Conference or Workshop Item:

Marhsall, M.B., Lewis, R., Dwyer-Joyce, R.S. et al. (2 more authors) (2004) Ultrasonic characterisation of wheel hub/axle interference fit pressures. In: 14th International Wheelset Congress, 17-21 October, Orlando, USA. (Unpublished)

Ultrasonic Characterisation of Wheel Hub/Axle Interference Fit Pressures

M.B. Marshall*[1], R.Lewis[1], R.S. Dwyer-Joyce[1], F. Demilly[2], Y. Flament[2]

[1]Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK.
[2]Valdunes, BP129, 59943 Dunkerque Cedex 2, France.
*Corresponding author

Summary: Railway wheels are secured onto the axle by means of an interference fit. The wheel is press fitted onto a pre-lubricated axle, and the resulting interference fit induces a contact pressure at the interface. Occasionally railway wheels fail by fatigue, with the initiation point for the failure frequently traced to the interference fit. The aim of this work is to use ultrasonic reflection to non-destructively determine contact conditions in the interference fit.

The rough surface contact at the interference fit interface behaves like a spring. If the contact pressure is high the interface is conformal with few air gaps, the stiffness is then high and the transmission of an ultrasonic wave is permitted. However, when pressure is low more air gaps exist, interfacial stiffness is then reduced and more of the ultrasound is reflected.

Normalised contact pressure was determined from this stiffness. Maps of the interface have been produced which show the contact pressure to peak at the edges of the fit, and to experience a continuous variation about a mean value elsewhere.

1. INTRODUCTION

Interference fits are a commonly used mechanical attachment mechanism. They represent a flexible and cost effective method for joining components having cylindrical geometry. An interference fit is constructed when a bush is shrunk and/or pressed onto a shaft with an interfering radial dimension. The strength of the interference fit assembly depends on the shaft and bush dimensions, and must be sufficient to withstand the force or torque reached during normal service.

One common example of the use of interference fits is found on railway wheel-sets. In this case the wheel is press fitted onto the axle, with a wax lubricant also used at the interface when constructing the fit. Railway wheels occasionally fail by fretting fatigue, and this failure often initiates at the interference fit. Thus a quantification of contact pressures and their distribution in the wheel/axle fit is essential.

Previous work [1] has shown the validity of a non-intrusive ultrasonic reflection based technique for measuring the contact pressure distribution in an interference fit. Here the work is advanced applying the technique to an actual railway wheel/axle interface. The contact at the interface is partially lubricated in this study, in contrast to the dry fits previously analysed. The wheelset investigated was from the high speed TGV train, and was manufactured by the French company Valdunes. This

Paper from 14th International Wheelset Congress, 17-21 October, Orlando, USA.

work is part of a wider project aimed at reducing the weight of the wheel. In order to reduce the weight wheel material must be removed, and this affects the interface pressure distribution. The interface pressure must be maintained at a certain level to ensure the wheel is safely secured. At present Valdunes perform finite element modelling of the wheel to map the interface pressure, and use this tool to then assess the effect of removing material on the pressure. The overall aim of this study is to validate the numerical model using the experimental ultrasonic technique.

2. ULTRASONIC REFLECTION FROM A DRY ROUGH SURFACE CONTACT

When two real engineering surfaces are pressed together contact occurs at asperity tips, with trapped pockets of air present where the surfaces do not touch. Figure 1 shows such an interface with an ultrasonic wave incident at it. The signal is transmitted at the asperity contacts and reflected back from the air gaps. Tattersall [2] defines the reflection coefficient as the fraction of the incident ultrasonic signal at the interface that is reflected from it.

