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Wire crimp connectors verification using ultrasonic inspection

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Abstract

The development of a new ultrasonic measurement technique to quantitatively assess wire crimp connections is discussed. The amplitude change of a compressional ultrasonic wave propagating through the junction of a crimp connector and wire is shown to correlate with the results of a destructive pull test, which previously has been used to assess crimp wire junction quality. Various crimp junction pathologies (missing wire strands, incorrect wire gauge, incomplete wire insertion in connector) are ultrasonically tested, and their results are correlated with pull tests. Results show that the ultrasonic measurement technique consistently (as evidenced with pull-testing data) predicts good crimps when ultrasonic transmission is above a certain threshold amplitude level. A physics-based model, solved by finite element analysis, describes the compressional ultrasonic wave propagation through the junction during the crimping process. This model is in agreement within 6% of the ultrasonic measurements. A prototype instrument for applying the technique while wire crimps are installed is also presented.

1. Introduction

A wire-crimp connector consists of a mating end and a crimp ferrule, which is installed on the end of a wire. This establishes a secure mechanical and electrical connection between the wire and the connector. A connector is installed onto the end of a wire by removing a portion of the insulation to expose a prescribed length of wire strands, and placing them 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. Thus formed, this connection possesses good mechanical and electrical continuity between the wire's end and the connector.

In critical applications specialized tools are used to assure optimum crimp quality. Typically, the tools are inspected before and after each use. The inspection procedure includes forming representative crimps that are pull-tested to failure. The tool passing an inspection means that it is certified for the next use. Other than visual inspection and a cursory electrical continuity check, however, the critical crimp connection to the wire is generally not independently verified for quality.

Crimp failures occur for many reasons. Causes of installation-related failures include wrong connector choice, wrong wire size, or wrong crimp tool. Improper crimping technique, such as failure to fully insert the wire into the connector or improper removal of the insulation also causes reliability problems. Further, if the crimp tool has worn joints or jaws, the mechanical reliability of the connection can be compromised.

During its service life the reliability of a crimped joint is affected by mechanical vibration or unforeseen mechanical loading. Corrosion effects caused by exposure to cleaning solutions, fluid spills, adverse environmental conditions, etc. can also lead to connector unreliability.

Present practices for assuring good crimps are based on following detailed crimping procedures, with quality assurance verifications. Such an approach can assure a good initial crimp, assuming that the connector integrity is good. No independent means of confirming crimp quality however, is currently available.

This paper presents results for an instrumented crimping tool whose purpose is to provide a nondestructive means of assessing crimp quality to ensure the electrical and mechanical integrity of an initial crimp during the installation process.

2. Ultrasonic Based Inspection Technique

A well-crimped junction provides both good electrical and mechanical coupling of wire to the ferrule. This condition is achieved by creating sufficient stresses between the surface of the wire and the connector by deforming the ferrule around the wire, which in turn holds onto the wire with the deformation-induced stresses. If these stresses relax or change, intimate contact is not assured, and hence the crimped connection fails.

The technique presented here uses an ultrasonic wave propagated 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 ultrasonic wave is generated by the ultrasonic wave transmit transducer and travels into the jaw of the crimp tool. Upon application of the correct pressure the jaw deforms the crimp connector around the wire with sufficient force to press the surfaces into good mechanical contact, allowing a portion of the ultrasonic wave to propagate through the connector, the electrical wire and into the opposite jaw to be received by an ultrasonic transducer. As the pressure increases, more of the ultrasonic wave propagates from the transmitter to the receiver through the ferrule-wire joint.

The transducer configuration requires that the ultrasonic wave propagate through the crimp and wire before reception. If insufficient contact exists between the wires and connector surface, or between the wire strands themselves, then the resulting signal is low. If the crimp produces sufficient contact, ultrasonic transmission is high. A necessary condition for a pulse to traverse the joint and be received is that the wire strands and ferrule must be in intimate contact. For analysis we choose examination of the first pulse transmission through the connector.

