Inspection reliability and periodicity for rail axle inspection

J Rudlin, A Muhammed and C Schneider

Periodic inspection of railway axles is carried out to avoid axle failures. Analytical methods for determining the periodicity of inspection require knowledge of load conditions, materials properties and inspection reliability. The Wheelset Integrated Design and Maintenance (WIDEM) Project is being carried out to acquire some of this data and to develop methodologies for axle design.

An example is given in this paper of the measurement of inspection reliability from a set of 11 cracked axles. The method estimates the POD of the in-situ inspection technique from the response versus size method, the size in this case being measured with Alternating Current Potential Drop (ACPD), phased array ultrasonics and time-of-flight diffraction. The results show that useful information is generated by such methods and a further experiment is planned on a different range of axles to obtain wider applicability of the data obtained.

Introduction

Design of rail axles is generally on the basis of rules that have been laid down by experience and this limits the possibilities when, for example, new materials with different properties become available. Therefore, some scientific information backing up and enhancing the rules may enable the development of new designs or design philosophies. The WIDEM Project started in January 2005. The objective of the project is to provide information that will assist in the future design of axles. TWI is involved primarily with attempting to measure NDT performance and the methodology of inspection periodicity within this project.

Designs of rail axles vary depending on their application (Figure 1). Except for simple designs, most axles will have wheel seats, but some will have additional seats for driving or braking. The design of the seats and the relative diameters of the seat and the main axle body determine the position of the cracking in these areas.

The inspection issues

Axles tend to crack either in mid-span or under or close to the wheel seats (Figure 2). The crack morphology can also vary. Figure 3 is from a UK axle approximately mid-span showing a typical crack group. Figure 4 shows a crack formed on a brake seat. Figure 5 shows a crack formed close to a seat.

In the UK, various inspection methods have been tried or developed for this particular application. Surface inspection methods (particularly MPI and electromagnetic) have been introduced for accessible areas since the Rickerscote accident in 1996(1). However, where the crack initiates from an inaccessible surface the inspection is by ultrasonics. The methods adopted are generally known as the high angle scan (applied from the axle body), the near end scan and the far end scan (applied from the axle ends). These scans are shown in Figure 2.

Hollow axles are also used, and the ultrasonic test used in this case is an angled beam scan from a rotating probe in the bore. This inspection is mechanised.

The primary difficulty and skill required for the inspections is discriminating between geometrical echoes and crack signals.

The inspection performance of these techniques (and from this the inspection periodicity) has been estimated previously(2). This reference shows a 90% POD of the near end and high angle scans for flaws of around 3 mm depth, and a 90% POD at around 12 mm

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Charles Schneider has worked in the fields of inspection reliability and theoretical modelling since 1985. He joined TWI from the power industry in 1997. Since then, his work has included the statistical analysis of data from fatigue tests as well as inspection trials, and he has chaired three Independent Qualification Bodies overseeing phased array inspections in nuclear installations. He was joint winner of BNDT’s Nemet Award in 1992 and the Ron Halmshaw Award in 2003.
For the far end scan. Because the far end scan is not very sensitive, this leads to a situation where the inspection, which requires removal and replacement of the bearing cover, has to be applied all too frequently. A question has arisen as to whether this technique is effective in preventing axle failures because of its low sensitivity. However, no experimental data exists to more accurately estimate the sensitivity and therefore the inspection continues to be deployed. Part of the WIDEM project is to get better data for the inspection sensitivity.

**Determination of probability of detection**

The generic methods and statistical processes of determining POD have been described earlier\(^3\). An experimental approach requires a set of samples with known, preferably natural, fatigue cracks. These are then inspected and either hit/miss or response versus size methods can be used to estimate POD.

**Experiment carried out at LBF (Darmstadt, Germany)**

A set of cracked axles from a metro system has been held at LBF. An opportunity arose to estimate the inspection sensitivity of the procedure used to inspect the axles in service (essentially a mid-axle inspection technique applied from the axle end).

The work involved consisted of:
- Inspecting the cracks with ACPD, TOFD and phased array UT to estimate crack depth;
- Inspecting the axles with the specified procedure (and two similar procedures) and recording the signal amplitude from each crack;
- Estimating the POD using response versus size method.

The samples at LBF are from an urban Metro system. There are 13 samples, 11 of which are cracked (the uncracked samples were not used).

The general geometry and crack location is given in Figure 6.

**Characterisation methods**

The cracks were initially detected with magnetic particle inspection (MPI). An example of these cracks has already been given in Figure 4. These indications were used to measure crack length.

The ACPD (alternating current potential drop) method was used to measure crack depth on all the cracks. This gives an estimate of crack depth at individual points on the crack and a profile can be built up. An example of the type of data is given in Figure 7.
Phased array pulsed echo ultrasonics was used as a check on the ACPD results for larger cracks. Smaller cracks could not be visualised with this technique applied from the same side as the crack due to the beamwidth of the available probe. This probe was also not large enough to provide a focused beam when applied to the other side of the axle. An example of the results from this technique is given in Figure 8.

