The Application of Ultrasonic Inspection to Crimped Electrical Connections

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ABSTRACT

The development of a new ultrasonic measurement technique to quantitatively assess wire crimp terminations is discussed. The development of a prototype instrument, based on a modified, commercially available, crimp tool, is demonstrated for applying this technique when wire crimps are installed. The crimp tool has three separate crimping locations that accommodate the three different ferrule diameters. The crimp tool in this study is capable of crimping wire diameters ranging from 12 to 26 American Wire Gauge (AWG). A transducer design is presented that allows for interrogation of each of the three crimp locations on the crimp tool without reconfiguring the device. An analysis methodology, based on transmitted ultrasonic energy and timing of the first received pulse is shown to correlate to both crimp location in the tool and the AWG of the crimp/ferrule combination. The detectability of a number of the crimp failure pathologies, such as missing strands, partially inserted wires and incomplete crimp compression, is discussed. A wave propagation model, solved by finite element analysis, describes the compressional ultrasonic wave propagation through the junction during the crimping process.

INTRODUCTION

A wire-crimp terminator is a fixture which consists of a mating end and a crimp ferrule, and is installed on the end of a wire. This establishes a secure mechanical and electrical connection between the wire and the terminator. A terminator is installed onto the end of a wire by removing a portion of the insulation to expose a prescribed length of stranded wire, and placing it inside the ferrule. The ferrule is deformed by a tool designed to force the wire surfaces and the ferrule's inner surface into intimate contact. This connection then maintains a residual force by the ferrule on the wire to assure good mechanical and electrical continuity between the wire's end and the terminator.

Previous work has shown that ultrasonic inspection provides a means of assessing crimp quality that ensures the electrical and mechanical integrity of an initial crimp before the installation process is completed. The amplitude change of a compressional ultrasonic wave propagating at right angles to the wire axis and through the junction of a crimp termination was shown to correlate with the results of a destructive pull test, which is a standard for assessing crimp wire junction quality. A quantitative measure of the quality of the crimped connection based on the ultrasonic energy transmitted, the crimp attenuation factor, was defined and shown to respond accurately to crimp quality[1,2].

ULTRASONIC BASED INSPECTION TECHNIQUE

The technique presented here uses ultrasonic wave transmission through the ferrule-wire joint (perpendicular to the geometric axis) to inspect a mechanically crimped connection. Figure 1 shows a schematic of the basic components. The transmit transducer is segmented so that it generates three identical ultrasonic waves, separated in time by 0.5 μs, which travel into the jaw of the crimp tool. Each element of the transmit transducer is aligned with one of the crimp locations on the tool. Upon application of pressure, the jaw deforms the crimp ferrule around the wire with sufficient force to press the wire and ferrule surfaces into intimate mechanical contact. This allows transmission of the ultrasonic wave through the ferrule, through the electrical wire, and into the opposite jaw to be received by an ultrasonic transducer. As the pressure increases, conformation between the crimp tool jaws, the ferrule, and the enclosed wire strands improves, and more of the ultrasonic wave energy propagates through the ferrule-wire joint.

The experimental setup consists of a commercial ultrasonic pulser-receiver (JSR Ultrasonics model PRC-50) in a pitch-catch arrangement as shown in Figure 1. Data acquisition of the received ultrasonic time record was performed using a commercial 12-bit digitizer (Agilent-Acqiris model DP308) controlled by a laptop computer. The transmit transducer is a three element, ultrasonic compressional wave transducer, custom made by Britek SA, Inc., using lead metoniobate, 7.5 MHz center frequency, damped to 5 cycles, with an active area 85mm^2 (5.0 mm width and 17.0 mm length). The 0.5 μs separation in the transmitted signal was achieved by the addition of Ultem® polyetherimide delay lines in two of the three elements of the transmit transducer. The receive transducer is a single element, compressional wave transducer, custom made by Britek, using composite lead zirconate titanate, 5.0 MHz center frequency, damped to 2.5 cycles with the same size active area. The crimp tool is a modified, commercially available unit. The modifications to the crimp tool consisted (1) removing mounting holes for the crimp guide, (2) machining parallel external faces, (3) spot welding mounting points, (4) cutting small EDM notches and (5) machining the contact point at the jaw tip to minimize contact area. Modifications (4) and (5) were to eliminate (or reduce) any path for the ultrasound to propagate near the jaw tip. Figure 2 shows photographs of the commercially available crimp tool (Raychem Model 80-1377) and the tool modified for these experiments. Figure 3 shows a photograph of the entire experimental setup.