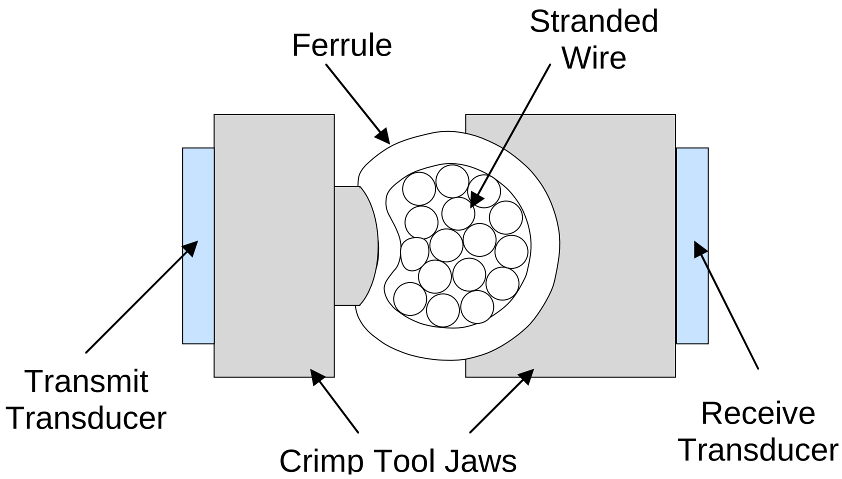

Figure 1. Schematic of arrangement for ultrasonic interrogation of crimp connector

The experimental setup for this technique consists of an ultrasonic pulser-receiver (Panametrics Model 5900PR) in a pitch-catch arrangement. The send and receive transducers are commercially prepared 7.5 MHz 1/4 inch diameter PZT-5 damped ultrasonic compressional wave transducers (Panametrics Model A121S). The crimp tool (Raychem Model 80-1377) is a commercially available unit that was modified by adding wedges to provide parallel send and receive planes for mounting the transducers. Only the center crimp dye is instrumented for this test. Figure 2 shows a photograph of the instrumented crimp tool in the laboratory.

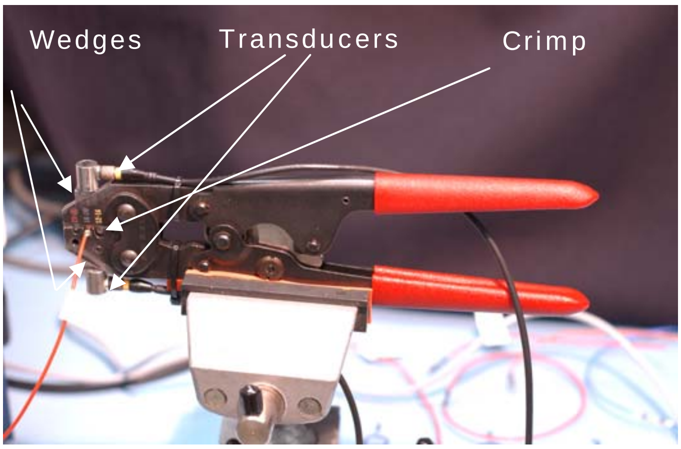

Figure 2. Photograph of the prototype instrumented crimp tool.

For this study 16-gauge (MIL 22759/34-16-9) wire size was selected. Sixteen gauge wire consists of 19 strands of 29 gauge copper (.29 mm diameter) with the insulation stripped and inserted into a copper ferrule on the connector (MIL M39029/31-228) with a 2.7mm outside diameter and 1.6mm inside diameter. The effective wire diameter of all strands is 1.37 mm. The pulser-receiver simultaneously triggers the oscilloscope and excites the transmit transducer, which generates the compressional pulse that traverses the crimp and travels to the receive transducer. Figure 3 shows the ultrasonic pulse received from a "good" crimp (one where full compression of the crimping tool is achieved, and which passed the pull test criterion). The zero time reference on the horizontal axis corresponds to the initiation of the transmit pulse.