Time-of-Flight-Diffraction (TOFD) ultrasonics were also attempted. This was difficult to apply because the geometry of the component did not allow ideal positioning of the probe (equidistant from the crack at the surface). The shallow areas of the crack were hidden, but some indications were obtained. Figure 9 shows an example of one of these.

The crack dimensions finally obtained are given in Table 1.

### Procedure

The standard procedure for inspecting these axles in-situ specifies a 5 MHz zero degree compression probe. The amplitude of the ultrasonic reflection is set up on a 3 mm-deep slot on an axle to 80% of full screen height.

In addition to this procedure, a zero degree 2 MHz compression wave probe was also used. The reporting threshold (-8.5 dB from the slot signal) was noted. The signals from each crack were optimised and recorded as a level above the reporting level.

### Analysis and results

The response versus size method was used to analyse the data. The data points are plotted on log/log scale of response versus size (Figure 10). Using maximum likelihood estimation, two parallel regression lines are plotted through the two sets of data respectively, together with the corresponding 10% and 90% confidence limits. 50% of each population is therefore above the appropriate regression line and 50% below. Thus, the point at which the regression line crosses the reporting threshold corresponds to 50% POD. The POD curve can be derived from the confidence levels that correspond to the various points along the reporting threshold line (for example 90% POD occurs when the 90% confidence limit crosses the reporting threshold line and so on).

Figure 11 gives the resulting PODs for the 0 degree probes.

### Discussion

The results from Figure 11 show that the 90% POD is at about 3 mm for the 5 MHz probe and about 4 mm for the 2 MHz probe. Since this method is detecting cracks at a relatively short range (less than the far end scan in full size axles) although using a method similar to the far end scan, this result appears to be slightly optimistic compared with the Benyon and Watson estimates.

<table>
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<tr>
<th>Table 1. Crack sizes in Darmstadt axles</th>
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<td>Length (mm)</td>
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However, there are some limitations to the experiment that may have led to this result and these need to be investigated further. The measurements were made by TWI personnel with no specific time limit to carry out the inspection rather than the normal personnel used for the inspection. Also, the braking system would be in place when the in-situ experiment was carried out. The result has been obtained by comparison with NDT data (mostly ACPD for the smaller cracks) and this is, of course, subject to inaccuracy. Further work is also needed to establish the repeatability of the information obtained.

The difference between the 5 MHz and 2 MHz probes is also in line with expectations. The 2 MHz frequency has a wavelength of around 3 mm so the response to flaws of this order of size is likely to vary considerably. It is therefore likely that some flaws will be missed, and the POD affected.

**Inspection periodicity – possible alternative methodologies**

The deterministic method of establishing periodicity is to make the period such that the maximum expected crack growth rate at the known loads will enable a crack to be detected before failure (usually giving two opportunities). Of course there is a great deal of uncertainty in both loads and material properties. This uncertainty is being addressed by a series of projects with which WIDEM is collaborating (see below).

An alternative method is to work backwards from a probability of failure. On average there are less than two axle failures per year on UK trains, but there are no figures available for how many potential failures have been saved by NDT (axles are simply scrapped if cracks are detected). Using reliability methods, the uncertainty in the various parameters (including POD) can be included in probability distributions and therefore a different calculation is needed to obtain the variation of failure probability in service. Then inspection can be set at appropriate intervals to limit failure probability to acceptable levels.

TWI is planning (with other partners) to compare the different methodologies and their outcome. Such calculations will enable the effectiveness of an inspection method to be directly related to an expected number of failures.

**Future plans**

TWI has now obtained a collection of 19 axles. Some of these were withdrawn from service because cracks were detected. Others were withdrawn from service for other reasons and have subsequently had cracks induced in them. Pooling these specimens with a collection of axles owned by Applied Inspection, further tests will be carried out to estimate POD. These tests will include some features to address human factors. Further work on the Darmstadt axles will also be carried out, and a series of trials on hollow axles are also planned.

**The WIDEM Project**

The WIDEM Project (Wheelset Integrated Design and Maintenance) is a part-funded EU project managed by Lucchini (Italy). The other partners are Politecnico di Milano (Italy), LBF (Germany), D2S (Belgium), UNIFE (Belgium), Alstom (France), TWI (UK), Microsystems (Italy), MTB (Sweden) and VUZ (Czech Republic).

The industry advisory group for the project includes UK Railway Safety and Standards Board (RSSB) and Trenitalia. The project is exchanging information with the UKAxle Project (funded by RSSB and led by AEA Technology – Rail) and the DeuFrako project (funded by Deutsch Bahn (DB) and SNCF).

**Acknowledgements**

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**References**