Long Range Guided Wave Monitoring of Rail Track

Philip W. Loveday\textsuperscript{1,a}, Craig S. Long\textsuperscript{1,b} and Francois A. Burger\textsuperscript{2,c}

\textsuperscript{1}CSIR Materials Science and Manufacturing, South Africa

\textsuperscript{2}Institute for Maritime Technology, South Africa

\textsuperscript{a}PLoveday@csir.co.za, \textsuperscript{b}CLong@csir.co.za, \textsuperscript{c}fab@imt.co.za

Keywords: Guided wave ultrasound, break and defect detection, monitoring of rail track.

Abstract. A guided wave ultrasound system was developed in South Africa for monitoring rail track used in heavy duty freight lines. This system operates by transmitting guided waves between permanently installed transmit and receive transducers spaced approximately 1km apart. The system has been proven to reliably detect rail breaks without false alarms. Improved transducers and signal processing have been demonstrated to achieve double the distance, which will reduce the cost of the system in future. Current research is aimed at improving the system by adding a pulse-echo mode of operation to detect, locate and possibly monitor certain cracks. Initial pulse-echo field measurement results are presented. These results were obtained using a small array of transducers to control the direction and mode of propagation and full matrix capture with subsequent array processing. The results demonstrate that a thermite weld can be detected at a range of 790m from the transducer array in new rail. A hybrid FE-SAFE model was used to compare the scattering from this weld to that expected from cracks. The numerical results suggest that certain cracks could be detected at a range of over 500m and that 1km of rail could be monitored from a single location.

Introduction

One of the advantages of guided wave ultrasound is the potential to inspect a large volume of a structure from a single transducer location. Continuously welded rail track is an example of a one-dimensional elastic waveguide and is therefore a strong candidate for structural health monitoring using guided wave ultrasound. Numerous distinct defects occur in rail track and different strategies are devised for managing different rail systems [1]. While rail defect management strives to detect damage before rail breaks occur, a large number of complete breaks do occur. For example, about 770 rail breaks per year occurred in the UK between 1969 and 2000 [1]. Fortunately, only a very small fraction of rail breaks result in derailments. Nevertheless the consequences of derailments can be so severe that detecting defects and breaks remains an important challenge. Depending on the application, guided waves can be exploited for this purpose in different ways.

Two different guided wave based approaches were reviewed in [2]. Firstly an inspection system was developed in the UK by Imperial College and Guided Ultrasonics Ltd [3]. This system was intended for periodic inspection of rail track during which train operation would be halted. The system could inspect 100m of rail from one location and could inspect buried rail at level crossings. An array of dry-coupled transducers, wrapped around the rail circumference, was used to transmit and receive different modes of propagation. Coupling between the modes was used to identify seven different defect types and relatively small defects could be detected. The second approach was to develop a permanently installed monitoring system to detect complete breaks in the rail. This system was developed in South Africa by the Institute of Maritime Technology with ultrasonic transducers developed by the CSIR and was intended specifically for monitoring heavy-haul rail
track. This was a relatively simple system using pitch-catch operation between transducers spaced approximately 1km apart.

The break detection system is described in the next section along with current developments aimed at making it more affordable by increasing the distance between transmit and receive transducers. The possibility of extending this system to perform defect detection prior to breakage is then discussed and initial experimental results are presented.

Rail Break Detection

Rail breaks were a serious problem on a dedicated iron ore line in South Africa and a need for a broken rail detection system was identified. A move to communication based train control systems rendered track circuits, which offered partial broken rail detection, obsolete. A study of various concepts was performed by the rail operator [4] and the acoustic detection concept illustrated in Fig. 1 was selected for development.

![Figure 1](image)

The Institute of Maritime Technology were contracted to develop the system and the CSIR was subcontracted to develop the ultrasonic transducers. While the concept is simple, obtaining reliable operation proved to be a great challenge. Issues such as large variations in signal propagation loss, train and other noise sources, hostile EMI environment with traction and lightning induced surges and theft of equipment had to be overcome. Eventually, a reliable system without false alarms was demonstrated in a 15 month test covering 34km of poor condition rail [5]. During this test, three complete breaks and six large defects were detected. Due to the success of this test the system is currently being installed on the entire 850km long line.

The transducer used in this system was developed experimentally with little understanding of guided wave ultrasound [6]. Since this development research has been conducted into the propagation and transduction of guided wave ultrasound in rails. Numerical modeling techniques combining three-dimensional finite element models, to model the piezoelectric transducer, with semi-analytical finite element (SAFE) models [7], to describe the guided wave propagation in the rail, were developed [8], [9]. 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 [10]. Fig. 2 shows the wave propagation in a rail measured 400m away from the transducer.
The modeling and measurement techniques, along with insights gained during their development, were used to develop a second generation transducer. This transducer was specifically designed to excite and sense a selected mode of propagation and produces an order of magnitude greater excitation while being more sensitive on receive. This transducer is currently being industrialized to make it ready for production and qualified to prove that it will survive in the harsh environment. This transducer will be used with modern digital signal processing in a future version of the rail break detection system. These improvements will allow the distance between transmit and receive stations to be increased from the current average of 900m to 2000m and will therefore make the system cheaper to install and to maintain.

Towards Defect Detection

While the broken rail detection system does sometimes detect large defects prior to complete breakage it is primarily intended to detect complete breaks. In the pitch-catch mode of operation it is possible to increase the sensitivity of the system to defects but this comes at the cost of increased probability of false alarms. In addition, if a defect is detected it has to be located (by hand held ultrasound) and the section of rail, containing the defect, has to be replaced before train operation can resume.

