Long Range Ultrasonic Testing of Ageing Aircraft Wires.

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Abstract

The inspection of wiring in aircraft has been given high priority because of recent catastrophic failures when frayed wire insulation has caused short circuits that have ignited aviation fuel. Long range ultrasonic has become an accepted tool for screening pipelines for corrosion. The purpose of this project was to investigate if this technology could be applied for testing wires. This required a reduction in scale from a test piece of several inches in diameter to one of only a few millimetres. There was also the added complication of cables being bundled together and twisted. Computer modelling was used to determine the viability of the ultrasound propagation in cables with twisted strands and this was supported with experiments using piezo-electric and magneto-strictive transducers. This paper shows pulse-echo ultrasound propagation was achieved over distances of 10m and describes a prototype tool, which has been developed for testing wires where they are obscured by bulkheads. Furthermore, this paper will describe the computer models used to derive dispersion curves for ultrasound propagation through wires and show some experimental results using laboratory equipment and highlight the field trials.

1. Introduction

There are a multitude of components that go into an aircraft and wiring is not an obvious concern in aircraft safety, other than from a control point of view. Therefore wiring has been regarded as a ‘fit and forget’ component. However, more recent events have altered this view. Faulty wiring has resulted in arcs that have ignited fuel and led to catastrophic failures of aircraft. For example, TWA airlines flight 800, a Boeing 747-131 on route between New York and Paris on July 17th 1996, which came down soon after take-off. This has been attributed by the US National Transportation Safety Board to an explosion in the centre wing fuel tank, caused by a short circuit outside the tank leading to a build up of excessive voltage in the fuel indicator system [1]. A thorough examination of the structure (Figure 1) and subsequent commission set up to formulate a strategy for dealing with the safety issues of ageing aircraft included in its remit for the first time ‘non-structural systems’, such as wiring. An example of a wiring bundle is shown in figure 2.

Figure 1 Re-constructed Wreckage of TWA flight 800

Figure 2 Wire Bundle

The commission surveyed the condition of wiring in a wide range of ageing aircraft and concluded that there were problems to be addressed and that a more proactive approach to inspection of aircraft wiring was necessary. What followed was a need for a suitable Non-destructive Test (NDT) method.

The AWARE research programme (http://aware.uk.com), supported by the Government's Technology Strategy Board (TSB), investigated three NDT methods for aircraft wiring. These are thermography (near and far-field infra-red), Time Domain Reflectometry (TDR) and Long Range Ultrasonic Testing (LRUT). TWI was charged with developing the LRUT method and this is the only method discussed in this paper.

The LRUT method employs guided ultrasonic waves that are propagated as pulses along the wire for distances of several metres. The pulses are reflected from discontinuities in the wire and its coating. The time-of-flight of these reflected pulses is measured between transmission and reception, and if the velocity of the ultrasound is known, the distance of the discontinuity from the ultrasound transducer can be found. The nature and size of the discontinuity is not determined by the LRUT method except in the broadest of terms, because the reflectivity of guided waves is a complex issue for reasons outlined below. The LRUT technique might be used to inspect wires, which are not accessible for thermography or visual inspection, for example where they are behind bulkheads.

2. The LRUT Method

2.1 LRUT

There are several factors that make LRUT very different from conventional ultrasonic testing. These include:

The existence of several wave modes: 'Guided waves' is a generic term for waves where the whole section of the component is excited, as in Lamb waves in plates. They may propagate along cylindrical shapes, such as tubes and wires, as well as plates. The attenuation rates of these waves is very low and in cylinders there is no divergence so that the waves can travel very long distances, the effect similar to the amplification of a voice when 'whispering' down a tube.

Where there are only two degrees of freedom in a plate, there are three degrees of freedom of motion in a cylinder, giving rise to even more wave modes. The fundamental ones are illustrated in Figure 3. They are longitudinal (L-wave), Torsional (T-wave) and Flexural (F-wave) waves. Harmonics of these can also exist, depending on the test frequency.

