J M M
Journal of Mechanics and MEMS
Editor-in-Chief: B Sun

ISSN: 0974-8407
© Serials Publications
9(1) 2017: pp. 1-5

REAL-TIME ULTRASONIC RAIL HEALTH MONITORING SYSTEM FOR BOTH HEAVY HAUL LOADS AND HIGH SPEED TRAIN – SOUTH AFRICA OVERVIEW

Bohua Sun and Nawaz Mahomed*

ABSTRACT

With increased rail traffic at higher speeds and with heavier axle loads today, critical crack sizes are shrinking and rail inspection is becoming more important. Although the inspection car are still play an important role on the railway line inspection, but due to its limitation, the real-time and continuously rail crack inspection is desired worldwide. Due to its heavy demand from transport iron ore from mine to export harbour, South Africa has done a comprehensive study and successfully installed a world fist real-time ultrasonic broken rail detector system in its Orex railway line. This paper is to overview the development of ultrasonic guided wave rail sensing technology in South Africa.

Keywords: ultrasonic, rail detector, guided wave, real-time, crack

1. RAIL INSPECTION

Rail inspection is the practice of examining rail tracks for flaws that could lead to catastrophic failures. The track defects are the second leading cause of accidents on railways after the human errors as the leading cause. Every year millions of dollars have been spent to inspect the rails for internal and external flaws. Nondestructive testing (NDT) methods are used as a preventative measures against track failures and possible derailment. With increased rail traffic at higher speeds and with heavier axle loads today, critical crack sizes are shrinking and rail inspection is becoming more important. In 1927, Dr. Elmer Sperry built a massive rail inspection car. Magnetic induction was the method used on the first rail inspection cars. This was done by passing amounts of magnetic field through the rail and detecting flux leakage with search coils. Since then modern inspection cars have been used for the rail inspection worldwide. Unfortunately, crack failures can be happened in between of car inspections, so real-time full line nondestructive detecting system is highly demanded by railways industry (Cannon, *et al.* 2003; Wikipedia).

Among all NDT techniques, the guided wave ultrasound is attractive because large potions of structure can be inspected, or even continuously monitored, from fixed transducer locations (Rose 2002; Loveday 2008). Long slender structures with constant cross-section, such as pipes and rails, are particularly well suited to this inspection method. The wave propagation in railway track was modeled and measured by Thompson [2], and the interaction of the modes of propagation with defects was modeled and measured by Wilcox *et al.* (2003). Piezoelectric transducers are frequently used to transmit and receive the elastic waves and have been successfully used to monitor extensive lengths of rail (Loveday 2008).

The rail inspection research in South Africa was drive by the Orex railway line is used to transport iron ore some 800km from the mine to the export harbor. The line has following problems: temperature swings of up to 50 °C in winter, heavy haul loads leads to rapid crack development and frequent breaks, cost and effort to perform preventative scanning and inspections, configuration of rail not suitable for other break detection techniques. The comprehensive research has been undertaken jointly by CSIR and Denel, and successfully developed a world first commercial real-time continuously railway integrity monitoring system installed to the Orex railway line.

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* Centre for Mechanics, Smart Structures and Micro-Systems and Dept. of Mechanical Engineering, Faculty of Engineering, Cape Peninsula University of Technology, P O Box 1906, Bellville 7535, Cape Town, South Africa, *E-mail: bohua.sun@gmail.com, sunb@cput.ac.za*

The SA Ultrasonic Broken Rail Detector system is designed to reliably detect breaks in continuously welded rails. The operation of the system is based on a simple “transmit receive” confirmation protocol. An acoustic signal is generated and inserted in the rail at one location (transmitter), propagates along the rail, and is received at a remote location (receiver). The integrity of the rail between the transmitter and receiver is confirmed as long as an acceptable signal is received. Should the rail develop a clean break between the transmitter and receiver, the inserted signal will not be received resulting in an alarm at the monitoring station. Transmitters are placed on the line some distance apart with receivers in between. The transmitters bi-directionally insert high-energy ultrasonic pulses into both rails. These signals propagate along the rail and are detected at the adjacent receivers. Transmitters insert different signal codes to enable receivers to establish the direction from which the signal originates.The system consists of the following major components: Transmitter, Receiver, Transmitter/receiver transducers and Communications system to allow remote monitoring. The design of the system makes it suitable to be solar powered.

This paper will mainly focus on the theory and technology overview of ultrasonic guided wave crack detecting developed by South Africa contributors (Sun 2010).

2. ULTRASONIC GUIDED WAVE DETECTION OF RAIL CRACKS

This ageing infrastructure suffers unpredictable rail breakages, which can cause derailments resulting in injury and financial loss. The complete breakage of the rail is typically preceded by internal fatigue cracks near the crown of the rail section as shown in Figure 1.

