Modelling Guided Waves in Complex Structures
Part 2 – Wire Bundles - With and Without Insulation

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Abstract

A separate paper (Part 1) describes the application of Finite Element Analysis of guided waves to the Long Range Ultrasonic Testing (LRUT) of rail. This companion paper describes the application of numerical modelling to another complex structure, namely a plastic coated wire bundle. A bundle typically consists of a number of wires twisted into a helix, which are encased within an outer annulus formed by the insulating coating. For critical applications, e.g. in aircraft, there is concern about degradation of the insulation. As with any elongated structure, there are advantages of using and inspection method capable of examining long lengths from a limited number of access points. Guided ultrasonic waves offer potential for these examinations.

There is little knowledge about the behaviour of guided waves and their application in plastic coated wire bundles. Such a structure can cause dispersion effects, wave attenuation and, more importantly, the existence of more than one wave mode in the low frequency region. Hence, the way in which guided waves propagate through such a structure is complicated. The aim of this paper is to model the behaviour of guided waves in such a structure numerically, identify suitable wave modes for the generation and propagation of guided waves, and validate the capability of the selected wave modes to detect different types of flaw. Typical flaw types in plastic coated wires are delaminations and cuts. These types of flaw occur during service and are generally due to environmental degradation. This work was carried out using an in-house semi-analytical Finite Element Modelling (SAFEM) technique to describe the behaviour of guided waves in the wire bundle. The SAFEM model was used because it provided a relatively fast calculation time, utilising a small computational memory, to calculate dispersion curves in the complex cross-sectional structure of the wire bundle. The COMSOL Multiphysics Finite Element Analysis software package was subsequently used to determine the mode of vibration and to simulate wave propagation in the structure. The information provided by these different numerical techniques provided information to predict a suitable method of excitation. Finally, this research has identified a number of wave modes that are most likely to be present in such a structure in the low frequency (kHz) range; these are the torsional, flexural and the longitudinal wave modes. An experimental trial confirmed the ability of the identified wave modes to detect typical flaws. However, the effective inspection range for guided waves was found to be limited by the presence of the coating.

1. Introduction

Electrical wires used in the aerospace industry can be considered as a critical component to flight safety. There are more than 300 km of different types of wires in a typical aircraft with different shapes, from single insulated wire to bundles of multi stranded twisted wires(1). These wires are subject to variations in temperatures, pressure and humidity level. As the wiring becomes aged the insulation may become brittle or cracked(1-3) and may suffer delamination from the core, becoming a potential source of unreliability or even a fire hazard. Therefore, there is a need for a technique to examine the condition of insulated wiring. There are number of Non-Destructive Testing techniques are used to inspect wiring, including Low Power Laser-Diode, Pulse Arrested Spark Discharge (PASD), Time Domain Reflectometry (TDR), Frequency Domain Reflectometry and Infrared Thermography (FDR)(4-7). However, some of these NDT techniques lack the ability to assess the condition of the insulation in the wire. Others require removal of wire insulation or disconnecting the wire ends. These methods might increase the risk of induced maintenance failure(4-7). Conversely, Guided waves have the potential to inspect wires, including insulation, from a single point of access. Guided waves use the cylindrical geometry of the wire as a wave guide to propagate through its structure (8-9). Under the assumption that there is a perfect contact condition between the two materials in the wire(10), guided waves propagate in both the conductor and insulator of the insulated electrical wires. Two types of wave mode exist in the cylindrical geometry, axi-symmetrical and flexural(8-10). The nature of these wave modes is a function of geometry, frequency, wave mode order, and the material stiffness of the conductor and the insulator. Hence, the behaviour of guided waves of a helical cylindrical shape wire with a protecting layer of viscoelastic coating will be affected by the condition of both the wires and the insulation. The behaviour of guided waves can be understood by calculating a number of parameters (i.e. wavelength, phase velocity and group velocity) at a fixed frequency. In this paper, a semi analytical finite element method was used to calculate the dispersion curves for such a complex structure and to investigate the behaviour of the guided waves in insulated wire bundles.

