Rail Track Monitoring using Ultrasonic Guided Waves

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ABSTRACT

Ultrasonic guided waves have been shown to propagate large distances in continuously welded rail track. This physical phenomenon was exploited in the development of an ultrasonic broken rail detection system which has been deployed on a heavy haul rail line. This system transmits ultrasonic guided waves between permanently installed transmitter and receiver stations spaced approximately 900m apart and can inspect the entire line every 15 minutes. Broken rails which could have caused train derailments have been detected by the system. Research into guided wave excitation and propagation in rails led to the design of a small but powerful transducer, which along with other improvements will allow the next version of the system to have double the spacing between stations. Research into long-range detection of defects by using two of these transducers as an array in pulse-echo mode indicated that it should be possible to detect relatively small cracks in the head of the rail and thereby eliminate this source of broken rails.

Keywords: Ultrasonic guided waves, rail track monitoring, broken rail detection

1.0 INTRODUCTION

Severe stresses are experienced by rails used in heavy haul railway lines. These lines use continuously welded rail where long sections of rail are welded together using aluminothermic welding during installation of the track. The rails are installed in tension to avoid compressive stresses at the highest expected temperatures because compression can lead to rail buckling. Variations in temperature give rise to fluctuations in the thermal stresses in the rail with the largest stresses being experienced at the coldest temperatures. In heavy haul lines the rails are subjected to very high loads at the point of wheel contact. These stresses can cause rolling contact fatigue cracks which, if not removed, may result in broken rails.

Regular non-destructive testing is performed on most tracks, using conventional ultrasound and magnetic induction inspection techniques, but some defects are not detected and may lead to broken rails. Depending on the effectiveness of the inspections rail breaks occur at a rate of one broken rail for every 10 to 20 defects that are detected [1].

In South Africa broken rails cause almost 60% of derailments on the iron ore export line known as ORELINE and operated by Transnet Freight Rail [2]. This 861 km long single line is continuously welded and uses axle counters instead of track circuits for signalling. Trains on this line are up to 4 km long, have a 30 tonne axle load and have locomotives distributed along the train. Monthly inspections by ultrasonic inspection cars are performed but a number of defects especially in the aluminothermic welds result in broken rails and sometimes derailments. The high cost of these derailments prompted the development of a system to monitor the rail and trigger an alarm when rail breaks occur. The rail operator reviewed different techniques for detecting broken rails and decided on the 'acoustic detection technique', which makes use of the fact that certain ultrasonic guided waves can propagate long distances in continuously welded rail track. This paper focusses on research and development performed in South Africa to develop rail monitoring systems using ultrasonic guided waves.

Systems which have been developed and deployed to detect broken rails are described in the next section. Research on the use of ultrasonic guided waves to detect defects before they cause a broken rail (and therefore prevent broken rails) will be described in the following section.

2.0 BROKEN RAIL DETECTION SYSTEMS

The development of a series of Ultrasonic Broken Rail Detector (UBRD) systems began in 1996 when the Institute of Maritime Technology (IMT) was contracted to develop the first such system. The system operated by transmitting ultrasonic guided wave signals between transmitter and receiver stations located along the length of the line as depicted in figure 1. The transmitter and receiver stations are solar powered and operate autonomously with the transmitter station programmed to transmit a sequence of signals every 15 minutes. If the signals are not received at the neighbouring receiver stations an alarm is sent to a control centre and train operation is halted.