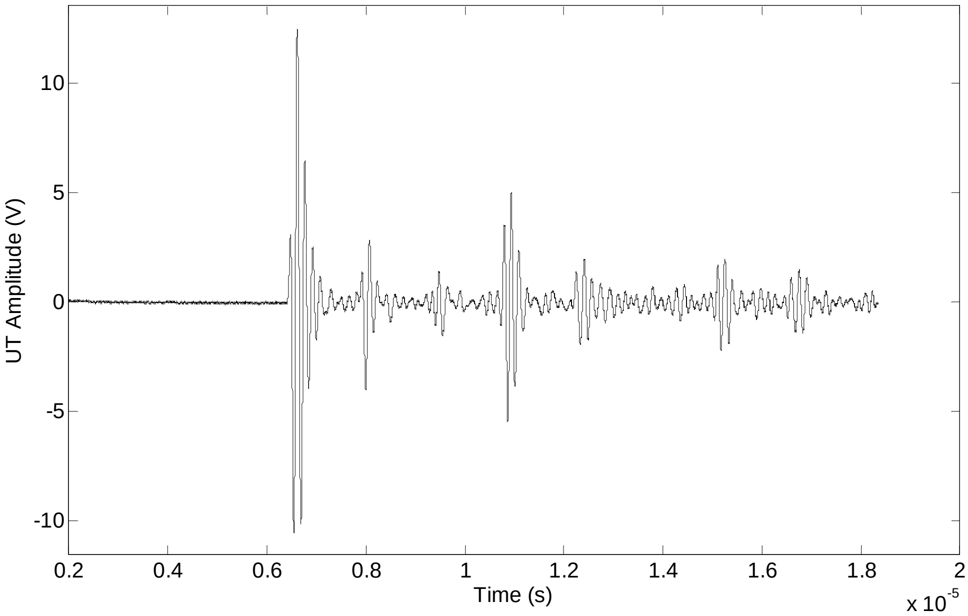

Figure 3. Ultrasonic response of a fully crimped 16 gauge wire. The initial transmitted pulse is seen at the excitation time (0 seconds) and the first received pulse occurs at approximately 6µs.

When the crimp is poor, the amplitude of the ultrasonic response is considerably smaller. Figure 4 shows the ultrasonic response of a poor crimp, caused by releasing the jaws before the compression cycle was complete, with the same vertical scale as Figure 3. We note that the arrival time of the first-received pulses is the same, but the amplitude of this pulse is considerably lower (~0.5 V for the poor crimp verses ~12 V for the full crimp). This indicates that the ferrule and wire surfaces are not in as intimate contact as is the case in Figure 3.

3. Relationship between Pull Tests and Ultrasonic Transmission Measurements

3.1 Incomplete Compressions

Data were acquired on a series of 16 gauge wire crimps with varying degrees of crimp compression. The opening distance of the crimp tool jaws 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 an Alphatron Model MPT-200A wire crimp pull tester and mechanically pulled to failure. The failure load was recorded.

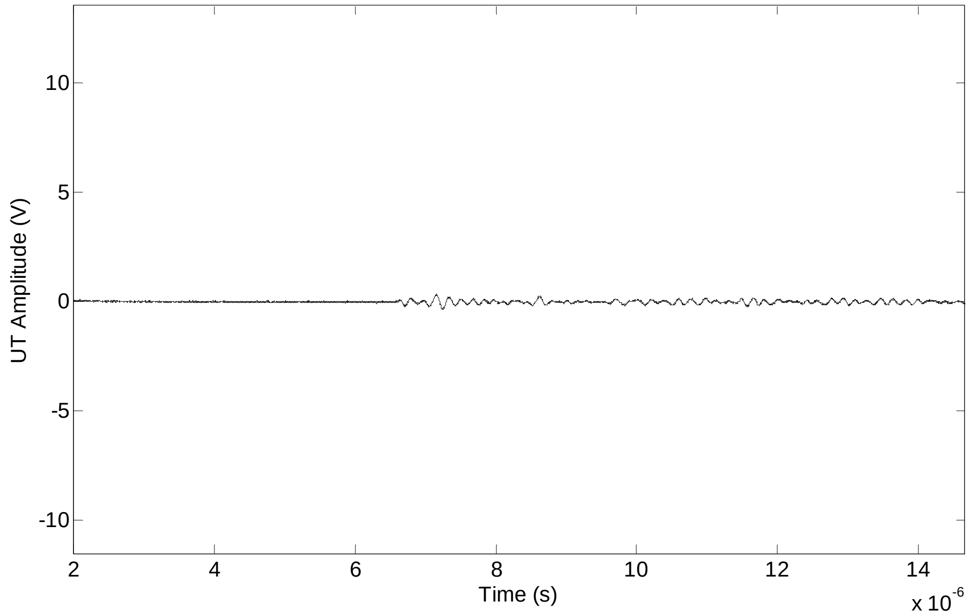

Figure 4. Ultrasonic response of a poorly crimped 16 gauge wire.

