Guided Wave Inspection and Monitoring of Railway Track

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Abstract

Cost-effective NDE of the vast length of ageing railway track around the world remains a challenge for the community. Continuously welded rail is installed in tension but temperature changes can result in rail buckling if the initial tension is insufficient or fatigue cracks and ultimately rail breaks if the initial tension is excessive. The NDE challenge therefore includes both the detection of defects and the measurement of axial stress. Since continuously welded railway lines may be thought of as one-dimensional elastic waveguides, they are natural candidates for guided wave ultrasound, which offers the potential to interrogate a large length of rail from a single position. Guided waves have been proposed as a means of detecting the axial stress in rails to prevent buckling and also as a means of detecting complete breakage and cracks prior to breakage. This paper reviews the approaches used and the modeling methods available to support the development of nondestructive inspection and monitoring systems. Possibilities for future systems are also discussed.

Keywords

Guided wave ultrasound, rail inspection and monitoring, axial load measurement

1 Introduction

Cost-effective NDE of the vast length of ageing railway track around the world remains a challenge for the community. An overview of common defects that occur and the mechanisms involved was provided by Cannon et al. [1]. Rail defect management aims to detect defects by inspection before breaks occur and a measure of the efficiency of the process is the ratio of the detected defects to rail breaks [1]. For this efficiency measure to be effective in reducing rail breaks it is required that defects that will result in rail breaks must be detected and rail must be replaced, while defects that will not result in a break should not be counted. It appears that typically between 10 and 20 defects are detected for every occurrence of a rail break [1]. Even in continuously welded rails, which are generally in tension, a break typically results in a gap of less than 30mm and does not immediately result in train derailment. In fact the number of derailments relative to the number of rail breaks is remarkably small [1]. Nonetheless, the consequences of a derailment make it essential to perform periodic inspections in an attempt to minimize rail breaks. A general review of non-destructive evaluation of rails [2] indicated that ultrasonic and magnetic induction techniques are used extensively for the inspection of rails in-service while a number of other techniques are under development. This paper considers only one of these techniques, namely guided wave ultrasound.

Since continuously welded railway lines may be thought of as one-dimensional elastic waveguides, they are natural candidates for guided wave ultrasound, which offers the potential to interrogate a large length of rail from a single position. Apart from the increased propagation range, a strong motivation for the use of guided waves (as opposed to conventional high frequency ultrasound) is that these waves can detect smooth vertical-transverse defects even if they occur under surface cracks or shelling [3]. A further motivation is that the lower frequency used is not strongly scattered by the large material grain size in alumino-thermic welds making it possible to detect defects within the weld [4].

Guided waves have been proposed as a means of detecting complete breakage and cracks and also of measuring the axial stress in rails. Continuously welded rail is installed in tension and consequently there is a elevated temperature at which there is zero axial stress in the rail. Above this temperature the rail is in axial compression, which can result in buckling. If there is too much tension in the rail this can lead to cracks and ultimately rail breaks.

This paper reviews the approaches that have been proposed for developing nondestructive inspection and monitoring systems and the modelling techniques used to support these developments.

2 Guided Wave System Approaches

The two major rail applications of guided waves being researched, axial load measurement and defect detection, are reviewed in this section. The different system level approaches are described.

2.1 Axial Load Measurement

The measurement of thermal stress (or axial load) in rails based on guided waves has been investigated by a few groups. The presence of axial load is expected to influence the propagation of guided waves and it was proposed that measuring the wavelength / wavenumber of a flexural mode at low frequency could indicate the axial load [5]. The rail was excited at 200 Hz and the lateral vibration measured at a set of locations along the rail. The wavenumber was then calculated from these measurements. This approach would require releasing the rail from the sleepers for a considerable length.

Measurements using higher frequencies have also been considered and Chen & Wilcox [6] showed that the phase and group velocities in rods are sensitive to changes in axial load. A numerical study [7] suggested that modes with the greatest group velocity could be measured over a reasonable distance and provide a measure of axial load. However, it was also illustrated that the influence of temperature induced changes in elastic modulus should be expected to be an order of magnitude larger.

It has recently been proposed that nonlinear parameters may provide a better measurement of axial load and a large scale experiment has been established at the University of California in San Diego [8]. The presence of double harmonic and internal resonance phenomena are described in [9]. A schematic of the experiment is shown in Fig. 1.

