Monitoring of Rail Track Using Guided Wave Ultrasound

Philip LOVEDAY 1, Dineo RAMATLO 1,2, Francois BURGER 3

1 CSIR Materials Science and Manufacturing, Pretoria, South Africa
2 University of Pretoria, Pretoria, South Africa
3 Institute for Maritime Technology, Simon’s Town, South Africa

Contact e-mail: ploveday@csir.co.za

Abstract. Continuously welded rail track is an example of an effectively one-dimensional waveguide where guided waves can propagate large distances making it possible to monitor a length of rail from a single location. In heavy duty rail lines the high axle loads and varying levels of tension in the rail cause cracks and eventually complete breakage of the rail. While inspections, using conventional ultrasonic and magnetic induction techniques, are performed periodically and repairs are made when cracks are detected a disturbingly large number of rail breaks occur around the world. Fortunately, only a small number of breaks result in train derailments. Nevertheless, the consequences of derailments led to the development of a guided wave ultrasound break detection system in South Africa. This system operates by transmitting guided waves between permanently installed transmit and receive transducers spaced approximately 1km apart. The system is currently installed on 840 km of a heavy duty rail line and is described along with performance achieved and challenges.

Research being conducted to add a pulse-echo mode of operation to the system for crack detection, location and monitoring is presented. This includes hybrid FE-SAFE modelling of the interaction of guided wave modes with different cracks and field measurements of reflections from welds using transducer arrays and model-based signal processing. Results indicate that it should be possible to detect cracks in the rail head at long range. Detection of cracks in the foot of the rail remains a difficult but important challenge.

1. Introduction

Continuously welded rail track used extensively in heavy haul rail lines experiences large mechanical and thermal stress variations, which can lead to cracks and complete breaks. Operators employ inspection techniques often comprising ultrasonic and electromagnetic inspection from inspection cars to detect cracks prior to breakage. Nevertheless a surprising number of rail breaks occur every year but fortunately only a fraction of these results in train derailments [1].

Ultrasonic guided waves offer the potential of inspecting a long length of an effectively one-dimensional waveguide, such as a continuously welded rail, from a single transducer location. This potential was realised in a system developed in the UK to inspect rail at level crossings for corrosion damage [2]. This system utilized an array of
transducers wrapped around the rail for guided wave mode and direction control and required interruption of train operation. An alternate approach was adopted for near real-time monitoring of a heavy haul rail line in South Africa. This system had permanently installed ultrasonic transducers along the length on the line and was designed to be primarily a rail break detector. A recent installation of this system is described in section 2.

The two approaches were reviewed in a paper presented at the 18th WCNDT [3] and the possibility of achieving some defect detection at long distances with a low number of transducers was considered. Progress towards this goal is described in section 3.

2. Rail Break Detection and Monitoring

Almost 20 years ago a need for rail break detection on heavy haul lines in South Africa was identified. A study was performed to compare different concepts and an acoustic concept was selected for development of the Ultrasonic Broken Rail Detection (UBRD) system [4]. The concept involved the transmission of ultrasound between permanently installed transmit and receive stations placed alternately along the length of track to be monitored as illustrated in figure 1. Low power electronics had to be developed as the stations are solar powered. The transmit stations operate autonomously and transmit a coded sequence of signals at a predefined time interval. If the neighbouring receiver station does not receive the signals within an appropriate time interval an alarm is triggered. Various logical checks are made to avoid false alarms.

While the concept is simple numerous iterations were required to achieve reliable operation [5]. A large scale installation of UBRD Version 4 was performed in 2013/2014 [6]. The spacing between each transmit or receive station was determined based on measured acoustic signal transmission levels with allowance made for further degradation of the signals as the rail ages. On average the stations were spaced 900m apart and 931 sites were selected for transmit or receive stations along the 840 km length of the line. Figure 2 shows equipment at one site.

![Fig. 1. Ultrasonic Broken Rail Detection Concept.](image)
The system was programmed to interrogate the entire rail length every 15 minutes. The receive stations transmit information to a server via GPRS or digital radio network. The information is recorded and displayed for each section of rail. Figure 3 shows an example display for one of the twenty rail sections.

The operation of the system is monitored daily and an equipment status report for the receive stations is generated such as the one shown in figure 4. Some problems with the reliability of the GSM network was experienced and some of these receive stations were changed from using the GSM network to the digital radio network for communications. The main cause of system unavailability is theft of equipment in areas close to human settlements. The theft of solar panels, charge controllers and batteries means that some parts of the system are not operational. These stations will be upgraded with theft hardened enclosures and solar panels. In the first two months of operation four broken rails were detected and approximately four cracks were detected before complete fracture occurred. It is believed that the system has prevented at least one derailment, the cost of which is similar to the cost of installing the system on the entire 840 km line.
The transducer used in the UBRD system up to Version 4 was developed experimentally with little understanding of guided wave ultrasound [7]. The propagation and transduction of guided wave ultrasound in rails was researched after this development. Numerical modeling techniques combining three-dimensional finite element models, to model the piezoelectric transducer, with semi-analytical finite element (SAFE) models [8], to describe the guided wave propagation in the rail, were developed [9], [10]. A technique for measuring the modes of propagation in the rail using a scanning laser vibrometer was developed and used to characterize transducers and to measure attenuation of individual modes of propagation in the field [11]. Fig. 5 shows the wave propagation in a rail measured 400m away from the transducer.

