velocity from below at higher frequencies, [2]. The flexural mode is highly dispersive in the low frequency regime and approaches the Rayleigh wave velocity with increasing frequency.

In this paper, the axisymmetric mode is examined for its use in detecting degradation in electrical wire insulation because of its non-dispersive characteristic in the low-frequency regime. Two ultrasonic transducers are used in a pitch catch configuration to generate and receive an ultrasonic guided wave in the wire. Part of the wave will travel in the wire and part in the wire insulation. The condition of the wire insulation, its stiffness, will affect the overall wave speed and amplitude of the guided wave. Thus, a measurement of wave speed will, in part, be a measurement of material stiffness or wire insulation condition.

2. EXPERIMENTS

The experimental system is schematically shown in Figure 1. This system consists of two piezoelectric transducers, ultrasonic pulse generator, ultrasonic pre-amp, and oscilloscope. The transducers were low frequency, broadband acoustic emission transducers with a bandwidth of 50 kHz to 1.5 MHz. The signal from the ultrasonic receiver is first fed through a pre-amplifier 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 recorded for later analysis. The transducers were mechanically attached to the rod or wire as shown in Figure 2. The clamp face opposite the transducer had a groove machined in it, to hold the wire along the center of the transducer surface. During measurements, a wire was held on a 30-cm long optical rail while the transducer separation was varied between 3 and 29 cm. The wires were nominally 60 cm long and the ends of the wires were clamped to hold the samples straight while measurements were taken.

The phase velocity was determined by taking a series of measurements of a constant phase point as a function of transducer separation. The separation distance varied from 30 mm to 240 mm over which 10 to 12 measurements were taken. 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.

3. RESULTS

Initial measurements were carried out on a simple model of an insulated wire to identify the axisymmetric and flexural wave modes. This model consisted of a solid aluminum rod with a polymer coating. The aluminum rod, simulating the wire, had a 3.23 mm diameter. The polymer coating, simulating the wire insulation had a thickness of 0.57 mm. The coating was a thermoplastic heat-shrink material of Polyolefin. Published [8] density and modulus of this material is 0.971 gm/cm^3 and 1.2 Gpa respectively, and the measured longitudinal wave velocity is 1870 m/s. The final diameter of the model was 4.37 mm. It was assumed that there was a perfect bond at the interface of the aluminum and polymer coating.

A typical ultrasonic signal in the bare aluminum rod is shown in Figure 3. A smaller amplitude wave can be seen at about 50 μs and a larger amplitude wave initiates at about 75 μs. To help identify the modes of these waves the angular dependence of the wave amplitude was examined. This was done by holding the transmitting transducer stationary while the receiving transducer, at a fixed distance, was rotated around the aluminum rod in increments of 10 degrees. The result showed that the amplitude of the 50 μs wave remained constant while the 75 μs wave amplitude followed a cosine shape with a minimum at 90^0. From theory the amplitude of the axisymmetric L(0,1) mode shows no angular dependence while the flexural F(1,1) mode is angle dependent, [1,2]. Thus the wave at 50 μs is the axisymmetric mode wave and the 75 μs wave is the flexural mode wave.

The measured phase velocity of the axisymmetric mode wave in the bare rod and the polymer coated aluminum rod, were 5128 m/s and 4663 m/s, respectively. The bare aluminum rod phase velocity measurement is consistent with a calculated bar velocity of 5119 m/s. The aluminum properties used here were 70.76 GPa and 2.7 gm/cm^3 for Young's Modulus and density, respectively. The measured changes in phase velocity between the bare and coated aluminum rod demonstrate the effect of the coating. It indicates that some of the ultrasonic energy is traveling in the insulation and may be sensitive to stiffness changes in the wire insulation.

To test this theory, some mil-spec wire samples were heat-damaged to change the condition in the insulation. It was assumed the heating did not change the insulation geometry or the boundary conditions between the insulation and the wire conductor because the temperature was not high enough to melt the insulation. The samples were 12, 16, and 20 gauge MIL-W-81381, MIL-W-22759/34, and MIL-W-22759/87 wires and were cut to length of approximately 60-cm. The MIL-W-81381 wire has a polyimide insulation, the MIL-W-22759/34 has a ethylene-tetraflouroethylene insulation, and the MIL-W-22759/87 has a combination of polyimide and flouroethylene polymer insulation. More specification for these wire types is given in Table 1.

Table 1: MILL-W specification of wire.

