The Influence of RCF Crack Propagation Angle and Crack Shape on the ACFM Signal

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Abstract. The alternating current field measurement (ACFM) technique can be used to detect and predict the pocket length of rolling contact fatigue (RCF) cracks in rails, based on a sizing algorithm developed for small cracks that have a planar semi-ellipse shape. RCF cracks usually grow at a shallow angle into the rail (vertical angle) that depends on train speed, axle loads and rail grade. Knowledge of the vertical angle is important, as this allows the crack vertical depth to be determined from the pocket length, which then determines the amount of material (rail depth) to be removed by grinding if RCF cracks are to be eliminated. No method for determining vertical angle for small cracks using electromagnetic type sensors is currently available. In the present work the relationship between ACFM signals and RCF crack vertical angle has been studied. The Bz trough-peak ratio is being proposed as a new method to determine the crack vertical angle. Results from computer simulations, using Comsol Multiphysics, and experimental measurements on calibration samples and rails removed from service containing multiple RCF cracks are reported. In addition, RCF cracks become complex in shape as they grow, which will affect the vertical angle predictions. X-ray tomography and progressive milling has been used to determine the crack shapes and angles for RCF cracks in rails removed from service. The crack profiles have been reconstructed and modelled to study the effect of crack asymmetry on the crack vertical angle prediction.

1. Introduction

Alternating current field measurement (ACFM) is an electromagnetic non-destructive technique used in the UK rail industry. It can detect and size (predict the pocket length) single and uniform clusters of RCF crack in rail tracks or wheels through charactering the disruption in the magnetic field due to the presence of a crack. ACFM signals can be used to effectively size the surface length and the pocket length (as shown in Fig.1a) of RCF cracks, based on a sizing algorithm developed for small (light to moderate, based on Network Rail classification, as shown in Fig.1b) cracks that have a planar semi-ellipse shape [1, 2]. ACFM array sensors are used in a walking stick system for manual inspection and its capacity to make measurements when moving at high speed over a rail has been reported [3]. A robotic inspection system using an ACFM probe sensor has also been developed to detect and characterise RCF cracks in rails [4].

RCF cracks, as shown in Fig. 1a, initially propagate at a shallow angle (10°-30°) [5] into the rail, the vertical angle, until they reach a critical depth (typically about 5 mm), then
can turn down at a steeper angle, potentially leading to a rail break, or turn up to the rail surface results in a spall. RCF cracks usually present in the form of clusters, with a range of spacing (0.8-20 mm) between individual cracks in a cluster reported, and typically the surface-breaking component extends at an angle (30°-75°) to the rail running direction, the horizontal angle [2, 5, 6]. It is reported that RCF crack shapes can be approximated by a semi-ellipse with certain elliptical ratios, but for some moderate, heavy and severe RCF cracks, they may deviate from the semi-ellipse shape as they grow [2]. Crack shapes where the deepest part extends significantly beyond the surface-breaking component have been reported and this asymmetrical shape can cause incorrect predictions of the crack dimensions if these are based on the algorithm for planar semi-ellipse shapes.

![Fig. 1.](image)

**Fig. 1.** (a) Schematic diagram of a single semi-elliptical RCF crack propagating at an angle into the rail; (b) the visual length-depth guidance diagram for RCF cracks currently in use by Network Rail, UK [7].

Knowledge of the vertical angle for RCF cracks is important, as this allows the crack vertical depth to be determined from the pocket length, which then determines the amount of material (rail depth) to be removed by grinding if RCF cracks are to be eliminated. Currently for EM-based techniques, this requires an assumed propagation (vertical) angle into the rail since no method to measure the crack vertical angle using EM signals has been reported previously. In addition, RCF cracks may become complex in shape when they grow and any asymmetrical shapes will affect the accuracy of crack pocket length and vertical angle predictions from ACFM signals.

