THE APPLICATION OF LONG RANGE ULTRASONIC TESTING (LRUT) FOR EXAMINATION OF HARD TO ACCESS AREAS ON RAILWAY TRACKS.

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Abstract

Following a number of severe accidents caused by rail breaks, there has been a significant improvement in NDT methods for the detection of rail head defects. However, current NDT methods are limited in their ability to detect defects in the rail foot, especially in the side edges away from the region directly below the web. Long Range Ultrasonic Testing (LRUT) is proposed as a complimentary inspection technique to examine the foot of rails, especially in track regions where corrosion and associated fatigue cracking is likely, such as at level crossings. The focus of this study is to demonstrate the ability of using LRUT to examine inaccessible railway tracks areas for corrosion and fatigue cracking. In this paper, the properties of guided waves in the three different parts of the rail section (head, web and foot) are examined and their capability to detect defects in each part is explored. The purpose of this work is to develop suitable arrays of transducers able to generate selected guided wave modes in rails which will allow a reliable long range inspection of the rail. This investigation has being carried out using Finite Element Analysis (FEA) as well as experimental trials. The findings have shown that ultrasonic guided waves can propagate in rails with the ability to detect common type of defects. The emphasis of the work is on the foot since currently applied NDT methods are less effective in this region. Nevertheless, work has been also carried out in the web and the head in order to develop a cost effective and global inspection solution.

1 Introduction

Recent advances in inspection and NDT techniques for rail head defects and other remedial methods such us grinding, have drastically reduced the incidence of rail breaks from cracks in the head. However, a residual number of rail breaks still occurs [2]. These tend to arise from corrosion and fatigue on the foot of the rail, particularly on the underside. This area is very difficult to examine by the NDT techniques applied by sensors scanned along the top of the rail, as are used for detection of defects in the head and web. An alternative solution is therefore needed to enable the foot of the rail to be adequately examined for corrosion and cracking that may cause a rail break.

Long range ultrasonic testing (LRUT) has the potential to examine the underfoot area over a range of approximately 20m for the test head [6]. The aim of this work is to develop a robust method of detection of corrosion and fatigue cracks the rail foot before they reach a size that will cause a fracture of the rail. As it is not practical to scan sensors along the underside of the rail, the focus of the work is where corrosion and corrosion fatigue are more likely, such as level crossings. The aim is to install permanently mounted sensors to monitor a defined length of rail at level crossings so that degradation of the rail can be detected before failure occurs.

LRUT relies on the use of ultrasonic guided wave modes in the kilohertz range (typically between 20-300 kHz) with relatively long ultrasonic wavelengths in comparison with conventional UT [6]. These waves propagate with low attenuation in steel, which allows the ultrasonic waves to propagate for many metres with full coverage of the cross section. Existing commercial guided wave systems perform well for elongated structures with a symmetric cross-section such as pipes. However, the utilisation of guided waves in rails is still very challenging since the wave modes which exist in rails are more complex than those in pipes. The work presented in this paper is a step towards establishing a reliable technique for long range defect detection in rails.

This investigation has been carried out for the project “Long range inspection and condition monitoring of rails using guided waves (MonitoRail)”, partly funded by the European Commission under the Framework-7 Programme. The

developed MonitoRail technology will be applied for the inspection and monitoring of rail web, head and foot sections. However, the focus of this paper will be on the results obtained from the rail foot since there is a need for monitoring defects in this section of the rail.

2 Modelling of guided waves in rails

Rails are an excellent application for long range ultrasonic testing because they are now installed as continuous welded lengths of up to more than 1km. As these are of constant cross section along their length, waves generated at one point will travel long distances. However, distinctly different wave modes travel in the head, web and foot [3].

In order to exploit the potential of utilising guided waves in the rail, there is a need to characterise their behaviour with respect to the rail structure of interest [3]. Guided waves are sensitive to the structure's cross-sectional shape, thickness and material properties (Poisson's ratio, Young's modulus and density). A large exercise has been carried out to determine the properties of waves in the three different parts of the rail section and their sensitivity for defect detection. The aim of this work is to answer the following questions:

- What kind of modes to use for the rail inspection?
- How to generate each selected specific mode in a specific zone of the rail?
- What is the optimum ultrasonic frequency for inspection?
- What is the sensitivity of the selected modes for the detection of defects?