Wire Type	**Gauge**	**Conductor**	**Insulation ID (mm)**	**Insulation OD (mm)**
MIL-W-81381/7	20	Stranded Silver Coated Copper	0.942	1.286
MIL-W 81381/21	16	Stranded Tin Coated Copper	1.326	1.628
MIL-W 81381/12	12	Stranded Nickel Coated Copper	2.086	2.496
MIL-W 22759/34	20	Stranded Tin Coated Copper	0.942	1.452
MIL-W 22759/34	16	Stranded Tin Coated Copper	1.326	1.096
MIL-W 22759/34	12	Stranded Tin Coated Copper	2.086	2.798
MIL-W 22759/87	20	Stranded Nickel Coated Copper	0.942	1.346
MIL-W 22759/87	16	Stranded Nickel Coated Copper	1.326	1.742
MIL-W 22759/87	12	Stranded Nickel Coated Copper	2.086	2.578

One sample of each gauge was used for the baseline measurements and one of each gauge was heated in and oven at 349^{0}C or 399^{0}C. Oven exposure times were arbitrarily chosen to induce heat-damage in the insulation, heating conditions are given in Table 2.

The insulation on the MIL-W-22759/34 baseline samples was smooth, flexible, and off-white in color, for the short exposure samples the insulation remained smooth and flexible, but its color change to gray, and the insulation for the long exposure samples became brittle, cracked, and black in color. 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, and for the long exposure samples the insulation cracked, and lost its original glossy shine, but remained white in color.

Table 2: Oven exposure time and temperature.

Wire Type	**Baseline**	**Short Exposure** Time (hours) / Temp. (^{0}C)		**Long Exposure** Time (hours) / Temp. (^{0}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

The phase velocity in these samples was measured following the same procedures described earlier and the results are shown in Figures 4, 5, and 6. These figures show a bar chart of phase velocity for each wire specification and each heat-damage condition. In each gauge family the baseline samples showed the lowest phase velocity. In the lower temperature or shorter heating time heat-damage condition the phase velocity increases and for the higher temperature or longer heating time heat-damage condition, the phase velocity increases again for all but the 12-gauge wire in Figure 4. This could be in part 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 axisymmetric phase velocity measurement is able to distinguish between the baseline and heat-damage conditions.

To examine the effect of heat damage in more detail, MIL-W-22759/34 wire samples of each gauge were oven aged at 270^{0}C for up to 200 hours. Wire samples of each gauge were removed from the oven about every three hours up to fifteen hours and then about every twenty hours. The samples were then ultrasonically examined as in previous measurements. Results in Figure 7 show the individual data points with an average phase velocity error for each gauge set and a Weighted Least Squared curve fit to highlight the trend of the data. The data for each gauge shows a rapidly increasing phase velocity at short oven exposure times and a slower increasing phase velocity at longer oven exposure times. It appears as if the condition of the insulation is approaching a limiting phase velocity value. In general the phase velocity increase as a function of oven exposure is consistent with the earlier results at a few temperatures and times.

3. CONCLUSION

This work demonstrated the generation of ultrasonic axisymmetric 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 axisymmetric and flexural wave modes. Even though the flexural wave mode was larger in amplitude than the axisymmetric mode, the axisymmetric mode's faster phase velocity, that is not very dispersive, made it easier to isolate constant phase points in a series of measurements. Thus, the axisymmetric mode wave was used for these measurements. The axisymmetric 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 mil-spec wires measurements, in general, showed the axisymmetric wave velocity increase for increasing heat damage or oven exposure. Thus, measurements of the axisymmetric mode phase velocity may be sensitive to stiffness changes in the wire insulation. Although the heat-damage conditions are not the same as aging conditions with further development and refinements, the small clip on transducers can be used to inspect wire insulation for detrimental aging conditions. Future plans include conducting oven-aging experiments on the other mil-spec wire types and measuring the stiffness of the insulation at the different aging conditions in a testing machine. Correlating the testing machine measurements to the phase velocity measurements will illustrate the material stiffness of the insulation can be measured by axisymmetric phase velocity.

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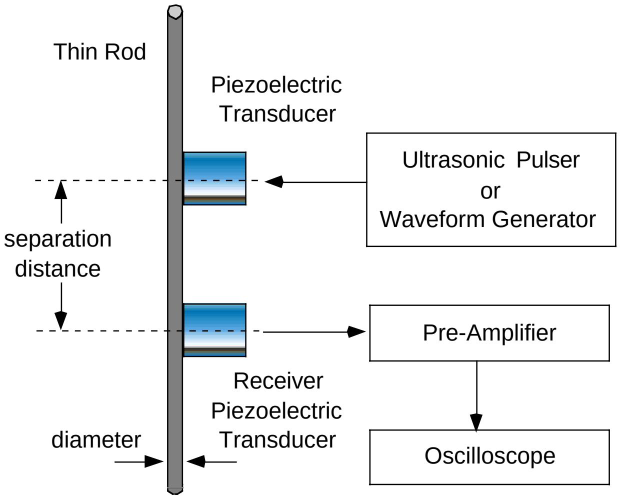

Fig. 1: Schematic of experimental setup.