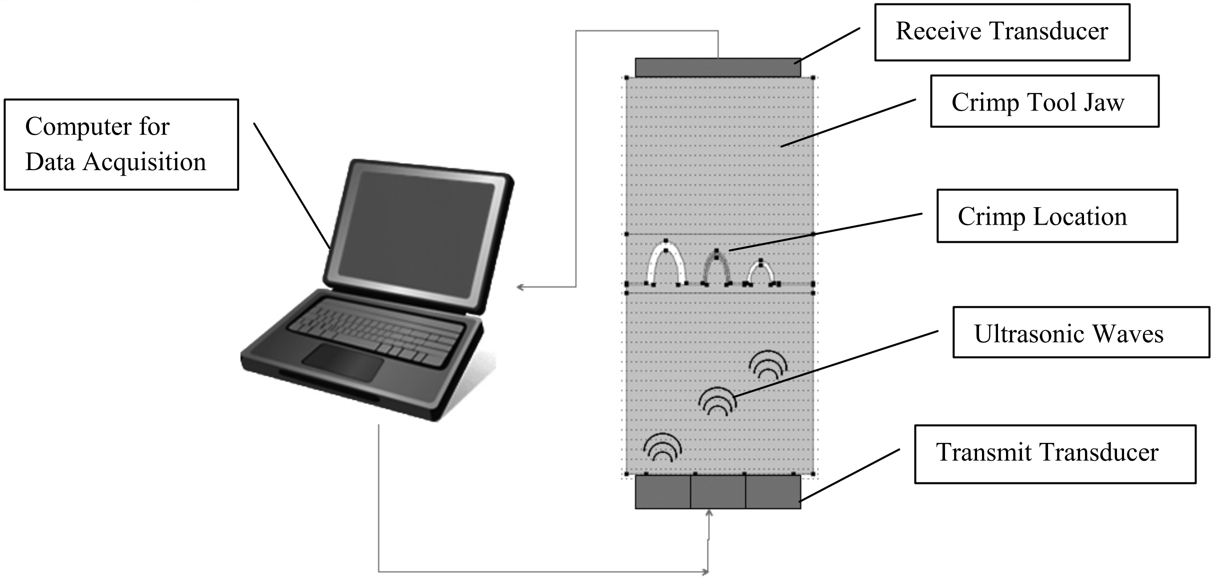
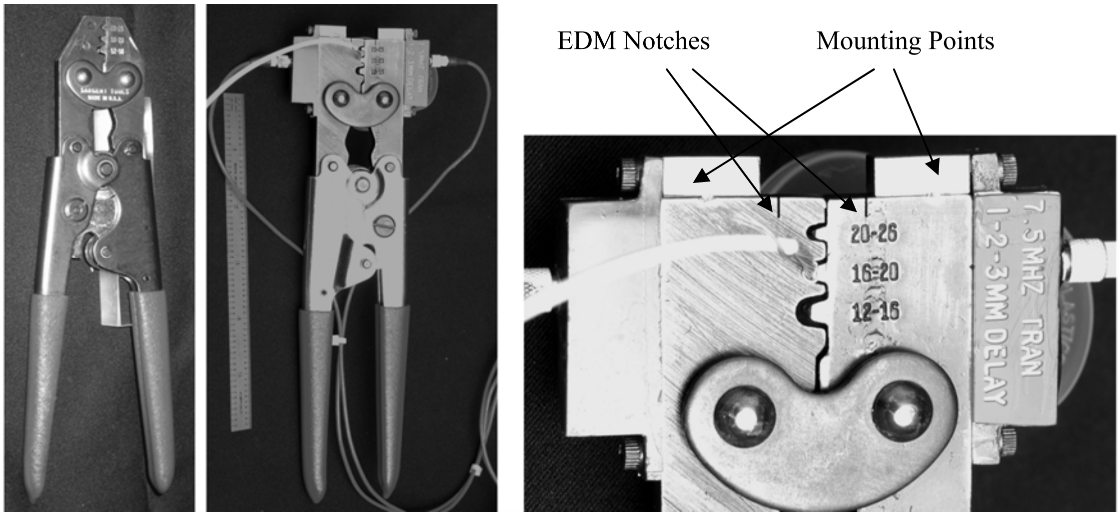


Figure 1: Schematic of the experimental setup for ultrasonic inspection during crimping.