In the present work the relationship between ACFM signals and RCF crack vertical angle has been studied and a new method, Bz trough-peak ratio for single and multiple RCF cracks, is introduced in section 2 for determining the vertical angle; the effect of crack profile asymmetry on the crack vertical angle measurements is described in section 3.

### 2. Vertical Angle Prediction for RCF Cracks

#### 2.1 Bz Trough-peak Ratio

Modelling work, using Comsol Multiphysics, was carried out to study the variations in current flow, magnetic field and the Bz signal caused by the crack vertical angle. The RCF crack shapes were chosen to be semi-ellipses with specific ellipse ratios in the model, based on a previous study [1] that showed the use of semi-ellipses to represent RCF cracks in the range of light to moderate size to be a good approximation. The details of the model can be found elsewhere [1, 2].

An ACFM Bz signal is generated as the current flows clockwise and anticlockwise around the ends of the crack surface-breaking component, causing a fluctuation in the z-component of the magnetic field. The Bz signal is used to determine the crack surface length by measuring the distance between the areas of positive and negative valued magnetic
field, as shown in Fig. 2a, provided that the ACFM sensor is oriented along the crack surface-breaking component such that current flows perpendicular to the crack.

In the presence of a single RCF crack, current rotation develops in the z-component of the magnetic field around the crack ends. This causes a trough and peak in the Bz ACFM signal of a scan taken along a line parallel to, or at a shallow angle to, the surface-breaking component of a crack, as shown in Fig. 2b. The characteristics of the rotation of the Bz field depend on the crack vertical angle; it is this phenomenon which is exploited to determine the crack vertical angle in the present paper. Fig. 2b shows the Bz signal changing with the vertical angle for the light (surface length of 8 mm and pocket length of 3.2 mm) crack, classified using Fig. 1b. The negative and positive valued areas of the Bz magnetic field move away from the crack surface-breaking component towards the side where the crack propagates in the rail as the vertical angle becomes shallower. This is detected by a measurement line across the centre of the crack surface-breaking component at an angle of 45° (as shown in Fig. 2a), as the negative valued area of Bz approaches the measurement line while the positive valued area shift away from it. Therefore, the Bz signal recorded along this measurement line shows the variability of the trough and peak values against the crack vertical angle.

![Fig. 2. (a) Contour plot of the z-component of the magnetic field above a semi-elliptical crack with vertical angle of 90° and 10°; (b) The Bz signals for the crack with surface length of 8 mm, pocket length of 3.2 mm and different vertical angles, showing asymmetrical magnitude of the trough and peak values caused by the smaller vertical angles.](image)

Although it is easy to observe from contour plots (e.g., Fig. 2a) that the Bz magnetic field changes with vertical angle, contour plots are established based on theoretical modelling and it is not possible to obtain them experimentally with a single pass of a single ACFM probe. A measurement line across the centre of the crack surface-breaking component at an angle of 45°, as shown in Fig. 2a, can indicate the asymmetric distribution in Bz with respect to the x-axis caused by the variation in crack vertical angle.

The Bz trough-peak ratio is proposed to determine the crack vertical angle, as this ratio represents the magnitude of the trough value to the peak value in the Bz signal along the measurement line, thus showing the asymmetric Bz magnetic distribution to the x-axis caused by the crack vertical angle. The Bz trough-peak ratio can be expressed as

$$\text{Bz trough - peak ratio} = \frac{\text{Bz}_{\text{trough}}}{\text{Bz}_{\text{peak}}}$$  \hspace{1cm} (1)

where $\text{Bz}_{\text{trough}}$ is the value at the trough of the Bz signal and $\text{Bz}_{\text{peak}}$ is the value at the peak of the Bz signal.
2.2 Measurements of Vertical Angle on Calibration Samples

Single and multiple angled cracks (schematically shown in Fig. 3) with semi-elliptical shapes were electro discharge machined on a calibration plate and an unworn rail, respectively to verify the modelling results for cracks with different vertical angles. The designed and final measured dimensions for these angled cracks are listed in Table 1. A 5 kHz Amigo 255 pencil ACFM sensor, produced by TSC Inspection Systems, was used for the measurements. The sensor was held parallel to the surface-breaking component of the crack to ensure the maximum perturbations in $B_z$ [8]. The sensor was held at 0 mm lift-off and moved by hand through the centre of the crack along a measurement line at 45° to the crack opening, as shown Fig. 3, and used in the modelling approach.