2.1 Guided wave mode characterisation in rails

Finite element analysis (FEA) has been used to have a better understanding of the behaviour of guided waves in rails and also to identify the suitable wave modes than can be excited and propagated in each section of the rail. FEA provided information about the potential modes of vibration in terms of their mode shape, natural frequency and wave length [6]. This allows the generation of the dispersion curves and prediction of the optimum wave mode excitation. The ideal mode/frequency combinations are thus determined in order to maximise sensitivity to damage occurring in rails.

TWI has developed dispersion curves for rails [3, 4]. The selection of the optimum wave mode is fundamental to guided wave developments. This modelling work has been based on the British standard dimensions BS113A which is the most similar to the E601 standard, one of the most common types of rails within UK. Figure 1 shows the dimensions of the rail structure of interest. The material properties selected for the model are density of 7830kg/m. Young's modulus of 207GPa, and Poisson's ratio of 0.33. More information about dispersion curve computation and procedures using FE can be found in [3],[4] and [5].

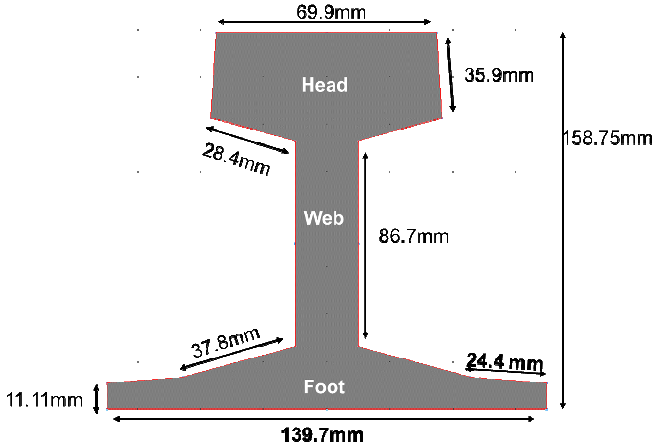


Fig. 1 Geometry of standard dimensions (BS113A)

The rail dispersion curves generated in [3] show that there are many wave modes within the frequency range of interest between 20-90 kHz. The existence of many wave modes adds further complexity in terms of mode selectivity and excitation conditions to propagate ultrasonic guided waves in rail. Propagating more than one wave mode along the rail length at the same time causes difficulties during data analysis. Therefore, in order to reduce the complexity of the data analysis, the rail cross sectional profile was divided into three sections, the head, web and foot [6]. Wave modes that uniquely occur in each section were identified. The different possible vibration pattern for each section of the rail for these wave modes is shown in figure 2. The naming of these wave modes is based on their vibration pattern as some propagate with a flexural displacement, hence F wave, whilst others have a twisting displacement; these are labelled as T wave.

The F3, T2 and F2 wave modes have been carefully chosen as suitable modes to propagate within each section of the rail (see figure 2) [6]. They were selected based on several considerations:

1. Their sole existence in one part of the rail with little expected leakage into the other parts.
2. The displacement of each mode occurs in the entire section of the respective part of the rail, suggesting that 100% coverage of the rail cross-section may be achieved.
3. The displacement patterns are similar to each other, so similar transducer arrangements can be used for the generation and reception of each wave mode. This facilitates the signal processing.
4. They are relatively non-dispersive in the 20-90 kHz range.

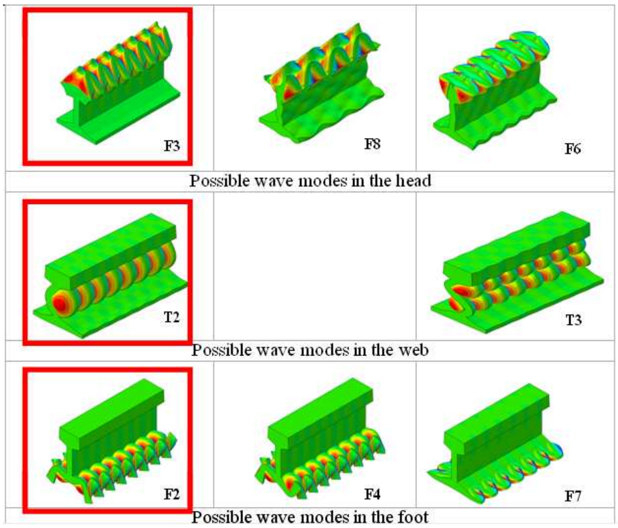


Fig. 2 Different suitable wave modes for different sections in rails [6].