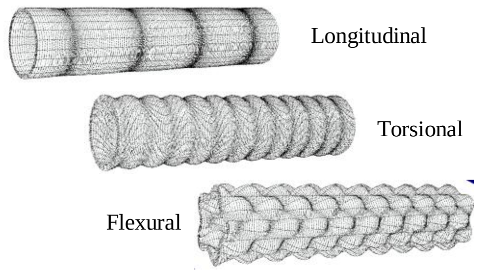


Figure 3 Guided Wave Modes in Pipes

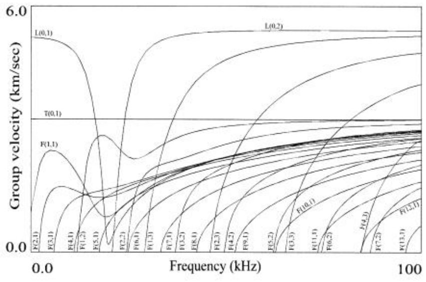


Figure 4 Dispersion Curves for Guided Waves in Pipe

The 'dispersive' nature of guided waves: Unlike bulk waves (compressional and shear) that travel at a constant velocity dependent on the nature of the medium through which they are propagating, the velocity of guided waves is dependent upon ultrasound frequency. Therefore a pulse of guided waves, containing a range of test frequencies will be seen to spread out or 'disperse' as it propagates. If pulses could be transmitted that are of purely one test frequency, this would not be a problem. In practice this is not possible and therefore test frequencies must be selected where the amount of 'dispersion' is at a minimum.

These frequencies can be found on the so-called dispersion curves (Figure 4), which show the existence of the various wave modes at different test frequencies.

Dispersion curves are derived by solving a period equation iteratively that includes terms for Young's modulus, Poisson's ratio, circular frequency, wave number, longitudinal wave speed and transverse wave speed.

An understanding of dispersion curves is fundamental to LRUT. Among other things, the dispersion curves show:

- Torsional waves are non-dispersive (they propagate at constant velocity at any frequency)
- There is a cut-off frequency, below which any particular wave mode will not exist. In general, as the ultrasound frequency increases so the number of wave modes (denoted by the suffix numbers in brackets) that can exist increases.
- By working at lower frequencies, the problem of multiple wave modes is alleviated.
- The curves all converge on a straight horizontal line as the frequency increase, which is in fact the Rayleigh wave (surface wave) velocity.
- Test frequencies that occur on a steep curve are to be avoided because dispersion will be greatest.

The LRUT method is used widely in the oil, gas and petrochemical industries for the inspection of pipelines for corrosion, both on the external and internal pipe surfaces [2,3]. Wires are much smaller in diameter and are not hollow. It was therefore expected that conditions for LRUT of wires would be very different, perhaps using higher ultrasound frequencies and micro-transducers. Computer modelling provided evidence that guided wave propagation through wires was possible, and test frequencies of less than 100KHz would provide the conditions necessary for guided wave propagation in both the wires and the insulation. The model showed that under certain conditions, propagation distances of several metres could be achieved, despite the presence of the wire insulation. In general, plastics do not propagate ultrasound waves efficiently and it was expected test ranges would be limited to a few metres.

2.2 Theoretical understanding of LRUT of wires

As already stated, the dispersion curves are fundamental to an understanding of guided wave propagation along wires. However aircraft wiring is normally multi-stranded, the strands are usually twisted and the wires are surrounded by a plastic insulating material. This requires a different approach. The one adopted in the AWARE programme was to use a semi-analytical finite element method (SAFEM). SAFEM is a hybrid technique that integrates finite elements with analytical solutions to calculate dispersion curves for complex cross section structures with fast calculation time and small computational memory. SAFEM is an attractive alternative to Finite Element (FE) modelling as it avoids the 3D meshing and uses only 2D meshing. The SAFEM models developed for AWARE were validated by comparing the dispersion curves obtained for a simple cylinder shape using commercially available software that derives dispersion curves analytically.

Figure 5 shows dispersion curves generated by SAFEM for a bundle of 7 wires. It shows that at 190KHz, L-waves travelling at about 3500m/s, T-waves at about 2000m/s and F-waves at about 1500m/s can co-exist.