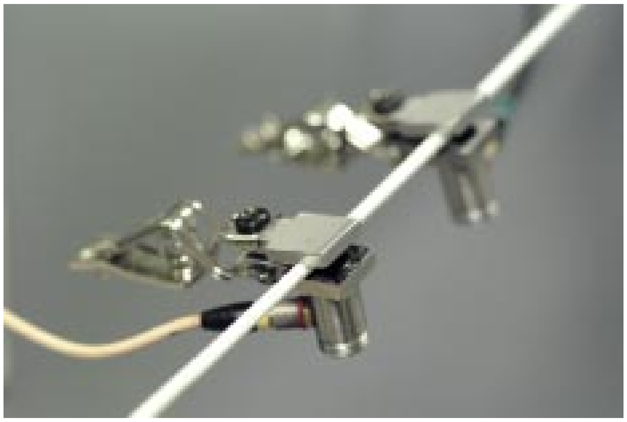

Fig. 2: Ultrasonic Transducers Clipped to Insulated Wire.

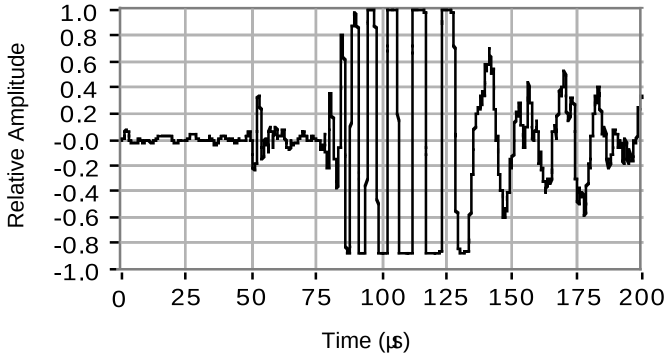

Fig. 3: A typical ultrasonic signal in the bare aluminum rod showing the first axisymmetric wave mode and the first flexural mode wave.

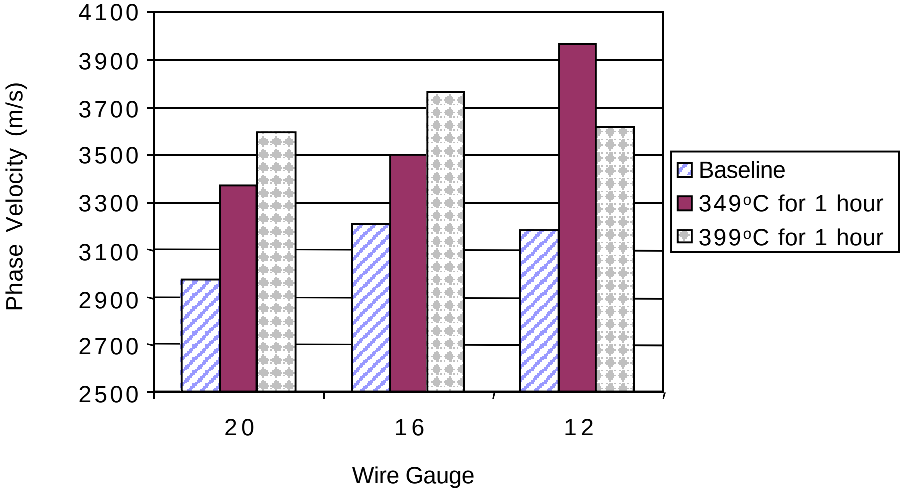

Fig. 4: Ultrasonic Wave Velocity In Heat Damaged MIL-W-22759/34 Wire.