These tools were used to develop a second generation transducer, which targets a selected mode of propagation and produces an order of magnitude greater excitation while being more sensitive on receiving. This transducer is currently undergoing long term testing on the rail. Modern digital signal processing techniques have been implemented and along with the second generation transducer will be available in UBRD Version 5. These improvements will allow the distance between transmit and receive stations to be increased from the current average of 900m to 1800m and will therefore make the system cheaper to install and to maintain. Version 5 will remain primarily a broken rail detector.
3. Rail Defect Detection at Long Range

The possibility of detecting cracks at long range prior to complete breakage is being investigated. It is proposed that adding a pulse-echo mode of operation to the UBRD system would make it possible to detect, locate and possibly monitor the growth of cracks. Research is being conducted with the hope that UBRD Version 6 will emerge as a defect detector, which reduces the occurrence of rail breaks.

For detection of a particular defect, guided wave modes that interact with that defect must be used. For long range detection it is also required that the guided wave mode can propagate over large distances with acceptable attenuation. If a monitoring system is to be developed it is also required that the modes used can be excited and sensed by permanently installed transducer arrays with a low number of transducers.

The mode used for break detection has energy concentrated in the head of the rail and would be suitable for detecting transverse defects in the head of the rail. For monitoring the web of the rail a mode with energy concentrated in the web should be used and such a mode is known to exist. Modes of propagation, computed by SAFE modelling, which are suitable for head and web monitoring, are illustrated in figure 6.

Sizeable cracks are not available for field testing as these would be repaired if they are known to be present in the rail. Instead we have used the reflections from aluminothermic welds (with weld caps) for experimental investigations. The reflection that would be obtained from a particular defect can be predicted by numerical modelling and compared to that predicted for a weld. For this purpose a hybrid SAFE – 3D FE method [12] was implemented and has been used to predict the scattering of guided wave modes by welds and other defects. Figure 7 shows a model of a weld and the reflection and transmission of the two guided wave modes illustrated in figure 6.
A defect such as a transverse defect can be modelled and compared to the weld reflections. Figure 8 shows the comparison for the mode propagating mainly in the rail head. We conclude that if the weld can be detected at a certain distance then a transverse defect of reasonable size should also be detectable.

Fig. 8. Numerical comparison of defect and weld reflections.

Experimental measurements have been performed to determine if welds can be detected at long range. Initial measurements used four transducers mounted under the head of the rail and a weld at a distance of 790m was detected [13]. Later measurements used only two transducers and achieved a distance of over 1000m. Photographs of an aluminothermic weld and two transducers are shown in figure 9.

Fig. 9. Aluminothermic welds and transducers with measured weld reflections using mode in rail head.

The signals received by the transducers operating in pulse-echo mode are processed using dispersion characteristics of the selected mode computed from SAFE modelling.
Array processing is performed to determine which side of the array (left or right) the reflection comes from and dispersion compensation was performed. The peaks in the graph in figure 9 correspond to the presence of aluminothermic welds along the rail. Based on the numerical modelling results in figure 8 it is expected that it will be possible to detect transverse defects in the rail head at a range of 1000m well before rail break occurs.

We are developing a transducer for testing the web mode. Numerical modelling was used to predict the response of the web mode when excited by a transducer design with remarkable accuracy [14]. Optimization of the transducer design was performed using design of experiments and 500 solutions of the numerical model. Initial lab measurements show remarkable agreement with numerical predictions and field measurements are planned.

Detection of defects in the rail foot is of great interest to rail operators as they do not currently have a satisfactory inspection technique let alone a monitoring technique for this part of the rail. Detection of defects in the foot of the rail using guided waves is significantly more difficult as energy in the foot of the rail is absorbed by polymer pads between the rail and concrete sleepers. Attempts by Hayashi et al. [15], [16], Wilkinson [17] and Moustakidis et al. [18] used guided wave modes having considerable energy in the rail foot and serve to illustrate the difficulties involved even for short range detection.

4. Conclusions

Guided wave ultrasound has potential for inspection and monitoring of rail track. In the extreme case when only complete breaks are to be detected a system operating in transmission mode has proven to be effective for near real-time monitoring. If cracks are to be detected prior to complete breakage then a pulse-echo mode of operation can be added and would be expected to locate the cracks and possibly monitor the growth of cracks. Regular welds occurring in rail track provide useful reflectors for developing measurement techniques and provide results for calibration of numerical models. These welds have been detected at kilometre range using a guided wave mode with energy concentrated in the rail head. It is expected that transverse defects in the rail head would be detectable at similar ranges. A guided wave mode with energy concentrated in the web exists and a transducer has been developed to excite this mode. Detection of cracks in the rail foot at long range remains a difficult but important challenge.

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References