2. Semi Analytical Finite Element Method

The finite element technique has been applied in all modelling fields in mechanics, including Long Range Ultrasonics (LRU) for the calculation of dispersion curves and mode characteristics. Imperial college have developed commercial software called Disperse®. This software uses the analytical solution of the wave equation in the frequency domain to calculate dispersion curves. However, this software is limited to cylindrical and plate structures. 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 has been presented as an alternative to FE as it avoids the 3D meshing and uses only 2D meshing. This is due to the usage of an analytical form of the considered displacements, the 3rd direction is simplified and 2D meshing is used for 3D displacement unknowns. Nigro(11) is one of the earlier researches who developed a semi-analytic solution based on function expansion of displacements called the Ritz method. This method faced difficulties in convergence and applying to different cross sections apart from a square cross sectional bars. SAFEM used to generate dispersion curves for non-homogeneous anisotropic I-beams. Taweel et al(12) used SAFEM for dispersion curves calculation of circular and rectangular cross section and also for three layers beam with anisotropic symmetry. Hayashi et al presented the SAFEM applied to flexural mode focusing in pipes in 2002(13). In addition, they have used the SAFEM in advanced LRU modelling as a simulation and visualisation tool of wave propagation in plate and pipe with elbow and later in 2004 (14-16) for square rod and rail.

2.1 Implementation

The implementation of an in-house SAFEM(17) is developed using Matlab® platform based on sparse technique matrix. The numerical program is using triangular finite elements and the Eigen-values are calculated based on numerical algorithm. Some solutions are obtained negative or complex. The negative wave-numbers correspond to the propagation in the opposite direction. The complex solutions are evanescent and will be cancelled.

The scan of the surface (f, ξ) is obtained in three different ways:

- Calculate all the ξ for a fixed frequency by changing the starting solution.
- Calculate all the ξ for a fixed starting solution by changing the frequency.
- Using the previous solution ξ as a starting solution in the next step by changing the frequency.

When more than one ξ solution exists in a small frequency interval, some difficulties are observed in finding all of them. In this case a first scan type is more suitable. When no clear idea is available about the existing modes, the second scan type is used to find at least one mode per mode curve. When aiming to calculate only one mode curve in the frequency range, the third scanning way is applicable and allows following the mode curve by using the present starting solution as the previous obtained. This calculation method presents further difficulties when the solution is *NaN* (not-a-number), in this case the next solution can not be obtained and the program is stopped. A combination of different ways is needed to find all the existing mode curves.

2.2 Meshing criteria and validation

The validation of the numerical implementations is based on comparison with results from Disperse® solution in the case of circular rods. Dispersion curves have been constructed using Disperse® and SAFEM for a circular wire. Figure 1 show a good agreement between the two different techniques to construct dispersion curves for the circular wire cross section. The circular cross section dimension is 0.1 x 0.1m and the meshing of 5 elements per square edge. The element length is 0.02m. For the non dimensional frequency/velocity validity range ([0 to 2.5 MHz mm], [0 to 5000m/s]) the minimum mode velocity is Cph=2900m/s, the minimum wavelength is about 0.011m. If we consider the mode Cph=4500m/s at the same frequency, the maximum wavelength is about 0.018m. Clearly the mesh element length can be used as half the wavelength i.e L_elem=2λ, because the deformation of the section occurs along the axial direction. In the cross section the deformation remains easy to interpolate and so the meshing criteria is low compared to habitually used in transient simulation (L_elem<5λ) (18).

