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# AN ULTRASONIC SENSOR FOR MONITORING WHEEL FLANGE CONTACT

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## ABSTRACT

The wheel/rail contact is critical to the successful operation of a railway network. Contact occurs at the wheel tread/rail head and wheel flange/rail gauge corner. Contact conditions are more severe in the latter, which occurs mainly in curves. The contact is small and supports large loads, therefore high contact stresses are generated. These, combined with the slip in the contact, are primarily responsible for driving the processes that lead to wheel and rail damage, whether by deformation, wear or a fatigue process. Multi-body dynamics software is useful for predicting the wheel/rail contact characteristics there is a shortage of experimental tools available.

In this study, the feasibility of a new approach is investigated based on an ultrasonic sensor mounted on the wheel. The sensor emits an ultrasonic pulse which is designed to impinge on the wheel flange. If there is no contact the pulse is fully reflected back at the flange and picked up by the same sensor. If flange contact takes place, a proportion of the pulse amplitude will be transmitted into the rail. The signal reflected back to the sensor is therefore reduced. The amount by which this signal reduces indicates how much flange contact occurs. This work had two aspects. Firstly, a standard ultrasonic ray-tracing software package was used to establish what it is possible to measure with sensors mounted in the wheel and to determine the best location and orientation. The second aspect was an experimental study to determine whether such measurements are feasible.

Test specimens were cut from sections of wheel and rail, and a 2 MHz ultrasonic contact transducer was bonded onto the wheel in a position best suited to detect the flange contact. The specimens were pressed together in a bi-axial loading frame to generate differing degrees of rail head and flange contact. The reflected signal was monitored as the normal and lateral loads were varied. It proved possible not only to detect the onset of flanging, but also to record a signal that varied monotonically with both normal and lateral applied load. A map of reflected ultrasound against the applied loading is presented.

The technology, while not currently suitable for full field implementation could be very useful in laboratory studies on, for example, a full scale wheel/rail rig.

## 1 INTRODUCTION

Ideally wheel/rail contact should be confined to the wheel tread/rail head where the geometry is such that the loaded is relatively mild. However, during curving contact can occur between the wheel flange and the rail gauge corner. Contact conditions are more severe in this location because the geometry is less conformal and the sliding greater. In such situations it is common to have two point contacts, at the wheel flange and tread. The contact is typically $1cm^2$ in size and supports a large load, therefore high contact stresses are generated. These combined with the slip in the contact are primarily responsible for driving the processes that lead to wheel and rail damage, whether it be by deformation, wear or rolling contact fatigue [1].

There is clearly a need for information about the wheel/rail contact interface in terms of position, area, contact stresses. This is particularly important when problems such as wear and rolling contact fatigue may occur. There are several analytical models routinely used for analysing the wheel/rail contact. The simplest of these, Hertz theory, however, assumes the two components are smooth elastic solids of revolution. To model the real shape of the profiles, numerical solvers have been developed, such as FASTSIM [2], CONTACT [3], or finite element approaches [4].

There are few experimental techniques for measuring contact parameters. Pressure sensitive films have been used to determine the extent of contacts [5]. However, these change the nature of the contact and therefore are of limited use. Dynamic wheel/rail contact area measurements have been taken using low-pressure air passing through 1 mm diameter holes drilled into the rail head [6]. The pressure variations caused as holes were blocked by passing wheels were monitored and areas determined. This, however, can only give very limited spatial data.

An approach that has shown promise is the use of reflected ultrasound. This make use of the fact that ultrasound will be transmitted through a rough surface interface where there is asperity contact and be reflected where there are small air pockets. Thus a scan of reflected ultrasound across an interface can be achieved. A map of reflection coefficients can be generated, which can be converted to a contact pressure via a calibration process. This approach has been used successfully to study static wheel tread /rail head interfaces [7-9] but cannot be easily used on the flange because of the more complex geometry and is no use for field measurements.

In this work the information that can be obtained from a single stationary transducer has been explored, particularly looking at the flange contact. This was with a view to mounting a transducer on a wheel to provide dynamic sensing of flange contact. This could provide important information on where on a rail network, wear and rolling contact fatigue may be a problem.

