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Development of ultrasonic guided wave techniques for examination of non-cylindrical components

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Abstract

In the past ten years ultrasonic guided wave systems have become widely used for the rapid large-scale examination of pipes and pipelines in pressure containing systems, for the detection of corrosion and other degradation in service. As a result, the characteristics of the guided wave modes existing in pipes have been studied extensively and are well understood. Advantage is taken of the fact that a pipe is essentially a one-dimensional object and that guided waves travelling along it will return to the sensor location for detection. Guided waves may also be applied to other components which are non-cylindrical, either those of constant cross-section such as railway rails or structural I beams, or constructions consisting of plates. However, in both cases the guided wave systems are more complex than in simple cylinders and successful application of this technique for large scale examination of these constructions requires further development of the understanding of the properties of the waves propagating and regularities of their generation. This paper describes work carried out under the EU-funded LRUCM project to develop techniques for detection of corrosion and cracking in railway rails and structural sheet piles used to retain earth embankments, river banks etc. The work described involved identification of wave modes present, derivation of dispersion curves to describe propagation behaviour and evaluation of experimental data to explain mode conversions and interactions with interfaces observed in the results.

Keywords: Ultrasonics; guided waves; rails; plates

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1. Introduction

Low frequency ultrasonic guided waves, in the 20 to 100 kHz range, have become widely used for the industrial non-destructive testing of pipes, mainly for the detection of corrosion. For pipes, axially-symmetric wave modes similar to longitudinal or shear-horizontal modes in plates are normally used, because they are largely non-dispersive in the frequency range of interest [2]. There are many advantages in the use of guided waves for other elongated components, for example railway rails, owing to their ability to examine large volumes of material from a

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limited number of test points. However, in non-cylindrical components such as rails the level of complexity of wave propagation increases significantly and analytical solutions for the propagation behaviour are hard to find. This paper describes the use of 3-Dimensional finite element analysis for the derivation of mode shapes, dispersion curves and reflectivity of crack-like defects in rails. Further, guided waves at the above frequencies may be used for large area examination of plate structures. However, owing to the low frequencies involved and the consequent large wavelengths, it is difficult to obtain good directional properties from transmitting and receiving transducer arrays unless they are very large. As a result the multiple modes are generated. The interaction of 'useful' and 'parasitic' waves with lateral boundaries of the object creates multiple reverberations possessing low decay what leads to essential extension of dead zone and complicates interpretation of the results. In order to evaluate possibilities of transducer array optimisation the regularities of generation of different guided waves modes in the case of plate like structures were investigated.

2. Guided waves in railway rails

Rose and Avioli [3] and Bartoli [1] have investigated the use of guided waves for the detection of defects in railway rails. Sources used to generate the ultrasound included the rolling contact between the train wheels and the rail and the use of a hammer impact. In both cases multi-modal propagation of the guided waves was used. In this work an attempt was made to identify the individual modes of vibration present in the rail section and to examine the capability of these modes to detect defects. Sanderson and Smith [4] developed a method of using finite elements to model the propagation characteristics of guided waves in rails and, from this, to generate both dispersion curves and the displaced mode shapes. From the study of the displaced mode shapes it was possible to identify individual modes which propagate only in the rail head, web and foot respectively. These are shown in Fig. 1.

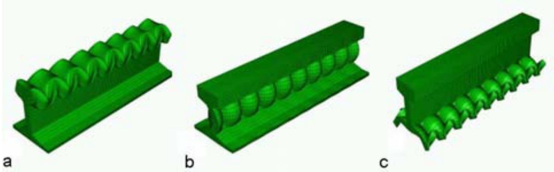

Fig.1 Mode F3 propagating in the head (a), Mode T2 propagating in the web (b), Mode F2 propagating in the foot (c)