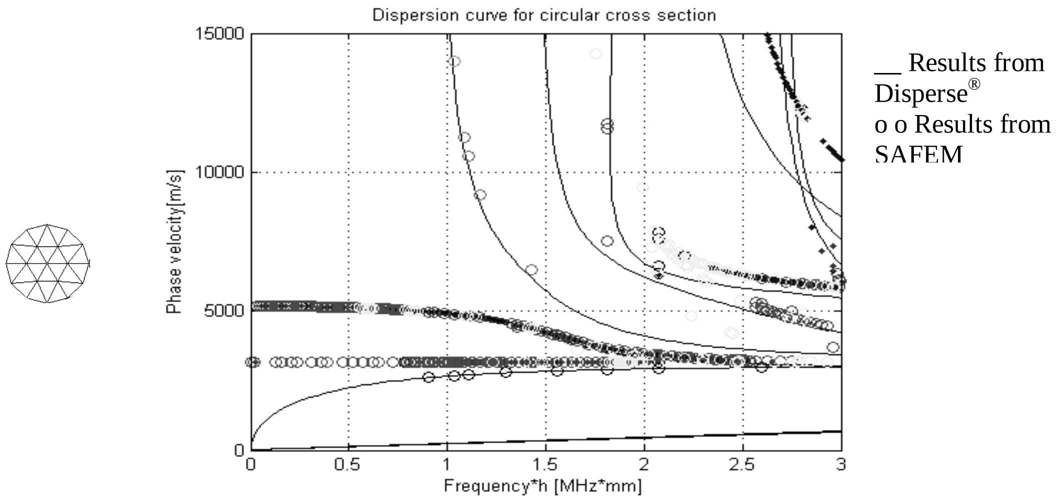

Figure 1.Validation of the SAFEM with comparison to Disperse results: circular steel rod.

2.3 SAFEM applications to a bundle of wires

The in-house developed SAFEM(17) was used to construct dispersion curves for a bundle of seven copper wires un-coated. SAFEM assumes for all of it is modelling a perfect contact conditions between each wire. Also, it does not account for the helical shape. Figure 2 shows the dispersion curves generated by SAFEM for a bundle of seven wires.

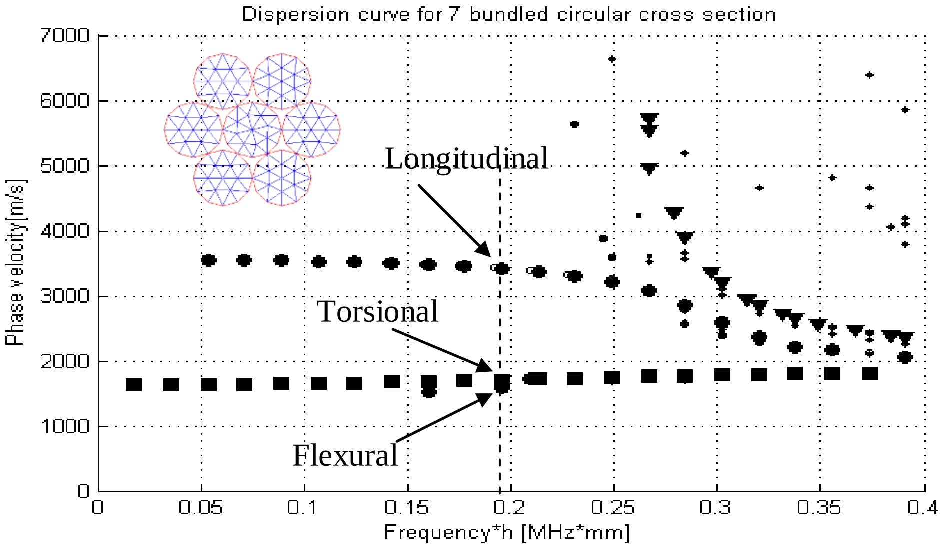

Figure 2: Constrcuted Dispersion Curves using SAFEM for a bundle of seven wires

The dispersion curves show that there are three potential wave modes that are present in the low frequency region for such a complex structure. This is might be the longitudinal mode travelling at a speed of 3500 m/s, Flexural travelling at a speed of 1500m/s and Torsional travelling at a speed of 2000m/s. For the longitudinal wave mode, the dispersion effect is occurring at lower frequency for the bundle (this is 0.2 MHz*mm), also the 2nd flexural wave is arriving earlier in the bundle. The occurrence of the dispersions and the presence of other wave modes at earlier frequency will reduce the inspection frequency range, and will add more complexity to excite one wave mode at one excitation at a time. However, in order to validate the SAFEM findings, the Finite Element Analysis (FEA) is used along with experimental tests to simulate the presence and excite potential wave modes. The next section will simulate wave propagation and mode of vibration in such a complex structure.