As the rail foot has been identified as the most critical area, further analysis was done on the modes propagating on the foot. The vibration patterns for the different wave modes in the rail foot were investigated. This is to ensure that the selected wave mode has an appropriate displacement distribution across the entire foot width, which will be sensitive to defects which currently cannot be detected by the conventional NDT techniques and are located in the bottom of the rail foot. F2 has a displacement distribution across the width of the foot with relatively higher displacement in the centre of the foot in comparison with the other wave modes studied: F4 and F7 (see Figs. 3, 4 and 5). Such an observation gave further justification for the selection of F2 wave mode as a suitable wave mode that can solely exist in the foot with displacement distribution sensitivity to defects at any location in the foot.

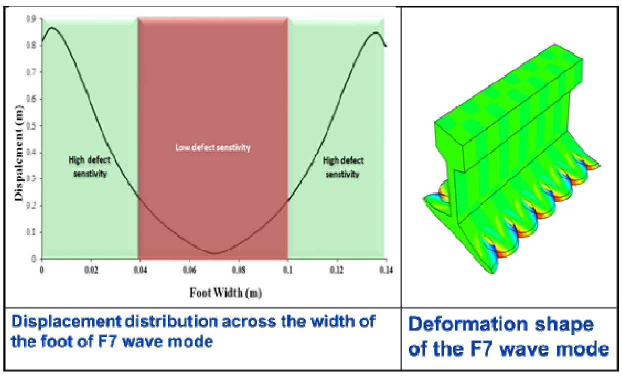


Fig. 3 Displacement distribution for F7 in the rail foot

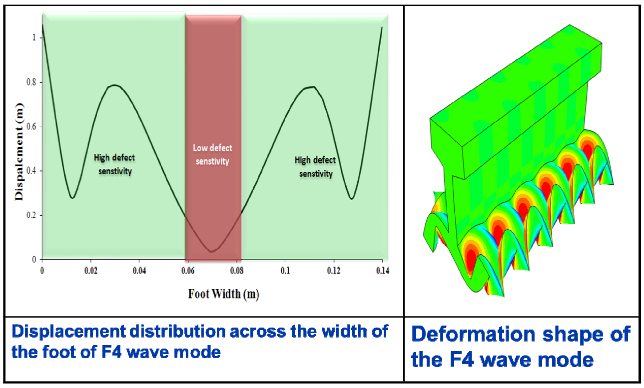


Fig. 4 Displacement distribution for F4 in the rail foot

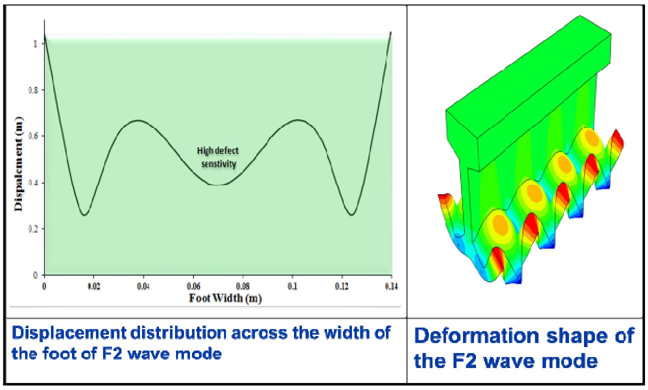


Fig. 5 Displacement distribution for F2 in the rail foot

2.2 Guided wave propagation in the foot and suitable excitation conditions

A significant amount of numerical modelling work has been done to understand the propagation of ultrasonic guided waves, with the emphasis on the F2 wave mode in this part of rail. Different excitation conditions with more than 20 different transducer combinations were investigated to include variation and optimise the number of transducers and arrays as well as location of the transducers and the directionality of excitations. The diverse excitation conditions investigated in this study can be summarised in the following figure.