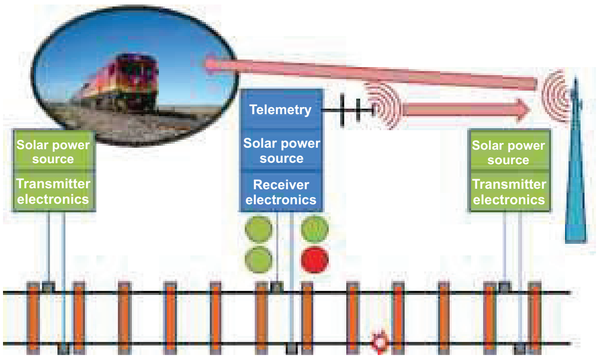
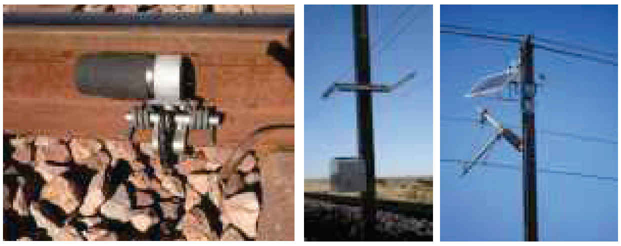


Figure 1. Ultrasonic Broken Rail Detection System Operation.

The operation of the system in a transmit-receive mode is conceptually simple but obtaining robust and reliable operation, without false alarms, was very difficult and a number of challenges had to be overcome. The piezoelectric ultrasonic transducers, which are permanently installed on the rail, were developed by the CSIR who had experience in the development of underwater sonar transducers but no knowledge of ultrasonic guided waves at that time.

The original transducers were developed by testing a few configurations on the rail track and selecting the configuration with the best performance [3]. The basic configuration of the transducer remained the same throughout UBRD versions 1 to 4 although many modifications were made to produce reliable operation in the harsh environment experienced by track-mounted equipment. Issues such as large variations in signal propagation loss, train and other noise sources, hostile EMI environment with traction and lightning induced surges, electronics reliability, poor availability of communications infrastructure and theft of equipment had to be overcome at the system level. After many years of development a system was shown to be reliable by completing a 15 month long test on 34 km of track in a poor condition without false alarms [4]. Three complete breaks and six large defects were detected during this test. Following this success the UBRD Version 4 system was deployed on 841 km of the ORELINE requiring 931 stations and the installation was completed in June 2014 [5]. In 2017 it was reported by the rail operator that the system had detected 12 rail breaks [2]. Equipment at a typical station is shown in figure 2. The UBRD V4 system is currently installed at two sites in India where it is being evaluated.



(a) (b) (c)

Figure 2. UBRD V4 components, a) piezoelectric transducer and spring clamp, b) mast mounted electronics cabinet and c) mast mounted solar panel.

Research was conducted at the CSIR, South Africa to numerically simulate the excitation of guided waves by piezoelectric transducers [6][7]. This involved the combination of a semi-analytical finite element (SAFE) model of the rail with a conventional 3D finite element (FE) model of the piezoelectric transducer. The model could predict the amplitudes of the guided wave modes that would be excited by the transducer and allows the design of the transducer to be optimised to excite a particular mode strongly [8]. Group velocity dispersion curve computed using SAFE modelling, mode shapes of three modes and a model of a piezoelectric ultrasonic transducer exciting a rail model are shown in figure 3.

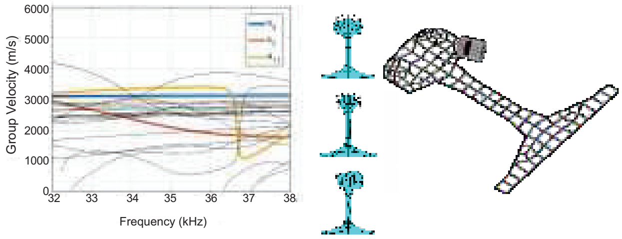


Figure 3. Computed group velocity dispersion curves for UIC60 rail. Modes s3 (top), s7 (middle) and a11 (bottom) are highlighted. 3D FE model of transducer exciting 2D SAFE model of rail.

A technique was developed to measure the excitation and propagation of the guided wave mode in operational rail track [9]. This confirmed numerical predictions and identified modes that are suitable for long range propagation. Figure 4 shows a measurement performed with a scanning laser vibrometer at a distance of 500 m from a transducer on an operational rail track.