For the ultrasonic data, a time window of 1.0 μs was selected starting at 6.25 μs after the ultrasonic excitation was selected. A Hilbert transform[(1)] was performed on the ultrasonic signal. The transform was multiplied by its complex conjugate, and integrated (summed) over the time window. This area gives a number proportional to the ultrasonic energy transmitted through the crimp[(2)]. These numbers are plotted against the load at failure for each specimen.

Figure 5 shows the results for the 96 specimens (which were divided into 6 data runs of 16 partial to full crimps each) that were examined during this study plotted on a log-log scale. The horizontal line drawn on the graph for reference is the load above which a 16 gauge crimp is deemed acceptable (50 lbs per SAE-AS7928/1). As can be seen, the integrated ultrasonic signal correlates well with the load at failure data for this investigation of under-crimped connectors with a 97% detection rate (93/96) and a 1% false call rate (1/96).

3.2 Missing Wire Strands

Another possible crimp fault is that of wire strands missing from the crimp. This fault can occur when insulation is stripped too aggressively, and results in removal of one or more strands. Figure 6 shows the average reduction of the ultrasonic energy for a 16 gauge crimped connector where successively more wire strands were removed before crimping. The UT response of 5 specimens was averaged for each level of missing strands to obtain the results shown in Figure 66. The minimum amplitude integrated signal obtained for a good crimp was used as a 0 db reference point. As can be seen from Figure 6, this method accurately detects missing strands.

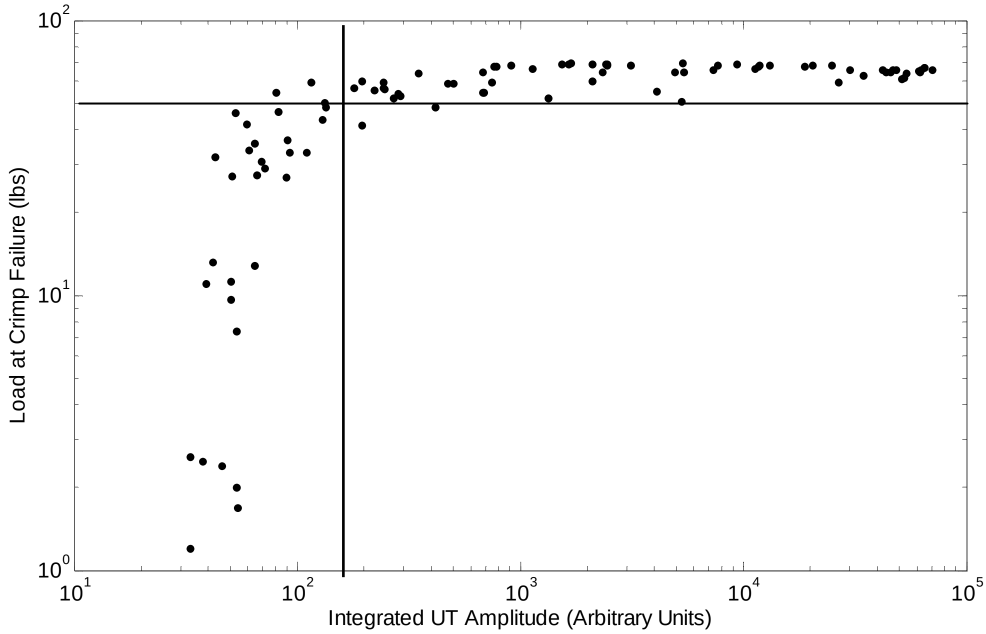

Figure 5. Plot of the crimp load at failure verses the integrated ultrasonic amplitude for the 16 gauge wire crimp specimen set. The horizontal line represents minimum load required for acceptable crimp. The vertical line represents a minimum amplitude integrated signal for an acceptable crimp.

