

LONG RANGE ULTRASONIC TESTING FOR INDUSTRIAL APPLICATIONS

Yousef Gharaibeh^{1,2}, Peter Mudge¹, Wamadeva Balachandran²

¹NDT Technology Group, TWI, Granta Park, Great Abington, Cambridge, UK, CB21 6AL

E-mail address: yousef.gharaibeh@twi.co.uk, Telephone no: +44 (0)1223 899000

²School of Engineering and Design, Brunel University, Uxbridge, UK, UB8 3PH

Keywords: Dispersion, Wave Mode, Guided Wave, Long Range Ultrasonic, Defect Detection

Abstract

Long Range Ultrasonic Testing (LRUT) uses guided waves in the kilohertz range to detect flaws in elongated components over many metres from a single point of access. This technique is well developed for pipes and pipelines in the oil, gas and chemical industries. However, there is potential to extend the application of guided wave testing to cover other industries, for example rail and aerospace. In order to exploit the propagation of guided waves in unfamiliar structures there is a need to establish the physical characteristics of guided waves in terms of their frequency-velocity relationship (i.e. dispersion curves), to identify suitable modes of vibration in terms of their displacement distribution and selection of non-dispersive characteristics and finally to establish a suitable means of excitation for the selected wave mode. This research has been performed to provide a basis for the selection of guided wave test conditions covering industrial applications where either large area coverage is required or where the component is inaccessible for local scanning of ultrasonic transducers. The work was carried out using a Finite Element Analysis (FEA) along with experimental validation. The findings show that there are many wave modes in the kilohertz frequency range and that many of these exhibit dispersive behaviour. In addition, the nature of the wave modes has a complex displacement distribution. However, wave modes with desired properties may be generated selectively by careful selection of excitation conditions. Finally, this research demonstrates the ability of ultrasonic guided Waves to propagate and inspect industrial engineering structures for different types of flaws at different locations.

1. Introduction

Long Range Ultrasonic Testing (LRUT) using low frequency guided waves has been shown to be effective in detecting defects over many metres in different types of structure, such as pipes and plates, from a single point of access[1-5]. On the other hand, LRUT has the disadvantage of having a relatively low defect detection sensitivity in comparison to conventional ultrasonic testing. In addition, guided waves are complex, with many wave modes possible, and are dispersive in nature (i.e. the velocity changes with frequency). This makes interpretation difficult. Guided waves experience mode conversion and scattering in all directions after interaction with discontinuities such as a cracks, metal loss due to corrosion, a change in structural stiffness or structural boundary [1-5]. Guided waves also experience loss of energy (attenuation) as they propagate. This will consequently reduce the inspection range. The severity of the attenuation depends on the surface roughness and on whether mechanisms of leakage and loss of energy from the wave guide exist, e.g. the presence of viscoelastic coatings.

The nature of ultrasonic guided waves is generally understood in simple structures such as pipes, plates and rods. However, there has been relatively little work published on the application of LRUT techniques to inspect complex structures such as rails and insulated wires [6-7]. This paper describes the development of effective techniques for the examination of railway rails and insulated electrical wiring using guided waves.

2. Industrial Needs

Inspecting railway tracks for defects is a major concern for the rail transport industry. Railway track is vulnerable to degradation arising from the operational conditions (mainly fatigue cracking) and from environmental effects (corrosion) [8-10]. These factors can lead to a rail failure, which might lead to loss of human lives and unnecessary costs. An example of a catastrophic accident caused by rail failure is the Hatfield rail accident in the UK [9,11]. This accident was caused by rail failure arising from a transverse defect caused by rolling contact fatigue. This accident left 4 passengers dead and 70 injured [11]. A major factor in the inspection of rails is the extremely long lengths of rails in a network which require examination and the restrictions on access for inspection caused by the need for track availability for the running of trains.

Another area where considerable lengths of safety-critical components are required to be examined carefully, but which are difficult to access, is that of electrical wiring in aircraft. Wiring in aircraft operates in fluctuating operational conditions, such as widely varying temperature and atmospheric pressure [12-14] which causes, amongst other things, degradation of insulation. Faults in wiring have been known to lead to a catastrophic failure. An example is Trans World Airlines flight 800 in 1996, which crashed into the sea shortly after leaving New York City. All 230 passengers died. The crash resulted from an explosion caused by an arcing wire near fuel tank[15]. Therefore, there is a need for an effective technique which can detect degradation in wiring systems before electrical faults cause other failures. There is considerable potential for guided wave testing to perform this task and the feasibility of this was investigated.