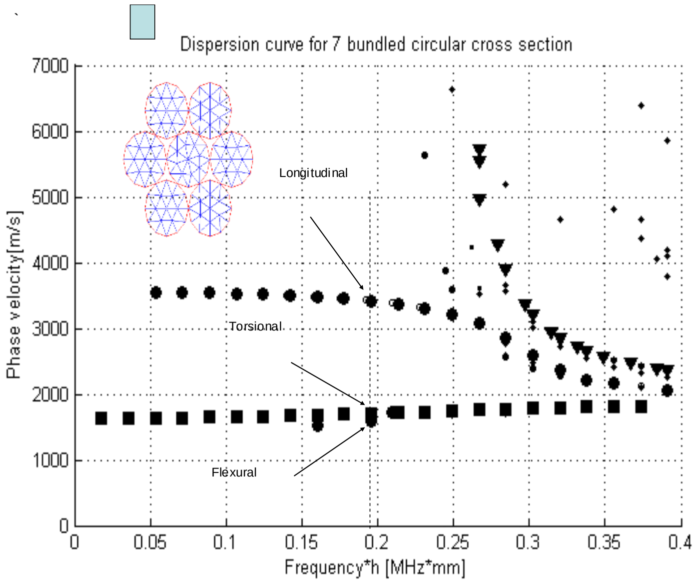


Figure 5 Dispersion Curves for Guided Waves in Wires Calculated in SAFEM

To take the modelling a stage further, and provide simulations of wave propagation along wires, Finite Element Analysis (FEA) was conducted using COMSOL multiphysics. For example a model was developed for a 2m long bundle of seven 1.59mm diameter wires twisted in a helical shape. As previously discussed, dispersion curves show that there are three wave modes that can propagate in the low frequency region for a bundle. Figure 6 shows the A-scan displacement plots for the surface. There are two identifiable wave modes that are travelling in the structure at 40kHz: longitudinal and the torsional. In addition, the longitudinal wave mode is travelling at a speed of 3225 m/s, which again is close to the theoretical velocity (3500m/s) obtained from the SAFEM-developed dispersion curves (Figure 5). The 2-D Fast Fourier Transform (FFT) technique was used to reconstruct wave number dispersion curves for the helical bundle. The 3-D displacement was recorded every 0.05m with time sampling of 1us. The results were converted to the frequency domain. Figure 7 shows the wave number dispersion curves for twisted wires. The results show that there are two dominant wave modes travelling in such a complex structure; these are longitudinal and torsional wave modes. The symmetric (longitudinal) wave mode has a wave number (k) equal to 75m^{-1} while the torsional wave mode has a 'k' equal to 225m^{-1}. By using the relationship between wave number and frequency, the velocity for these wave modes can be calculated to be 3351m/s and 1117m/s for the longitudinal and torsional wave modes respectively.