(a) (b) (c)

Figure 2: Photographs of (a) the commercially available crimp tool (Raychem Model 80-1377), (b) the tool modified for these experiments and (c) a close-up of the crimp jaws showing the details of the modifications.

The wires included in these experiments consisted of three types: (1) Gauges 12-20 (with the exception of 14 AWG) are nickel plated copper (M22759/34), (2) 14 AWG is unplated, bare copper commercial grade wire and (3) gauges 22-26 are silver plated copper (M22759/11). The insulation is stripped and inserted into one of three nickel plated, copper ferrules (MIL M81824/1) depending on the wire gauge and the crimping location on the tool. The ferrules are color coated such that red-banded ferrules accommodate 20-26 AWG wires, blue-banded ferrules accommodate 16-20 AWG wires and yellow-banded ferrules accommodate 12-16 AWG wires. The red-banded ferrule has a 2.03 mm minimum outside diameter and 1.14 mm minimum inside diameter. The blue-banded ferrule has a 2.69 mm minimum outside diameter and 1.62 mm minimum inside diameter. The yellow-banded ferrule has a 3.89 mm minimum outside diameter and 2.46 mm minimum inside diameter. These terminators are used when making butt-splice type connections. The ferrule end of the terminator is inserted on the wire, and then the loaded ferrule is placed in the slot of the jaws of the instrumented crimp tool. The ultrasonic pulser-receiver is connected to the appropriate transducers, and the crimp tool is compressed while the ultrasonic sensors are active.

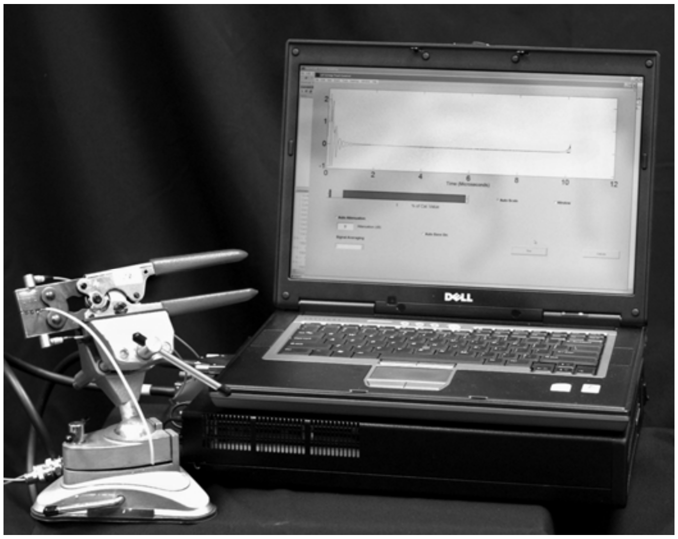


Figure 3: Photograph of the crimp tool data experimental setup.

DATA ANALYSIS

The data analysis consists of performing a Hilbert transform[3] on the time record. Because the transmitted ultrasonic wave consists of three wave fronts each separated in time by 0.5μs from the last, arrival time of the peak of the Hilbert transform can be used to determine into which of the three crimping positions the ferrule/wire assembly has been placed. Figure 4 shows the normalized Hilbert transform of three representative crimps (one in each crimping location).