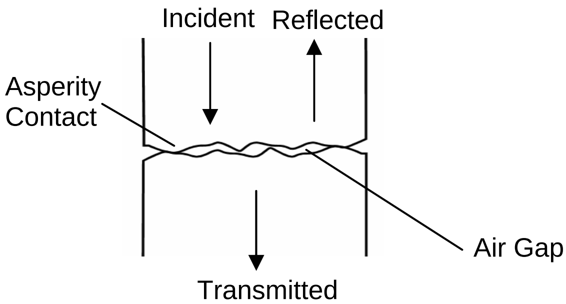

Figure 1. Partial Reflection of Ultrasound at a Rough Surface Contact

The response of the interface to an incident ultrasonic signal depends, amongst other things, on the wavelength of the sound relative to the size of the air gaps. When the wavelength of the ultrasound is long compared to the magnitude of the air gaps, the interface as a whole behaves like a reflector. Kendall and Tabor [3] investigated this case, and found ultrasonic reflection to be governed by the *spring* like behaviour of the interface. For two similar materials in contact the relation is:

$$|R| = \frac{1}{\sqrt{1+(2K/\omega z)^2}} \quad (1)$$

where ω is the angular frequency of the wave ($\omega = 2\pi f$), and z the acoustic impedance (the product of density and wave speed through the material).

Drinkwater et al. [4] investigated the applicability of the *spring* model to ultrasonic reflection data from rough surface contacts in a series of experiments. The results showed that the model could be successfully applied to reflection data up to ultrasonic frequencies of 50 MHz, after which scattering of the wave occurs at the interface and Equation 1 is no longer valid.

The interfacial stiffness, K, is the nominal contact pressure required to cause unit approach of the mean lines of the surfaces at the interface. As the load supported at the interface is increased the proximity of the surfaces rises, as does the number of contacting asperities. The stiffness also increases, as a greater load is required to further reduce surface separation, since the extra asperity contacts must also be deformed. In this way stiffness may vary from zero when the surfaces are just touching, to infinity when the interface is completely conformal. The stiffness is thus dependent on the load applied to the interface and hence contact pressure.

However, as well as contact pressure, interfacial stiffness is dependent on the size, number, and distribution of asperities at the contact. Although, for a given pair of contacting surfaces over a short pressure range interfacial stiffness has been found to be proportional to contact pressure [5]. A calibration experiment may therefore be performed to find the relationship between stiffness and pressure for a given rough surface contact. In this way ultrasonic reflection data may be used to determine contact pressures.

3. ULTRASOUND AND A PARTIALLY LUBRICATED CONTACT

The ultrasonic technique and concept of interfacial stiffness can similarly be applied to a partially lubricated interface [1]. The pockets of air previously at the interface are now filled with lubricant as shown in Figure 3.

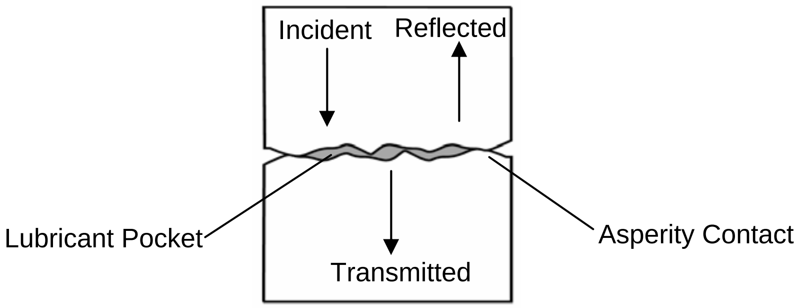

Figure 3. Reflection of Ultrasound at a Partially Lubricated Rough Surface Contact

For a partially lubricated interface the following equation for total stiffness, K_T, applies:

$$K_T = K_L + K_S \tag{2}$$

where K_L is the stiffness of the constrained lubricant, and K_S the solid stiffness from the asperity interaction. The stiffness of the lubricant film, K_L, is:

$$K_L = \frac{\rho_L c_L^{\;2}}{h} \tag{3}$$

where ρ_L and c_L are the density and speed of sound in the lubricant respectively, and h the average separation of the interface surfaces.

The presence of the lubricant increases the stiffness of a given rough surface contact at each and every contact pressure when compared to the un-lubricated case. This is due to the addition of the lubricant stiffness to the existing solid stiffness. The spring model shown in Equation 1 is still applicable to find the total interface stiffness from a lubricated contact [6]. If the lubricant stiffness is subtracted from the overall value the solid stiffness may be determined, the solid stiffness as for the dry case is proportional to contact pressure. In this way contact pressure can be determined using ultrasonic reflection data from a lubricated contact.