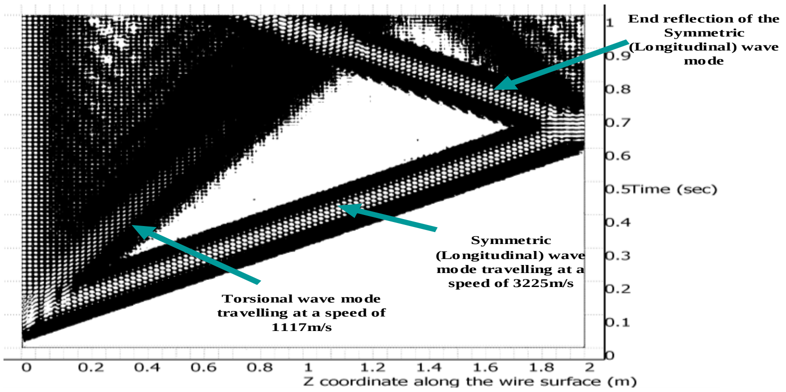


Figure 6 Surface Plots Developed by FEA

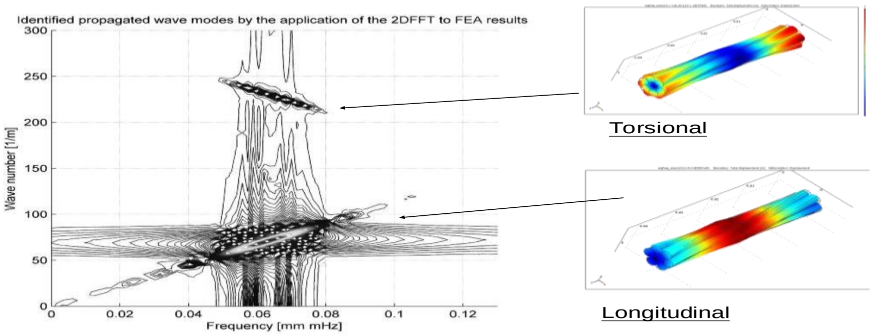


Figure 7 Identified Propagated Wave Modes by the Application of 2DFFT to FEA Results

The modelling demonstrated the presence of guided waves in the wire bundle, and illustrated the possible effects of helical twisting in adding a torsional to the longitudinal mode.

3. Practical Demonstration of Guided Wave Propagation in Wire Bundles.

3.1 Experimental Set-Up

The modelling had demonstrated the possibility of guided wave propagation in wires. However, it was necessary to determine if this could this be converted into a practical method for inspecting wires in aircraft. An experimental programme was therefore conducted along the lines of an NDT procedure qualification.

The LRUT system used comprised the following three components:

1. The ultrasound transducer for transmitting and receiving the pulses of ultrasound.
2. The instrument with the pulser-receiver for activating the ultrasound transducer, processing the received signals, and transmitting them to the lap-top.
3. The laptop with software for controlling the test, calibrating the instrument and displaying the test results.