3. FEA Modelling

COMSOL Multiphysics was used to simulate the wave propagations and mode of vibrations in different complex structures. Each wire in the bundle had a diameter of 1.59mm. In FEA 8 elements per wavelength were used in the third direction to simulate the wave propagation in the wire structure. The modelling work has covered a bundle of seven wires twisted in a helical shape. The model length is 2m and meshed with an element size of 6 elements per wavelength. Dispersion curves show that there are three wave modes that can propagate in the low frequency region for a bundle. Therefore, it was decided to select the longitudinal wave mode as mode of propagation in the complex structure. A symmetric excitation is chosen to excite the bundle with a 40 kHz tone burst signal. Figure 3 shows the excitation points for the bundle. Figure 4 shows the A-scan displacement for a surface plots. There are two identifiable wave modes that are travelling in the structure. These two wave modes are the symmetric and the torsional modes. Where the symmetric wave modes is the most significant wave mode. In addition, the symmetric wave mode is travelling at a speed of 3225 m/s, which again this speed is a close to the theoretical velocity (3500m/s) obtained from the SAFEM developed dispersion curves in section 2.3. 2-D FFT was used to reconstruct wave number dispersion curves for the helical bundle. The 3-D displacement is recorded every 0.05m with time sampling of 1us. The results were converted to the frequency domain. Figure 5 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 wave number (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 found equal to 3351m/s and 1117m/s for the longitudinal and torsional wave modes respectively.