![Fig. 3. Schematic diagram of the calibration samples and the experimental procedure.](image)

<table>
<thead>
<tr>
<th>Table 1. Designed and measured, in brackets when different from designed, crack dimensions used for the experimental verification.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack (cluster)</td>
</tr>
<tr>
<td>Surface length ($S$), mm</td>
</tr>
<tr>
<td>Pocket length ($P$), mm</td>
</tr>
<tr>
<td>Horizontal angle ($\alpha$), °</td>
</tr>
<tr>
<td>Vertical angle ($\theta$), °</td>
</tr>
<tr>
<td>Spacing in the cluster ($I$), mm</td>
</tr>
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</table>

Fig. 4 shows the modelling and experimental $B_z$ trough-peak ratio obtained from the 45° measurement line (45° with respect to the crack surface length) for single and multiple calibration cracks with a range of vertical angles between 12° and 90°. Modelling has been carried out for cracks of the measured dimensions. The experimental measurements agree with the modelling results for the calibration cracks in that they show the same tendency that the ratio decreases as the crack becomes shallower. The $B_z$ trough-peak ratio changes correspondingly with the vertical angle and it changes rapidly when the vertical angle is smaller than 30° due to the strong asymmetry in the $B_z$ magnetic field.

For the single cracks, the experimental $B_z$ trough-peak ratios are lower than the modelling results with a mean difference of 6.2 %, indicating that the magnitude of trough and peak values for measured signals are more asymmetrical than the modelling results except for the 90° case. This is because the machined calibration cracks are slightly asymmetrical themselves. Consequently, the actual $B_z$ magnetic field deviates from the centre of the crack, increasing the difference between the trough and the peak values meaning the actual $B_z$ trough-peak ratios are slightly lower than the model results.

For the crack cluster 7, the experimental $B_z$ peak-trough peak is lower than the modelling result by 9.5 %. As the crack cluster 7 is machined on an unworn rail, with the
cracks in the curved gauge side, the ACFM probe sensor does not conform fully to the rail surface, leading the trough and peak values to be more asymmetrical than the result with the flat steel plate.

Fig. 4. Model and experimental results of the Bz trough-peak ratios against different vertical angle for single and multiple cracks. The experimental results show standard errors for both measured vertical angles and the Bz trough-peak ratios.

2.3 Measurements of Vertical Angle on Samples Taken from Service

A single RCF crack (crack 8) and two RCF crack clusters (crack cluster 9 and 10) on rails taken from service were selected to study the Bz trough-peak ratio for vertical angle prediction, as shown in Fig. 5 with MPI used to enhance the cracks. These cracks were scanned by the ACFM probe sensor before progressive milling to investigate their vertical angle and pocket length. For the single crack 8, the sensor was held at 0 mm lift off and moved across the centre of the crack at an angle of 45°, with an orientation parallel to the crack surface-breaking component. The crack clusters 9 and 10 were selected to be grid scanned using the ACFM probe sensor installed on a robotic arm. The robotic arm allowed accurate control of lift off distance (0 mm) between the single pencil probe and the railhead through use of a laser range sensor. Fig. 6 shows the robotic arm used in the trial and the ACFM probe sensor installed on the robotic arm scanning over the RCF cracks.