## 2. BACKGROUND

When an ultrasonic pulse strikes an interface between two materials it is partially transmitted and partially reflected. The proportion reflected, known as the reflection coefficient, R depends on the acoustic impedance mismatch between the two materials according to equation (1). The ratio of the amplitude of the reflected wave, $A_r$, to the amplitude of the incident wave, $A_i$, is determined by:

$$R = \frac{A_r}{A_i} = \frac{z_1 - z_2}{z_1 + z_2} \tag{1}$$

where z is the acoustic impedance (the product of density and wave speed) of the media and the subscripts refer to the two sides of the interface. If the wave strikes a steel-steel interface and there is perfect contact, then it will be fully transmitted ($z_1$=$z_2$). The impedance of air and steel are 412 and $46.02\times10^6$ kg/m$^2$sec respectively. Thus an ultrasonic wave will be virtually completely reflected at a steel–air interface, but will be fully transmitted at a complete steel to steel contact.

Thus if the transducer is positioned in the correct orientation it can detect when contact occurs. The contact between the wheel and rail will never be complete, i.e. 100% contact. There will be microscopic air gaps between the regions of asperity contact. This means that equation (1) represents a lower bound and R never reaches zero. Experience suggests that R reduces to around 0.2 for highly loaded rough surface contacts [7].

## 2. MODELLING APPROACH

A convenient method for determining the ideal position for a transducer is to use ray-tracing software. Ray-tracing is achieved by finding the intersection points of the rays and the solid bodies. Intersection points are kept or discarded according to the logical relationship between the combined objects. The software models the propagation of ultrasonic waves and internal reflections at any number of interfaces within a solid structure. The transducer is modelled as a source and the signal amplitude at any location in the structure can be determined.

In this work, the geometries of the wheel and rail were created and exported into the software (in this cased Imagine3D (see http://www.imaginefa.com/ for further details of the software)). They were extruded (for rail) and revolved (for wheel) as solid to generate the 3D solid bodies for the simulation (Figure 2).

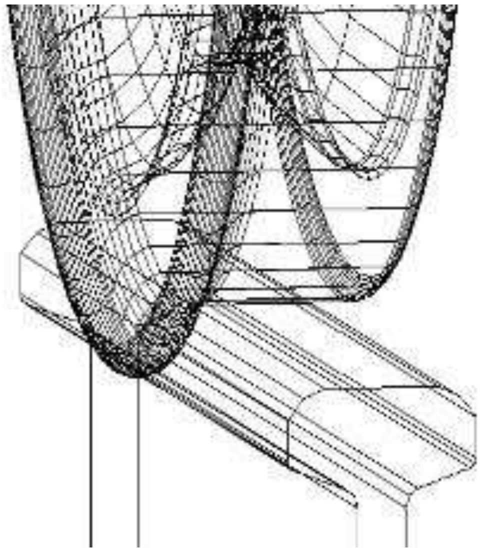
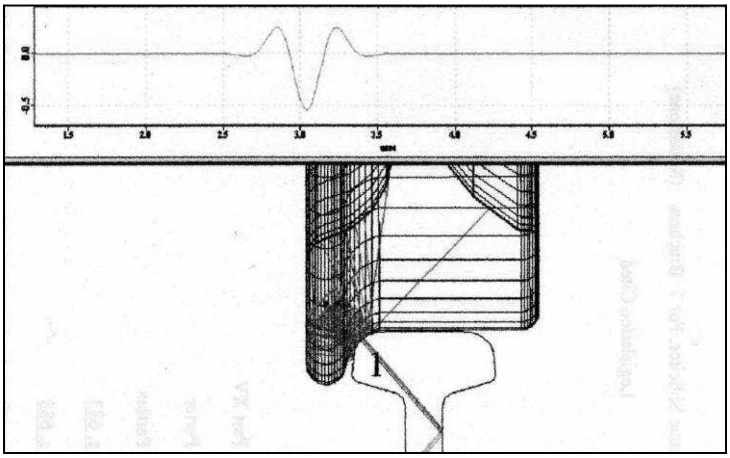


Figure 1. Solid-body model of the wheel and rail used in the ray-tracing software

Once the geometry was created, a longitudinal mode transducer was specified and located on the wheel body. The concept was to use the same transducer to both send and receive ultrasonic signals (pulse-echo mode). The software predicted the ray path within the wheel and the signal reflected back to the transducer or transmitted through the interface with the rail component. The transducer design and location was then modified to investigate the response and spatial resolution.