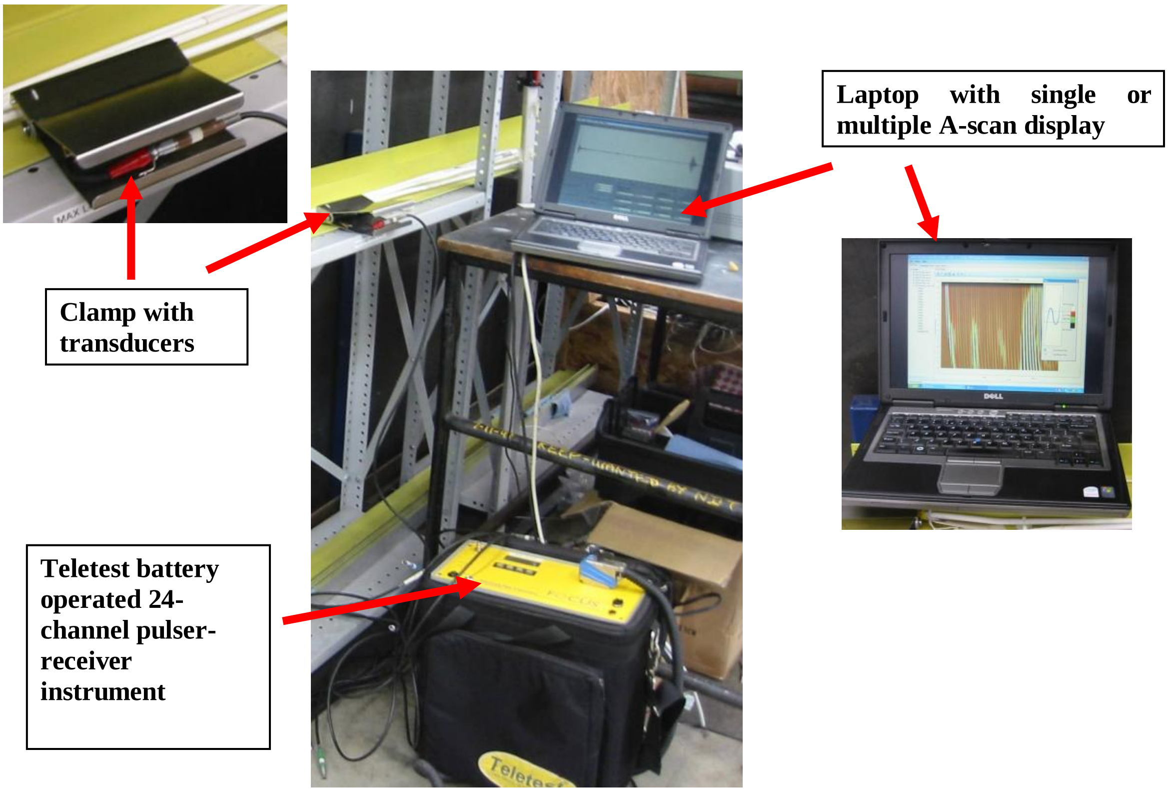


Figure 8 Teletest LRUT Equipment used in Laboratory Trials

The transducers were held within a clamp, which clips to the wire. In the initial laboratory trials mentioned below, in which a wide range of wire types were tested, ranging from fine data cables to thick power cables, the transducers were held in a clamp that could be adjusted to fit the different wire diameters.

The Teletest instrument used in the trials was of a type used in LRUT of pipelines and is commercially available. In common with other computer aided, site useable inspection systems, a laptop was used to supply the graphical user interface to control the test, store data and display results. The laptop used commercially available LRUT software. A continuous frequency sweep display was used, in which A-scans collected at individual frequencies are stacked together. The A-scan in figure 9 shows a single A-scan while figure 10 illustrates a frequency sweep. The amplitude of the signal is a measure of the size of the discontinuity. The distance along the time base of the A-scan, if the velocity of the signal is known will provide measure of the distance of the discontinuity from the transducer. Aircraft wires for the laboratory trials were supplied by one of the partners in the AWARE project. These included a variety of power and data cables. In addition, to illustrate the range capability of the LRUT, a 15m long 7.6mm multi-stand power cables were also investigated.

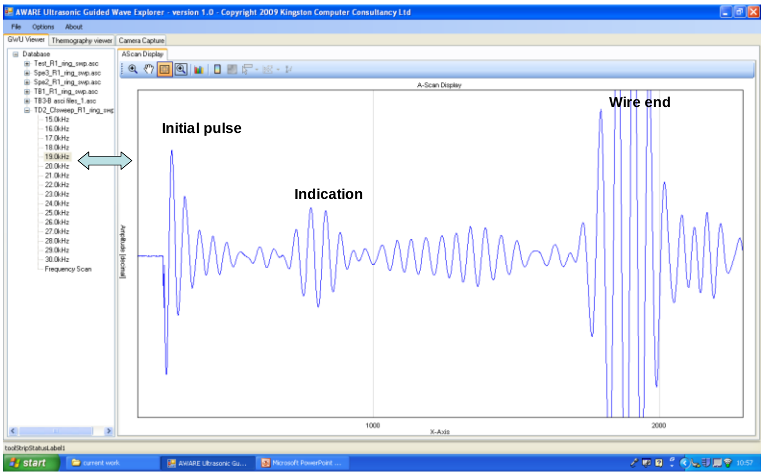


Figure 9 A-Scan Display

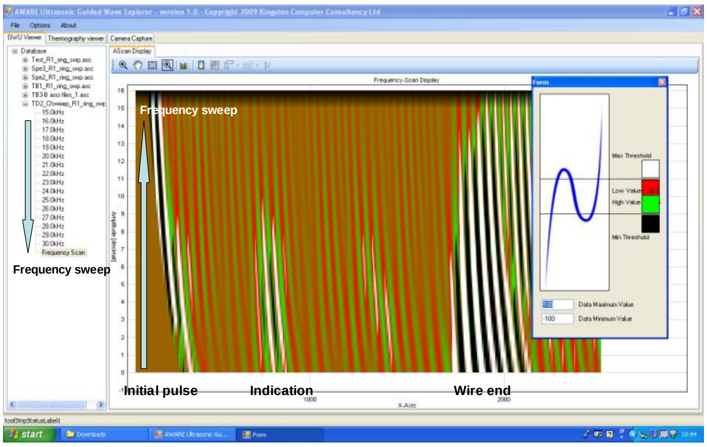


Figure 10 Frequency Sweep Display Developed within the AWARE Project

3.2 Results

Laboratory trials were carried out on different types of aircraft wires. Figures 11 and 12 illustrate the A-Scans for various wires with different geometry and size of defects. The Teletest LRUT system has been able to detect most of the defects, such as insulation split, major and minor abrasion, cracking and removed insulation.