The possibility of using a pulse-echo mode of operation, similar in principle to that used by the UK group [3], but with few transducers and at a range compatible with the monitoring system was suggested in [2]. The pitch-catch mode of operation would be retained as this provides a false alarm free broken rail detection system while the addition of the pulse-echo mode, for defect detection, would add significant value to the system if it can be implemented at reasonable cost. The system layout for combined pitch – catch and pulse – echo operation modes is illustrated in Fig. 3.
This section describes an initial investigation of the feasibility of performing pulse-echo defect detection at long range with an array of only a small number of transducers.

Field measurements were performed to determine which modes of propagation could be transmitted over large distances. A small ultrasonic transducer was used to excite the rail and a scanning laser vibrometer was used to measure the response of the rail. The response in the vertical direction was measured at numerous measurement points as shown in Fig. 2 and the amplitude of each mode of propagation was estimated. These scans were performed at different distances up to 400m from the transducer so that the attenuation with distance could be estimated. It was found that only two modes could be detected at large distances. These two modes, computed using the SAFE method, are shown in Fig. 4.

These two modes have similar wavenumber with one being symmetric while the other is anti-symmetric. An array comprising only four transducers was used to excite and sense these modes in either direction. Although an array with so few transducers would also excite and sense other modes, it was expected that the propagation characteristics of the rail would filter out unwanted modes.

The four transducers were bonded to the rail as shown in Fig. 5 and simple diode circuits were used to allow pulse-echo operation. The transducers were excited one at a time and the response on all four was measured simultaneously to provide a total of 16 signals. Four typical time signals obtained when one transducer was excited are shown in Fig. 5. In these measurements the excitation was a 17.5 cycle tone burst with 35 kHz center frequency.
The signals were post processed in the frequency domain to transmit and receive the two targeted modes in either direction. The signal processing included dispersion compensation [11] and deconvolution. It was found that the anti-symmetric mode did not work effectively and it should be noted that the rail had been replaced with new rail since the scanning laser vibrometer measurements were performed. The symmetric mode produced clear reflections as shown in Fig. 6.

The reflections in the positive direction at approximately 50, 300, 540 and 790m were found to coincide with the location of thermite welds performed in the field during installation of the rail. One such weld and the measured reflection are shown in Fig. 7. The spacing between these welds is approximately 250m. There are other welds that are performed in the factory known as butt welds, which do not have the prominent weld caps. These welds are not obvious either by visual inspection of the rail or in the measurements.
The large reflection at approximately -190m was found to be from a weld that joined old rail to new rail as shown in Fig. 8. The surface of the old rail had been ground numerous times and this resulted in a step change in the rail profile across this weld. There were frequent welds in the old rail sometimes with only six metres between welds. This caused multiple reflections after -190m and it would be difficult to detect cracks in rail which is in such poor condition.

It is clear that welds can be detected in new rail at large distances. The next question is how the reflection from a crack compares to the reflection from a weld. Numerical modeling was used to provide an answer to this question [12]. An efficient hybrid method, which models the volume containing the defect with conventional solid finite elements and the semi-infinite incoming and outgoing waveguides with the SAFE method, was used [13]. Cracks in various locations in the rail cross-section and welds have been modeled as illustrated in Fig. 9. Transverse defects in the rail head are important in heavy-haul rail systems [1]. Reflection coefficients computed for one mode are shown in Fig. 10, which compares the reflection from a weld (as per Fig. 9(c)) with a crack of 5mm and 10mm radius (as per Fig. 9(a)). From these results it is anticipated that a transverse crack in the rail head will provide a stronger reflection prior to breakage than a typical thermite weld. We therefore believe that if we can detect a weld at a certain range we will also be able to detect a transverse crack in the rail head at that range. Cracks at other locations will be more difficult to detect.
Fig. 9. Defect geometries analysed. (a) Cracks of various sizes in the rail crown. (b) Cracks in various locations in the rail cross-section. (c) Thermite weld with 6mm thick weld cap. (d) Thermite weld (with 6mm cap) of new rail to an old rail with 10mm ground from the crown as encountered in the field.

Fig. 9. Mode of propagation and computed reflection coefficients for thermite weld and transverse cracks in the rail head.

Conclusions

A guided wave monitoring system has been developed that can reliably detect complete breaks in rail track using transmission between stations spaced approximately 1km apart. This system is currently being installed on an 850km long heavy duty rail line.

Improved transducer design and modern signal processing have demonstrated the potential to double the range of the system to 2km between stations. This system is being industrialized and will be available in future providing reduced installation and maintenance costs.

Research has started to add a pulse-echo mode of operation to the system to detect, locate and possibly monitor cracks prior to complete failure. Numerical modeling has been performed to understand and quantify the interaction of the guided wave modes of propagation with different defects. Initial experimental results have shown that it is possible to detect thermite welds at a range exceeding 0.5km in rail in relatively good condition while this was not achieved in very old rail. We therefore expect to be able to detect certain cracks with such a monitoring system covering 1km of relatively good condition rail from a single location.
References


Acknowledgements

Access to the railway track for field measurements was provided by Transnet Freight Rail and is gratefully acknowledged. Funding for this project was provided by Transnet Freight Rail, CSIR, the Department of Science and Technology and the National Research Foundation of South Africa (Grant No’s: 78858 & 85330).