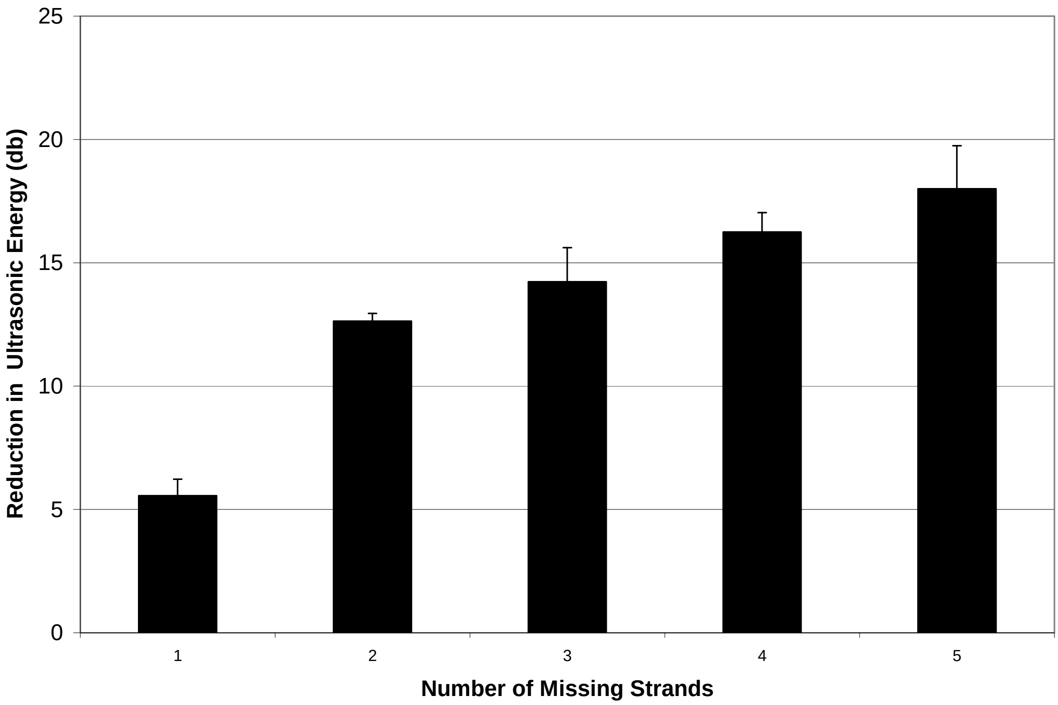

Figure 6. Reduction in UT energy verses number of missing strands for 16 gauge crimped connector. The standard deviation of the averaged data is shown atop each bar.

4. X-ray Computed Tomography of Electrical Crimp

To assist in developing a physical understanding of the propagation of sound in an electrical crimp, x-ray computed tomography (CT) was performed on three 16 gauge wire crimps with varying levels of compression of the ferrule. The CT system used is a custom microfocus system with 25 µm spot size and 12.5 µm resolution. Figure 7 shows a photograph of a fully crimped connector and eight CT slices across that connector demonstrating the amount of compression achieved. In addition to a fully compressed crimp, one was also produced at a very small amount of compression and one at approximately 50% of full compression. As before, crimp compression was measured by closure of the crimp tool handle: 5mm closure corresponds to very little compression, 20mm corresponds to approximately 50% of full compression and 32.5mm corresponds to full compression. The CT slices in Figure 7 show regions of linear porosity that decrease in volume with increasing crimp compression. Changes in ultrasonic attenuation have been used to measure porosity in composite materials[3-6].

Figure 8 shows a graph of the ultrasonic signal generated at each compression level. For comparison a single CT slice across the region with the largest compression is provided for each crimp. It can be noted from Figure 8 that the amplitude of the first received pulse through the crimp increases with an increasing level of crimp compression, supporting the relationship between ferrule-wire compression and ultrasonic transmission mentioned previously.