Fig. 5. Single and multiple cracks inspected by the ACFM probe sensor for vertical angle.
The Bz signals obtained from grid scanning can be used to construct the z-component of the magnetic field mapping (i.e. contour plot using experimental signals). The signal mapping can provide a more complete image of the magnetic field distribution over the cracks, especially for multiple cracks. This can be used to analyse how the ACFM signal responds to multiple cracks, and then predict the vertical angle of the crack. The Bz trough-peak ratio derived from the 8th of the grid scanning lines was used to determine the crack vertical angle, as this scan line across the centres of the majority cracks at an angle close to 45°.

Table 2 lists the crack dimensions obtained from MPI images (for surface length, horizontal angle and spacing) and progressive milling (for pocket length and vertical angle). The predicted vertical angles are also compared in the table. Crack dimensions for crack clusters 9 and 10 are the average values of each crack within the cluster. The vertical angles were predicted using the measured Bz trough-peak ratio by comparison to the modelling results for cracks with a uniform size (taken as the average surface length and average inner spacing from the MPI data) and assumed semi-ellipse ratio (of 1).

The predicted vertical angles are similar to the maximum measured values for all these cracks; the maximum angle is more significant as this will give a greater vertical depth of the crack into the rail, which is the critical measurement as this determines how much material needs to be ground off to remove the cracks. The predictions give a maximum error of 11.8%, which would give a difference in vertical depth (for the 6 mm pocket length crack) of 0.37 mm. The results indicate that the method of using the Bz trough-peak ratio for vertical angle prediction can be used on single and multiple cracks in rails taken from service.

**Table 2:** Summary of the crack dimensions and the vertical angle prediction.

<table>
<thead>
<tr>
<th>Crack (cluster)</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface length, mm</td>
<td>12.6</td>
<td>11.6</td>
<td>12.7</td>
</tr>
<tr>
<td>Pocket length, mm</td>
<td>6.0</td>
<td>5.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Horizontal angle, °</td>
<td>53.2</td>
<td>43.3</td>
<td>43.0</td>
</tr>
<tr>
<td>Spacing in the cluster, mm</td>
<td>-</td>
<td>3.9</td>
<td>4.4</td>
</tr>
<tr>
<td>Vertical angle (average), °</td>
<td>25.1</td>
<td>25.7</td>
<td>24.2</td>
</tr>
<tr>
<td>Vertical angle (maximum), °</td>
<td>36.3</td>
<td>30.7</td>
<td>26.7</td>
</tr>
<tr>
<td>Predicted vertical angle, °</td>
<td>32.0</td>
<td>33.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Relative error for the maximum vertical angle, %</td>
<td>11.8</td>
<td>7.0</td>
<td>4.6</td>
</tr>
</tbody>
</table>
3. Influences of Crack Shape on Bz Signals

3.1 Tomography and Progressive Milling of Cracks

The shape of RCF cracks can generally be approximated by a semi ellipse with specific elliptical ratios (from 1 to 1.75) when they are in the light to moderate category, Fig. 1b [2]. However, RCF cracks can deviate from this regular shape and become non-planar with complex shapes, for example it has been observed that the subsurface portion of a RCF crack, whose surface length belongs to the moderate category, extends significantly beyond the surface-breaking component [5]. This may cause the vertical angle and pocket length prediction from a single ACFM scan to be inaccurate since the non-surface breaking component is not detected [2]. Therefore, it is important to investigate the influence of an asymmetrical shape on the crack vertical angle and pocket length predictions from a single ACFM scan.

The single crack 8 and crack clusters 9 and 10 were progressive milled to investigate their crack profile and crack 8 was also inspected using X-ray tomography. Fig. 7 shows the X-ray tomography image for crack 8, indicating a maximum pocket length of 6.01 mm with a vertical angle of 25.7°. Fig. 8 shows the cross section of crack clusters 9 and 10 after the whole railhead sample was milled to remove 12 mm from gauge side.

![Imaging and milling direction](image)

(a) Single crack 8 removed from the rail head sample; (b) X-ray tomography image for crack 8 showing the position of the maximum pocket length of 6.01 mm and the vertical angle of 25.7°.