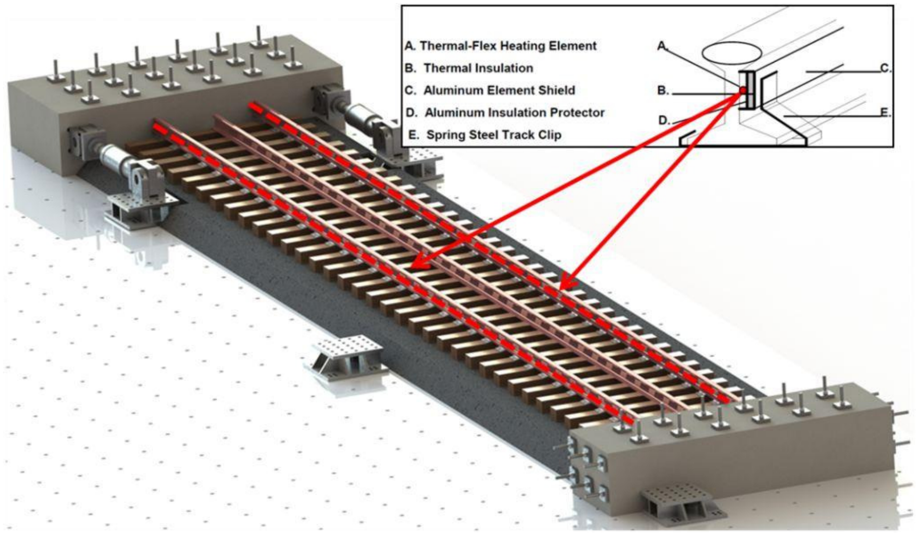

Fig. 1 Axial load measurement set up at UCSD (courtesy of Prof. F. Lanza di Scalea)

2.2 Defect Detection

Rose et al. [10] performed various measurements and concluded that there are three possible approaches to defect detection: fixed (permanently attached) sensors on the rail; a guided wave inspection car; and sensor on train systems. A forth approach, deployable sensor arrays for inspection has been developed into a product. Non-contact sensors mounted on an inspection car and permanently attached sensors for continuous monitoring have also been developed into products. These approaches are described in this section.

Deployable Sensors for Inspection

The guided wave inspection system shown in Fig. 2 was developed by Imperial College and Guided Ultrasonics Ltd [4]. The aim was to detect smooth transverse-vertical defects and the volumetric examination of alumino-thermic welds. This system utilized a dry-coupled piezoelectric transducer array wrapped around the circumference of the rail to transmit and receive guided waves, such that the array as a whole effectively operated in pulse-echo mode. The array could be used to transmit and receive individual modes of propagation and coupling between these modes was used to identify the nature/location of the damage to the rail. Seven different defect geometries were modeled and measured and the resulting reflection coefficient maps were used in an automated feature extraction algorithm to identify defects [11]. The system could inspect 100m of rail from one position and could inspect rail buried at level crossings. This was a very sophisticated instrument and could detect relatively small defects. This is an inspection system that would require interruption of the operation of trains on the line being inspected.

Fig. 2 Inspection system developed at Imperial College and Guided Ultrasonics Ltd (courtesy of Prof. P. Cawley).

Guided Wave Inspection Car

Surface or subsurface defects may prevent traditional ultrasonic wheel probes from detecting more serious deeper defects. The ability of guided waves to detect transverse defects under shelling has motivated extensive research at the Pennsylvania State University [12], [13]. This work led to the development of a "Portable Rail Inspection for Strategic Maintenance" inspection system by Waves in Solids (www.wins-ndt.com). The system is fitted to a Hy-Rail® vehicle for scanning the rail and uses electromagnetic acoustic transducers (EMATs) to transmit and receive the guided waves [3].

Another system based on guided waves was developed at UCSD [14]. Again the system was motivated by the possibility to detect vertical cracks hidden below horizontal cracks. In addition, the potential for extremely high inspection speeds was mentioned. This system uses laser excitation of guided waves and air coupled transducers for receiving. Discrete wavelet transform signal processing was used to improve the signal–to–noise ratio of the non-contact testing method. The possibility of using different modes and frequencies to detect different cracks was investigated in [15].

Permanently Installed Monitoring Systems

The idea of using the noise generated by a moving train to detect damage was considered by Rose et al. [10]. Receive transducers (accelerometers) placed along the rail listen passively. When a train approaches a sudden increase in noise level could indicate that the train has passed a discontinuity in the rail or similarly a sudden decrease when the train departs. Analysis related to this approach has been performed by Ryue et al. [16], [17].

An active approach is to permanently attach transmit and receive transducers to the rail. A system developed in South Africa by the Institute of Maritime Technology (IMT) used piezoelectric transducers developed at the Council for Scientific and Industrial Research (CSIR) [18] to detect complete breaks in heavy duty freight lines. The transmit and receive stations are positioned alternately along the rail and operate in transmission mode. The distance between transmit and receive stations depends strongly on the condition of the rail and 1 km is typical. The system has recently reached the level of reliability where false alarms are rare and trains are stopped when alarms are triggered. Recently, three breaks were detected in 15 months on a 34 km long test section and potential derailments were prevented [19]. The system has also detected defects before complete breakage. Fig. 3. shows the hardware at a transmit station.