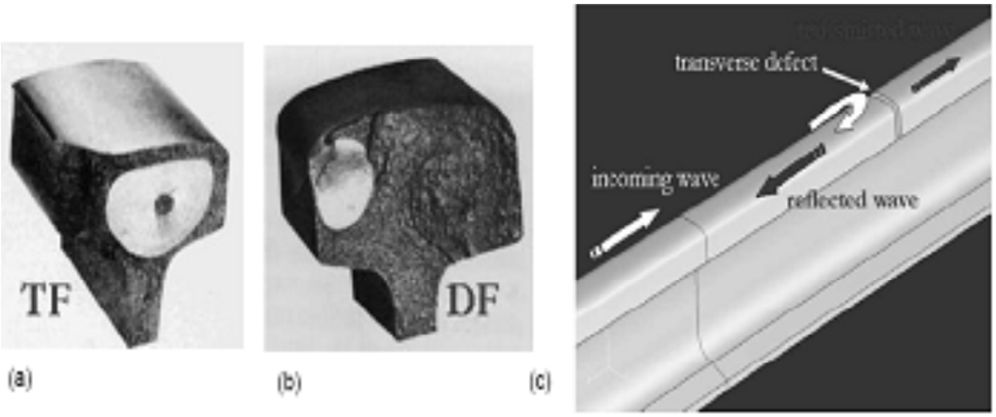


Figure 1: (a) Transverse Fissure; (b) Detail Fracture; (c) Ultrasonic Guided Wave Detection of Transverse Defects (“Reflection” and “Transmission” Modes)

A system which could interrogate the entire rail length every 10 minutes and detect complete breaks was required. A system, which can detect the presence of cracks prior to breakage occurring, would have additional value if this could be achieved. An “acoustic propagation” detection concept was selected after considering nine different approaches’. In the system, elastic waves are transmitted along the rails, between transmit and receive stations spaced at 2.5 km intervals along the length of the track as shown in figure 2. The transmitters periodically launch sequences of bursts, which are detected at the neighboring receivers if the rail is intact. The frequency of the signal or the time period between the bursts in a sequence can be altered so that the receiver can determine whether a detected signal is arriving from the transmitter to the left or right of the receiver. Initial experiments showed that satisfactory propagation along the rails was obtained at frequencies within 30-35kHz (Loveday 2000).

The ultrasonic is generated by a piezoelectric sandwich transducer shown in Figure 3.

3. MODELLING

The modelling of the acoustic detecting system consists of two aspects: one is the modelling of transducer, that is the dynamic deformation of rail compressed by the transducer; the second is to simulate the guided wave propagation along the rail and frequency analysis.