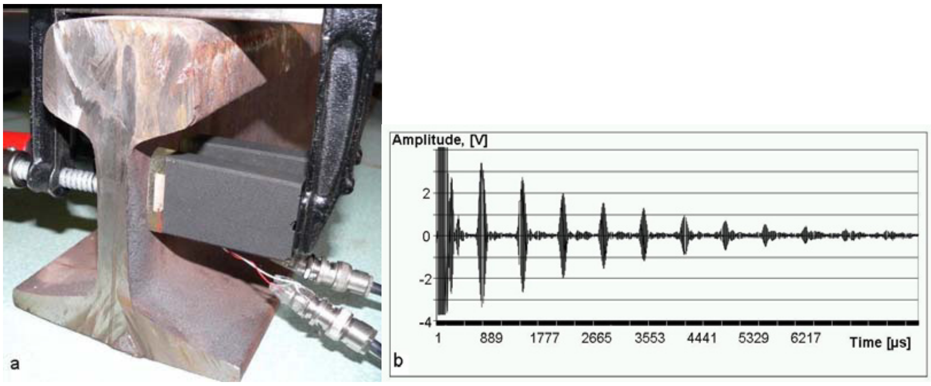

Fig.2 Transducer arrangement (a) and resulting signal (b) from repeat echoes of mode T2 propagating in a 1.5m long rail sample

Information about the mode shapes and the nature of the dispersive behaviour enabled practical excitation conditions to be determined, in terms of frequency and transducer position. The results for generation of Mode T2 in the web are shown in Fig. 2. It is clear that a single, non-dispersive mode is present.

The ability of this mode to detect defects is shown in Fig. 3. The transducers were applied to a 6.64m long section of rail, which contained two reflectors, a stud welded electrical connection and a hole for a mechanical fastener. The signals show that these reflectors were clearly detected.

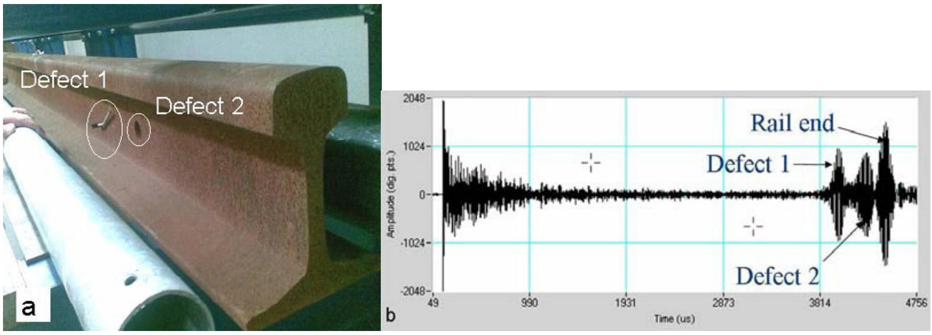

Fig.3 Rail specimen showing reflectors and responses obtained by Mode T2

2.1. *Influence of plate edges on guided wave behaviour*

Presences of the boundaries of the object on the way of propagating guided waves create the reflection and mode conversion of them. In the case of plate like structure such as sheet piles (Fig. 4a) the waves propagating in lateral direction are reflected and mode converted by the side boundaries and such 'parasitic' signals (Fig.4b) overlap with the'useful' signals generated in a front direction. As can be seen (Fig.4b) in the front part of the received signal there is a long zone of the reverberations, which masks even the bottom signal. This parasitic 'noise' creates a very long dead zone essentially complicating or even making impossible analysis and interpretation of the results.