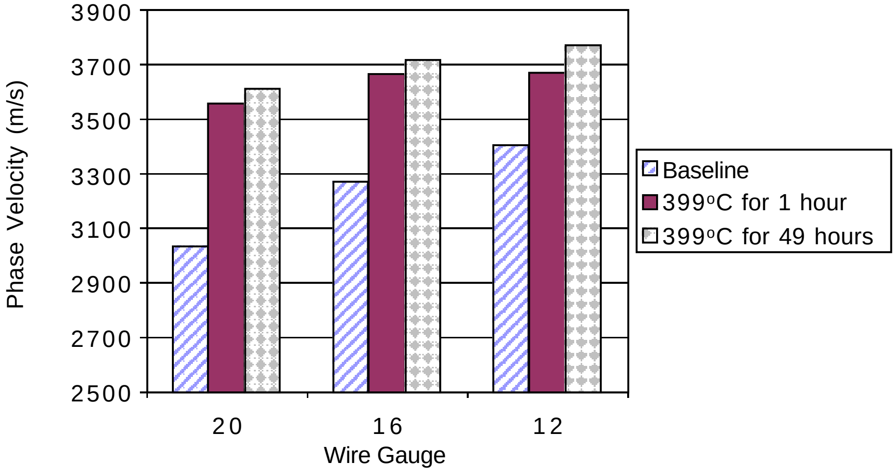

Fig. 5: Ultrasonic Wave Velocity In Heat Damaged MIL-W-81381 Wire.

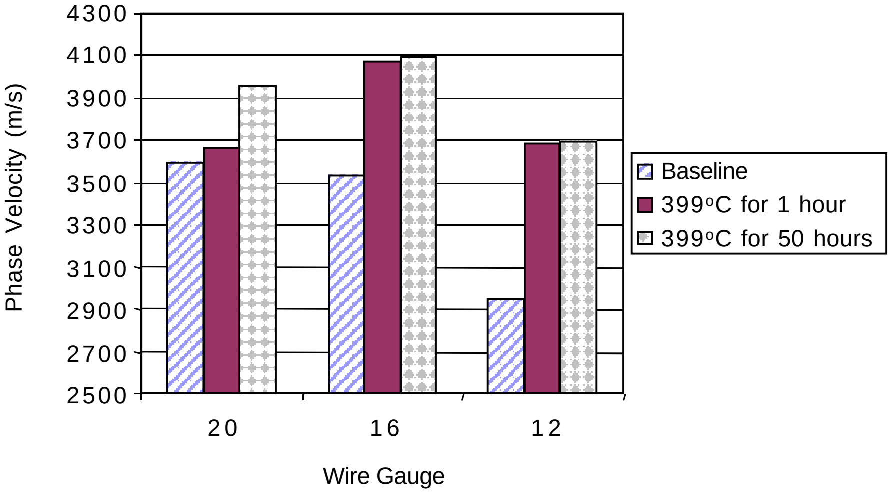

Fig. 6: Ultrasonic Wave Velocity In Heat Damaged MIL-W-22759/87 Wire.

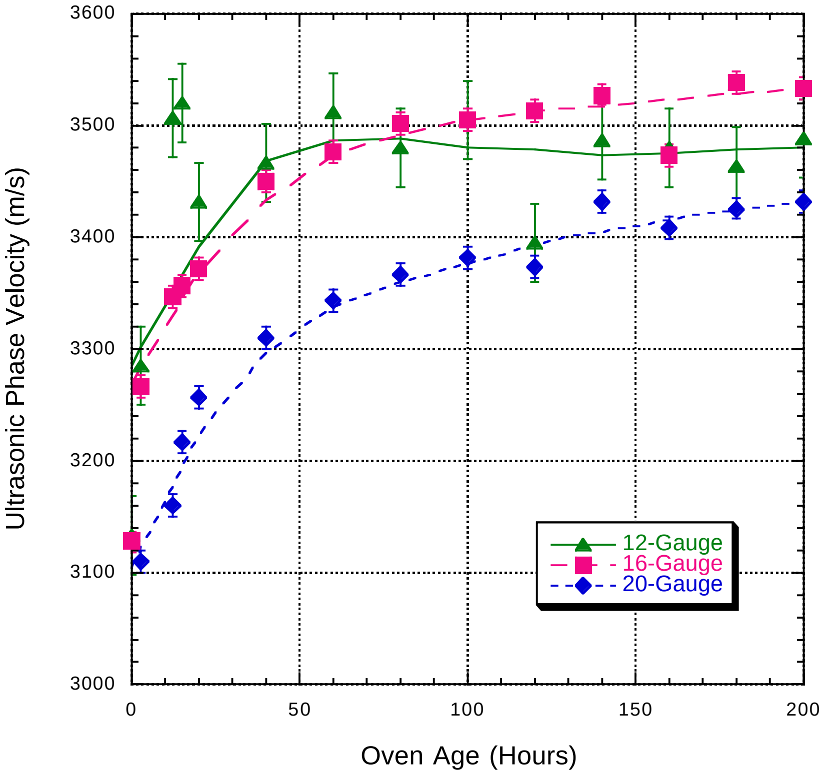

Fig. 7: MIL-W-22759/34 phase velocity as a function of oven age.