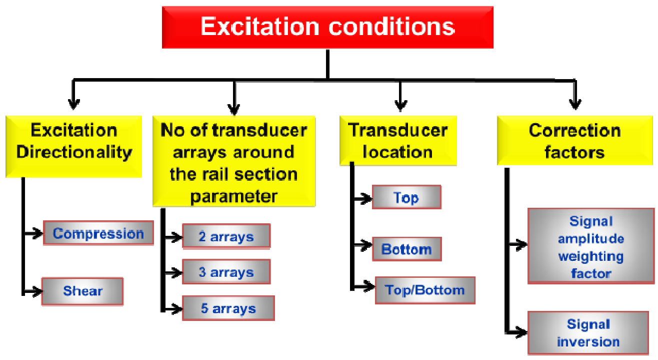


Fig. 6 Different excitation conditions simulated in the rail foot

Different numbers of arrays were simulated. The arrays of transducers are displaced by 37.3mm from each other. This distance between arrays is to enhance the wave propagation in one direction. Three types of array locations were studied for the different number of arrays and directionality: sensors mounted on the top side of the foot only, on the underside only and on both top and bottom faces. This was done to consider the most appropriate excitation/reception conditions for future practical implementations (relating to accessibility to mount transducers on a real rail track). The propagated pulse was monitored at the excitation/reception points. The predicted response amplitude from the far end of the rail and the signal to noise ratio along the time base were used to assess the signal quality. As the speed of the waves is known from the dispersion curves, the time is converted to distance accordingly. It is desirable to detect the reflection from the rail far end at the expected time of arrival. However, in reality this can be difficult due to the number of possible wave modes that potentially can exist when guided waves propagate along railway track within the typical frequency range (between 20-90 kHz). The results obtained for each group are presented as follow.

2.2.1 Excitation from the top side of the foot

These conditions assume that access to the bottom side of the rail is not available; therefore the ultrasonic point sources (simulating the transducers) are mounted at the top side of the rail foot. Figure 7 shows the ultrasonic path length for the propagated F2 mode with respect to the excitation conditions from the top side. It can be seen that a strong reflection has been recorded from the rail far end at approximately 13.3m. However, other significant responses are recorded between distances 1-4m. These are indications of the presence of higher order wave modes, which are due to many reasons such as the complex interaction of ultrasonic guided waves with the structural boundary of the rail geometry, as well as reflections from the rail near end, which may cause the wave modes to convert to higher order wave modes.

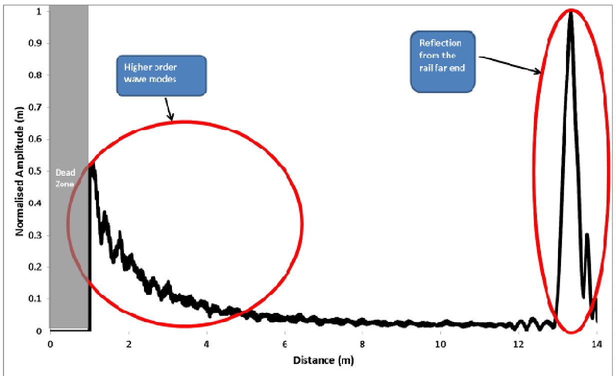


Fig. 7 FEA generated ultrasonic path length for the F2 wave mode in the foot with respect to the excitation conditions from the topside of the foot

2.2.2 Excitation from the bottom side of the foot

These conditions assume that the ultrasonic point sources are mounted at the bottom side of the rail foot. Figure 8 shows the ultrasonic path length for the propagated F2 mode with respect to the excitation conditions from the bottom side. It can be seen that a strong reflection has been recorded from the rail far end at approximately 13.2m with propagating group velocity of 2950m/s. In comparison with Figure 7, little reflections are recorded between distances 1-4m in comparison with the reflected pulse from the far end. This indicates improved excitation conditions.

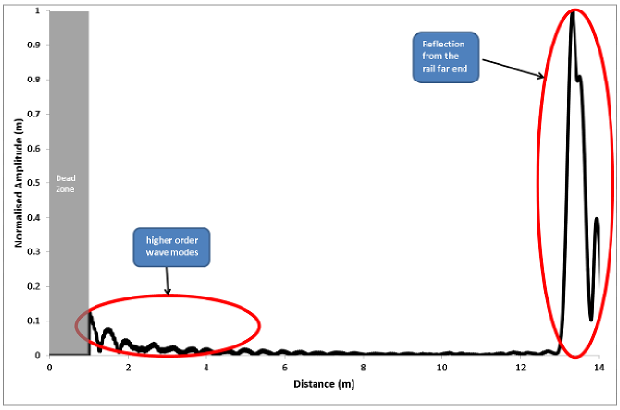


Fig. 8 FEA generated ultrasonic path length for the F2 wave mode in the foot with respect to the excitation conditions from the bottom side

2.2.3 Excitation from both top and bottom of the foot

In this section excitations from both the top side and bottom side of the rail foot are considered. Figure 9 shows the ultrasonic path length for the propagated F2 mode with respect to these excitation conditions. It can be seen that a strong reflection has been recorded from the rail far end at approximately 13.5m with propagating group velocity of 2950m/s. Significant responses are recorded between distances 1-4m . Furthermore, mode quantification using 1-Dimensional Fast Fourier transform (1-DFFT) has been used to assess the mode purity with respect to different excitations.