The location of the ultrasonic transducer is critical in determining whether it can 'see' the occurrence of flange contact. The sensor must also be located in a position on the wheel so it is both accessible and easy to install. The first series of simulations were performed to determine the optimum location and orientation of the transducer. Figure 2 shows the sensor ray passage for two positions of transducer. Position (a) is the best since part of the wave has been reflected back from the flange contact. At position (b) the reflection wasoblique and so the received signal is virtually zero.

(a) 

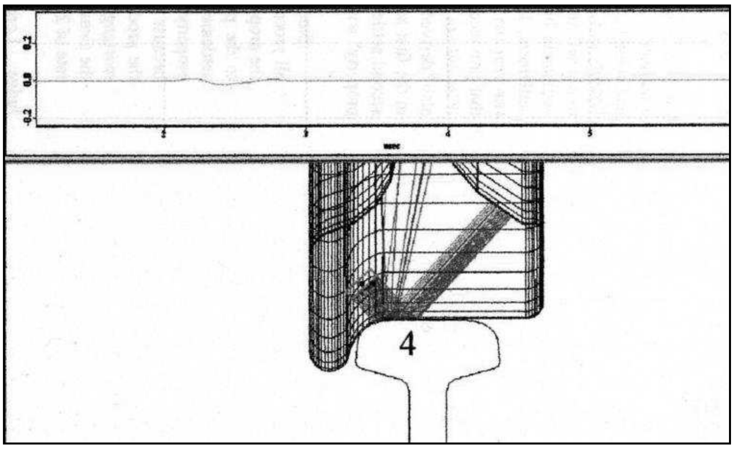
(b) 

Figure 2. Ray-tracing results for two transducer positions (the wave form above each plot indicates the magnitude of the reflected signal)

Once the optimum transducer position was selected (an angle of 47° and a height above the contact point of 21 mm) a suitable mounting point for the sensor was machined on the wheel specimen used in the experiments.

The greater the size of the region of contact, the more of the sound wave will strike a solid-solid interface and be transmitted. A further series of simulations were carried out (from no contact to complete contact) to observe the change in the reflected pulses and the reflection coefficient. Figure 3 shows the results. As the width of the contact arc, b was increased more than 6 mm, it was enough to let all the pulses pass through the surface. The reflection coefficient remained constant at, 0.17. This corresponds to a value consistent with a rough surface contact. It should be noted that the ray-tracing software is not a contact model. ‘Contact’ is achieved by simply overlapping the bodies in the software.

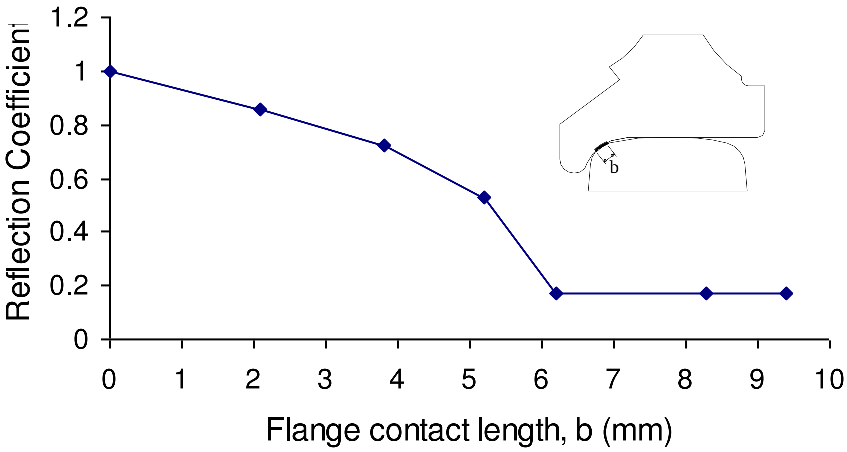



Figure 3. The relation between reflection coefficient and flange contact size

## 3. APPARATUS AND PROCEDURE

The wheel and rail specimens used in the experimental work were cut from sections of UIC 60 900A rail steel and R8T wheel steel (shown in Figure 4). A frame and two hydraulic cylinders shown in Figure 5 were used to normally and tangentially load the specimens together.