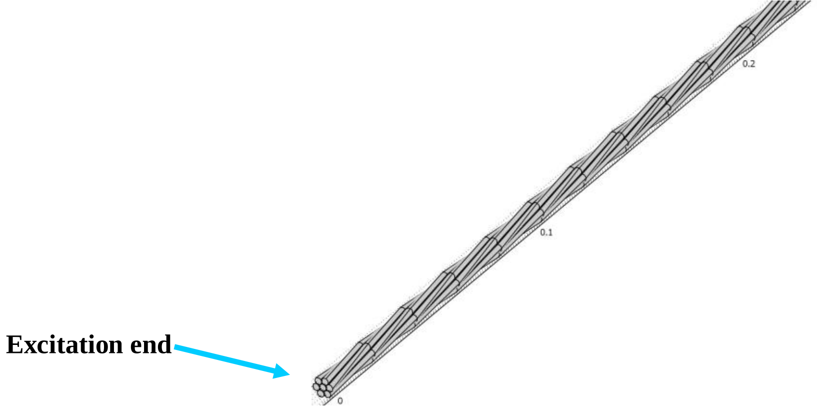

Figure 3 : A bundle of seven helical wires with symmetric excitation points

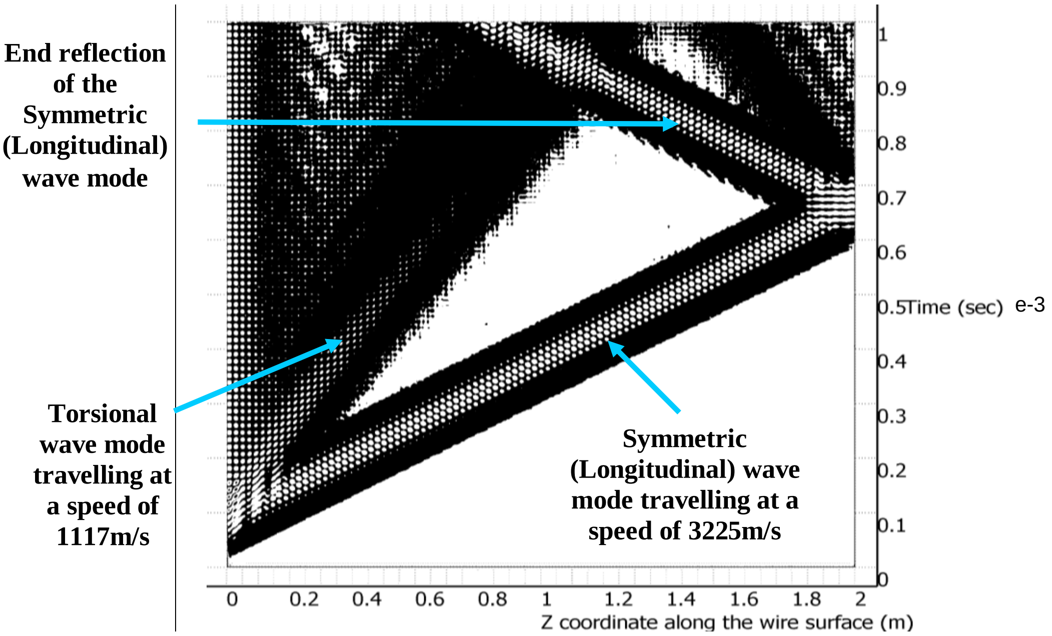

Figure 4: A scan results for the surface displacement

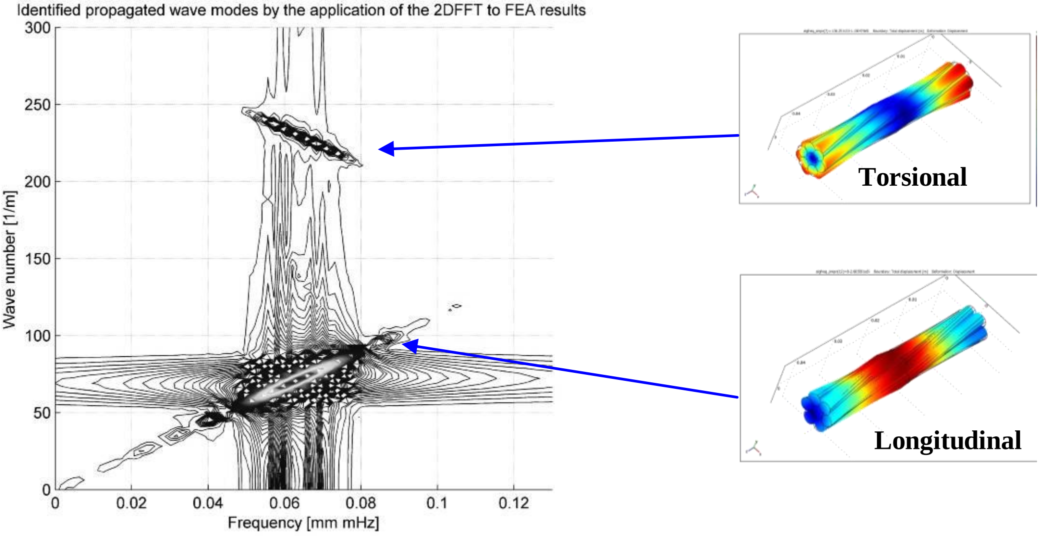

Figure 5: Identified propagated wave modes by the application of the 2DFFT to FEA results

FEA demonstrated the ability of guided waves to propagate in the bundle. Moreover, it has demonstrated the mode of vibration and identified the nature of guided waves that are likely to be present. These wave modes are the longitudinal and the torsional modes. The presence of the longitudinal wave mode is much significant with respect to any other wave modes in the complex wave guide. This is might be due to the nature of excitations. However, the presence of the torsional wave mode might be due to the natural shape of the wave guide i.e. the helical shape, which might orient the guided wave to behave in a manner where the displacement will be in the circumferential plane in the cross section of the bundle. Furthermore, FEA show that these wave modes travel at speed that is close to the theoretical speed that obtained from SAFEM. SAFEM also shows that there is an additional theoretical wave mode; this is the flexural wave mode. However, FEA did not show the presence of these waves. This is might be due to the nature of excitation and operating in a frequency region bwlow the cut off frequency for the flexural wave mode. Finally, SAFEM and FEA show a certain degree of agreement between each other in terms of predicting the behaviour of guided waves, mode of vibrations and wave mode propagation in this complex structure. However, it is important to validate these modelling results from experimental perspective. The next section will demonstrate the propagation of guided waves experimentally in different bundles of wires with different physical characteristics.