Determining the average separation of surfaces in a loaded interface is difficult. This causes problems when calculating the contribution of the lubricant to overall stiffness. However, the work of Gonzalez et al. [6] showed that a good approximation for initial surface separation is found by adding together the roughness values for the two contacting surfaces at the interface. Further, they also showed that at low pressures (those typically less than 2 GPa) the effect of increasing interface load on the lubricant stiffness is minimal. Thus, a good approximation for the lubricant film stiffness at low pressure can be found from the surface roughness and lubricant properties.

4. EXPERIMENTAL DETAILS

4.1 Ultrasonic Scanning Apparatus

A 10 MHz spherical focusing transducer was used to investigate the wheel/axle interference fit. The transducer contained an active piezo-electric element, which emitted an ultrasonic pulse in response to an electrical excitation. Longitudinal ultrasonic waves can be focused by refraction. In this study the waves were focused onto the wheel/axle interface, at which point the ultrasonic spot diameter was 1.8 mm. The focused spot diameter is the resolution of the ultrasonic technique. Along with the transducer, the ultrasonic equipment also consisted of an oscilloscope, an ultrasonic pulser-receiver, and a PC to which the reflected ultrasonic measurements were downloaded. A schematic of the ultrasonic equipment set-up is shown in Figure 4.

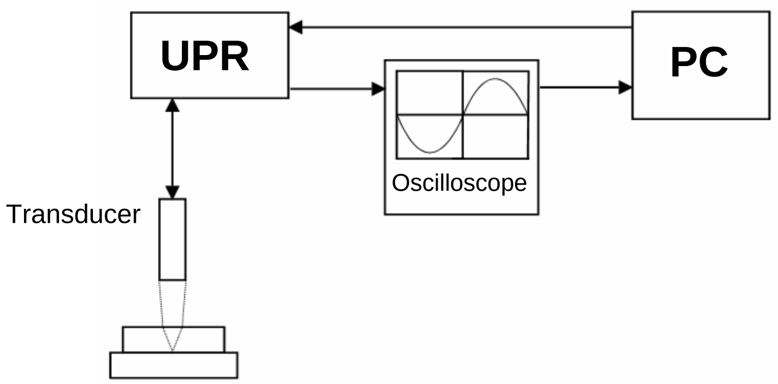

Figure 4. Schematic of Ultrasonic Scanning Apparatus

4.2 Experimental Details

In order to provide a study of the wheel/axle interference fit a stand was manufactured to accommodate the wheel. The stand was then placed in front of a scanning table automated for *x*, *y* scanning. It was constructed, as the wheel was too big to successfully mount on the scanning table. The stand also had bearing mountings onto which the wheel was seated; these enabled it to be easily rotated for scanning.