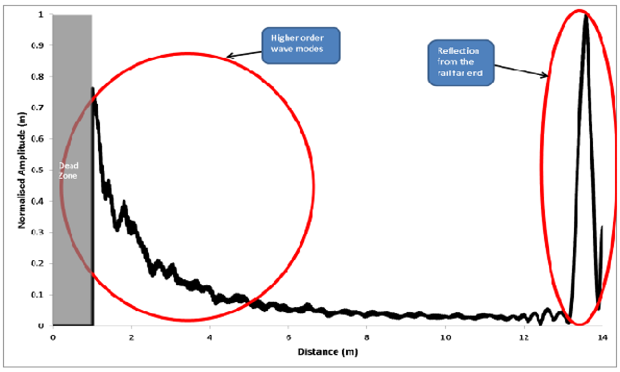


Fig.9 FEA generated ultrasonic path length for the F2 wave mode in the foot with respect to the excitation conditions from the both top and bottom sides of the foot

3. Experimental trials

The main objectives of the experimental trials are to assess the sensitivity of guided waves for defect detection in rail geometry. For that purpose, several tests were carried out on a 4.3m rail sample at TWI with different defect sizes in the foot. The experiments have been carried out in parallel with the theoretical FEA study in order to select the best wave mode excitation conditions given by the models.

The commercial guided wave ultrasonic system, Teletest® [8] was used to excite and to receive the guided waves. For these experiments, 2 arrays of transducers were mounted on the foot of the rail specimen in the different excitation locations mentioned in section 2.2 (Fig.10). As in the modelled excitation conditions, the arrays of transducers were displaced by 37.3mm from each other so that to enhance the wave propagation in one direction. At the moment, detection defect sensitivity has only been assessed experimentally from the excitation from the top of the foot. The transducer array arrangement used is shown in Figure 11. Further test evaluating the defect sensitivity from the bottom and top-bottom of the foot are in progress.

Fig. 10 Rail sample used for pilot experiments

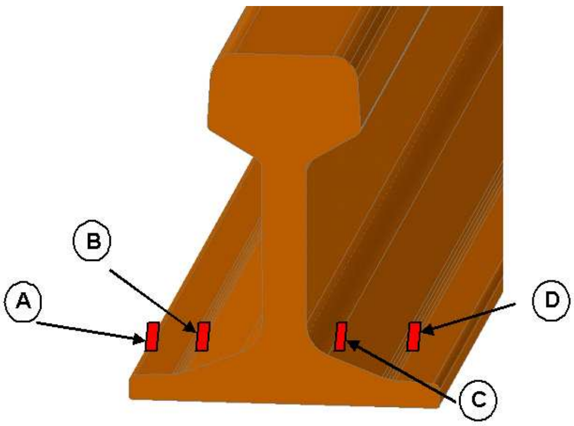


Fig. 11 Experimental set-up to generate guided waves in the foot.

For the baseline records and identification of the most suitable test parameters, the rail sample used was free of defects. A tone burst signal at a centre frequency of 70 kHz was used to excite the desirable wave modes [6]. The pulse travelled along the rail and was reflected back from the rail end. The echo was recorded at a distance of approximately 8.6 m (i.e. 2 x rail length). Subsequently, a defect was introduced in the foot with different depths in order to evaluate the defect detection sensitivity. Transverse slots were cut on the one side of the rail foot (Fig.10) at different depths. These slots have been induced in the foot at 3m from the excitation point with depth varying from 1mm to 4mm. Table 1 summarises the dimensions of the different defect sizes.

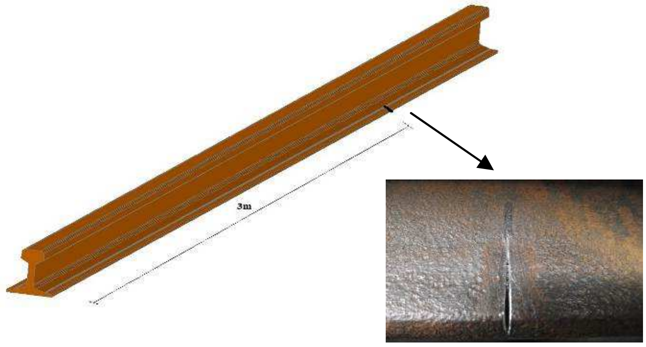
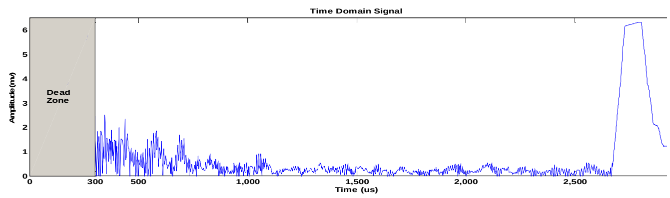