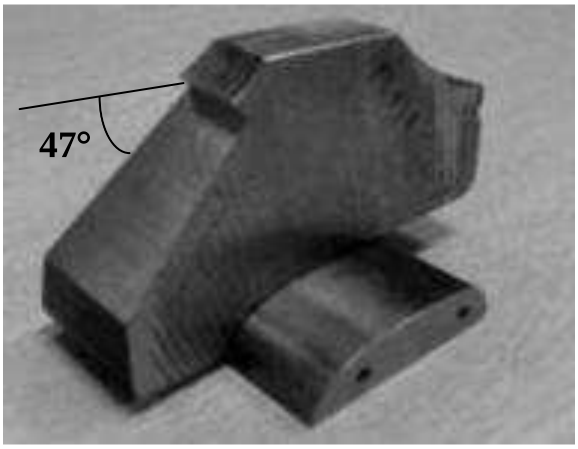



Figure 4. Test samples cut from wheel and rail sections (note the slice made on the wheel periphery at an angle of 47°)

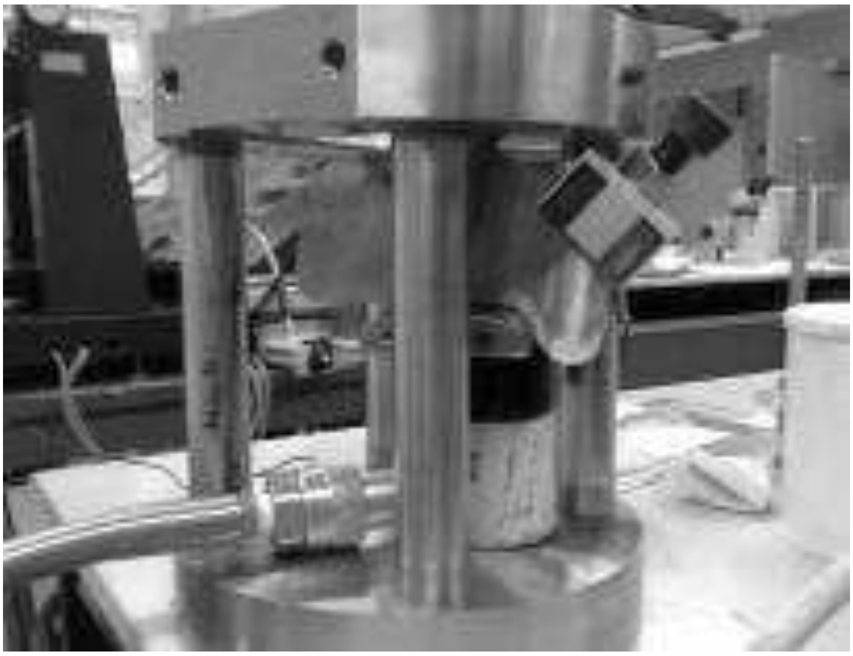


Figure 5. Loading frame and hydraulic cylinder

Normal forces, varying from 0 to 80 KN in the vertical direction, were applied using an Enerpac hydraulic cylinder which was located below the wheel/rail specimens. Another hydraulic cylinder was used to generate lateral forces from 0 to 9 kN in the horizontal direction. As the wheel/rail components had no constraint in the horizontal direction, lateral force would cause relative sliding between wheel and rail. A large enough normal load must be applied to prevent this sliding.

Figure 6 shows a sketch of the experimental layout. The instrumentation consisted of an ultrasonic pulse receiver (UPR), oscilloscope, data processing computer and transducer. The UPR provides a voltage step which excites the transducer to produce an ultrasonic pulse. The signals reflected at the wheel/rail interface were received by the same transducer passed to the UPR and amplified. The oscilloscope was used to digitise the received signal and download it to the computer. LabView was used to control the UPR and extract the reflection from the wheel/rail for further processing.