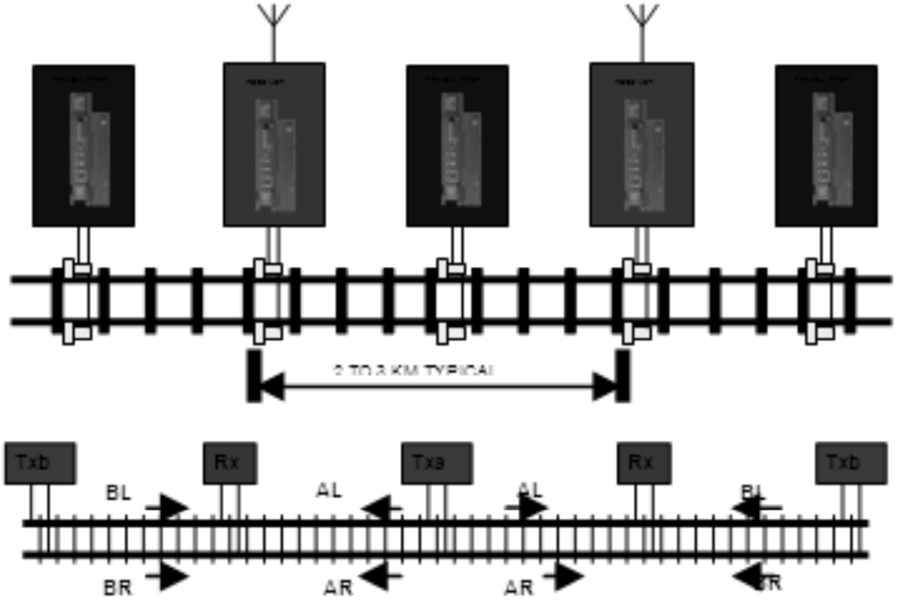


Figure 2: Railbreak Alarm System

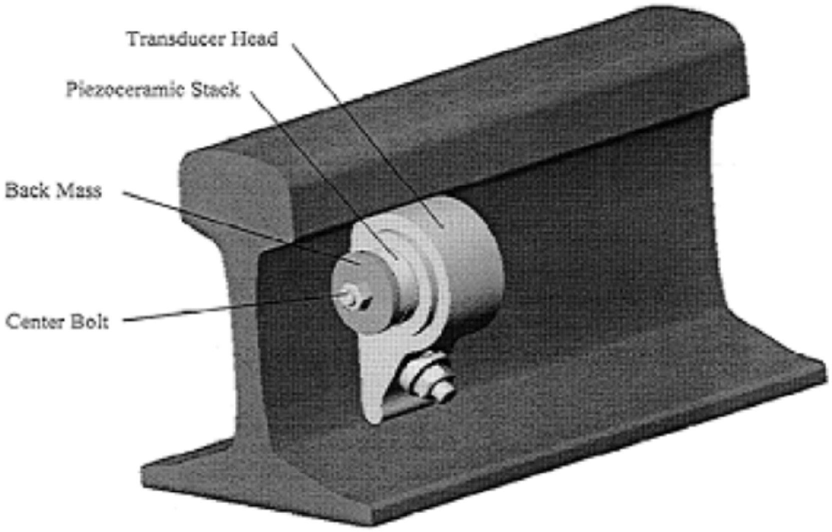


Figure 3: Conceptual Design of Transducer Attached to Rail

3.1. Finite Element Model of Transducer (Loveday 2000)

The difficulty in applying finite element modeling to the problem of transducer design lies in the representation of the infinite rail. Various researchers have analyzed wave propagation in rails but these studies are generally restricted to low frequencies where train-generated noise is an environmental issue. Models based on Tirnoshenko beam theory have been applied to this problem, but are not suitable at higher frequencies. Three-dimensional FEM models of short lengths of rail with symmetry and antisymmetry boundary conditions at the ends, to represent a fraction of a wavelength, have been used to verify the beam theory models3. The standing waves (natural modes) predicted by the FEM. models are directly equivalent to the traveling waves that occur in the infinite rail with the same wavelength. This approach can produce dispersion curves (wave number versus frequency) for low frequency waves traveling in the free rail. A second approach is to develop special finite elements which can represent the traveling wave propagation in an infinite free rai14. Complex exponentials were used to describe the wave propagation along the rail and in this way two-dimensional finite elements can model the wave propagation along a three-dimensional waveguide. Results were presented only for frequencies below 5kHz but this method is applicable to the higher frequencies considered in this paper. Unfortunately these elements are not available in commercial finite element software packages. Neither of these approaches is suitable when it is necessary to include a transducer in the model. A good approach to this problem would be to model a length of rail with the transducer attached to it using conventional three-dimensional finite elements and to attach the two-dimensional wave propagation elements to the ends of the rail model so that energy can radiate out of the model. As our interest is mainly in the design of the transducer, the transducer was modeled initially without attachment to the rail to verify the accuracy of the model. The transducer was then modeled attached to a length of rail with impedance boundary conditions to reduce the reflections from the ends of the rail.

3.2. Waveguide Finite Elements and Analysis of Wave Propagation (Loveday 2008)

The displacement distribution along the waveguide is described in waveguide finite elements by a complex exponential representing the wave motion we wish to analyze. Only the displacement distribution across the cross-section of the waveguide is represented by conventional finite element interpolation functions and, therefore, only a 2-D mesh is required to describe the infinite waveguide.

The elements used here were implemented based on the formulation presented by Gavri (1995) who wrote the displacement field as

$$\begin{aligned} u(x,y,z,t) &= u(x,y)\cdot e^{-j(kz-\omega t)} \\ v(x,y,z,t) &= v(x,y)\cdot e^{-j(kz-\omega t)} \\ \omega(x,y,z,t) &= j\cdot\omega(x,y)\cdot e^{-j(kz-\omega t)} \end{aligned}, \quad (1)$$

Where z is the coordinate corresponding to the direction long the waveguide, κ is the wavenumber, and ω is the frequency.

The strain (ε) and strain energy (k) of the waveguide can be separated into terms that are independent, linearly dependent, or quadratically dependent on the wave number:

$$\begin{aligned} \varepsilon(x,y,z,t) &= \varepsilon(x,y)\cdot e^{-j(kz-\omega t)} \\ \varepsilon(x,y) &= \varepsilon_0(x,y)+k\varepsilon_1(x,y) \end{aligned}, \quad (2)$$