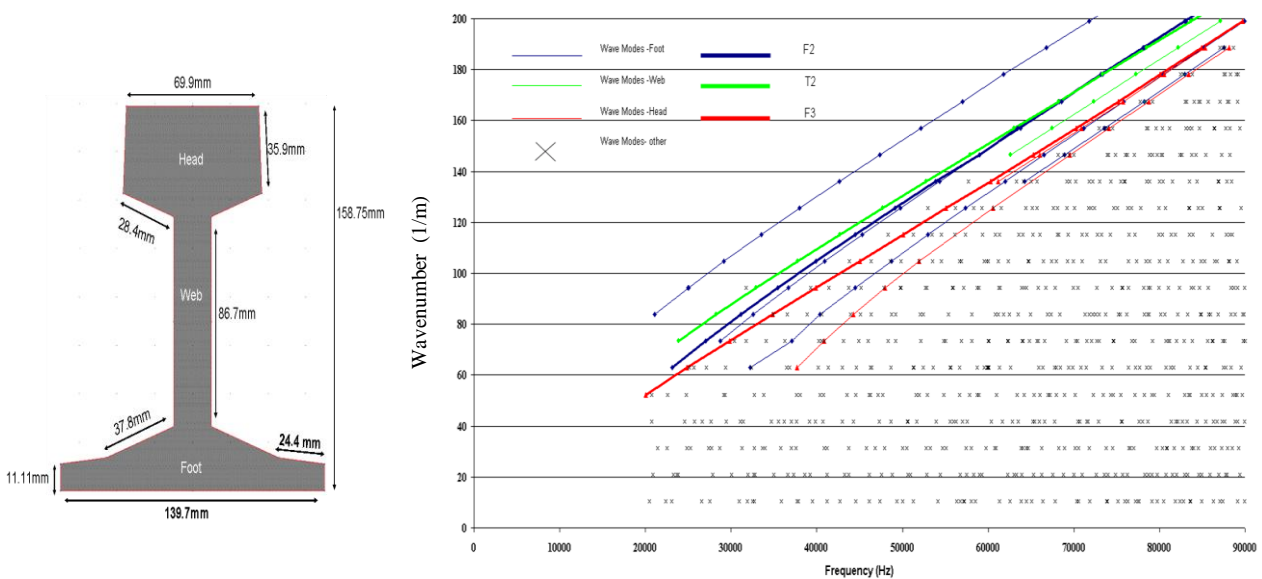
3. Guided waves in rails and wires

Rails

In order to exploit the potential of utilising guided waves in any structure, there is a need to characterise their behaviour with respect to the structure of interest [16-17]. Guided waves are sensitive to the structure's cross-sectional shape, thickness and material properties (Poisson's ratio, Young's modulus and density). The behaviour of guided waves can be described by the relationship between wave number and frequency range. This relationship is represented by the so-called

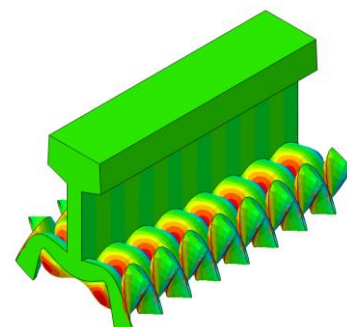
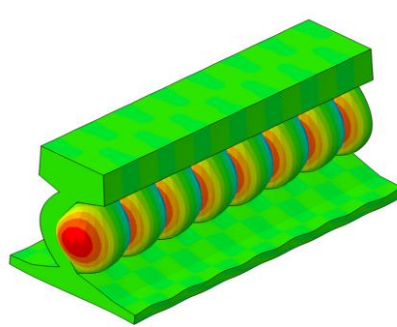
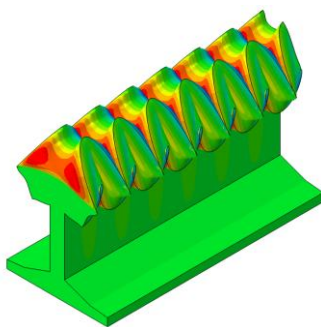
dispersion curves in which wave number is plotted vs. frequency. Knowledge of wave number at a particular frequency can determine wave speed. For this work, a finite element (FE) computer aided package was used to determine the standing wave modes using Eigensolver.