Fig.12 Illustration of the rail specimen with the position of defects

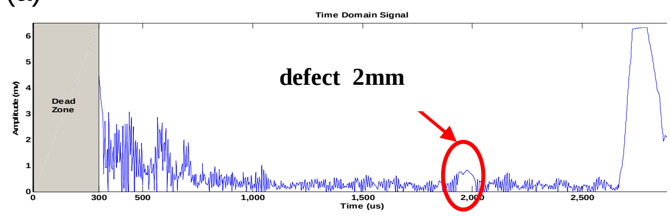
Defect depth (mm)	Defect length (mm)	Defect width (mm)	Defect area (mm^2)	Loss of cross-sectional area (%)
1	17	1	17	0.60
2	18	1	36	1.27
4	16	1	64	2.27

Table 1 Defects sizes in the foot section of the rail.

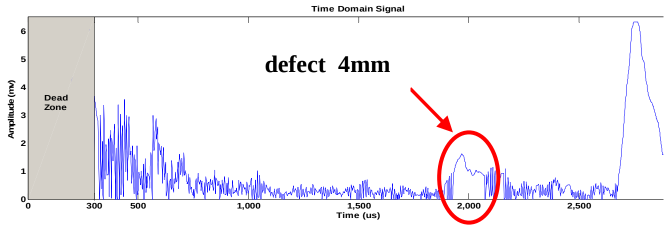
The following figures present the pulse-echo response of the far-end of the 4.3m rail with the addition of the defect. All the signals have been repeated (64 times) and averaged to minimise the effects of any random noise.



(a)



(b)



(c)

Fig. 13 The pulse-echo response for 1mm (a), 2mm (b), and 4mm (c) depth defect, respectively.

These results demonstrate the detection capability of 2mm depth defect. This defect represents an area of 36mm^2 which was the target of detectable defect area stated by the Monitorail project. Further trials are also being conducted in a different sample located at the Rail Research Centre (University of Birmingham) to determine the effect in the wave mode propagation caused by common rail features such as clips and welds. Such features will affect the wave propagation within the rail foot, as the ultrasonic wave will have the tendency to leak to such a feature and may cause a reflection depending on the bonding condition strength between the rail foot and the features. The aim of this work is to identify the rail features and to monitor the signal response over time in order to detect any significant change over time that might indicate the presence of a defect. This work is still in progress.

4. Conclusions

The characteristics of ultrasonic guided waves in the rail complex geometrical profile have been identified. A finite-element model has been used to predict the behaviour of ultrasonic guided waves in rail. Also, experimental trials have been conducted to assess the defect detection sensitivity. The findings of this study are the following:

- It is possible to generate specific wave modes in the head, web, and foot of the rail, which propagate in each part of the rail with little propagated energy into the other parts.
- Suitable wave modes based on their sole existing in the rail foot have been identified. F2 has been selected as the wave mode most suitable to inspect the foot
- An improved excitation/reception conditions has been proposed.
- The availability of the model has provided the basis for the design of a robust testing method for the detection of defects in rails.
- The ability of the selected wave modes to detect transverse defects in each part of the rail agreed with the predicted sensitivity.
- Experimental trials showed that detection of transversal defect 2mm depth on the rail foot is possible. However, more analysis is needed.

5. Future work

The future modelling work includes assessment of the sensitivity of guided wave tests for the detection of a wider range of sizes, locations, and types of defect. Further, the influences of environmental factors, such as the presence of sleepers and retaining clips, on the propagation of the waves will be also studied. The model utilised for this study may be used as a means of further investigation of the ability of guided waves to detect in rails under more realistic conditions, such as in the presence of sleepers and securing clips. For the experimental signals, improvement of the quality of the propagated wave will be achieved by using further signal processing analysis The difficulties associated with the dispersive properties of the guided waves for SHM will increase with their use on rail structures in service as this effect also occurs for the additional vibration caused by the traffic. Characterisation of the rail vibration induced by train passage will be also done to understand the effect of guided wave propagation under such vibration conditions.

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