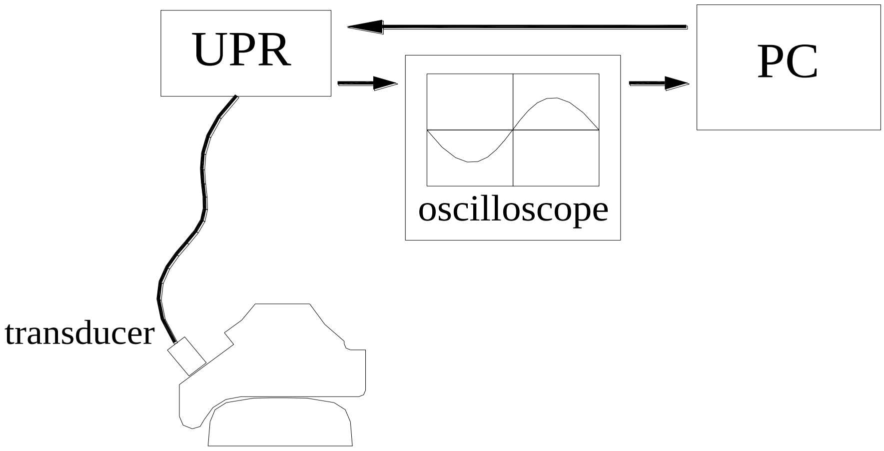



Figure 6. Schematic of the apparatus system

Initially a reference amplitude is received when the wheel and rail are out of contact. In this case the ultrasound is reflecting from steel-air interface so R=1 and all the wave amplitude is reflected. The reference reflected signal is then equal to the incident signal. Subsequent reflections are divided by this reference signal to give the reflection coefficient. The reflection coefficient amplitude is recorded. In practice it is easier to pass the time domain pulse through a Fast Fourier Transform (FFT) to obtain a reflection coefficient spectrum. The amplitude is easily obtained from the peak of this spectrum.

Normal and lateral forces were applied in sequence and for each load case the reflected signal was recorded and the reflection coefficient amplitude determined.

Figure 7 shows a series of reflected pulses as the normal load is increased. The transducer has a centre frequency of 2.2 MHz and a band width of 1.1 to 3.4 MHz.

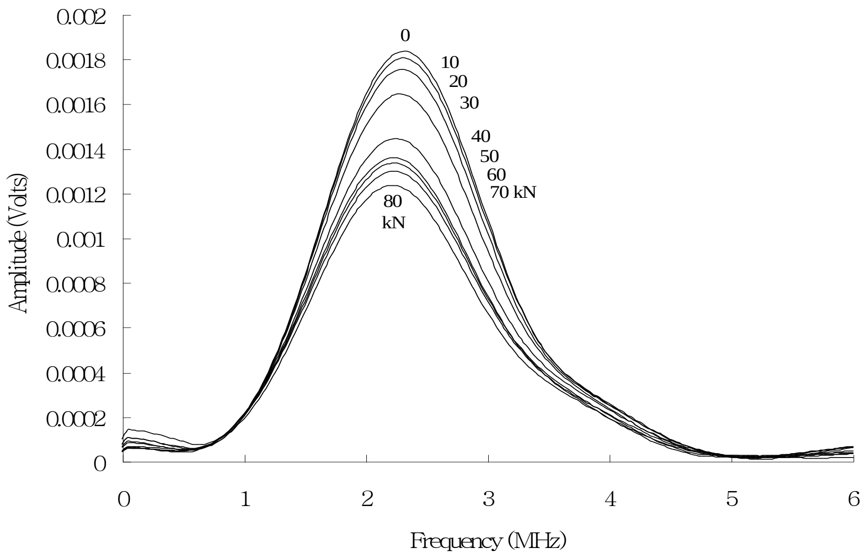



Figure 7. Amplitude of the reflected pulses in the frequency domain.

The reflection coefficient is obtained by recording the amplitude at the transducer centre frequency (2.2MHz) and dividing by the amplitude for the zero load case. This data is shown as figure 8 for increasing normal load on the specimens.

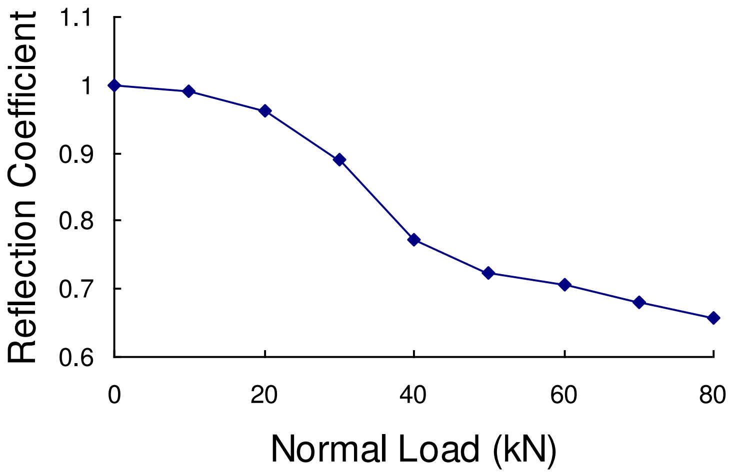



Figure 8. Variation of reflection coefficient with normal load.