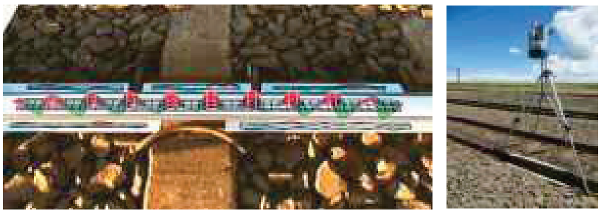


Figure 4. Scanning laser vibrometer measurement of ultrasonic guided waves.

The knowledge generated by this research was used to design a small transducer specifically to excite the s3 mode illustrated in figure 3. While this transducer is small enough to fit under the rail head on the inside of the rail it produced an order of magnitude more displacement in the desired mode of propagation, than the previous transducer, and was also an order of magnitude more sensitive for receiving this mode. The small transducer was industrialised for use in an upgraded system UBRD V5. Two transducers being tested during the industrialization phase are shown in figure 5. The upgraded system also included modern digital signal processing hardware and signal detection techniques which allows quicker interrogation times. Radio communications between stations allow the receiver station to request a neighbouring transmitter station to send the signals when there is no train noise present or to resend signals if they are not detected to reduce the probabilities of false alarms. The UBRD V5 system is being tested on the ORELINE with transmitter and receiver stations spaced 2000m apart [10].

3.0 BROKEN RAIL PREVENTION RESEARCH

A sophisticated guided wave inspection system aimed at detecting smooth transverse-vertical defects and volumetric examination of aluminothermic welds in rail track was developed by Imperial College and Guided Ultrasonics Ltd [11]. An array of dry-coupled piezoelectric transducers around the circumference of the rail was used to transmit and receive selected guided waves in pulse-echo mode. The system could inspect 100m of rail from one position and would be moved to another position to inspect the next section of rail. Train operation would have to be interrupted during the inspection. While this system was not suitable for monitoring of rail track it did demonstrate that small defects can be detected, located and classified using different guided wave modes. The possibility of adopting some of these ideas to extend the broken rail detection system to a defect detection system was raised in [12]. For such a monitoring system to be feasible it would be necessary to use an array of only a few permanently installed transducers in pulse-echo mode at each station and to be able to detect defects at long ranges.

Numerical modelling of the scattering of guided wave modes was performed using a hybrid SAFE-3DFE method [13].

Suitable defects are not available for measurement but aluminothermic welds are readily available. The predicted reflections from aluminothermic welds and transverse defects in the head of the rail were compared as shown in figure 5. It was found that even a relatively small vertical crack in the rail head will reflect the selected mode of propagation in a fashion similar to that of a weld cap. Therefore if we can detect the aluminothermic welds we expect to be able to detect relatively small cracks.

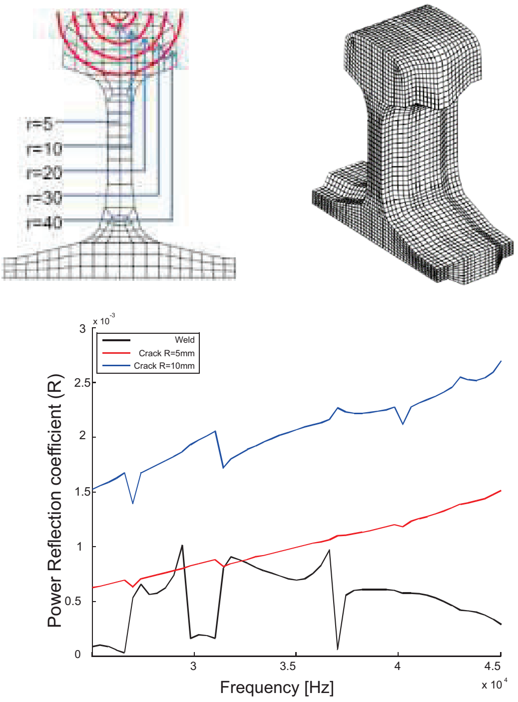


Figure 5. Numerical modelling to predict and compare scattering by cracks and welds.

