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Determination of surface crack orientation based on thin-skin regime using triple-coil drive-pickup eddy-current sensor

Mingyang Lu*, Xiaobai Meng, Ruochen Huang, Liming Chen, Zezhi Tang, Junshi Li, Anthony Peyton, Wuliang Yin*

Abstract — Electromagnetic sensors have been used for inspecting small surface defects of metals. Based on the eddy-current thin-skin regime, a revised algorithm is proposed for a triple-coil drive-pickup eddy-current sensor scanning over long surface crack slots (10 mm) with different rotary angles. The method is validated by the voltage measurement of the designed EC sensor scanning over a benchmark (ferromagnetic) steel with surface defects of different depths and rotary angles. With an additional sensing coil for the designed EC sensor, the defect angle (or orientation) can be measured without spatially and coaxially rotating the excitation coil. By referring to the voltage change (due to the defect) diagram (voltage sum versus voltage different) of two sensing pairs, the rotary angle of the surface crack is retrieved with a maximum residual deviation of 3.5 %.

Index Terms — Eddy current sensor; defect orientation; angled crack, thin-skin regime; non-destructive testing.

I. INTRODUCTION

Eddy current (EC) sensors are used for the monitoring of structural integrity [1-9] and measurement of material properties [10-17]. For the inspecting of defects, ultrasonic transducers are efficient in the identification of defect clusters [18]. Moreover, magnetic flux leakage (MFL) sensors have a higher probability of the inspecting of near-surface (or breaking-points) defects [19]. Compared to ultrasonic and MFL techniques, the EC testing commonly applies to the measurement of small surface defects like head checks and gauge corner cracking, particularly for the high-speed inspection (especially above 15 km/h) applied to inspect the rolling contact fatigue (RCF) of the rail [18,20].

Both analytical [21-23] and numerical methods [24,25] have been proposed for the interaction analysis between EC sensors and surface crack slots on metals. For the analytical technique, combining the Harfield-Bowler eddy-current thin-skin model [26] with a two-port system of surface-integral formulas proposed by Auld [27], Burke and Ditchburn have proposed the analytical model of mutual impedance change due to an ideal surface crack [28]. Moreover, Theodoulidis has proposed the revised analytical model for the tilted single-coil sensor above the surface slot [29]. For the numerical method, both Finite-element (FE) models [30] and boundary element (BE) models [31] have been used for the impedance analysis of EC sensors inspecting the surface crack. Proposed techniques are based on different models and strategies, including the alternating current field measurement (ACFM) [32,33], rotating field inspection [34,35], multi-frequency EC sensor [36], scanning EC sensor [37], and perturbed matrix method [38].

For measuring the orientation of surface defect, Theodoulidis, Panas, and Kriezis have proposed an elliptical excitation, which can precisely measure the crack orientation. However, the method needs to spatially and coaxially (with respect to the crack) rotate the excitation coil [39]. Besides, the method is based on the approximation that the thickness of the plate is relatively small (compared to the electromagnetic (EM) skin depth). Moreover, the rotational GMR-EC magnetometer [40] and SQUID probe [41] have been used to detect the orientation of surface defects. Hamia, Cordier, and Dolabdjian have proposed a 3D FE based numerical model to simulate and predict the corresponding signal of an Improved Giant Magneto-Resistance Magnetometer (IGMRM) [18]. The proposed method has an improved detection sensitivity but only applies to the pseudo-rotating magnetic field generated by the excitation inducer.

In this paper, instead of using the numerical method, a revised analytical algorithm based on the eddy-current thin-skin regime is proposed for the triple-coil driver-pickup EC sensor scanning over surface slots of steels with different angles. Compared to the single (or co-axial) coil setup, the driver–pickup has an extended frequency range, higher gain (and spatial resolution) [42], and less affected by the thermal drift [43]. Moreover, with an additional sensing coil, the designed sensor is able to detect the crack angle without spatially rotating the driver-pickup orientation. By using the voltage measurement apparatus with a controlled scanning stage, experiments have been produced on the triple-coil sensor scanning over a benchmark (carbon steel) with machined surface slots of different depths and rotating angles (using a rotary mount underneath the sample). The crack angle is retrieved by referring to the normalised voltage diagram (voltage sum versus voltage difference).