As may be seen in figure 1(a), the rail has a complex cross section. For the purposes of designing a test regime using guided waves, it was decided to divide the rail into three sections; the head, the web and the foot. Figure 1(b) shows the dispersion curves for guided waves in the rail section. It may be seen that there are a number of wave modes present in the frequency of range of interest (between 20-90 kHz). Three separate potentially suitable wave modes have been identified, one for the head, one for the web and one for the foot. These are F3, T2, and F2 respectively. These wave modes have been found to have similar vibration patterns (i.e. wave mode deformation shape), with relatively similar propagation (group) velocities at 70 kHz (3100m/s for F3, 3000m/s for T2 and 3027m/s for F2) and each propagates in a specific part of the rail (see Figure 1c to 1e).



(a) rail cross section

(b) Dispersion curves



(c) F3 wave mode in the head

(d) T2 wave mode in the web

(e) F2 wave mode in the foot

Figure 1: behaviour of guided waves in rail (a) cross section of the rail, (b) dispersion curves wavenumber (1/m) vs. frequency (Hz) for rails, (c) selected wave modes in different section of the rail

Insulated Wires

The study was carried out on a wire bundle consisting of 7 solid copper wires 2.12mm in diameter with 6 wires in a helical twisted pattern around a straight central wire. The dispersion curves for the 7-strand wires are shown in the Figure 2 (a). Two wave modes have been identified; one longitudinal travelling at a phase velocity of 3225m/s and the other torsional travelling at a phase velocity 1117m/s (see Figure 2b and c). However, unlike the rail results in Figure 1, the wire bundle has been excited with a transient signal and a 2-D FFT was used to calculate the dispersion curves.