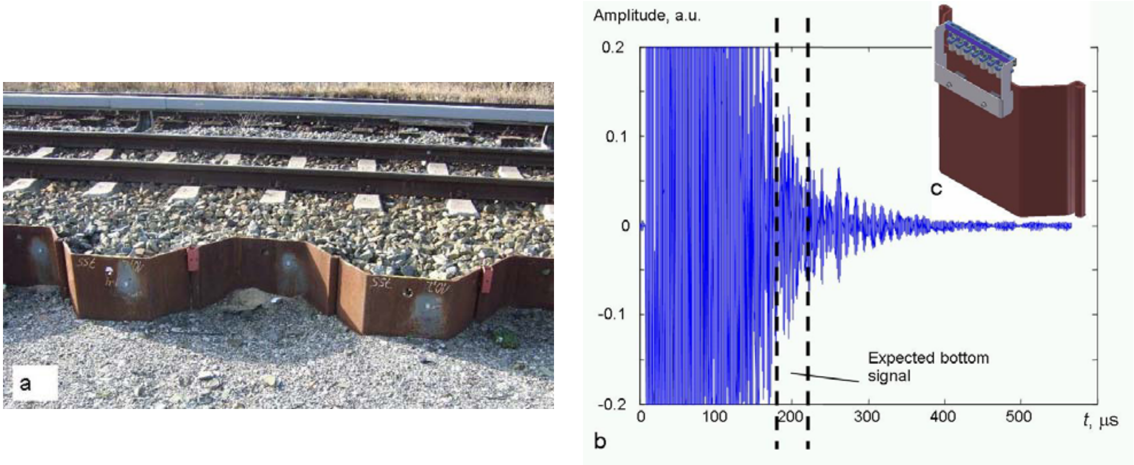

Fig.4 The sheet piles (a) and measured signals obtained in a pulse-echo mode (b) and the drawing of the transducer array (c) attached to the top of the sheet pile.

The inspection is even more complicated in the case when transducers are attached close to the edge, one of the ends of the object because some other modes are generated which propagate along the edge of the object.

The objective of this part of the work presented was to investigate the differences of the excitation of guided waves at close and far distances from the edges in a rather simple steel plate case. In the previous our work [5] it was demonstrated by modelling that in the case of the shear type excitation attached to the middle of the steel plate all three zero modes are generated: A_0, S_0 propagating in front and backward directions and S_H propagating in side directions. It was also shown that directivity patterns possess symmetry with respect to the excitation point. So, in the case when the excitation point is close to the boundaries the waves generated in backward direction will be reflected and will overlap with the waves propagating in the front direction. In order to investigate the regularities of the guided wave excitation the numerical experiment have been carried out using a finite element method. The setup of the modelling is presented in Fig.5. Generation of different Lamb waves was investigated using 3D model of the 10mm thickness steel plate with the dimensions 0.5x0.5m. The parameters of the steel used in the modelling were the following: density, ρ_{Al} - 7800 kg/m^3, Young modulus, E_{Al}, - 203 GPa, Poisson's ratio, ν – 0.29. The point source of a shear (in-plane) excitation force was added at the middle of the steel plate edge on the top surface and oriented perpendicularly to the edge. The obtained distribution of the particle velocity modulus

$$v_{t=50}(x,y)=\sqrt{v_{x,t=50}^{2}(x,y)+v_{y,t=50}^{2}(x,y)+v_{z,t=50}^{2}(x,y)}$$

on the surface of the plate at the time instance 50μs is presented in Fig.6. The several modes of guided waves propagating from the excitation point can be observed. The distributions of the components of the particle velocity at different time instances of the waves propagating in the front (line A) and the lateral (line B) directions demonstrate presence of multiple modes (Fig.7-8). The direction *x* corresponds to the lateral direction (Fig.5) and *y* axis corresponds to the front direction, *z* – across thickness of the plate. The patterns of S_0 and A_0 modes of Lamb waves propagating in the front direction can be seen in Fig.7. These modes contain both *y* and *z* components of the particle velocity. However the *x* component of these waves is equal to zero due to the symmetry of the task.

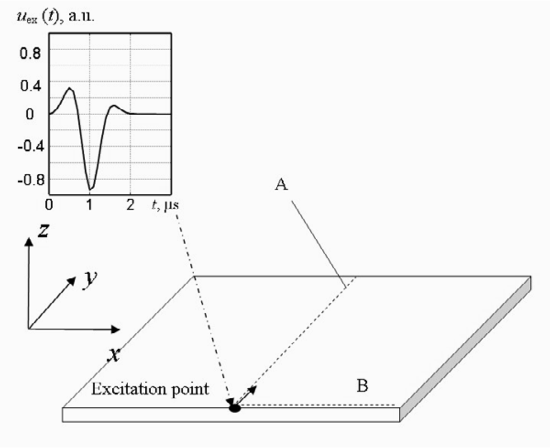

Fig.5 Set up of the modelling. The applied shear excitation force is denoted by arrow. Two dashed lines A and B denote points at which the signals were analysed.