Figure 9 shows the results when a lateral load is applied in steps when the normal load is 80 kN. As the lateral load is increased the flange contact gets larger and the reflection coefficient reduces.

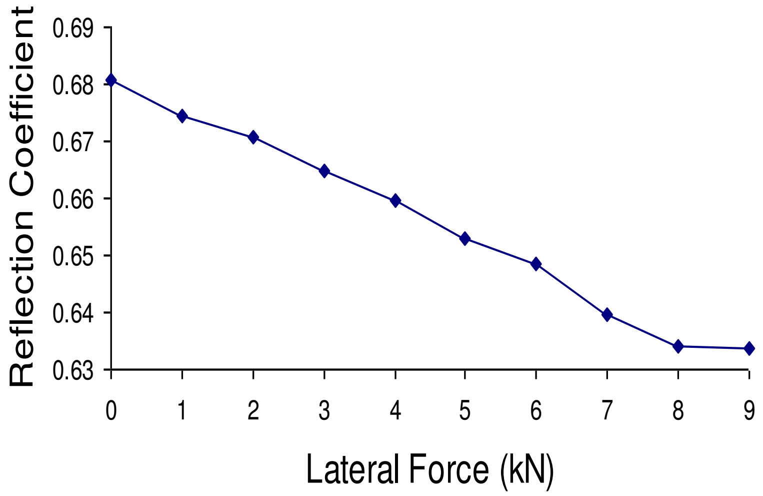



Figure 9. Variation of reflection coefficient with lateral load for a normal load of 80 kN

In further tests, series lateral as well as normal loads were applied to the specimens. Figure 10 shows a map of the measured reflection coefficient as it varies with both normal and lateral loads.

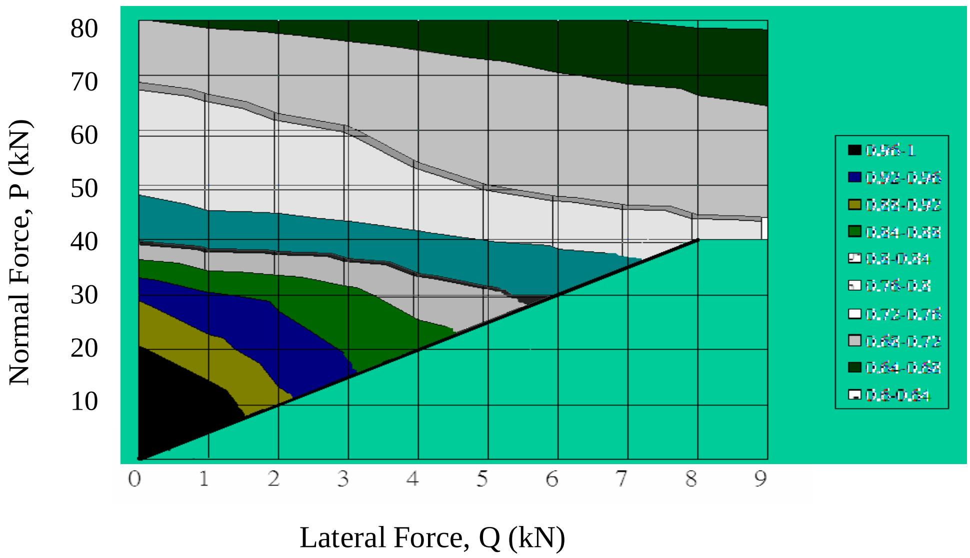



Figure 10. Map of the variation of reflection coefficient with normal and lateral load

## 5. DISCUSSION

While the map of reflection coefficient in Figure 10 clearly shows that reflection is sensitive to both normal and lateral load and it may therefore be feasible to detect the onset of flange contact using this ultrasonic approach there are many issues that would need to be resolved and as such at the moment it will probably have to remain a tool that is used mainly in research/testing within a laboratory rather than something that is transferred to the field. Some of the hurdles to implementation are discussed below as the performance of the technique is evaluated and then a first step to using the technique is suggested.