Fig 3. Transmit electronics and installed ultrasonic transducer [19]

3 Modeling waves in rails

The development of guided wave inspection systems is informed by theoretical knowledge and in the case of rails this knowledge is often obtained by numerical modeling. In this section a review of relevant modeling approaches will be presented.

3.1 Computation of Wave Propagation Characteristics

Dispersion properties of one-dimensional waveguides such as pipes may be computed analytically but complex geometries such as that of rail require numerical techniques. Conventional finite element codes, which are available commercially, may be used [20]. A length of the waveguide is modeled with appropriate boundary conditions applied at each end and the natural modes are computed. The shape of these modes may be inspected to determine what fraction of a wavelength they correspond to and each mode (of the finite model) produces a point on a wavenumber – frequency dispersion curve. The length of the model is changed and the process repeated to obtain another set of points. Alternately, many research groups are now using semi-analytical finite element (SAFE) models to compute dispersion characteristics [21–24]. These elements are formulated to include the wave propagation as a complex exponential in the element formulation and require only a two-dimensional mesh of the rail profile. Dispersion curves for a UIC60 rail are shown in Fig. 4.

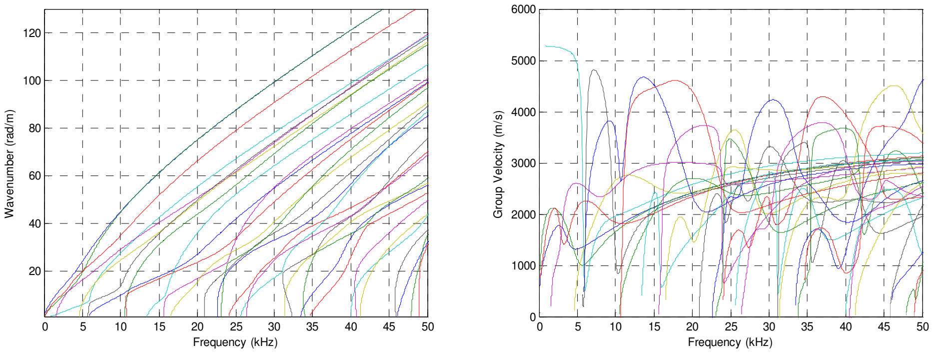

Fig 4. Dispersion curves computed using SAFE

The influence of axial load on the dispersion characteristics can be computed using commercial FE codes as was done by Chen & Wilcox [25]. It was demonstrated that the axial load is remarkably simple to include in SAFE codes [26]. The advantage of this approach, in addition to computational efficiency, is that it retains some analytical features and analytical computation of sensitivities is easy and can be used to compare different influences such as elastic modulus variations compared to axial load variations both due to temperature changes [7]. The method has been generalized to include non-axial loads [27], which makes it applicable to other problems such as pressure in pipes and bending stresses in rails.

Waveguides with nonlinear material properties were studied by Srivastava et al. [28] who used the modes from a linear SAFE analysis in a perturbation method. The cumulative growth of a phase matched mode at twice the frequency of the primary generating mode was demonstrated numerically. The purpose of this study was to provide a theoretical foundation for the use these phenomena to measure axial load in rails.

The dispersion characteristics are of great value when designing guided wave inspection and monitoring systems. The mode shapes provide information needed for designing transducer arrays to selectively transmit or receive individual modes of propagation. When long range operation is required, the SAFE models can be extended to include damping and then used to predict which modes will propagate with lower attenuation [16]. A large source of damping is the fastening of the rail to the sleepers via a rubber mat and it is seen that modes that have small motion of the foot of the rail will propagate with low attenuation. These modes only occur at higher frequencies and explain why long range transmission can be achieved at higher frequencies when one would intuitively expect low frequencies to transmit further.

3.2 Interaction with Defects

The selection of modes to use in an inspection system is also influenced by the way that the modes interact with the damage which is to be detected. An incident mode can convert to many other reflected and transmitted modes. Understanding the mode reflection and transmission and coupling to other modes provides a basis for inspection system design. Extensive research is available on numerical techniques to predict the interaction of guided waves with damage. These techniques vary from time domain simulations using commercial finite element codes [4], [29] to sophisticated custom developed hybrid codes which incorporate standard finite elements with SAFE [30] or spectral finite elements [17]. While the commercial codes are immediately available these methods are computationally very expensive even if explicit time integration schemes are used. In addition pre and post processing are required to excite only a selected mode and to separate the reflected and transmitted signals into the individual modes. When working at higher frequencies where 20 to 40 modes propagate, it is necessary to implement the custom techniques. The interaction of guided waves with a cut through a rail was investigated by Ryue et al. [17] using a combination of SAFE and spectral super elements. It is believed, by the current author, that this analysis could have been performed with only SAFE modeling as the cut is normal to the rail axis and of negligible axial extent and a similar analysis of a Lamb wave in a plate with a normal crack has been performed in this manner [31]. An efficient combination of SAFE and conventional FE has been recently presented by [30] who reformulated the SAFE elements to provide the matrices needed to combine these with the FE.

