Long range inspection and condition monitoring of rails using guided waves

Adam Wilkinson
TWI Ltd
Cambridge, CB21 6AL, United Kingdom
Tel: 01223 899000
Fax: 01223 890689
E-mail: adam.wilkinson@twi.co.uk

Abstract

MONITORAIL is a collaborative project for small-to-medium sized enterprises, partially funded by the European Union under the FP7 framework under Grant Agreement number 262194. The 2-year project began in February 2011 and is being co-ordinated by TWI.

The objective of MONITORAIL is to develop a cost effective, wireless, long range ultrasonic inspection and acoustic emission condition monitoring system in order to improve and better maintain the European railway system for better efficiency and safety.

The rail track is a natural wave guide where waves could easily propagate for long distance and detect defects in different areas such as the web the head and the foot. Flexible sensors will be embedded in the railways and a collection data system will be developed and integrated on the existing systems. This will also extend the life of the materials through early repair of rail tracks. The system will offer 100% coverage up to 50m from one single location. Multiple sensors will be used to cover long distance inspection.

Each autonomously powered installation will use renewable energy, energy harvesting and wireless communications to replace unreliable periodic inspections by a continuous early warning system for rail irregularities that are not immediately accessible or visible. This will reduce the maintenance, traffic disruption and operational cost while reducing the possibility of accidents and potential fatalities.

1. Introduction

Rail travel is a popular and efficient means of passenger and freight transport all over the world. The infrastructure owned by Network Rail in the UK carries 1.3 billion journeys and 28 billion tonne kilometres per year(1). Disruption of the rail network due to maintenance work has a significant opportunity cost while catastrophic failure of rail components may result in even greater costs and possibly fatalities.

To ensure the smooth running of the network and minimise the opportunity costs of network downtime, preventative maintenance e.g. targeted re-railing and cyclic grinding programs is necessary along with regular and thorough inspection of all aspects of rail infrastructure. The inspections are necessary to identify defects before they cause an unscheduled disruption or catastrophic failure. Timely identification of defects enables remedial work to be scheduled so as to minimise opportunity cost.

The network disruption and costs incurred by inspection can be reduced by using automated systems which improve the speed of inspection with minimal human involvement e.g. instrumented trains[2,3].

1.1 The Problem

Transverse cracks in the foot of the rail may develop through tensile overload from points of external stress concentration e.g. corrosion pitting. Rails will experience high tensile loading during straightening at manufacture and in service during spells of cold weather but will, in addition, experience intense dynamic loading where there are changes in vertical geometry e.g. dipped welds, head corrosion, or where there are abrupt changes in support stiffness.

Automated ultrasonic inspection systems on instrumented trains are able to successfully discover and characterise defects within the head, web and central sections of the foot of the rail. Ultrasonic energy is coupled into the head of the rail so that only defects within the head and in line with the head and web are able to be inspected. Transverse cracks in the foot of the rail away from the centre line cannot be detected. Because these defects are difficult to detect, they are a significant cause of rail failure.

There are parts of the network which are particularly susceptible to corrosion and consequently susceptible to this kind of failure. Rails in tunnels are often difficult to access and inspect. The tunnels can also provide damp environmental conditions which cause rapid corrosion damage and other defects. Level crossings are also difficult and inconvenient to inspect because of the requirement to remove the level crossing panels to carry out an inspection. The inspection disrupts road and rail traffic. Level crossings are highly susceptible to corrosion due to road salt being applied in the areas around the crossing and being further spread in the tyre tread of road vehicles. The disruption to both rail and road traffic from failures and repairs at level crossings are significant.

1.2 The Solution

The MonitoRail project aim is to develop equipment and monitoring methods based on the combination of a passive and active guided wave techniques. Acoustic Emission(AE) and Long Range Ultrasound Technology(LRUT) will check for any degradation or changes over time. As the defects of interest tend to occur over sustained periods of time, the LRUT monitoring may only need to be conducted intermittently, perhaps weekly or monthly.

2. Guided Waves

As described earlier, conventional ultrasound is already widely employed to automatically inspect the rail network across Europe. Conventional ultrasound employs acoustic waves which have a wavelength which is insignificant in comparison to the dimensions of the medium in which they are travelling. The wavelength is similar to features within the medium which causes scattering and attenuation. As the frequency of the acoustic waves is decreased and the wavelength increases, the acoustic waves become confined or guided and the scattering effect is much reduced. These guided waves can travel long distances without significant attenuation and are sensitive to changes in the geometry and acoustic characteristics of the medium. Guided waves are therefore eminently suitable for permanently installed automatic monitoring systems allowing coverage of significant lengths of infrastructure from a small number of monitoring points[4].