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X. Meng is with the Faculty of Art, Science and Technology, University of Northampton, Northampton, NN1 5PH, UK
II. ANALYTICAL MODEL – EDDY CURRENT THIN-SKIN REGIME

A. Original formulas of thin-skin regime - mutual-impedance of T-R coil scanning vertically over long surface crack

The electromagnetic skin depth, \( \delta \), can be computed by the following equation.

\[
\delta = \sqrt{\frac{1}{\pi \sigma \mu}} \quad (1)
\]

where \( \sigma \) and \( \mu \) are the electrical conductivity and relative magnetic permeability of the test piece, \( \mu_0 \) is the vacuum magnetic permeability, \( \mu \) is the frequency of the excitation current.

In Fig. 1, the circular drive-pickup coil windings scanning vertically (along \( x \) axis) over a long ideal surface slot of a conductive half-space. The analytical mutual impedance change caused by the surface slot is reported in [28], which is based on the eddy-current thin-skin regime proposed by Harfield and Bowler [26]. That is, for the case that the crack length and depth are over 3 to 4 times of the eddy-current skin depth, the impedance change due to the surface slot is reported in [28], which is approximately 3 to 4 times of the eddy-current skin depth.

Moreover, the impedance for the driver-pickup EC sensor over the surface slot with an angle of \( \varphi \) is assumed that a reference signal from an additional sensing pair needs to be spatially superimposed to remove the spatial rotating procedure.

In (7), \( r_1 \) and \( r_2 \) are the inner and outer radius of the coil windings respectively; \( N \) and \( h \) are the number of turns and the height of the coil windings respectively, \( l_0 \) is the horizontal distance between the coil windings and test piece. \( M \) denotes the integral defined in (8).

\[
M = \int_{\alpha_1}^{\alpha_2} \tau l_1(\tau) d\tau \quad (8)
\]

where \( \alpha_1 \) denotes the first-order modified Bessel function of the first kind. The calculation of \( M \) can be accelerated by using the Struve functions, as shown in (9).

\[
M = \frac{j\pi}{2} \left[ r_1 l_0 (j\alpha r_1) L_0(j\alpha r_1) - l_1 l_0 (j\alpha r_1) L_0(j\alpha r_1) \right] - r_2 l_0 (j\alpha r_2) L_1(j\alpha r_2) - l_1 l_0 (j\alpha r_2) L_1(j\alpha r_2) \quad (9)
\]

Moreover, the impedance for the driver-pickup EC sensor above the half-space without defect is

\[
z_0 = j4\pi \mu_0 f \int_{-\infty}^{\infty} \left\{ \bar{h}(-u, -v) \bar{h}(u, v) \frac{e^{i\mu\alpha s}}{\alpha (\mu \alpha + \alpha)} \right\} du dv \quad (10)
\]

where \( s' \) is the distance between the transmitter and receiver.

In Fig. 1, \( s' \) is defined as

\[
s' = \sqrt{s^2 + (x_t - x_r)^2} \quad (11)
\]

B. Revised algorithms - Mutual impedance for triple-T-R sensor scanning over long surface crack with different angles

Considering the blind scanning in the practical testing (where the orientation of the surface crack is an unknown factor), the EC sensor scans over the surface slot with an angle \( \varphi \). For a certain displacement \( x_0 \) of the EC sensor with a single transmitter-receiver (T-R) sensing pair, it needs to spatially rotate the orientation of the T-R sensor pair for the aim of retrieving the crack angle (\( \varphi \)) information. Therefore, it is assumed that a reference signal from an additional sensing pair could avoid the spatial rotating procedure.