The practical implementation of a sensing system of this nature in the field would be difficult in terms of actually mounting and then of feeding back the data. The sensors are relatively robust and can be permanently glued in place and should be able to withstand the aggressive environment. Either a small hole would be drilled into the wheel side, or it could also be possible to bond a small boss (at the correct angle) onto the wheel. Connecting wires must then be fed back through slip rings to an on-board pulser receiver and data capture unit. It would also be feasible to have a small ultrasonic pulser (similar to that built into ultrasonic flow meters and level sensors) mounted directly on the wheel which uses telemetry to send the post-processed signal back to an on-board receiver.

It is envisaged that the transducer would be continuously pulsed during wheel rotation. This means that only when the sensor is over the contact location would a change in the recorded signal be observed. Typically, using conventional ultrasonic equipment, pulsing can be achieved at a repetition rate of 20 kHz. Therefore signals can be recorded at intervals of 50 μs. It is likely therefore that, depending on the contact patch size and the train speed, something like 5 to 10 signals could be recorded from a contact patch as the sensor location on the wheel passes overhead. Then a full revolution must be completed before signals are recorded again. This means that only flange contact events that exist for more than one revolution could be picked up by a single sensor on the wheel periphery. Flange contact would actually be intermittent in one wheel revolution.

One advantage is that the sensor is effectively "self referencing". This is because for much of its operation it the wheel and rail are out of contact. This means that the signal is reflected back from the steel air interface. Since all subsequent signals are referenced to this signal any changes in the transducer output with say for example temperature or bond degradation are cancelled out.

With a single sensor it would be difficult to separate the increased reflection caused by a either a change in normal load or a change in lateral load so the technique as outlined here would rely on the normal force remaining constant, which of course, particularly in curving, it certainly does not. The location of the sensor is also critical to what region of contact across the flange that can be observed. Here we have just considered contact between the rail shoulder and the throat of the wheel flange. When the wheel mounts the rail so that the contact occurs on the tip of the flange then the sensor, in its current location, may not be able to observe this region. Also there could be more than one contact. Possibly more than one sensor is needed; this is an area for further study. Work has been initiated to study the wheel tread/rail head contact using ultrasonic arrays [10]. This may help provide a solution to seeing more of the flange contact as well as dealing with varying forces.

There are potentially implications from third body interfaces between wheel and rail such as curve grease or top of rail friction modifier. This can be dealt with and in fact work has been carried out recently on wheel axle/hub interference fits that involved the presence of a lubricating wax [11]. The issue would be actually accounting for this as it changes along a length of track.

It is also worth noting that it would also be possible to use the ultrasonic sensor to detect wear of the wheel contact face. The time for the pulse to travel from the sensor to interface and back is readily available from the reflected signal. As the wheel wears the path length will reduce and the time of flight decrease. It is simple matter to convert this reduced time of flight to a wear measurement. Estimates of worn depth accurate to tens of microns should be quite feasible.

One immediate step that could be taken with the technology is to mount it on a full-scale wheel rail testing rig (see for example [12] where the wheel rolls for a fixed linear distance down a piece of rail (not achieving a full rotation normally) before returning to the start to begin a new cycle). This would allow loads to be fixed, slower operating speeds are used, angle of attack can be controlled etc. so a full parametric study could be carried out and the influence of third-body materials could be assessed as well.

## 6. CONCLUSIONS

This study has demonstrated that it is possible to detect flange contact using an ultrasonic sensor mounted on the wheel. A modelling approach, using ultrasonic ray-tracing software, was used to determine the best location for the sensors. This sensor location was used in the design of some simple specimens that were cut from sections of wheel and rail. The specimens were subjected to combined normal and lateral loading and the sensor response monitored.

The ultrasonic signal was processed into a reflection coefficient. This varied from 1 to 0.68 as the normal load was applied up to 80 kN. As the contact area grows more of the ultrasound is transmitted and so less reflected. When the lateral load was increased from zero to 9 kN, the flange contact grew and the signal dropped from 0.68 to 0.65.

The approach has so far only been carried out on static specimens in a hydraulic press. It is potentially feasible to extend this to a full-scale wheel/rail rig and use continuous pulsing to ensure that the contact is captured as the sensor passes over the rail. Full implementation in the field is probably not possible at the moment, but a lot could be learned in laboratory tests.

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