3.3 Excitation and Sensing Guided Waves

Excitation and detection of the guided waves can be performed by a number of techniques depending on the application. Non-contact methods are attractive and EMATs [13] and laser excitation [15] have been modeled and used. For long range transmission it is possible to attach piezoelectric sandwich transducers similar to those used in underwater sonar systems [18]. These transducers can be effectively modeled by combined SAFE and conventional FE methods [32], [33]. These models can be used to optimize the transducer design to transmit significant power at a particular frequency and into a particular mode of propagation. Further mode selectivity and additional power can be achieved by using arrays of transducers.

4 Future perspectives

The use of linear guided wave techniques to measure axial load in rails appears to be very difficult to implement in practice. This has led to nonlinear techniques being investigated numerically and experimentally. This is not a simple problem and it remains to be seen if a practical solution will emerge.

Guided waves are being used in a commercially available inspection car system. It is anticipated that the success of this system will indicate whether the ability to detect vertical defects under shelling is attractive to rail operators.

Track circuits have been used extensively in railway signaling systems to detect the presence of a train in a particular section of track known as a block. Insulated joints in the rail separate the block from the neighboring blocks and an electrical power source is connected across the two rails at one end of the block with a relay connecting the two rails at the other end of the block. A train in the block causes electrical contact between the two rails and is detected. In addition, a complete break in one rail will also generally be detected provided that it does not occur between the insulated joints and the electrical connection points. Today, rail operators are moving away from track circuits to communication based train control, which uses communication between the train and the track equipment to accurately determine the location of the train. This trend is creating an opportunity for guided wave monitoring systems that detect broken rail and was the motivation for the study in [34].

Rail defect management aims to detect defects before breaks occur and this appears to be possible. There are a number of technical challenges that have to be met before a system will be adopted and trusted. Most importantly a system cannot produce false alarms as it will quickly be discarded. There are many sources of signal variation such as temperature changes, profile grinding, sleepers, welds etc. This is a tough environment and equipment has to be qualified to avoid false alarms due to equipment failure. Ideally a system should be able to distinguish between an equipment failure and a rail problem.

Guided wave inspection and monitoring systems have been successfully applied to pipelines. In this case, inspection systems were developed first and only later followed by monitoring systems. These systems do not require interruption of the operation of the pipeline. Ideally a rail inspection system should not interfere with train operation and should be autonomous. Perhaps in rail applications monitoring systems that do not interfere with train operation will succeed first.

The inspection system developed by Imperial College and Guided Ultrasonics Ltd [4] was technically very sophisticated in that it used a transducer array and coupling between different modes to classify damage. This system was based on successful pipeline inspection systems and operated at a fairly low frequency and it was not intended to achieve very long ranges as would be required for permanently installed rail monitoring systems. It has been shown that certain modes can propagate long distances at higher frequencies and a simple permanently installed broken rail monitoring system using transmission has been developed. It is interesting to consider what could be achieved by combining the inspection approach [4] with the monitoring approach [19]. Could a permanently attached array effectively excite and sense the modes that propagate large distances without interfering with train operation? At what range would a pulse-echo system operating at these frequencies be able to detect and locate defects, such a transverse cracks in the head, before breakage? Would other defects be detectable? Could such a system be produced and operated at a cost that would be attractive to rail operators? Efficient modeling tools for guided waves in rails have been developed in recent years. These tools should be able to answer some of these questions, while field measurements would be required to answer others. These measurements should be performed on a range of rails including old rail in poor condition, which are in most need of monitoring.

Different rail operators will have different requirements and systems would need to be tailored to meet these. Heavy duty freight rails will not require as frequent monitoring as busy passenger rails where the frequent trains can cause their own challenges. Rail operators often have data on the most frequently occurring defects on their rails and may want the system to focus on these defects. The size of a defect before breakage occurs and the rate at which the defects grow are also important factors. If the defect achieves an easily detectable size before breakage occurs then periodic inspections may be effective and the interval between inspections would be determined by the defect growth rate. If the defect grows rapidly or if breakage occurs without a detectable defect then a broken rail monitor operating in near real-time may be the only practical solution. There can be sections of rail line that are known to fail more regularly than others and monitoring systems may only be installed on these sections.

Possibilities for multi-functional systems exist if for example axial load monitoring could be combined with rail break monitoring or if the deterioration of a rail can be monitored and replacement scheduled. It is anticipated that inspection and monitoring systems will complement each other.

Rail operators are likely to combine different technologies in different ways to achieve cost effective solutions suited to their particular needs. Guided wave ultrasound is believed to have the potential to contribute to these solutions.

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