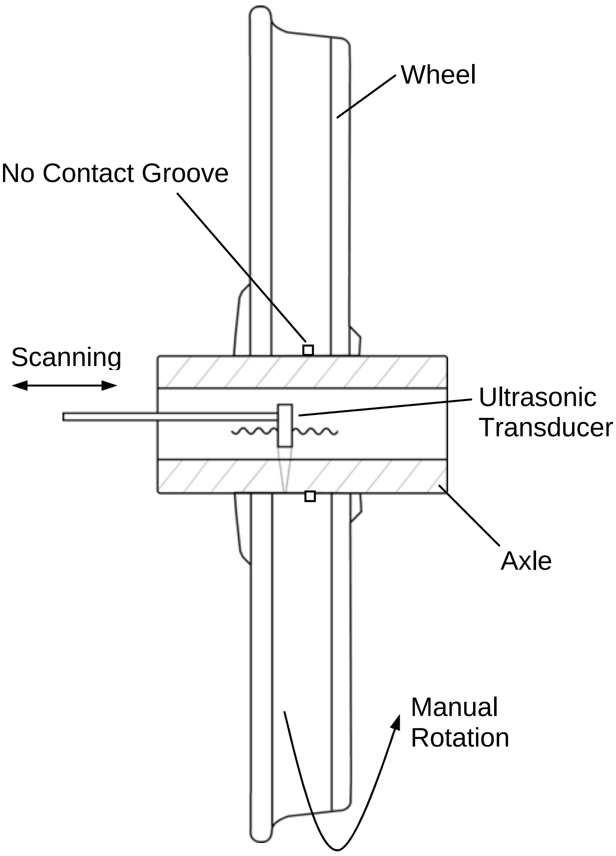

Figure 5. Schematic of Wheel/Axle Scanning

The axle had a constant diameter bore down its centre axis. It was decided that due to the complex external geometry of the wheel it was preferable to scan the wheel/axle interface from this bore. Therefore, an arm was constructed and attached to the bed of the scanning table, and the transducer secured onto it within the bore. Figure 5 depicts the transducer mounted in the bore. As shown, a water couplant is used between the transducer and axle material. The transducer is positioned in the water bath so as to focus the ultrasonic signal onto the interference fit interface. Using the automation of the scanning table *x*-axis the transducer can then be scanned along the wheel/axle fit with ultrasonic measurements recorded at prescribed points. In this way line scans were recorded at a step size of 0.5mm at 10-degree intervals around the contact.

Reflected ultrasonic signals from the wheel/axle interface were recorded during the scanning, with temporal averaging used to minimise any electrical noise. The reflected voltage from the interface is smaller than the emitted signal from the transducer. This is because the ultrasound is attenuated as it travels in the material bulk, as well as being only partially transmitted at the rough surface contact. A reference trace is also recorded; this is measured from the groove on the interface indicated on Figure 5 (the groove shown is present as it is used to apply an external pressurisation when removing the wheel from the axle). The reference trace is only diminished by attenuation, as all the ultrasound is reflected back from the air filled groove at this point. If the reflected voltage values are divided by the reference trace, the attenuation is cancelled out. This leaves the fraction of ultrasound incident at the interface that is reflected from it, or in other words the reflection coefficient, R. In this way reflection coefficient line scans were produced of the wheel/axle interference fit interface at 10-degree intervals.

Applying Equation 1 to the reflection coefficient data produced values of total interface stiffness for the partially lubricated contact.

4.3 Interface Pressure Profiling

The line scans recorded around the interface were assembled into a map of total stiffness. Surface roughness measurements were then taken from both the wheel and axle. It was found that for both lathe finished specimens the mean value of surface roughness was 1.5 microns. This value was then used, along with the lubricant density and speed of sound, to estimate the stiffness of the lubricant at the wheel/axle interface using Equation 3. It was found that the lubricant stiffness was 0.53 GPa/micron, compared to an average value of 4.4 GPa/micron for the total stiffness. The value of lubricant stiffness was then subtracted from those of total stiffness. In this way, a map of solid stiffness for the wheel/axle interface was constructed.

The solid stiffness is linearly proportional to the contact pressure. This is empirical result at low pressure first shown by Hodgson et al. [5]. Thus, by dividing the solid stiffness by the mean value for the whole interface, a map showing the ratio of pressure to mean contact pressure was determined.

5. ULTRASONIC RESULTS

Figure 6 shows the contact pressure profile of the wheel/axle interference fit; a line scan of the interface is also shown in Figure 7a. These scans has not yet been calibrated for pressure, instead they show the relative magnitudes of pressure in the contact. As shown, the contact pressure along the length of the interface is not constant. However, as may be expected, there is a high degree of radial symmetry. Contact pressures rise at the edge of the interference fit before falling away again. The edge of the interference fit magnifies the contact pressure, as it is a stress-raising factor. However, the wheel hub is also tapered at the edge of the fit with the interference reducing (see Figure 7b). The reducing interference acts to lower the contact pressure. These two factors in combination lead to the observed initial increase then subsequent decrease in the contact pressure at the edge of the fit.

Similarly, the contact pressure rises near the edge of the no contact groove. However, here the pressure rises to a higher value than that at the edges of the fit. This is because at the groove there is no tapering to counteract the stress raising effect of the discontinuity.

