Sizing and tomography of rolling contact fatigue cracks in rails using NDT technology – potential for high speed application

G. Nicholson, A. Kostryzhev, H. Rowshandel, M. Papaellias, C.L. Davis, C. Roberts

Birmingham Centre for Railway Research and Education, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

Abstract
Rolling contact fatigue (RCF) cracks in the rail head progressively grow due to in-service loading. Early detection and sizing of RCF cracks allows more efficient mediation treatment such as grinding. In this paper the capability of an Alternating Current Field Measurement (ACFM) technique to detect and size light to moderate RCF cracks, both at high speed (up to 120 km/h) is discussed. Experimental and computer modelling results have shown that crack detection with improved characterisation information can be achieved using a single ACFM probe. Further work is now in progress that brings together a multi-probe sensor with high speed electronic processing to provide a practical system suitable for attachment to a specialist measurement train.

Keywords
Non-destructive testing; Alternating Current Field Measurement; Rolling Contact Fatigue.

Introduction
An increase in capacity (higher travel speeds and axle loads) on modern railways increases the dynamic loading on the rails and hence track degradation. To maintain high operational safety at minimal cost, condition monitoring of rail tracks requires methods for early detection of rolling contact fatigue (RCF) cracks and their growth in service. Currently ultrasonic inspection is carried out by a variety of different instruments ranging from hand-held devices, through to dual-purpose road/track vehicles to test fixtures that are towed or carried by dedicated rail cars. Unfortunately, the performance of existing conventional ultrasonic probes in detecting small (<4 mm depth) surface defects such as head checks and gauge corner cracking is inadequate during high speed inspection. In addition, the presence of larger and more critical internal defects can be shadowed by smaller surface cracks during inspection. This is also one of the reasons that the current international practice is to combine non-destructive evaluation of the rail network with preventative maintenance procedures, such as rail head grinding, in order to optimise the trade-off between maintenance cost and structural reliability [1-8].

Inspection systems based on the simultaneous use of conventional ultrasonic transducers with magnetic flux leakage (MFL) sensors have a higher probability of detecting smaller near-surface and surface-breaking defects in the rail head. However, as inspection speed increases, the performance of MFL sensors tends to deteriorate rapidly due to a reduction in the magnetic flux density [8-11]. More recently, pulsed eddy current (PEC) probes have been added on certain ultrasonic test trains to offer increased sensitivity in the detection of surface defects at high inspection speed [12-14]. PEC probes perform far better than MFL sensors at higher inspection speeds but are affected more by lift-off variation and typically need to be position at <2mm from the rail head.

Alternating current field measurement (ACFM) sensors are less sensitive to lift off (up to at 5 mm lift off from the rail head) than the PEC probes, have the potential to operate at high speeds and provide information that can be used to size and shape RCF cracks, the system can be used in the form of a walking stick on the UK network. This paper summarises some of the recent advances in using the ACFM technique for rail NDT.

Proof of principle: ACFM operation at high speed
ACFM experiments were carried out at inspection speeds up to 121.5 kmh⁻¹ using a turning lathe-based test rig. A high-speed single channel micro pencil probe manufactured by TSC Inspection Systems Ltd. was utilised during testing. The pencil probe operated at a frequency of 50 kHz and was driven by a commercial TSC AMIGO instrument [15]. The data obtained were logged using customised software on a PC that incorporated a high-speed data acquisition board. The data acquisition rate during tests was 1 MHz. To test the overall capability and performance of the ACFM system at high inspection speeds under controlled experimental conditions a special rotary test piece was manufactured. The material used for manufacturing the rotary test piece was a 0.9 wt % C steel to make sure that the microstructure, as well as the relative magnetic permeability and electrical conductivity are similar to those exhibited by conventional 260 rail steel grade (typically 0.7-0.8 wt % C), with both steels having a predominantly pearlitic microstructure. The rotary test piece had a 230 mm diameter and was 60 mm thick with a bore in the centre 190 mm in diameter and 50 mm deep. Four transverse notches (2 x 2 mm and 2 x 4 mm deep with a flat
Challenge C: Increasing freight capacity and services

profile) were spark eroded at the centre of the 20 mm wide rim of the sample. Each notch was 10 mm long and 0.5 mm wide. The sample was placed in a turning lathe capable of rotating the test piece between 1 to 3000 revolutions per minute (rpm). The rotational speed of 1 rpm for this experimental setup corresponded to the equivalent of a surface speed of 0.0405 kmh\(^{-1}\) at the centre of the notch (i.e. 10 mm away from the edge of the rim) and hence at 3000 rpm the surface speed of the sample at the centre of the notches was 121.5 kmh\(^{-1}\).

The ACFM probe was positioned opposite to the centre of the notches and at a 0° angle with reference to their surface orientation. Figure 1 shows the ACFM signal obtained for a probe lift-off of 2mm at an inspection speed of 121.5 kmh\(^{-1}\).