Rails are an excellent application for long range ultrasonic testing because they are now installed as continuous welded lengths of up to more than 1km[5]. As these are of constant cross section along their length, waves generated at one point will travel long distances.

2.1 Modelling of guided waves

In order to exploit the potential of utilising guided waves in the rail, there is a need to characterise their behaviour with respect to the rail structure of interest. Guided waves are sensitive to the structure's cross-sectional shape, thickness and material properties (Poisson's ratio, Young's modulus and density). A large exercise has been carried out to determine the properties of waves in the three different parts of the rail section and their sensitivity for defect detection[6].

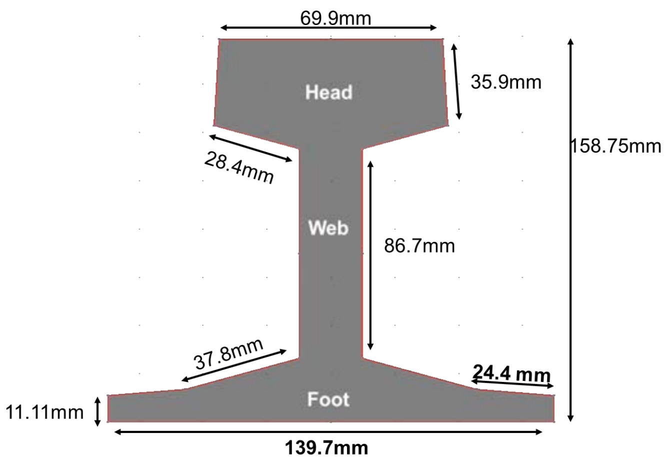

Figure 1. Geometry of standard dimensions (BS113A)

This study was carried out on a steel rail of dimensions as shown in Figure 1, with a density of 7830kg/m. Young's modulus of 207GPa, and Poisson's ratio of 0.33. The element length was equal to a tenth of the minimum wavelength. This enabled the model to simulate the wave modes present efficiently. The element type used in the models was an 8-noded brick (ABAQUS element type C3D8). The FE model has been symmetrically constrained at both ends in the in-plane direction. An Eigensolver was used to calculate the resonant frequencies and mode shapes for the rail model. Each calculated resonant frequency corresponded to a standing wave over the length of the model. The integer multiple of half wavelengths and the corresponding frequencies for the standing wave enabled the calculation of wave number and ultimately phase velocity.

As a consequence a number of modes have been identified which are confined to the regions of the rail which require monitoring. Figure 2 shows a summary of the identified modes.

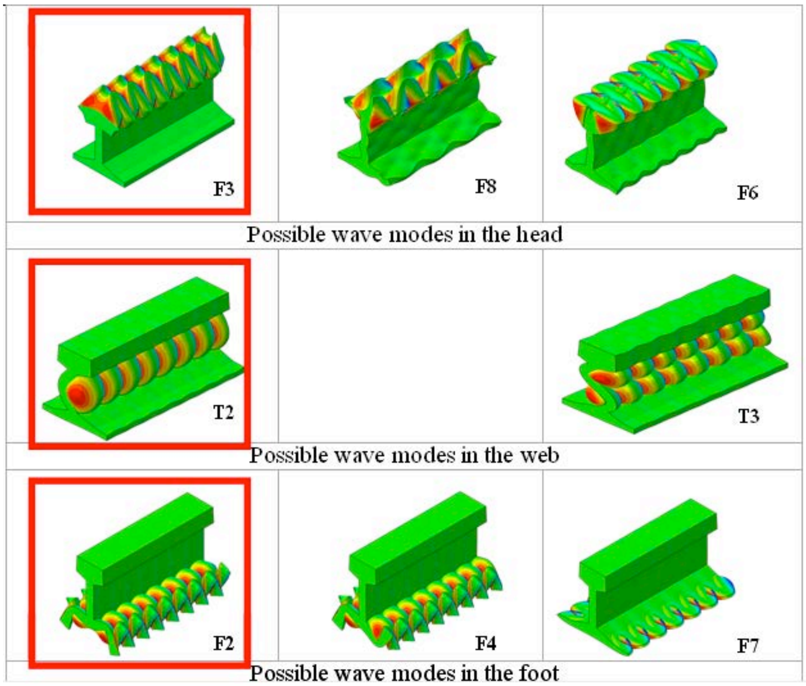

Figure 2. A range of wave modes confined to specific parts of the rail

Continuing work is looking into the interaction of these wave modes with specific defects within the different areas of the rail.