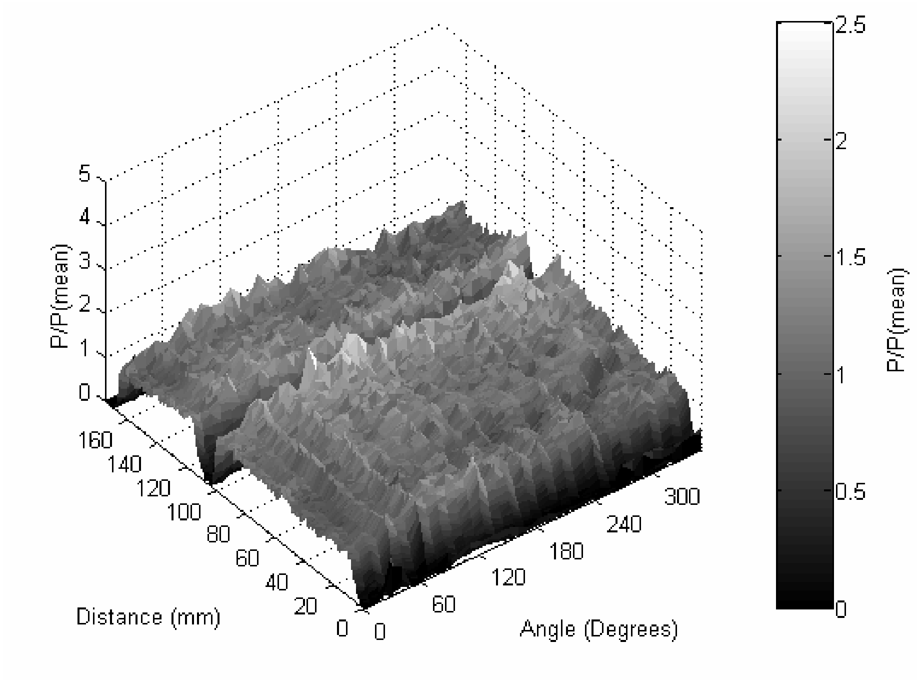

Figure 6. Scan of Wheel/Axle Interference Fit Pressure Profile

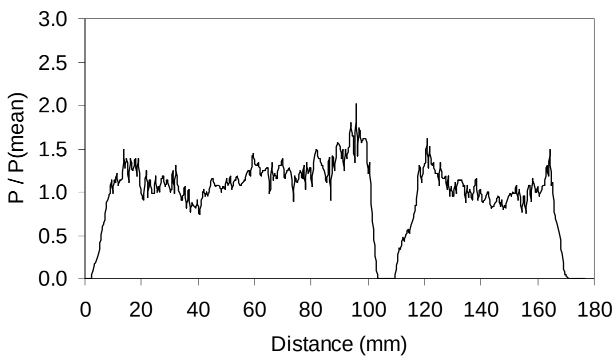

Figure 7a. Line Scan of Pressure Profile

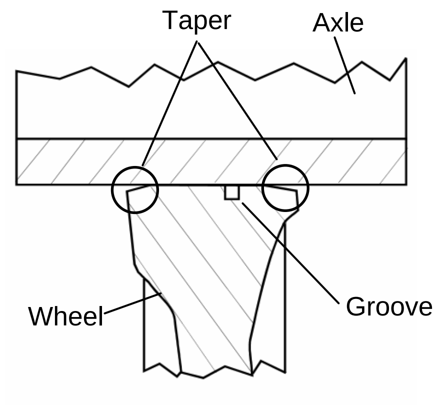

Figure 7b. Interference Fit Geometry

Away from the edges in the plateau regions the contact pressure shows a continuous variation about a mean value. Previous work on smaller scale interference fits showed this to be due to real surface effects (Marshall et al. [1]). From the manufacturing process there will be some variation in surface profile and roughness of the wheel and axle. Similarly, when the fit is assembled some regions may deform more than others. The combination of these factors leads to the subtle variation in contact pressure observed in the plateau regions. In previous studies of interference fits surface damage was frequently detected at the interface [1]. Such damage was detectable as it equated to a sudden reduction in reflected signal strength and quality. Surface damage was not detected on the wheel/axle interface, and was not present due to the lubricant used preventing any seizure during assembly.