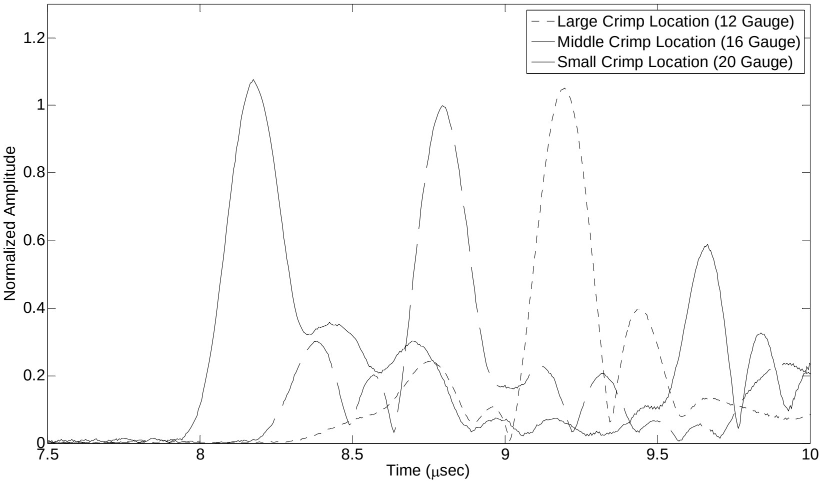


Figure 4: Normalized amplitude of the Hilbert Transform as a function of time for three crimps showing the different arrival times of the peak energy which is used to determine crimp location in the crimp tool.

Next, the modulus of the transform is integrated (summed) over the time window:

$$\eta = \sum_{t_1}^{t_2} HH^* \tag{1}$$

Where t_1 and t_2 are the starting and ending times of the time window and H is the Hilbert transform of the ultrasonic signal. The time window was selected to correspond to the full-width of the Hilbert transform at one half its maximum value (FWHM) for the main peak (first received pulse). This analysis yields a value (η) proportional to the ultrasonic energy transmitted through the crimp.

ULTRASONIC TRANSMISSION MEASUREMENTS FOR ALL CRIMP LOCATIONS

Data are acquired randomly on a series of wire crimps varying from 12 to 26 AWG. Ten full compression crimps were performed at each gauge for each crimping location on the tool. Specifically, the smallest crimp location accommodates 20-26 AWG wires, the middle location 16-20 AWG wires, and the largest location 12-16 AWG wires. The final closing distance of the crimp tool jaws, as referenced by the number of detents on the crimp tool ratchet mechanism, is used to ensure uniform compression for all crimps. Ultrasonic transmission data are collected after compressing the jaws to the last ratchet point before release of the jaws. Figure 5 shows the average value of η (defined previously) plotted versus AWG for the 100 specimens with the vertical error bars indicating one standard deviation of the data. For each crimp location on the tool, a linear least-squares curve fit of the value of η as a function of the AWG was performed to demonstrate the monotonic relationship.

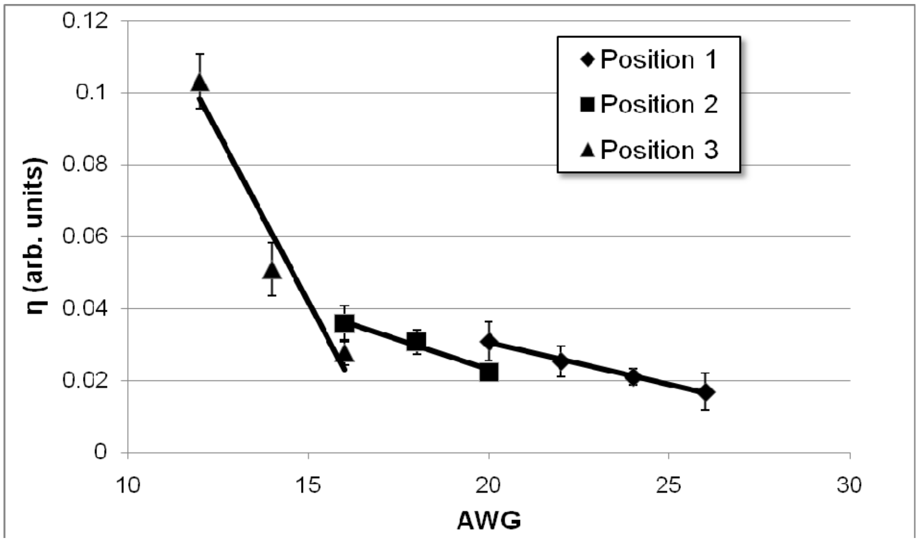


Figure 5: Plot of η verses American Wire Gauge spanning the entire usable range of the modified commercially available crimp tool used in this study.