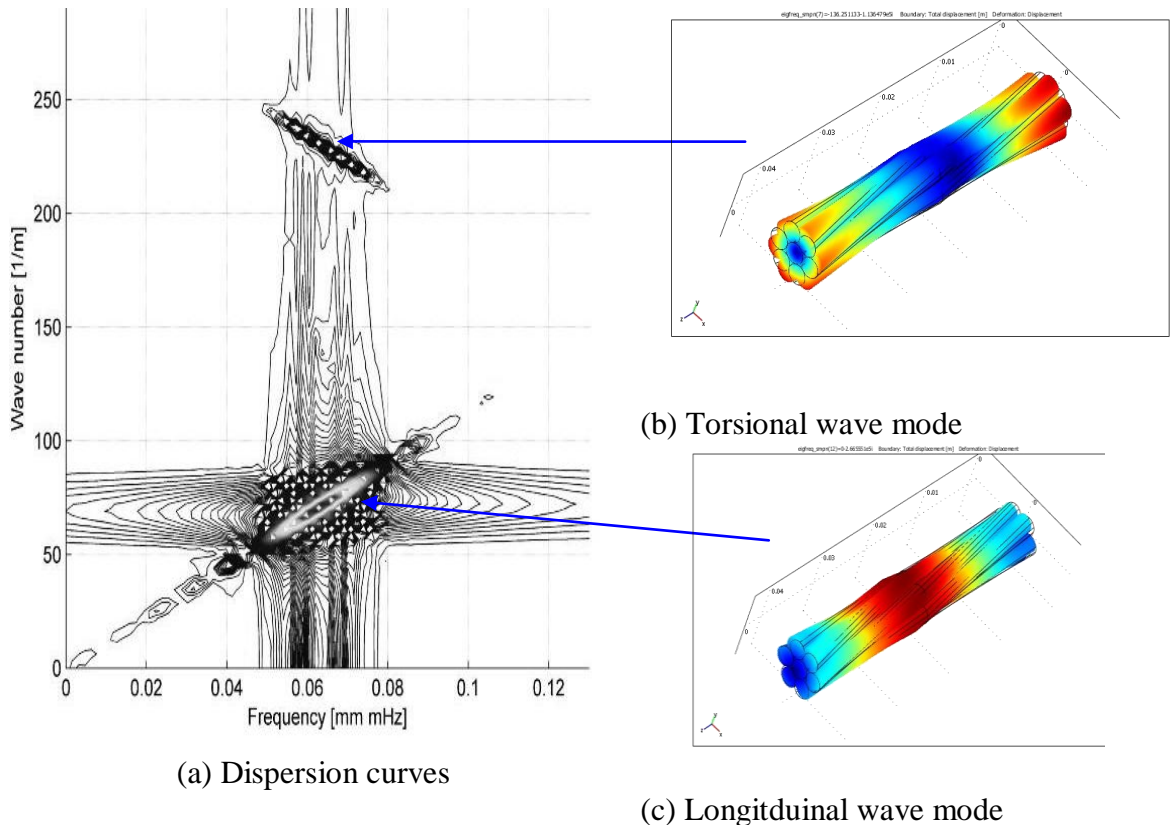


Figure 2: behaviour of guided waves in wires (a) Dispersion curves for a bundle of 7 wires in helical form, (b) Torsional wave mode in the bundle, (c) Longitudinal wave mode in the bundle.

4. Wave propagation in rails and wires

Rails

The information provided from the dispersion curves was used to design an experimental setup to impose a desired wave mode in each case. Ideally, to be able to perform an inspection there is a need to propagate one wave mode with a known velocity at a given frequency. This section discusses the findings from the experimental trials to inspect features in rails and wires:

As stated previously, the F3 and F2 wave modes were selected to inspect the rail head and foot respectively. Flaws which are likely to affect the integrity of the rail may occur in these two sections. These selected wave modes were excited in a rail specimen 6.64m long using piezoelectric transducers bonded on to the head and foot. The tests were pulse-echo i.e. the same transducers were used to transmit and receive the signal. The transducers are connected to a guided wave generator (Teletest®) and controlled via a desktop PC. Figure 3 shows a schematic diagram of the experimental set up.

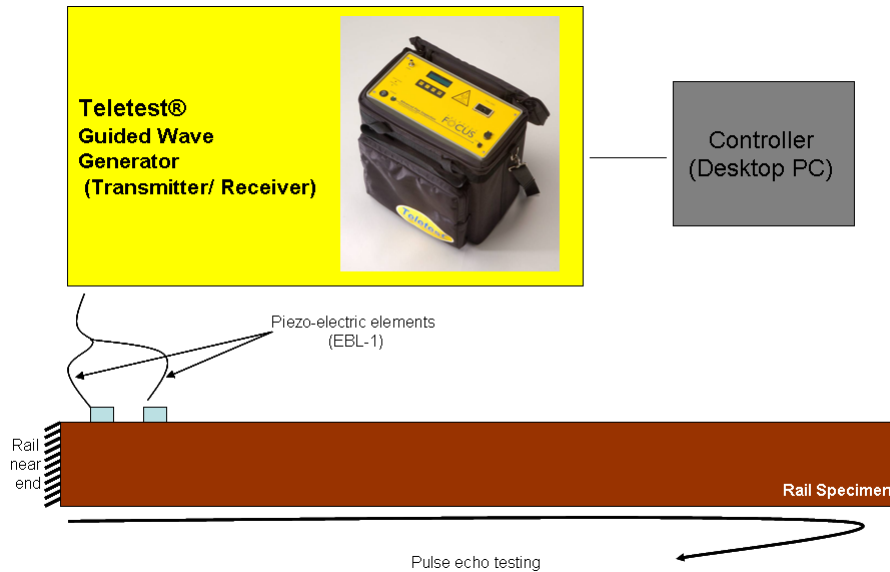
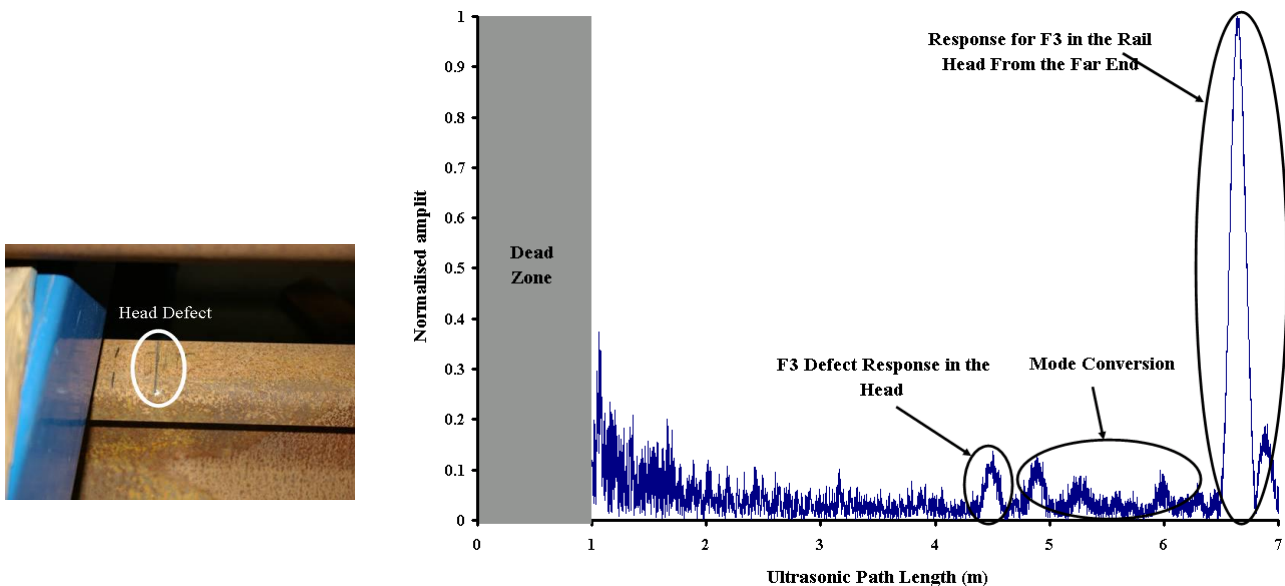