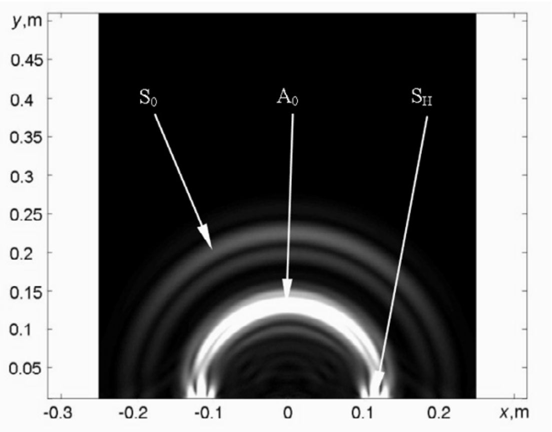

Fig.6 The distribution of the modulus of the particle velocity *v* of at the time instant 50 μs after the excitation.

In the lateral direction (Fig.8) one wave mode is dominating. It propagates with the velocity 2841m/s and was named as a surface edge (or shear horizontal on the edge) wave S_{RE}. Comparison of the relative amplitudes shows that the amplitude of the wave propagating on the edge is more then twice bigger then the amplitude of the A_0 mode and about 7 times then the S_0 mode.

The investigations carried out demonstrate that in the case of plate like structures when the transducer or transducer arrays are attached at the positions close to the edge of a plate the parasitic guided waves are generated which propagate along the edge(s) and possess the larger amplitudes comparing to the waves propagating in a front direction.

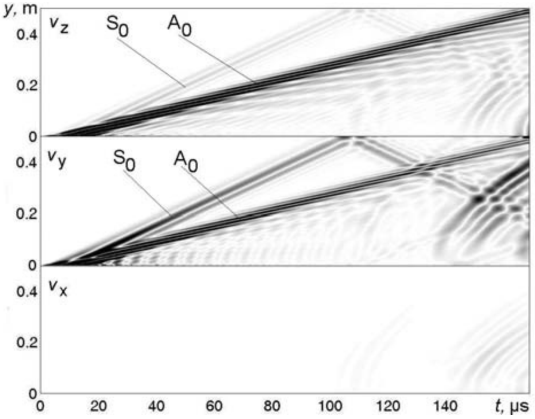

Fig.7 Distribution of the components v_x; v_y; v_z of particle velocity in the front direction (line A)

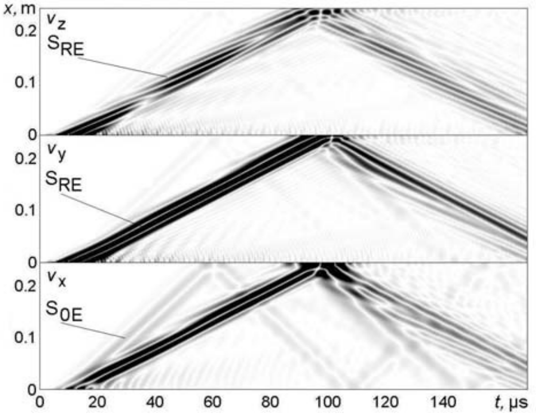

Fig.8 Distribution of the components v_x; v_y; v_z of particle velocity along the edge (line B)

3. Conclusions

It was shown that the ultrasonic inspection of the non-cylindrical components differs essentially and the techniques used in the inspection of pipes can not be applied directly.

The ultrasonic techniques based on the selective excitation of the wave's modes necessary for inspection of different parts of the rail were developed and demonstrated.

It was shown also, that in the case of sheet piles very strong surface waves propagating along edges of piles complicate non- destructive inspection.

Acknowledgements

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