2.2 Detection of defects in the presence of rail fastening systems

One of the earliest experiments of the project was a brief investigation of guided wave propagation in a clipped rail at Birmingham University using a Teletest[7]. Figure 3 shows a section of rail with a Pandrol PR clip system.

Figure 3. Pandrol PR clip system on an experimental section of rail at the University of Birmingham.

The figure clearly shows the lack of insulation so that the system is acoustically coupled to the rail. This is evident from the complexity of the waveform shown in Figure 4. The figure is labelled with the estimated arrival times of a pure F2 wave mode propagating at 2900m/s reflected by the features of the rail. These include a series of PR clips, an Aluminothermic weld and the far end of the rail.

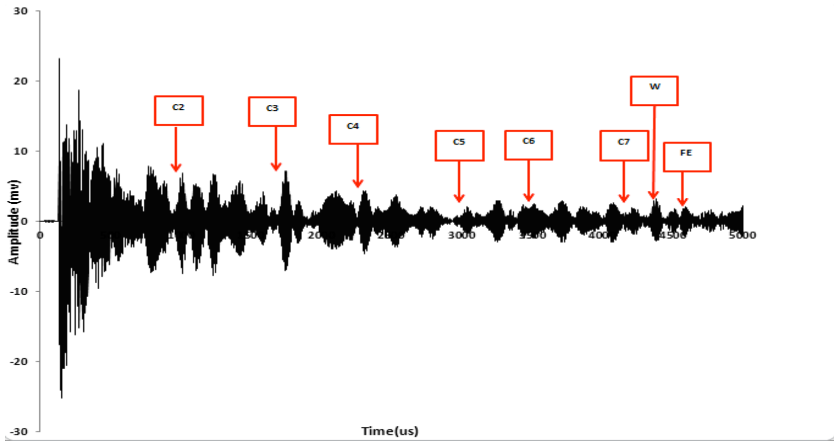

Figure 4. The A-scan acquired from the rail end at 77kHz for 5ms.

The figure clearly shows a superposition of other modes, excited by the signal injection and also created by mode conversion at the various features in the rail.

Subsequently the project constructed a small rail laboratory at TWI, Cambridge UK, where the effect of alternative rail fastening systems could be investigated. Figure 5 shows the laboratory.

Figure 5. Rail laboratory facilities at TWI.

Figure 6 shows the attachment of shear transducers to the rail using an early experimental prototype.

Figure 6. Experimental transducer mounting for rail foot examinations.

Again, the Teletest was used to acquire a simple A-scan from an unclipped rail. Figure 7 shows the result.

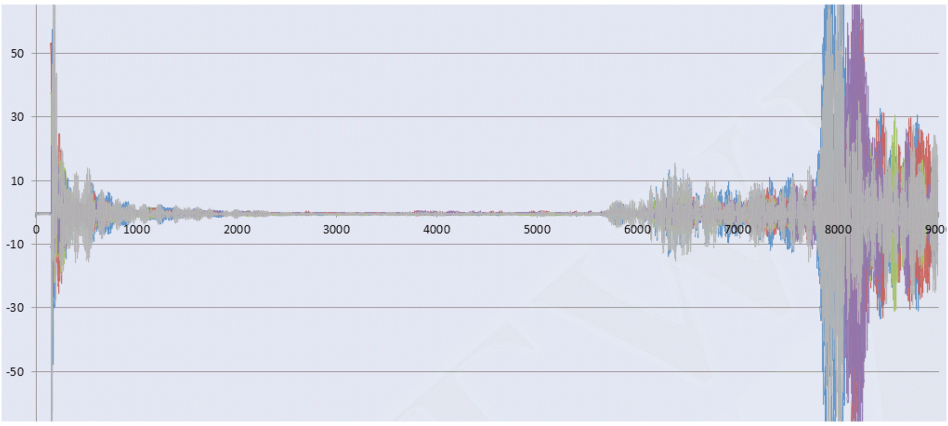

Figure 7. Complex multi mode signals reflected from the rail end

Figure 7 shows the many wave modes stimulated by the excitation and created by mode conversion at the end of the rail. The figure also shows a clear time window in which defects can be introduced without contamination from the fastest wave modes reflecting from the end of the rail. A position for a simulated defect was calculated accordingly and introduced progressively while monitoring the A-scans. Figure 8 shows the manner in which the defects were introduced and the increasing energy being reflected by the defect as its size increased.

Figure 8. Progressive introduction of a transverse slot and the reflected signals

Independent signals are distinguishable through simple observation at approximately 8mm^2 (olive trace). The blue trace is generated by a defect of approximately 42mm^2.