CRIMP DEFECT PATHOLOGIES

Various crimp junction defect pathologies such as undercrimping, missing wire strands, incomplete wire insertion, partial insulation removal, and incorrect wire gauge are ultrasonically tested, and their results are correlated with pull tests. To investigate the quality of wire ferrule interface for various pathologies, it is useful to define a dimensionless quantity, crimp attenuation factor (AF_C) as:

$$AF_C \equiv -10 Log_{10} \frac{\eta}{\eta_g} \tag{2}$$

where, η_g and η are for a reference crimp and a crimp of interest, respectively[1,2]. This definition of AF_C results in larger values of AF_C as η decreases relative to η_g, therefore AF_C correlates inversely with crimp quality.

The first pathology investigated was undercrimping, where the crimp is not fully formed due to a failure to completely close the jaws of the crimp tool. Data were acquired on a series of 16 AWG wire crimps with varying degrees of crimp compression. The opening distance of the crimp tool jaws, as referenced by the distance between the two handles, was used as a measure of the amount of compression. Ultrasonic data were collected after compressing the jaws to a prescribed distance. The jaws were then released, and the wire/crimp removed. The wire/crimp was mounted on the specimen stage of a wire crimp pull tester (Alphatron Model MPT-200A) and mechanically pulled to failure. The failure load was recorded.

The next pathology examined was missing wire strands in the crimp. This fault can occur when insulation is stripped too aggressively resulting in the removal of one or more strands. A typical aerospace wire (M22759/34) is comprised of 19 individual strands of tinned copper. For 16 AWG each strand is 29 gauge (0.29 mm diameter). The ultrasonic energy for a 16 AWG crimped connection was recorded where successively more wire strands were removed before crimping. From one to five wire strands were removed during this investigation.

Incomplete wire insertion may occur when insufficient wire insulation is removed or if the wire is not properly seated in the ferrule. The average attenuation of ultrasonic energy measured for 16 AWG wire terminations with varying levels of wire insertion was recorded. A fully inserted wire is equivalent to approximately 7 mm of insertion. Specimens were crimped with wire insertion depths corresponding to 28%, 43%, 57% and 71% (2, 3, 4 and 5mm) of full insertion were measured ultrasonically.

Other crimp termination faults include partial insulation removal and selection of incorrect ferrule size for a given wire gauge. The ultrasonic energy levels for these pathologies were likewise recorded. For partial insulation removal tests, approximately 50% of the 16 AWG wire insulation thickness of both Kapton and Tefzel insulation types was removed prior to crimping in a 16 AWG termination ferrule. This fault type might escape detection using electrical continuity tests since a fully inserted wire with insulation may still expose sufficient conductor area at the strand ends to achieve contact with the wire stop in the ferrule. Use of this termination in service could lead to intermittent operation, costly diagnosis and troubleshooting or, complete loss of function.

For the incorrect gauge tests, a properly stripped 22 AWG wire was crimped to a ferrule designed for a 16 AWG wire (blue-banded ferrule). The exposed wire conductors were not folded over to achieve a larger wire diameter prior to insertion.

Figure 6 provides a summary data plot showing all crimp pathologies in relation to crimp load failure vs. ultrasonic energy. The horizontal line drawn on the graph for reference is the load above which a 16 AWG crimp is deemed acceptable (50 lbs per SAE-AS7928/1). The vertical line at 22,000 arbitrary energy units represents a η_g reference level chosen for the AF_C measurements. This value was established to ensure that all defect pathologies would be detected. It should be noted that only the five rightmost (largest η) data points represent a properly performed crimp. Figure 7 provides a comparison of various crimp failure pathologies vs. AF_C based on the η_g reference level of figure 6.

FINITE ELEMENT MODEL FOR ULTRASONIC TRANSMISSION THROUGH FERRULE-WIRE COMPRESSION REGION

A finite element model (FEM) was developed using the commercial software COMSOL Multiphysics®. The two-dimensional, time-dependent, model consisted of 106288 elements and 213981 degrees of freedom. The jaw of the crimp tool is made from steel (compressional wave speed is 5.9 x 10^3 m/s and the density is 7.9 x 10^3 kg/m^3); the crimp ferrule and wire are copper (compressional wave speed is 5.0x 10^3 m/s and the density is 8.9 x 10^3 kg/m^3)[4]. To model the response of the transmit transducer, the ultrasonic excitation is a 7.5MHz sine wave modulated with a Gaussian. The modulated response is then truncated for amplitudes below the -40dB level.