4. Experiment

A bundle of seven helical twisted wires was used with and without insulation (see figure 6-7). However, no information provided about the type of insulation, but it is believed that polyethylene is the coating material for this specific wire. The excitation used two Micro Fibre Composite (MFC) transducers, arranged in a sandwich shape excitation, where the wire is centred in the middle between the two MFCs. Figure 8 shows the excitation arrangements. A Teletest® Mark-2 Unit was used to generate ultrasonic guided wave signals (see Figure 9).

Figure 6 A bundle of seven helical wires

Figure 7 A bundle of seven helical coated wires

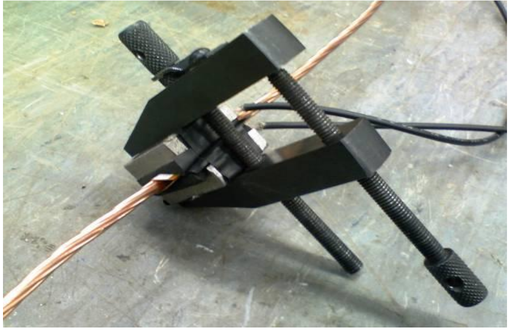

Figure 8 MFC sandwich excitations arrangement

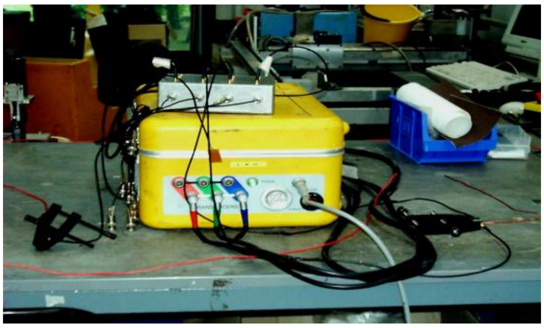

Figure 9 Ultrasonic Guided Waves Generator (Teletest®)

Figure 10 shows the A-scan results for a bundle with length of 1m. The A-scan shows that there is one significant wave mode that is propagating in the bundle. This is the longitudinal wave mode. However, there are other additional wave modes that are presence. This is might be due to the contact conditions between the MFCs and the test piece, as this will have significance on the directionality of the waves. Figure 11 shows the A-scan results for the wire bundle. The presence of coating has reduced the frequency inspection range significantly. This is between 20 kHz-25 kHz. The Figure shows that there are two reflections; they are identified as longitudinal and flexural wave modes. The reflection were obtained based on the time of arrival, which they reflect the speed of the wave.

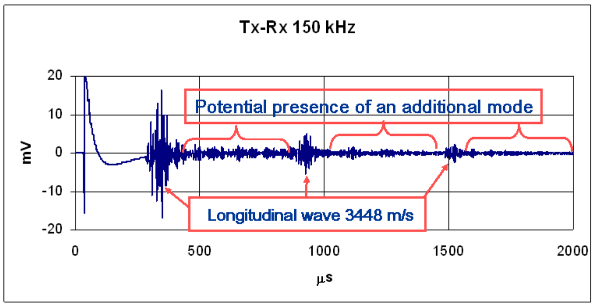

Figure 10 A-scan results for longitudinal wave travels in a bundle of seven helical wires

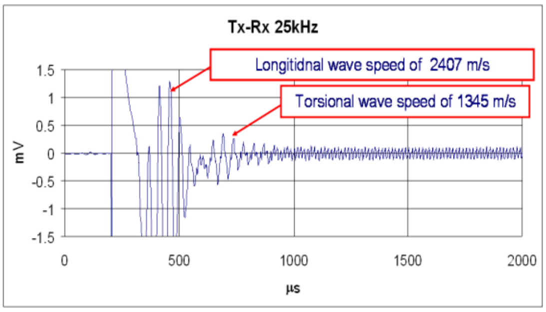

Figure 11 A-scan results for longitudinal wave travels in a bundle of seven helical coated wires

Figure 12 shows the correlation between FEA finding and experimental result. The correlation is done on a 1m length with seven helical wires. The results show that the longitudinal wave is travelling at approximately the same speed, experimentally and numerically. However, there is a slight time shift this is might be due to different excitation conditions, numerical rounding error, laboratory conditions and meshing convergence. The finding from experiments shows that there is a longitudinal wave mode imposed over other potential wave modes in such a complex structure, provided that the excitation is a symmetric excitation. The longitudinal wave is travelling at speed of approximately 3440 m/s. However, the presence of coating has reduced the velocity of the longitudinal wave to 2670m/s. Also, the coating has reduced the inspection range from both the frequency and distance perspectives. These findings confirm the observations from numerical modelling.