Measurements were performed to investigate the feasibility of this idea for detecting defects in the head of the rail using the transducers developed for the UBRD V5 system. Initially and array of four transducers were used with two transducers on the inside and two transducers on the outside of the rail. Later an array of only two transducers was used as shown in figure 6. Also shown in Figure 6 are a pair of typical aluminothermic welds and a graph of reflections versus distance showing large reflections from the aluminothermic welds. Note that the signals from the two transducers have been processed to determine the direction of the welds from the transducers.

The experiments revealed that it was possible to detect aluminothermic welds that are 1000m away from the transducers. It is therefore expected that cracks will be detected at this range well before they result in rail breaks. The measurement shown in figure 6 is similar to a once-off inspection. When the system is permanently installed a large amount of data can be gathered and then analysed to detect the growth of defects. This approach is being used in pipelines where permanently installed guided wave systems have been shown to detect corrosion at a size that would not be possible with a once off inspection [14]. If the only change occurring in a system was the growth of a defect it would be possible to detect very small defects by subtracting an earlier baseline signal (assumed to be defect free) from the current signal. Unfortunately there are numerous other variations that take place due to environmental operating conditions such as changing temperatures.

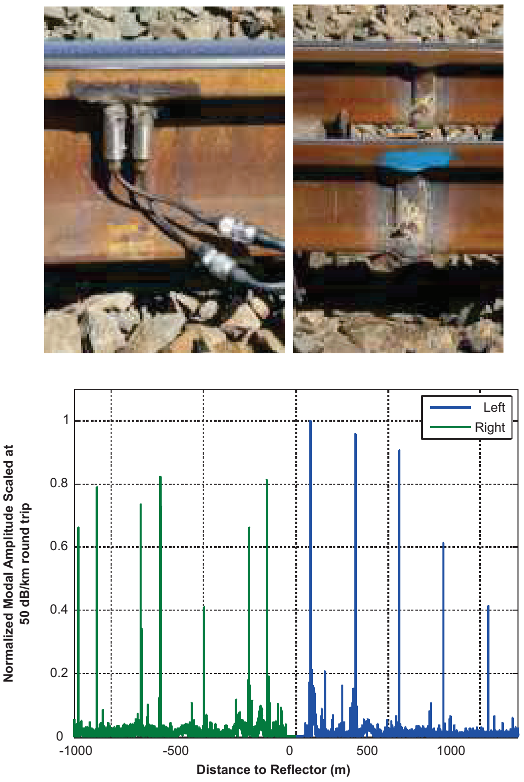


Figure 6. Experiments performed to detect reflections from aluminothermic.

Machine learning techniques have been applied to the pipeline data to distinguish the defect growth from other variations [15]. These techniques are being investigated for the rail track monitoring application and have been applied to data obtained from an operational rail track over a two week period with and artificial defect glued to the rail. The results are promising and it is anticipated that a vertical crack in the rail head of 20 mm2 area would be detected [16]. This work only considered defects in the head of the rail. Defects that can lead to rail breaks are also found in the web and the foot of the rail. Long range propagation in the web of the rail is possible and it is expected that defect detection should be possible.

Future rail monitoring systems could use this technique but it is expected that a robust commercial system would require considerable development.

4.0 CONCLUSIONS

Many years of development were required to develop a robust broken rail monitoring system. This system known as UBRD V4 has been applied on a large scale and has detected broken rails and prevented possible derailments on a heavy haul line. An upgraded system, UBRD V5, was developed based on a small but powerful transducer which was designed using knowledge of guided wave ultrasound.

This system is being tested with transmitter and receiver stations spaced 2000m apart although this is dependent on the condition of the rails.

Broken rails could be prevented by early detection of cracks. This appears to be feasible for cracks in the head of the rail although a system would need to be developed to do this without false alarms. Current research is aimed at quantifying the probabilities of detection and false alarm for such a system. Broken rails could be prevented by early detection of cracks. This appears to be feasible for cracks in the head of the rail although a system would need to be developed to do this without false alarms. Current research is aimed at quantifying the probabilities of detection and false alarm for such a system.

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