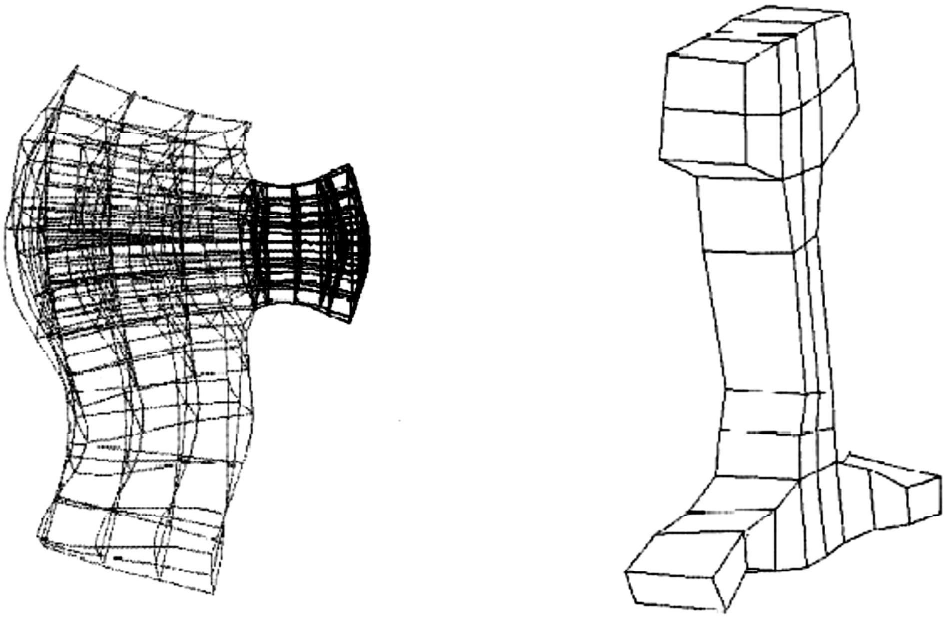
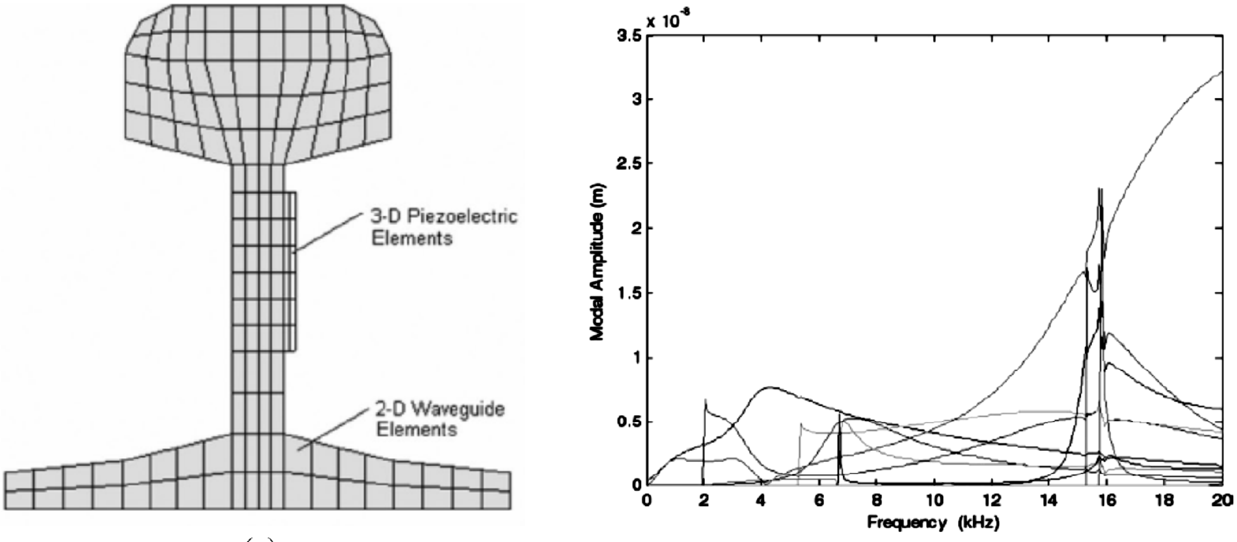


Figure 4: (a) Deformation of Transducer at Resonance (29.4 kHz). (b) Displacement of Rail Cross-Section at 31.5 kHz.



(a) (b)

Figure 5: Finite Element Mesh and Modal Response (Loveday 2008)

Applying a conventional finite element discretization to these terms yields the elemental mass and stiffness matrices, which are assembled to produce the system equations of motion for the waveguide, given by

$$M\,\ddot{u} + \left[k^2 \cdot K_2 + k \cdot K_1 + K_0\right] u = f\,, \tag{3}$$

Detail calculation has been carried out by Dr Loveday (2008).

4. CONCLUSIONS

This paper give a glance overview of ultrasonic rail crack detecting research and development in South Africa. Both theory and world first installation has approved the ultrasonic guidedwave is the best candidate for real-time and continuuosly monitoring technology of rail flaws inspenction. It can dramtically reduce the operational cost and improve the safety of railway line. For that we recommend the thenology to the rest of the world.

Acknowledgement

The authors wish to acknowledge Dr. Philip W. Loveday and SA Institute of Maritime Technology for supplying information on the subject.

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