This experiment was repeated for a rail that was to be fastened to the concrete sleepers. Figure 9 shows the simple A-scans from that experiment. The top trace shows the defect at 5000us with a completely free rail. The middle trace shows the signals from the rail having been dropped onto the dimpled rubber pads. The bottom trace shows
The signals after all of the clips between the transducer and the defect have been added.

The signals show primarily a significant attenuation of the A-scan and some weak reflected signals from the clips, but, importantly, the signal from the defect is still distinguishable by eye without any processing of the signals or attempts to generate pure mode excitations.

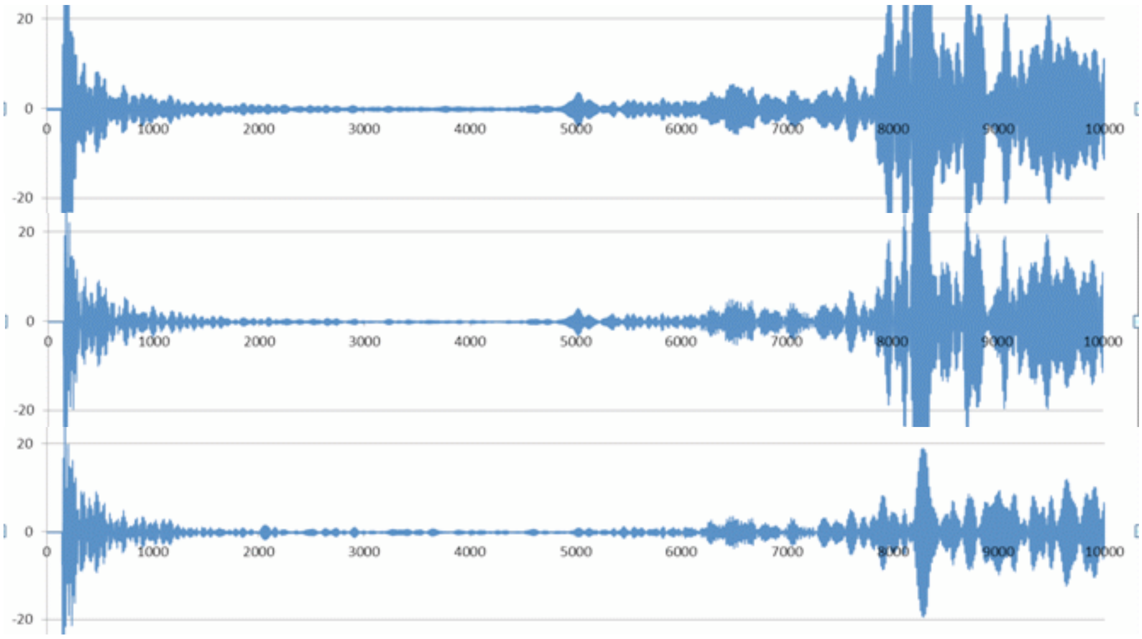

Figure 9. Experimental transducer mounting for rail foot examinations.

2.3 Automated defect detection

Where multi-mode signals from defects are superposed with those from other rail features, as in Figure 4, identification of defects by eye is impossible. In these circumstances, the project has demonstrated that robust defect detection is still possible. Moustakidis et al.[8] have demonstrated an array of techniques for normalization, temperature compensation, feature extraction and selection and have used the Support Vector Machine (SVM) to perform classification.

While this described method is able to detect the defect, the position of the defect will only be determined in the presence of other signals if multi-mode signals can be decomposed to deliver accurate range information or if a degree of mode purity can be achieved at excitation with minimal dispersion and minimal mode conversion on reflection from the rail features.

3. Acoustic Emission

Acoustic emissions or transient elastic waves are generated when there is any sudden release of strain energy within a material[9] e.g. a crack propagating up from the foot of a rail under excessive tensile load.

A sudden release of strain energy within a rail can be expected to be a broadband acoustic excitation so that a portion of the acoustic energy released might propagate over long distances as guided waves, as described above.

If a rail is monitored for acoustic emission events at 2 or more points in a length of rail, then an originating location of the acoustic emission can be determined by time-of-flight techniques. This assumes that there is not significant attenuation of the AE signals in the chosen length of rail.

Location of a defect by acoustic emission has an advantage over conventional guided wave ultrasound. As discussed above, guided wave ultrasound signals reflected from a defect can be buried in multi-mode signals from other rail features. Acoustic emission signals, on the other hand, are not reflected but directly transmitted. The location is determined by the time-of-flight of the wavefront of the fastest travelling mode.