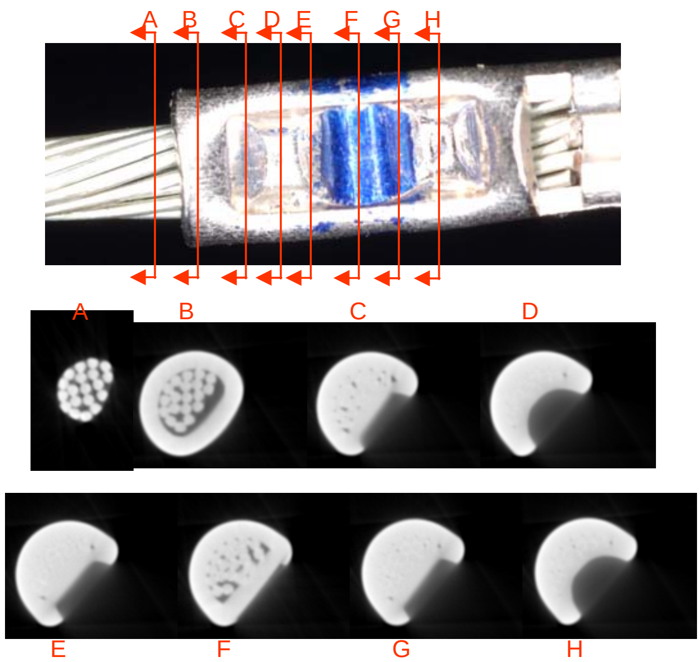

Figure 7. Photograph of fully crimped connector and computed tomography slices at eight locations across the crimped connection.

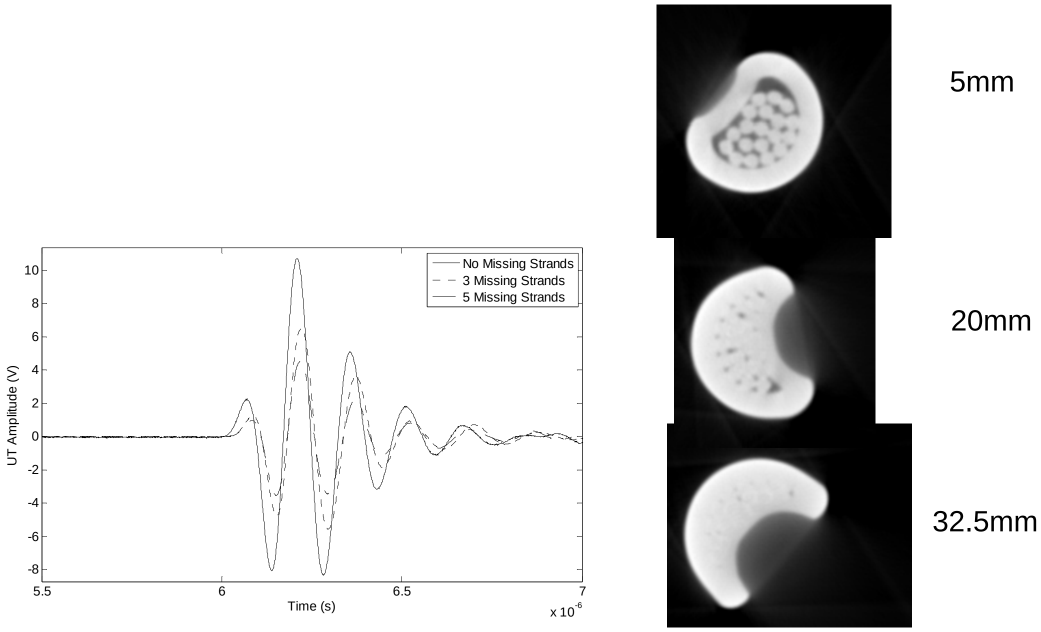

Figure 8. Time windowed ultrasonic response and CT images of three compression levels.