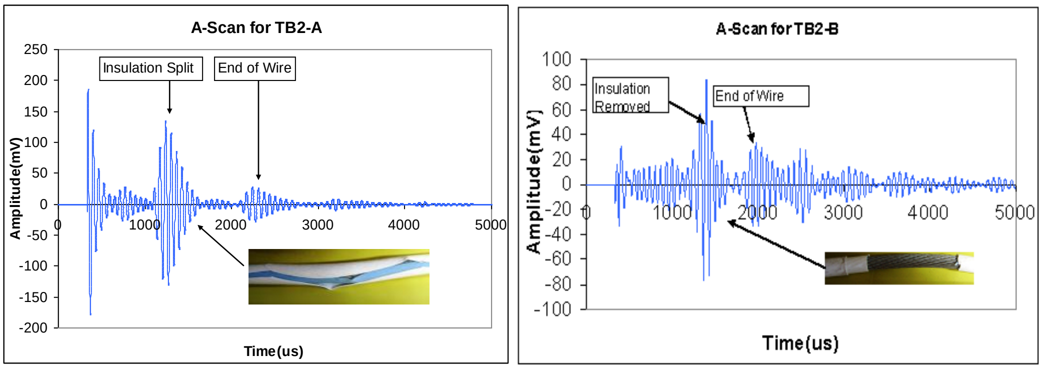


Figure 11 A-Scans of TB2-A and TB2-B

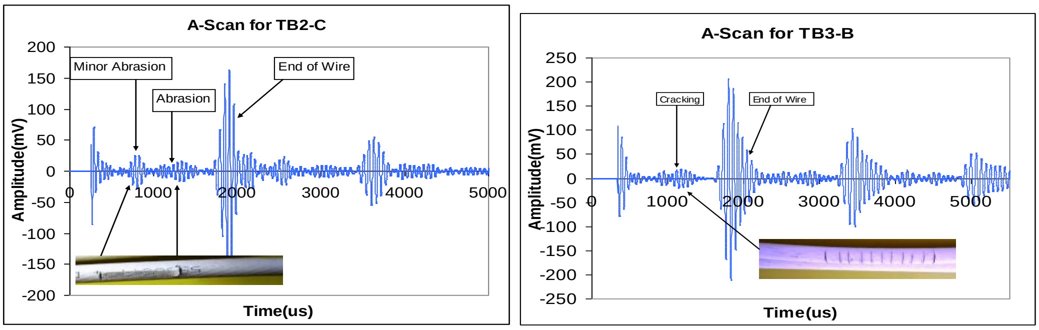
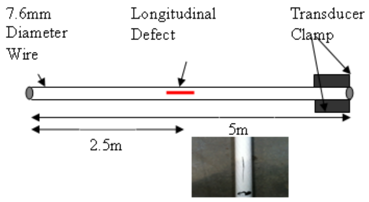
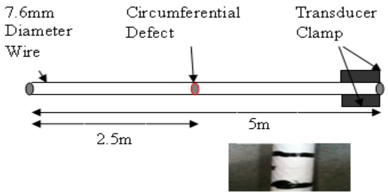
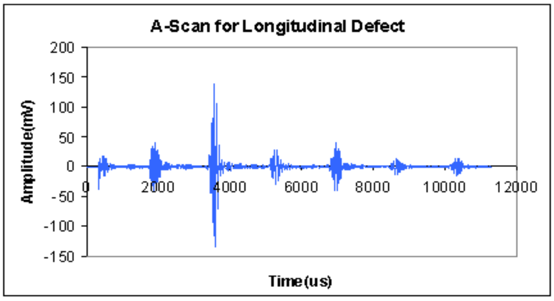
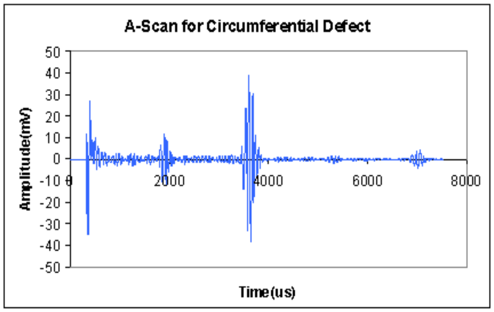
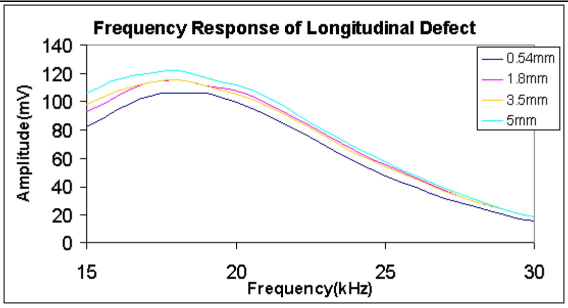
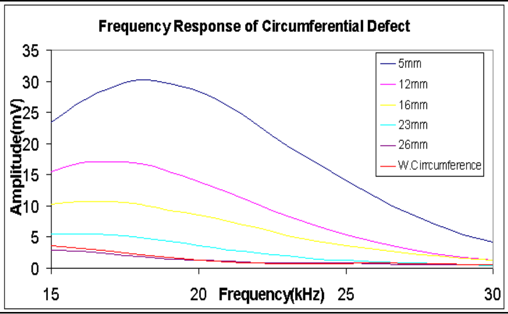