Figure 3 : schematic diagram shows the experimental set up to inspect rails

The results from the test on the rail head are presented in Figure 4. The distance axis was calibrated using the F3 velocity of 3100m/s obtained from the FE model. A strong reflection was recorded from the far end of the rail specimen at the expected distance from the transducers of approximately 6.64m, which demonstrates that the wave mode propagating is as predicted from the model. This response may be seen in Figure 4(b), where it is still present after the introduction of a notch defect. The transverse notch was introduced into the head, 4.46m from the transducer, with a depth of 2mm and the test was repeated. The response is shown in Figure 4(b). It is clearly detected. The mode-converted signals also appearing in Figure 4(b) are a consequence of the interaction of the wave with the notch and were not present before the notch was introduced.

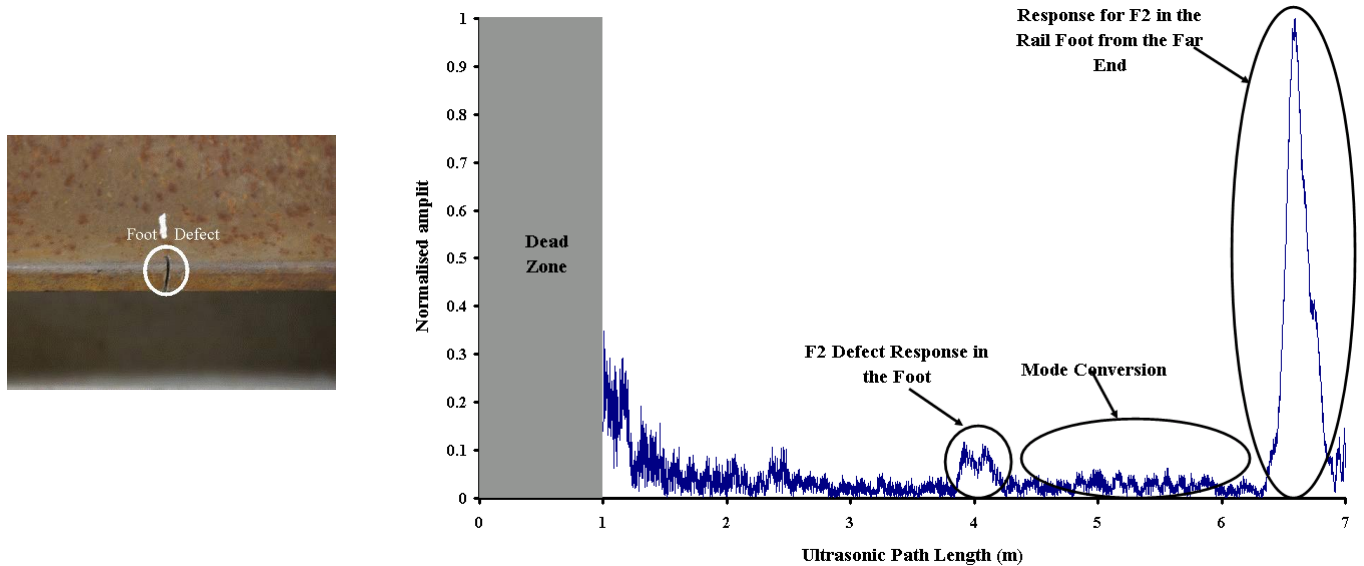


(a) 2mm deep defect in the head (b): Guided wave response for F3 wave mode propagating in the head when the 2mm defect was present.

Figure 4: Guided wave response for mode F3 propagating in the rail head

The experiment was repeated with the transducers mounted on the foot of the rail to excite the F2 mode. Figure 5 shows the results. Again, the far end of the rail produced a response at the expected distance, so that it was evident that the desired wave mode was being excited. Tests were first

performed with no defects in the foot then a gradual transverse defect from 1mm to 5mm deep notch was introduced at a distance of 4.0m from the transducer. No response was detected until the notch depth reached 5mm (see Figure 5(a)). The response may be seen in Figure 5(b). Again the notch was clearly detected at the expected distance.



(a) 5mm deep defect in the foot (b): Guided wave response for F2 wave mode propagating in the foot with the 5mm defect present.

Figure 5: Guided wave response for the F2 mode propagating in the foot

Wires

Two Micro Fibre Composite (MFC) transducers were bonded at one end of a 1.9m defect-free wire bundle (this arrangement is sometimes referred to as a sandwich excitation) to examine the potential of propagating axisymmetric guided waves along the bundle. The experiment was carried out in the pulse echo mode. The MFC's were connected to a guided wave generator (Teletest®) which was controlled via desktop PC. Figure 6 shows the experimental set up.