5. Simulation: Finite Element Model for Ultrasonic Transmission Response

A finite element model (FEM) was developed using the commercial software COMSOL Multiphysics™. The two-dimensional, time-dependant model, shown in Figure 9, consisted of 9000 elements and 19507 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 5.0 x 10^3 m/s and the density is 8.9 x 10^3 kg/m^3)[(7)]. The ultrasonic excitation is a 100 ns wide square pulse of unit amplitude.

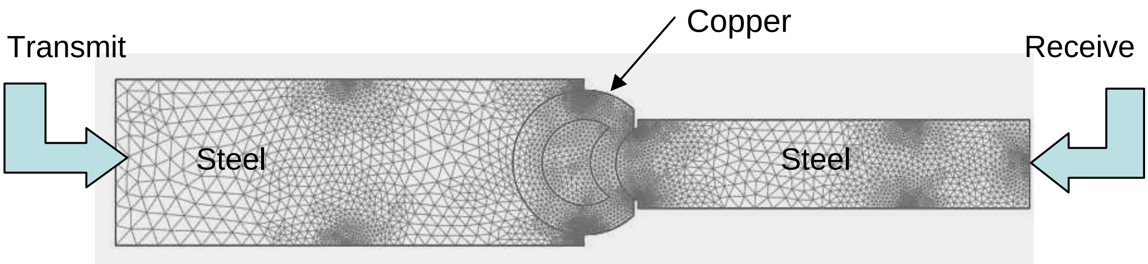

Figure 9. Model geometry of crimp jaws, ferrule and wire.

Figure 10 shows a comparison of the experimental results and the FEM of the crimped connector. To minimize the effects of transducer response, which was not included in the model, the Hilbert Transform of each signal is shown in figure 10. When integrated over a 1μs time window (6.25 – 7.25 μs), the model agrees with the experiment to within 6%.

Simulations were conducted calculating the UT response due to a number of missing strands. 10% of the total volume of wire was removed from a contiguous region inside the ferrule. This roughly corresponds to removing 2 strands (out of 19) of 16 gauge wire. Figure 11 shows a comparison of the normalized, integrated Hilbert Transform experimental and modeled results for both a complete crimp and one missing the equivalent of 2 strands of wire. The experimental results showed 12.62 db decrease in integrated signal for 2 missing strands verses a 12.23 db decrease for the modeled response.

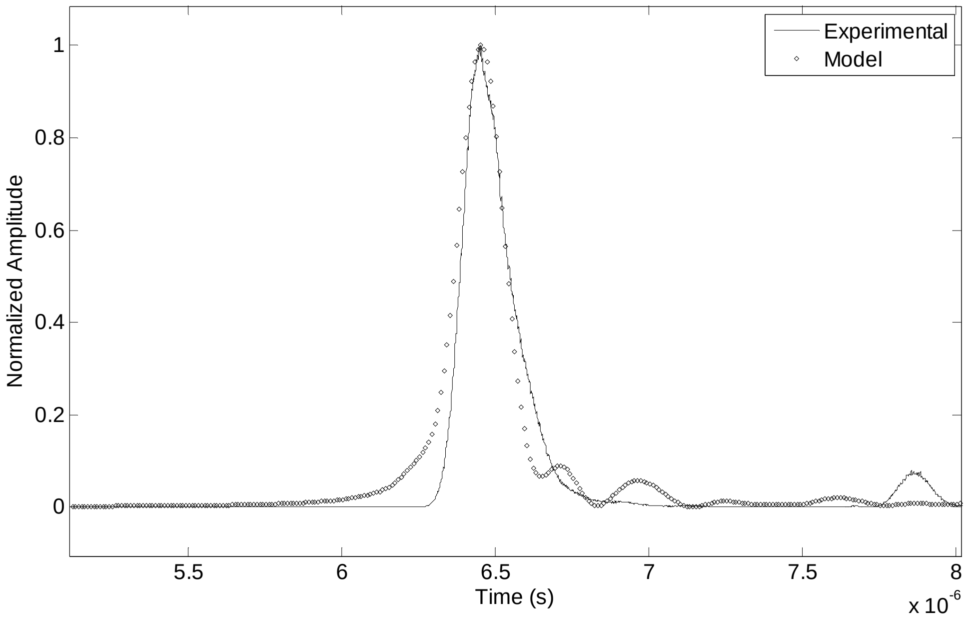

Figure 10. Comparison of the Hilbert Transforms of experimental and simulated response for a fully crimped connector.