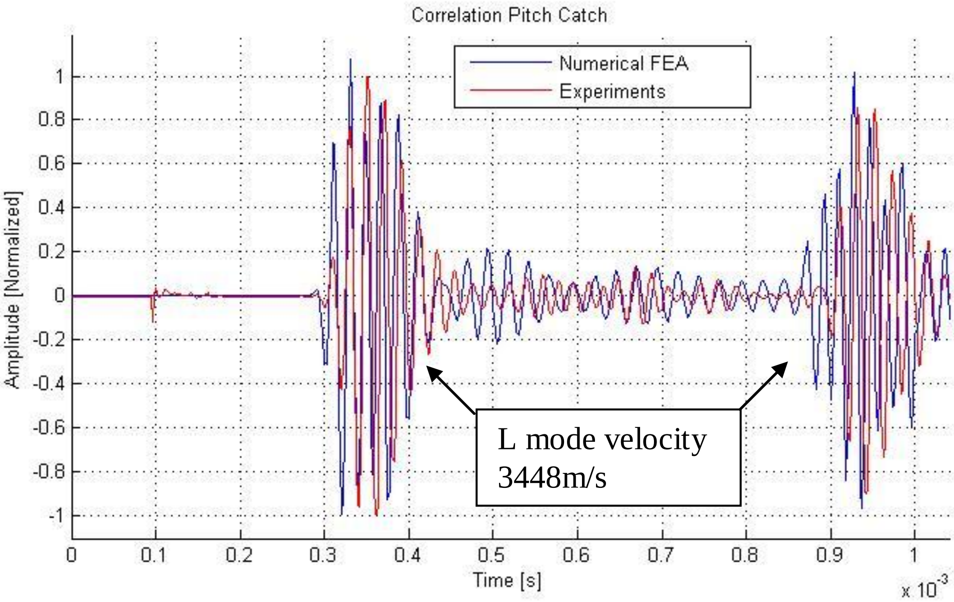

Figure 12: Correlation between experimental results and FEA for a bundle of 7 twisted wires.

5. Application of Guided waves in the aerospace industry

Another test piece was tested. This test piece had an operational conditions generated type of flaws. The wire is identified as H26G18 with a diameter of 2.33mm. The conductive material is copper with a length of 2.55 meter. Figure 13 shows the wire sample along with its different types of visible flaws.