3.1 Modelling of acoustic emission events

The project simulated a sudden release of strain energy within a rail to investigate the propagation of any resulting guided waves. A model was constructed and Elasto-Dynamic Finite Integration was used to calculate the effect of a step change in the body forces acting on a seed placed on the surface of the foot of the rail.

Figure 10 shows the results of the simulation for a short time interval after the step change.

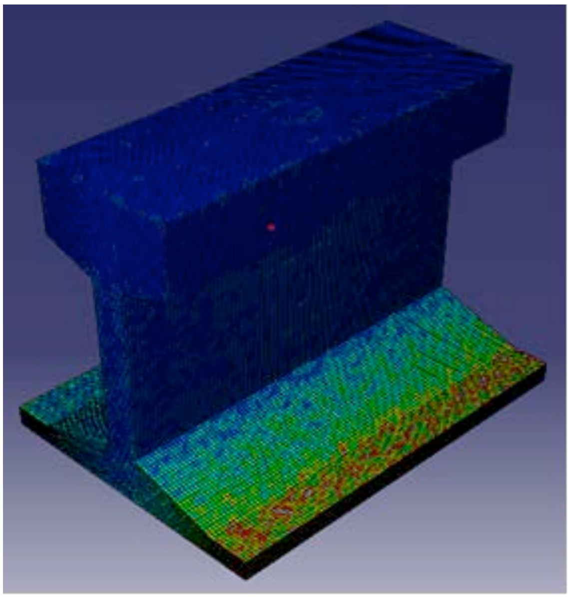

Figure 10. Surface perturbation shortly after a step change in body forces at the seed element.

The energy released by the simulated crack propagation event remains largely confined to the foot of the rail and is propagating along the rail. The energy also remains confined to one side of the rail. This may allow even greater accuracy when locating the source of acoustic emission events.

3.2Characterisation and distinguishing acoustic emission events

Crack propagation is not the only source of suddenly released strain energy. Wheel/rail interactions, especially where the wheel or rail are damaged, will generate intense acoustic emission events. Even rain or hail can generate acoustic emission events.

To further complicate the situation, the greatest tensile forces in the bottom of the rail can be expected to occur while a locomotive wheel is passing over that section of rail i.e. the acoustic emission event associated with a crack propagation is most likely to occur in the presence of noise from the wheel/rail interaction.

Figure 11 shows the measurement of events from a propagated head crack using a Mistras 1282[10].

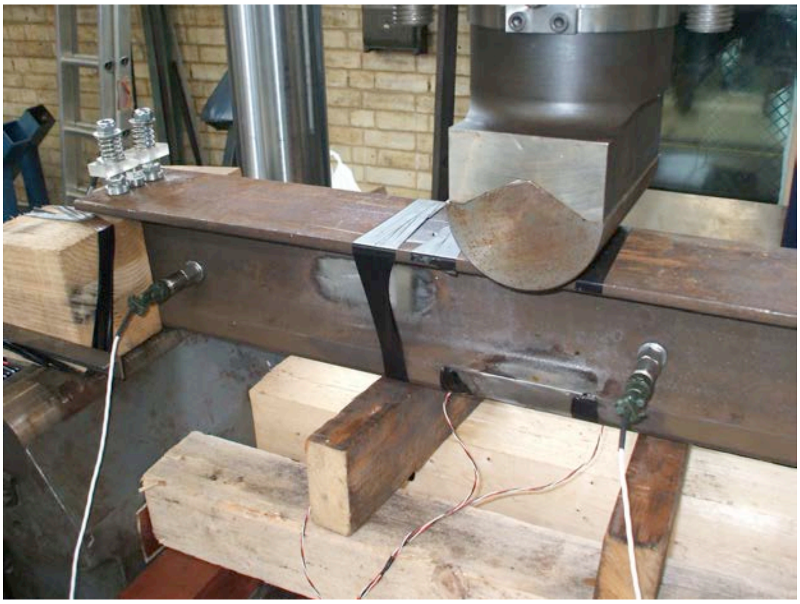

Figure 11. Acoustic emission monitoring during crack propagation in a section of rail on a 3 point bending machine.

The project intends to reject spurious acoustic emission events by virtue of the characteristics of the events but also on the basis of calculated location to raise confidence in the system.

4. Conclusions

The importance of rail monitoring has been highlighted. The chosen techniques and technologies have been described and their suitability shown. The utility of guided ultrasound for this project has been demonstrated.

Work continues to a create a practical implementation of the Monitorail system, to improve signal purity in real situations and to fuse the information provided by both of the main techniques to produce confident defect detection and localisation.

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