6. Conclusions

We report here a new measurement technique to quantitatively assess the quality of wire crimp connections during attachment of a connector to a wire. The application of this technique to under-crimped conditions has been studied and the signals obtained were shown to correlate with destructive wire pull tests. Because the timing of the received pulses remains nearly constant for all compression conditions, with only the amplitude changing, a simple Hilbert Transform calculation of the received transmission ultrasonic waveform data with integration over a fixed time window has been shown to produce a quantitative measure of crimp quality for these cases. This method was applied to crimped connectors with missing wire stands and a 5 db attenuation in the ultrasonic energy was observed with a single missing strand. A finite element model of wave propagation through the crimp tool was shown to agree to within 6% of the experimental results for both a good crimp and one missing 2 strands of wire.

A prototype instrument for applying the technique during the wire crimping procedure was also presented along with a basic physical explanation of the technique.

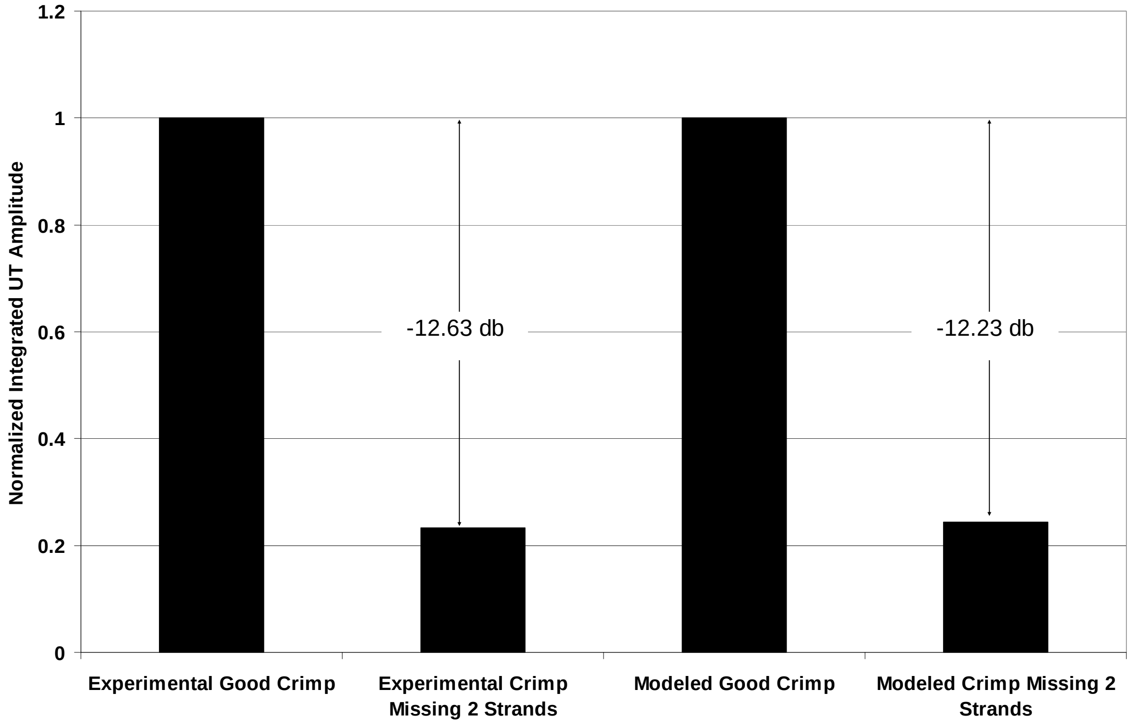

Figure 11. Comparison of normalized experimental and model response for both a complete crimp and 2 missing wire strands.

7. Future Work

Future work includes refining the finite element model to include an accurate temporal representation of the transmitted ultrasonic wave to increase agreement with the experimental results. Investigation of other crimp geometries (i.e. 4-sided crimping) will be performed in the future.

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