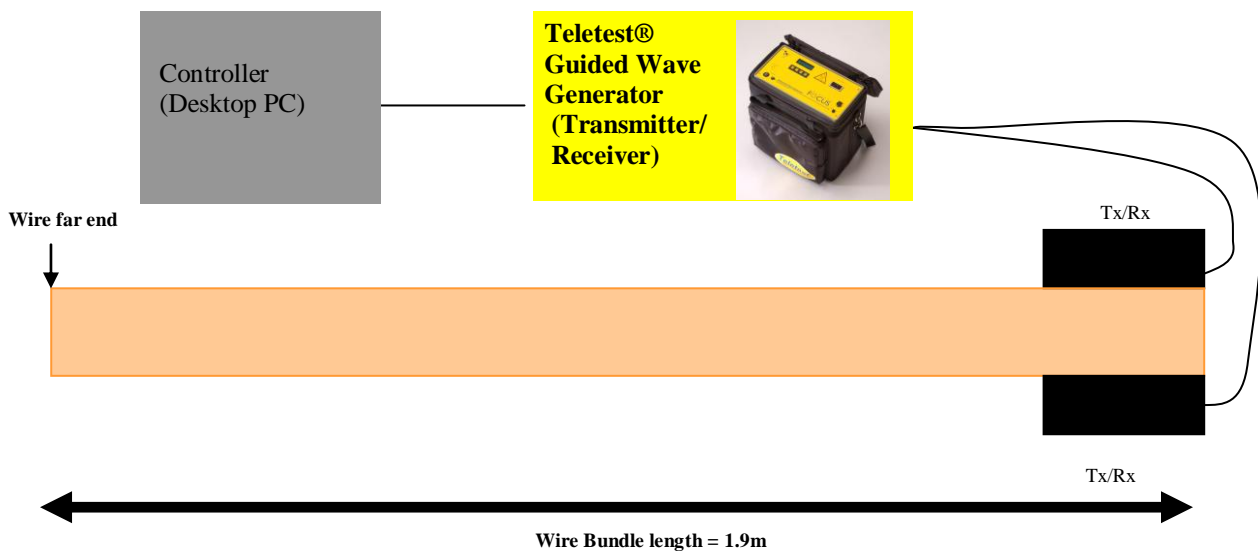


Figure 6; Schematic diagram for experimental set up to inspect wire bundle

Figure 7 shows a frequency sweep signal response between 20 and 100kHz from the far end of the wire bundle. The most significant responses are from the longitudinal wave mode travelling at predicted velocity (approximately 3040m/s) being reflected from the end of the wire and reverberating up and down the wire bundle. There are three reflections which suggest a 5.7m (3x1.9m) test distance in the pulse echo test mode. However, there are weak signals from other wave modes present in the A-scan, which indicates the potential of propagating other wave modes.

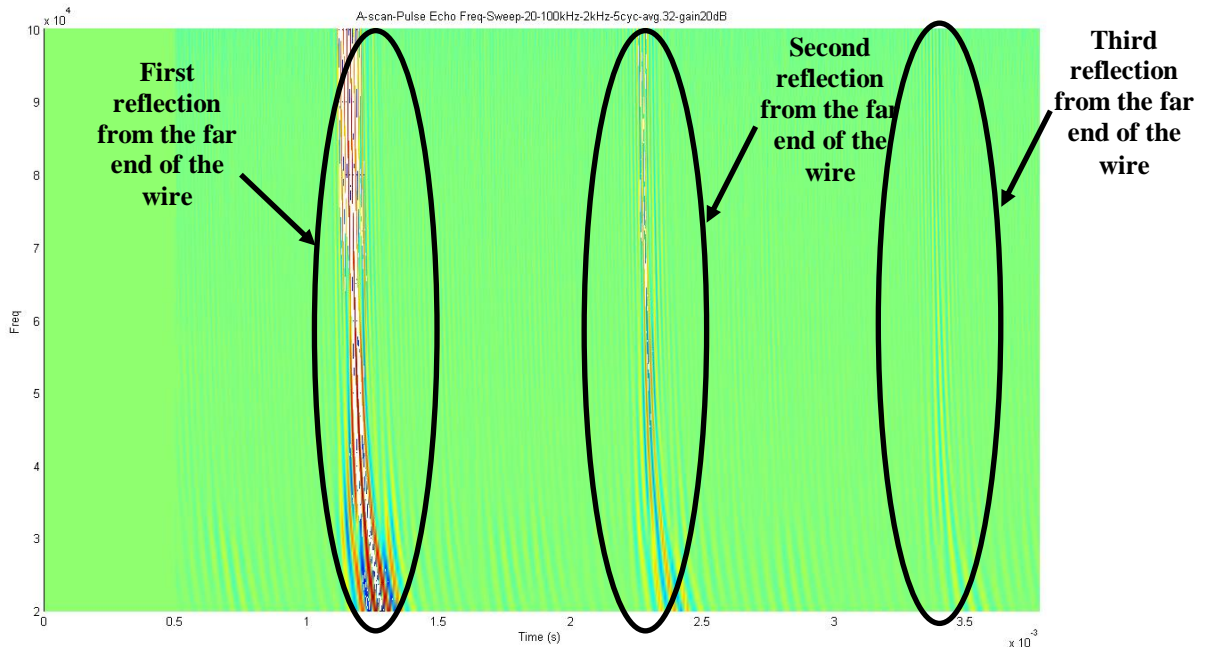


Figure 7: Longitudinal guided wave response for a frequency sweep between 20-100kHz. Multiple reflections from the far end of the 1.9m long wire are observed.

5. Discussion and conclusion

This paper has demonstrated the potential of utilising long range ultrasonic testing to inspect industrial components such as railway rails and wire bundles. It has the potential to inspect such structures from single point of access for many meters.