![ACFM signal for an inspection speed of 121.5 kmh\(^{-1}\) and 2 mm lift-off](image1.png)

To extend the analysis to consider inspection of rails a 3.6 m diameter spinning rail rig, capable of rotating at speeds between 1 to 80 kmh\(^{-1}\), with a special set of eight 1.41 m long rails containing artificially induced defects (including half-face slots machined normal to the railhead surface, clusters of angled slots, and pocket defects more typical of real defects) was used. The ACFM probe was installed on a customised trolley placed on the rails while the rig was rotated at 1.6 kmh\(^{-1}\), progressively increasing its speed up to 48 kmh\(^{-1}\). Figure 2 shows the ACFM signal obtained at 48 kmh\(^{-1}\) showing that the artificial defect clusters can be successfully detected, further results are published elsewhere [16, 17].

![ACFM signal for an inspection speed of 48 kmh\(^{-1}\)](image2.png)
Modelling of light-moderate RCF cracks for size and shape analysis:
A finite element method (FEM) model, using COMSOL Multiphysics software, has been developed to model the ACFM sensor response to both ideal and real defects in rail. The commercial AMIGO software currently sizes crack using estimations based on the theory for regularly sized cracks, in addition the walking stick ACFM system has had empirical corrections added in, based on experimental data from destructive tests of RCF cracks (for cracks with pocket length > 4 mm). The COMSOL model allows non-regular cracks with a wider variation of pocket length and shapes, as well as overlapping cracks to be accurately assessed. In addition, comparisons between elliptical approximations and actual RCF crack shapes (for light-moderate RCF cracks) have been carried out.

The defects are modelled in three dimensions, with a very fine mesh concentrated around the regions of interest, namely the defect and a layer above the surface of the rail where measurements are taken. Modelling was carried out using an impedance boundary condition between the rail surface and the surrounding air. This implies that the current travels along the boundary, greatly simplifying the model and allowing solutions to be found for complex crack shapes. The error of this assumption is negligible due to the very small skin depth in steel at the high probe operation frequency. Additional detail on the modelling approach are presented elsewhere [18].

Two RCF cracks, a ‘light’ crack (according to the Railtrack classification system [19] with a surface length of 4.93 mm) and a ‘moderate’ crack (surface length of 12.92 mm) that had developed in a section of rail taken from service, have been assessed. Figure 3 shows images of the two real RCF cracks and a virtual reconstruction of the moderate crack from X-ray tomography images. The vertical angle of propagation was found to be 34° for the light crack and 25° for the moderate one. Contour plots have been reconstructed from the experimental and model scans and are shown in Figure 4 for the moderate crack. Plots (a) and (b) show the experimental results, plots (c) and (d) the reconstructed crack model data and (e) and (f) the results from an elliptical approximation to the crack shape. It can be seen from Figure 4 that there is very good qualitative agreement between the experimental results and the model results, both for the actual crack shape and elliptical

Figure 2: ACFM signal obtained at an inspection speed of 48km/h for rail containing clustered artificial detects

Figure 3: a) Machined cylinders containing the RCF cracks (taken from a rail removed from service) for X-ray tomography and b) reconstructed three dimensional view of the ‘moderate’ RCF crack overlaid with the semi-ellipse used to approximate it
Challenge C: Increasing freight capacity and services

Figure 4: Reconstructed contour plots for the moderate RCF crack: (a) Bx and (b) Bz field patterns for the experimental data, (c) Bx and (d) Bz field patterns for the reconstructed model data and (e) Bx and (f) Bz field patterns for the elliptical approximation to the crack

approximation, a similar level of agreement was seen for the light RCF crack. Figure 5 shows the Bx data for the scan line across the moderate RCF crack that achieved the minimum normalised Bx values (this approach represents using an array of sensors (for a high speed approach) or a single probe sensor and, for example, a robot arm to conduct multiple scans for tomographic information [20]). Overall it can be seen that the predicted ACFM signal changes from a COMSOL model using a semi-elliptical crack to represent the moderate RCF crack in a rail removed from service provides good agreement to the measured ACFM signals. It should be noted that the effective rail maintenance planning requires the vertical depth to which the cracks reach, if grinding regimes are to be optimised to remove the RCF defects. In order to predict this from the ACFM data the model requires the crack angle of propagation into the surface of the rail (typically 20°-35° before the cracks turn down at approximately 5 mm vertical depth). The effect of variations in crack shape, orientation and size, including for larger RCF cracks, which are known to be non-elliptical in shape [21], on the ACFM signal is being researched at present.