Fig. 7. (a) Single crack 8 removed from the rail head sample; (b) X-ray tomography image for crack 8 showing the position of the maximum pocket length of 6.01 mm and the vertical angle of 25.7°.

![Rail cross section](image)

Fig. 8. Rail cross section for crack clusters 9 and 10 showing the profile of the cracks propagating into the rail when the rail sample was milled to remove 12 mm from the gauge side.

3.2 Influences of Asymmetrical Shapes on Vertical Angle Prediction

Four crack shapes were reconstructed based on the crack dimension data obtained from progressive milling. Fig. 9a shows the reconstructed crack profiles with measured dimensions, denoted as A-D. Shape B indicates that there is a subsurface portion of the crack extending beyond the surface breaking component, as reported in the literature [5]. Shape C is significantly asymmetrical with respect to the centre of the surface breaking component with one side extending much deeper into the rail. Shape A is slightly asymmetrical but could
be approximated as a semi ellipse. Shape D is also slightly asymmetrical and has a relative flat bottom profile.

Fig. 9. (a) Crack profile reconstruction with measured dimensions from progressive milling; (b) Influences of asymmetrical crack profiles on the Bz trough-peak ratios

The crack profiles were imported into the Comsol Multiphysics model using interpolation and a modelling study on the influence of crack shape on vertical angle prediction was carried out. In the modelling work, all the crack profiles were set to have the same surface length of 15 mm and maximum pocket length of 6 mm and considered to be planar so that the influence of crack profile could be determined. A semi elliptical crack with the same dimensions was also modelled. The Bz signal was determined from the measurement line across the centre of the crack surface-breaking component at an angle of 45° representative of the experimental inspection procedure using the ACFM probe sensor. Fig. 9b shows the modelling results on how Bz trough-peak ratio responds to the asymmetrical crack profiles. The result for shape A is close to the Bz trough-peak ratio obtained from the perfect semi ellipse for vertical angles changing from 10° to 90°, indicating that this slight asymmetrical profile does not influence the determination of vertical angle. Shape D, with a slightly asymmetric shape and flat bottom also shows similar results except for when the vertical angle is 10°, where a difference of 10.1 % in value is seen compared to the semi ellipse shape. Shape B and shape C are significantly asymmetrical, which causes an asymmetrical distribution of the z-component of the magnetic field. The maximum (peak) and minimum (trough) values along the single measurement line are therefore asymmetrical. This can be seen by the difference in Bz trough-peak ratio for the 90° (vertical) crack compared to the semi ellipse case, with this difference become magnified as the vertical angle decreases.

The asymmetrical crack profile therefore results in an error in the crack vertical angle when using the Bz trough-peak ratio obtained through a single ACFM scan – the predicted vertical angle will be smaller than reality if using an assumed semi ellipse shape for the predictions. Therefore the vertical depth of the crack will be also underestimated when using the predicted pocket length (from the Bx signal [1, 2]). These results indicate that for accurate sizing of RCF cracks using an ACFM sensor the cracks should be small, where the assumption of semi ellipse shapes is appropriate.

4. Conclusions

In this paper, the Bz trough-peak ratio is proposed to determine the propagation angle into the rail (vertical angle) of single and multiple RCF cracks. The approach has been verified
through measurements on cracks in calibration samples and rail samples taken from service. The influence of asymmetrical crack profiles have been discussed. The main conclusions are as follow:

- The Bz trough-peak ratio determined along a 45° (with respect to the crack surface length) measurement line can be used to predict the vertical angle of single or multiple RCF cracks. The results have been validated through modelling and experimental measurements on calibration and real single and multiple RCF cracks, with a maximum relative error of 11.8%.

- Asymmetrical crack profiles cause an underestimation of the crack vertical angle if the Bz trough-peak ratio is determined from a single scan using the ACFM probe sensor. It indicates that for accurate sizing of RCF cracks using an ACFM sensor the cracks should be small, where the assumption of semi ellipse shapes is appropriate.

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References