Figure 8 shows a comparison of the experimental results and the FEM of a 16 AWG crimped connector. Both signals have been normalized since the total energy introduced by the transducer, in the experimental case, has not been measured. When integrated over a time window corresponding to the FWHM the model agrees with the experiment for each location on the crimp tool to within 4.28% as can be seen in Table 1.

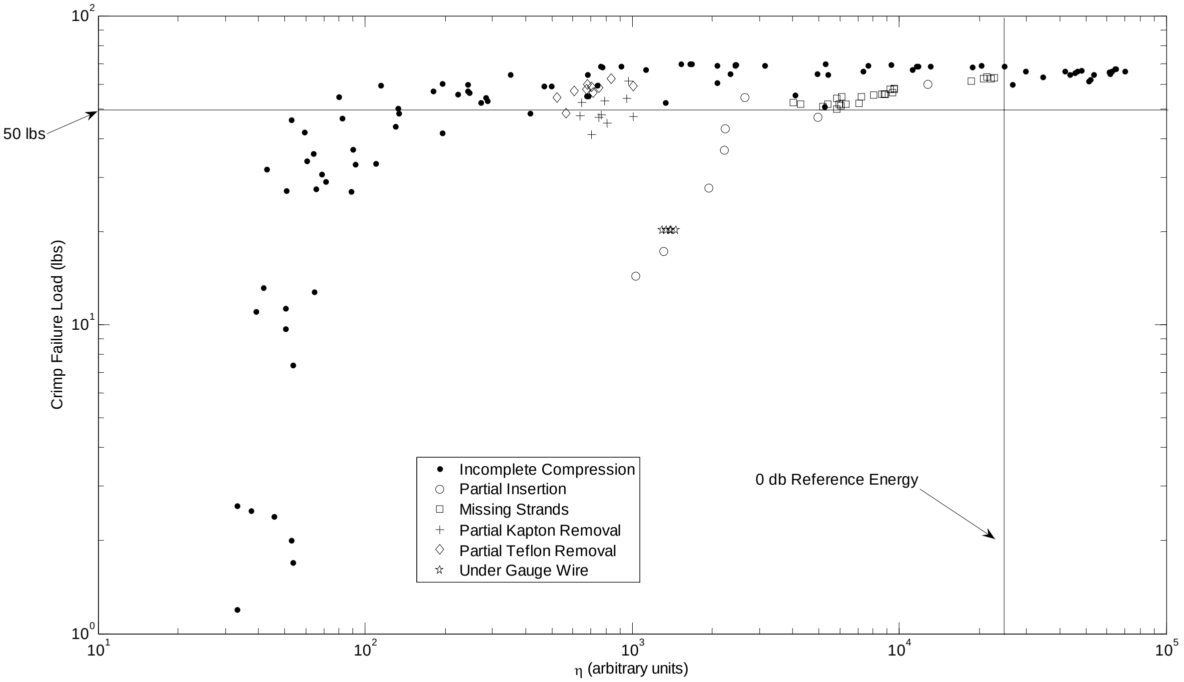


Figure 6: Plot of the crimp load at failure verses η for the 16-gauge wire crimp specimen set. The horizontal line represents minimum load required for acceptable crimp (50 lbs). The vertical line at η = 22,000 arbitrary units represents the 0 dB reference level (η_g) chosen for the AF_C calculations.