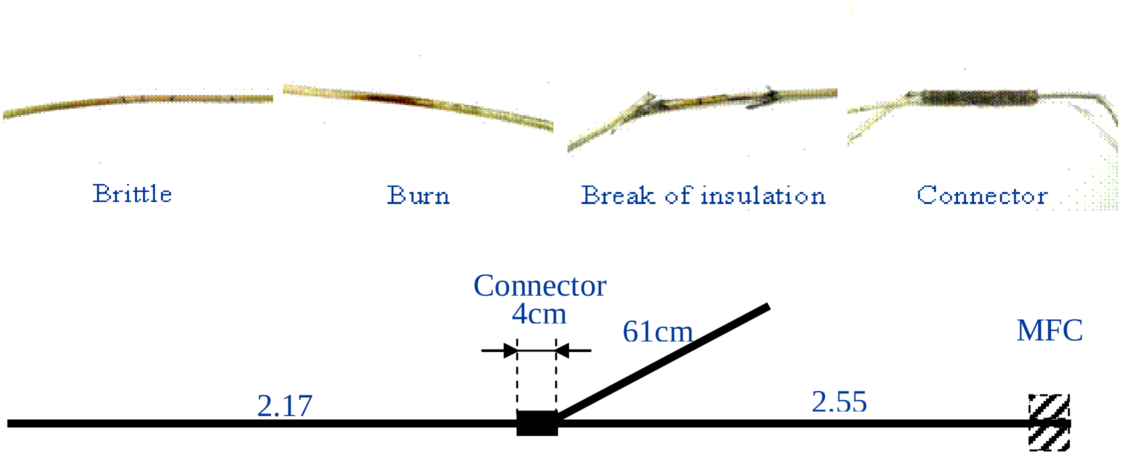

Figure 13 Real aircraft faulty wire bundle

Table 1 and Figure 14 show the different reflections that have been reflected as resultant of the symmetric excitation. Each reflection is arriving at approximately speed of 2670 m/s, with higher reflection amplitude from the connector. This suggests that a symmetric wave is travelling at a constant longitudinal velocity.

Table 1: List of visible fault locations

Distance (cm)	Description	Reflection No.	Time arrival (ms)
30	Slightly burnt		224
60	Slightly burnt		449
128	Burnt & insulation brittle	1	957
148	Slightly burnt	2	1107
176	Slightly burnt	3	1316
206	Slightly burnt	4	1541
220-236	Burnt & insulation brittle	4	1645-1765
245	Slightly burnt	5	1832
255	Connector or break	5	1915

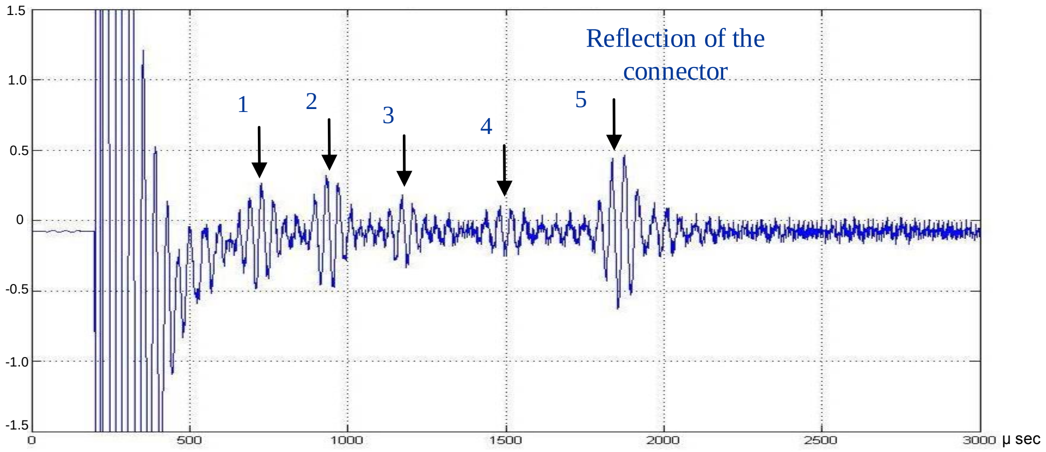

Figure 14: A-scan results with flaw identifications

6. Conclusion

SAFEM has identified three potential wave modes that can exist in such a complex structure; these are the flexural, torsional and longitudinal wave modes. However, SAFEM assumes that there is a prefect contact conditions between the wires within the bundle, but it dose not account for the helical shape or the attenuation phenomena exhibited by the coated bundle. FEA has described the mode of vibrations for the potential wave modes that might exist providing a symmetric excitation is used. These wave modes are the longitudinal wave mode with the most significant amplitude, and the torsional wave mode that travels at much lower velocity. The recorded velocity for the travelling wave modes from FEA results using 2DFFT show that these wave modes have velocities that are close to the predicted velocities obtained from SAFEM. The presence of coating in a wire bundle has affected these travelling velocities significantly. In addition, coating has decreased the frequency inspection range. Experimental results show that there are torsional and longitudinal wave modes with similar behaviour of what has been observed in the FEA. The excitation that is used in the FEA and experimental is aimed to excite the structure with symmetric excitations. However, due to the physical nature (i.e. helical shape) of the complex structure (i.e. wave guide) this has induced the torsional effect.

6. References

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