Figure 12 A-Scans of TB2-C and TB3-B

The above results were achieved on different 7.6mm diameter power cables, each of length less than 3m. A defect sensitivity test was conducted on the same type of wire, but of length 5m. A longitudinal defect was introduced mid-way through the wire, and the latter was grown in length. The same procedure was repeated on a another defect-free wire, but with a growing circumferential defect. The Teletest LRUT system was used to collect the frequency sweep data of range 15-30kHz for the different sizes of defects for both configurations.

A frequency response graph was produced for both defects geometries. It was found that the amplitude of the signal from the longitudinal defect increases with increasing length. On the other hand, increasing the length circumferential defect showed a decrease in amplitude of the corresponding signal. This preliminary experiment illustrates the variation in sensitivity of different defect geometry. The experimental set-up, the A-Scans and frequency response of the longitudinal and circumferential defect respectively are shown in table 1.

Table 1 Longitudinal and Circumferential Defect Sensitivity

	Longitudinal Defect	Circumferential Defect
1. Experimental Set-up		
2. Example of A-scans for each type of defect.		
3. Frequency Response of each type of defect for different sizes.		

3.3 Field Trials

The final stage of the project was a field trial which was conducted on wiring inside the fuselage of a Hercules C130 aircraft (Figure 13). The Teletest LRUT equipment successfully detected an abrasion in the cable that was implanted to simulate an in-service defect.

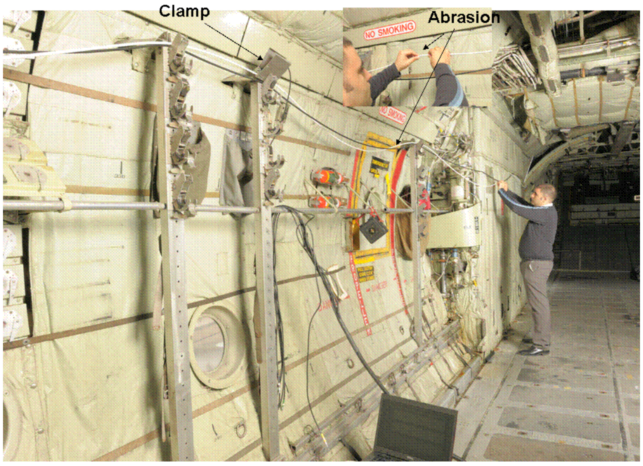


Figure 13 Field trials on C130 Aircraft

4. Conclusions

The ability of the Teletest LRUT system to propagate pulses of ultrasound along wires to detect discontinuities in the wire insulation has been demonstrated. In addition, experimental results have shown that the propagation ultrasound has different response with respect with the different defect geometry. Subsequently, the procedure developed offers a pulse-echo technique, with a good evaluation of the present discontinuities based on the amplitude and time-of-flight, with also a significant improvement in inspection length.

References

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