Optimisation of ACFM inspection on rail

RCF cracks on rails form at varying angles to the rail length, frequently between 30° and 45°, and at varying propagation angles (typically 20-35°) [21, 22]. The ACFM sensor signal is sensitive to the size, shape and orientation of the RCF cracks. In order to determine whether accurate sizing of cracks can be achieved in principle the sensitivity of the signal to these factors needs to be determined.

Figure 6 shows the effect on the Bx signal of changing the size of modelled semi-elliptical cracks. Semi-ellipses of surface length 1 to 20 mm for four elliptical ratios, a:b, for a = 1, 1.25, 1.5 and 1.75 and b = 1, where a is the semi-major axis and b is the semi-minor axis, have been modelled. The model is based on a 5 kHz ACFM sensor.

In Figure 6 the minimum Bx value for each semi-ellipse is plotted against the crack pocket length. This value, along with the distance between the Bz trough and peak and the background Bx value may be used to give an accurate estimate of the crack pocket length. This is achieved in the AMIGO software using a lookup table based on analytical theory [23, 24]. However, above a certain crack pocket length, sensitivity of the Bx signal to increasing pocket length saturates.
Figure 5: Scan line Bx data, which contains the minimum recorded Bx values for the experimental, model and elliptical data, for the moderate RCF defect

Figure 6. Sensitivity of the Bx signal to the size of the RCF crack (assuming an elliptical shape)

From Figure 6 it can be seen that the minimum Bx value initially decreases steeply as crack pocket length increases. For cracks with a pocket length in this region, the ACFM Bx signal can effectively be used to size...
the crack. However, as pocket length increases further, the sensitivity of the ACFM Bx signal to increasing pocket length begins to saturate; for the semi-ellipses modelled here, this occurs at between 10 mm pocket length (for the 1.75:1 ratio semi-ellipse) and 19 mm (for the 1:1 semi-ellipse), corresponding to crack surface lengths of 35 to 38 mm.

The orientation of the probe relative to the crack is also of importance for crack sizing. In order to achieve the maximum change in Bx value in the presence of a defect, the probe should be oriented parallel to the crack such that the current flows perpendicular to the length of the crack (see Figure 7a). Figure 7b shows the effect of varying the probe angle relative to a 15 mm surface length, 5 mm pocket length (1.5:1 ratio) crack, oriented at a horizontal angle of 45° to the running direction of the rail. It can be seen that the minimum normalised Bx value occurs when the probe is oriented parallel to the crack. Referring to Figures 6 and 7, it can be deduced that if the probe is oriented at an angle of -5° relative to the crack, the pocket length would be underestimated by 0.06 mm, which is of little significance. However, for relative probe angles of -10° and -15°, crack pocket length would be underestimated by 0.46 mm (9.2%) and 1.01 mm (20.2%), respectively. A difference of 15° between probe and crack angle could easily occur in an automated system given that RCF cracks often lie between 30° and 45° to the running direction of the rail. Therefore, for accurate sizing of cracks, it is of importance that the probe is oriented at or very close to the angle of the crack.

a)

![Schematic diagram showing the potential relative orientation of the sensor to an RCF crack on rail](image)

b)

![The sensitivity of the Bx signal change to the relative orientation](image)

Figure 7. a) Schematic diagram showing the potential relative orientation of the sensor to an RCF crack on rail and b) the sensitivity of the Bx signal change to the relative orientation.

Note also that knowledge of the vertical angle of propagation of the crack is necessary to determine crack depth for implementation of a grinding regime. The ACFM signal does not give information about crack propagation angle, or equivalently crack depth.
Implementation and future work
Experimental and computer modelling results have shown that crack detection with improved characterisation information can be achieved using a single ACFM probe. Work is now underway to develop a specialist rail test sensor that incorporates eight individual pencil probes. This sensor will be used on a test train. Using such a sensor it will be possible to inspect the whole rail head with a single passage.

In order to be able to process the data from the eight probes in parallel, and at a speed that would allow a sensor to be fitted to a practical measurement train (i.e. up to 120 km h\(^{-1}\)), it is necessary to utilise advanced high speed electronics. The existing pencil probe processing is based around analogue electronics. In order to address the requirement of high speed, parallel processing a new digital, data acquisition and processing architecture has been developed based that uses field programmable gate array (FPGA) technology. FPGAs are integrated circuits that contain programmable logic blocks and reconfigurable interconnections. Complex functions can be programmed using hardware description language (HDL). The results of this work will be demonstrated as part of the European Commission FP7 Project INTERAIL.

References
5. Schöch, W., Heyder, R., Grohmann, H. D. Contact geometry and surface fatigue guidelines for appropriate rail maintenance, Proceedings of the 7\(^{th}\) International Conference on contact mechanics and wear of rail/wheel systems, Brisbane, Australia, 2006.


23. **Lugg, M., Topp, D.** Recent developments and applications of the ACFM inspection method and ACSM stress measurement method. ECNDT. Berlin, Germany, 2006.