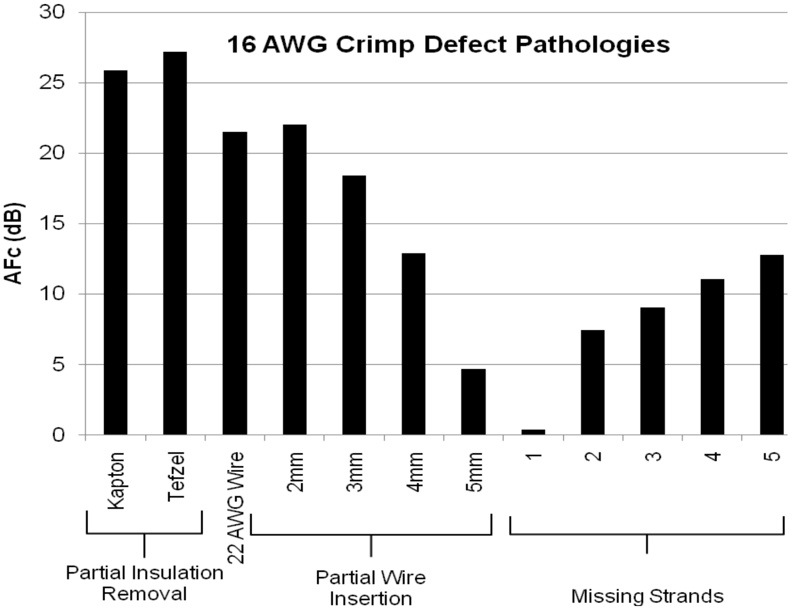


Figure 7: Comparison of crimp attenuation factors for some of the crimp pathologies considered in this investigation.

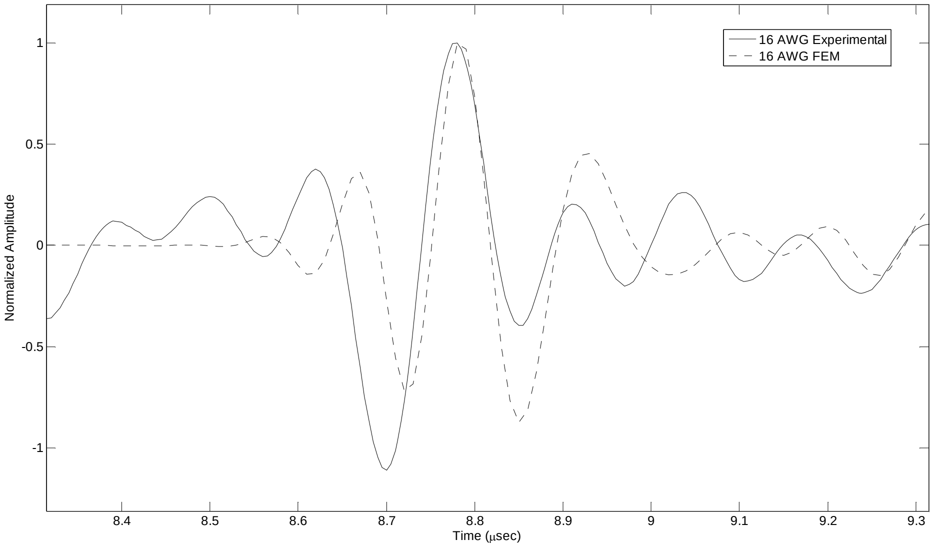


Figure 8: Comparison of normalized amplitude vs. time for both experimental and FEM results for a 16 AWG crimped connector.

Table 1: Comparison of η for both experimental and FEM results across all three crimping locations on the crimp tool.

Location	Experimental η	FEM η	% Difference
Small (20 AWG)	0.1522 ±0.020	0.1546	1.6
Middle (16 AWG)	0.1486 ±0.013	0.1550	4.3
Large (12 AWG)	0.1553 ±0.004	0.1570	1.1

CONCLUSIONS

We report here a new measurement technique to assess quantitatively the quality of wire crimp terminations during terminator installation. A transducer design has been developed that allows for interrogation of each of three crimp locations on the crimp tool without reconfiguring the device. Because the timing of the received pulses remains nearly constant for all test conditions, with only the amplitude changing, a Hilbert Transform calculation (square-root of the Hilbert Transform modulus) of the received transmission ultrasonic waveform data with integration over a time window, corresponding to the full-width at half maximum amplitude, has been shown in this paper to produce a reproducible, quantitative measure of crimp quality for the cases examined. For each of the three crimp locations investigated, a linear relationship between the ultrasonic energy measured and the wire gauge has been demonstrated. The AF_C was shown to correspond quantitatively to various crimp pathologies including under-crimping, missing wire strands, incomplete wire insertion, partial insulation removal, and incorrect wire gauge to ferrule size. The AF_C values obtained were shown to be more sensitive to these pathologies than wire pull tests, the current (destructive) measurement technology for crimp terminator evaluation. A finite element model of wave propagation through the crimp tool was shown to agree to within 4.3% of the experimental results for a good crimp.

ACKNOWLEDGEMENTS

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