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What is This?
An ultrasonic sensor for monitoring wheel flange/rail gauge corner contact

Rob S Dwyer-Joyce, Chris Yao, Roger Lewis and Henry Brunskill

Abstract
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 at 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; however, there is a shortage of experimental tools available. In this study, the feasibility of an approach based on an ultrasonic sensor mounted on the wheel is investigated. 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 has occurred. This work had two aspects. First, 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.

Keywords
Wheel/rail contact, ultrasonic measurement, ultrasonic reflection, flange contact

Introduction
Ideally wheel/rail contact should be confined to the wheel tread/rail head where the geometry is such that the loading 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 points of contact, at the wheel flange and at the tread. The contact is typically 1 cm² 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 and contact stress level. This is particularly important when problems such as wear and rolling contact fatigue may occur. There are several analytical models routinely used to analyse the wheel/rail contact. The simplest of these, Hertz theory, however, assumes that 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, CONTACT and finite element approaches.2–4
There are only a few experimental techniques that can be used to measure contact parameters. Pressure-sensitive films have been used to determine the extent of contact. However, these change the nature of the contact and therefore are limited in their range of application. Dynamic wheel/rail contact area measurements have been taken using low-pressure air passing through 1 mm diameter holes drilled into the rail head. In this technique the pressure variations caused by holes becoming blocked by passing wheels are monitored and the areas determined. This, however, can only give very limited spatial data.

An approach that has shown promise is the use of reflected ultrasound. This makes use of the fact that ultrasound is transmitted through a rough surface interface when there is asperity contact and is reflected when 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 into a contact pressure when 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 into a contact pressure via a calibration process. This approach has been used successfully to study static wheel tread/rail head interfaces, however, it cannot be easily used on the flange because of the more complex geometry and it is of no use for field measurements. Another ultrasonic method used for interrogating contacts relies on surface waves, this again would be impractical to use in this situation.

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.

### 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 as shown in equation (1). The ratio of the displacement amplitude of the reflected wave, \( A_r \), to the amplitude of the incident wave, \( A_i \), is determined by

\[
R = \frac{A_r}{A_i} = \frac{z_1 - z_2}{z_1 + z_2}
\]

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 \( \times 10^6 \) kg/m\(^2\)s, respectively. Thus, an ultrasonic wave will be virtually completely reflected at a steel/air interface, but will be fully transmitted at a homogeneous 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.

### Modelling approach

A convenient method for determining the ideal position for an ultrasonic 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.

Diffraction and scattering in reality will result in a reduction of amplitude of the reflected signal; however, it does not affect the bulk ultrasonic wave paths, especially in the high-quality materials in question. If one was to investigate a rough cast iron or similar materials with irregular material structures, one might benefit from including this information in the simulation. The ray-tracing works using Snells law and geometry. It is a powerful tool that can be used to not only find the optimum sensor position, as in this case, but also to predict complex ultrasonic phenomena such as the change in frequency content at an interface.

In this work, the geometries of the wheel and rail were created and exported into the software (in this case Imagine3D (see http://www.imaginefa.com/ for further details of the software)). They were extruded (for rail) and revolved (for wheel) as a solid to generate the three-dimensional solid bodies for the simulation (Figure 1).

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
wheel axle/hub interference fits that involved the presence of a lubricating wax.\textsuperscript{13} 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 the 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 a 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. Severe wear would, however, affect the profile such that the reflection of ultrasound would alter significantly.

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, Stock et al.\textsuperscript{14} 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 to be used, angle of attack to be controlled, etc. so a full parametric study could be carried out and the influence of third-body materials could be assessed as well.

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. The value of this coefficient varied between one and 0.68 as the normal load was applied up to 80 kN. As the contact area grew larger more of the ultrasound was transmitted and so less was reflected. When the lateral load was increased from zero to 9 kN, the flange contact grew and the coefficient value dropped from 0.68 to 0.635.

The proposed 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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References