6. DISCUSSION

This study has demonstrated that the ultrasonic technique previously employed to assess contact conditions in sample interference fits, can be used on large-scale industrial components. A normalised contact pressure distribution has been determined for a railway wheel/axle interference fit, and judgements have been made regarding the nature of the contact. There are, however, some areas in which this study needs extending. At present absolute values of the interface contact pressure have not yet been determined. The next stage of this work is to perform a calibration for the partially lubricated contact. A calibration would relate the total stiffness directly to the contact pressure. This would remove the need to make simplifying assumptions about surface separation, required to calculate the lubricant stiffness at the interface. By removing this assumption the accuracy of the technique is improved. In this way a complete contact pressure map of the interface can be determined. Further, scanning at 10-degree intervals around the interface produces a coarse radial scan. This is because the overall diameter of the wheel/axle contact is large. Indeed, scanning at 10-degree intervals equates to radial steps of 7.5 mm. Future scanning should be performed at finer radial increments; this will enable the determination of subtle changes in the pressure profile around the interface.

The ultrasonic method presented may be successfully applied to many other rough surface contacts. It is best applied to large contacts with gradual pressure variations, like the wheel/axle interface investigated here. This is because the technique is limited by the size of the focused ultrasonic spot. However, by using higher frequency ultrasound the spot size can be reduced, indeed spot diameters of less than 0.1mm are possible. Although, when using higher frequency sound the attenuation of the sound signal can increase, and will lead to a loss in signal strength when measurements are made through thick components. The effect of the water couplant on the specimen surfaces should always be considered. However, gels and oils can be used where water may prove otherwise destructive.

7. CONCLUSIONS

- A method has been established to determine interface pressure profiles in a wheel/axle interference fit. The method relies on the measurement of reflected ultrasonic signals from the contact.

- Contact pressure was seen to increase at the discontinuities at the edge of the fit and internal groove. Elsewhere the pressure showed a constant deviation about a mean value.

- A full calibration is now required to produce a complete map of contact pressure for the wheel/axle interference fit.

- The approach is limited by the need for a separate calibration to determine contact pressure directly from the reflection measurements and the spatial resolution (presently coarse at 1.8 mm spot diameter in this study).

8. REFERENCES

1) Lewis, R., Marshall, M.B., Dwyer-Joyce, R.S., “Measurement of Interface Pressure in Interference Fits”, submitted to *Journal of Mechanical Engineering Sciences*, *Proceedings of the IMechE Part C*.

2) Tattersall, A.G. "The Ultrasonic Pulse-Echo Technique as Applied to Adhesion Testing", *J. Phys. D: Appl. Phys*, 1973, Vol. 6, pp819-832.

3) Kendall, K., Tabor, D. "An Ultrasonic Study of the Area of Contact between Stationary and Sliding Surfaces", *Proceedings of the Royal Society, Series A*, 1971, Vol. 323, pp321-340.

4) Drinkwater, B.W., Dwyer-Joyce, R.S., Cawley, P. "A Study of the Interaction between Ultrasound and a Partially Contacting Solid-Solid Interface", *Proceedings of the Royal Society Series A*, 1996, Vol. 452, No. 1955, pp. 2613-2628.Thomas,

5) Hodgson, K., Dwyer-Joyce, R.S., Drinkwater, B.W., "Ultrasound as an Experimental Tool for investigating Engineering Contacts", *Proceedings of the 9th Nordic Symposium on Tribology, 'Nordic 2000'*, Eds. Andersson, P., Ronkainen, H., Holmberg, K., 2000, Vol. 2, pp377-386.

6) Gonzalez-Valadez, M., Dwyer-Joyce, R.S., Lewis, R., "Ultrasound and Mixed Liquid-Solid Contacts", *Accepted for Presentation at the 31st Leeds-Lyon Symposium on Tribology*, Leeds, 7-10th September 2004.