A finite element model has been used to predict the behaviour of guided waves. It was found that the behaviour of guided waves in such structures is unique and highly dependent on the specific geometry. This research has identified wave modes that can be used for testing the integrity of such structures. The capability of these wave modes for detection of notch type defects has been proven experimentally over many meters along the structure from single point of access. Clearly, there is a scope to utilise long range ultrasonic testing to inspect such complicated industrial structures. Furthermore, there is a need for further examination to optimise mode of excitation and the ability to detect different types of defects.

6. References

- [1] P. Mudge, P. Catton, 2006, "Monitoring of Engineering Assets using Ultrasonic Guided Waves", Proceedings of the 9th European Conference on Non-Destructive Testing, Berlin
- [2] P. Mudge, 2004, "Practical enhancement achievable in long range ultrasonic testing by exploiting the properties of guided waves", The 16th World Conference of Non-Destructive Testing, Montreal Canada, 30 August -3 September 2004

- [3] J. Rose, 2002, "A baseline and vision of ultrasonic guided wave inspection potential", Journal of Pressure Vessel Technology, Vol.124, Iss.3, pp.273-282
- [4] M. Lowe, P. Cawley, 2006 "Long Range Guided Wave Inspection Usage – Current Commercial Capabilities and Research Directions", Imperial College London,
URL: http://www.imperial.ac.uk/ndt/public/publications/LongRange_GW_Review.pdf
- [5] P. Mudge, J. Rose, 2007, "Guided Wave testing for inspection of unpiggable pipelines", URL: <http://primis.phmsa.dot.gov/rd/mtgs/020707/PeterMudge.pdf>
- [6] Y. Gharaibeh, C. Ennaceur, P. Mudge, W. Balachandran, 2009, "Modelling Guided Waves in Complex Structures – Part 1 – Rail", Proceedings of the British Institute of Non-Destructive Testing, Blackpool, UK
- [7] Y. Gharaibeh, S. Soua, G. Edwards, P. Mudge, W. Balachandran, 2009, "Modelling Guided Waves in Complex Structures Part 2 – Wire Bundles - With and Without Insulation" Proceedings of British Institute of Non-Destructive Testing, Blackpool, UK
- [8] H. Thomas, T. Heckel, G. Hanspach, 2007 "Advantage of a Combined Ultrasonic and Eddy Current Examination for Railway Inspection Trains", Insight, Vol.49, No.6, pp341-344.
- [9] D. Hesse, P. Cawley, 2007, "Defect Detection in Rails using Ultrasonic Surface Waves", Insight, Vol.49, No.6, pp.318-326
- [10] D. Cannon, K. Edel, S. Grassie, N. Sawley, 2003, "Rail Defects: an Overview", Fatigue & Fracture of Engineering Materials and Structures, Vol.26, No.10, pp.865-886
- [11] Official of Rail Regulation, 'Train derailment at Hatfield: A final report by the independent investigation board.' 2006
- [12] E. Tucholski, 2004, "Non-destructive Evaluation of Aromatic Polyimide Insulated Aircraft and Spacecraft Wiring", The 16th World Conference Non-Destructive Testing, Montreal Canada, 30 August -3 September 2004
- [13] C. Kim, N. Johnson, 2006, "Detection of intermittent faults in aircraft electrical wire by utilising power line communication", The 9th joint FAA/DOD/NASA Conference on Aging Aircraft, March 7, 2006. Atlanta, GA.
- [14] R. Anastasi, E. Madaras, 2001, Ultrasonic Guided Waves for Aging Wire Insulation Assessment, Technical Report, NASA Langley Research Centre.
- [15] National transportation safety board, 1996 "Air accident report PB2000-910403 NTSB/AAR-00/03 DCA96MA070 In-flight breakup over the Atlantic ocean Trans World Airlines Flight 800, URL: <http://www.nts.gov/Publictn/2000/AAR0003.pdf>
- [16] R. Sanderson, S. Smith, 2002, "The Use of Guided Waves for Non Destructive Testing of Rails: A Finite Element Approach", ABAQUS UK users group conference
- [17] I. Bartoli, F. Scalea, M. Fateh, E. Viola, 2005, "Modelling guided wave propagation with application to the long range defect detection in railroad tracks", NDT&E International, Vol.38 Iss No.5, pp 325-334