As shown in Fig. 2, the EC sensor is designed as three identical coil windings, which is arranged in a line with the same spacing of \( s \). Considering the balance of the background signal on two receiving (or sensing) coils (\( R_1 \) and \( R_2 \) ) in the free space, the driving transmitter is placed between two pick-up

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Fig. 1 Circular drive-pickup coils scanning vertically over long surface crack

The electromagnetic skin depth, \( \delta \), can be computed by the following equation.

\[
\delta = \sqrt{\frac{1}{\pi \sigma \mu}} \quad (1)
\]

where \( \sigma \) and \( \mu \) are the electrical conductivity and relative magnetic permeability of the test piece, \( \mu_0 \) is the vacuum magnetic permeability, \( \mu \) is the frequency of the excitation current.

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Moreover, the impedance for the driver-pickup EC sensor over the surface slot with an angle of \( \varphi \) is assumed that a reference signal from an additional sensing pair needs to be spatially superimposed to remove the spatial rotating procedure.

In (7), \( r_1 \) and \( r_2 \) are the inner and outer radius of the coil windings respectively; \( N \) and \( h \) are the number of turns and the height of the coil windings respectively, \( l_0 \) is the horizontal distance between the coil windings and test piece. \( M \) denotes the integral defined in (8).

\[
M = \int_{\alpha_1}^{\alpha_2} \tau l_1(\tau) d\tau \quad (8)
\]

where \( \alpha_1 \) denotes the first-order modified Bessel function of the first kind. The calculation of \( M \) can be accelerated by using the Struve functions, as shown in (9).

\[
M = \frac{j\pi}{2} \left[ r_1 l_0 (j\alpha r_1) L_0(j\alpha r_1) - l_1 l_0 (j\alpha r_1) L_0(j\alpha r_1) \right] - r_2 l_0 (j\alpha r_2) L_1(j\alpha r_2) - l_1 l_0 (j\alpha r_2) L_1(j\alpha r_2) \quad (9)
\]

Moreover, the impedance for the driver-pickup EC sensor above the half-space without defect is

\[
z_0 = j4\pi \mu_0 f \int_{-\infty}^{\infty} \left\{ \bar{h}(-u, -v) \bar{h}(u, v) \frac{e^{i\mu\alpha s}}{\alpha (\mu \alpha + \alpha)} \right\} du dv \quad (10)
\]

where \( s' \) is the distance between the transmitter and receiver.

In Fig. 1, \( s' \) is defined as

\[
s' = \sqrt{s^2 + (x_t - x_r)^2} \quad (11)
\]
receivers. The EC sensor scans along (x – axis) the vertical direction of the EC sensor orientation (R1 – R2). Assume the coordinate of T, R1, and R2 coils (i.e. the centre for the bottom surface of the coil windings) are (x₀, 0, l₀), (x₀, s, l₀), and (x₀, −s, l₀) respectively. When the surface slot rotates from vertical (along y – axis) to an angle (φ), the Cartesian coordinate system transfers from the x – y – z (originates at o) system to the x′ – y′ – z′ (originates at o′) system. Consequently, the coordinate of T, R1, and R2 coils in the x′ – y′ – z′ system becomes (x₀cosφ, 0, l₀), (x₀cosφ + ssinφ, cosφ, l₀), and (x₀cosφ − ssinφ, −cosφ, l₀) respectively. Therefore, the free-space magnetic scalar potential generated by T, R1, and R2 coils becomes

\[
\tilde{H}(u, v) e^{jux_{0}cosφ}
\]

\[
\tilde{H}(u, v) e^{j(u(x_{0}cosφ + ssinφ) + vscosφ)}
\]

\[
\tilde{H}(u, v) e^{j(u(x_{0}cosφ − ssinφ) − vscosφ)}
\]

Thus, the Fourier transform of the magnetic scalar potential along y – axis at z = 0 (for the test piece without defect) generated by T, R₁, and R₂ coils are expressed as the following equations.

In the practical measurement, discrepancies may occur between the measurement and calculated voltage. Therefore, voltage change in (18) or (19) is generally normalised by the non-defect absolute voltage (for the EC sensor above the test piece without defect, or the non-defect region), which can be expressed as

\[
V_{0} = |\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{h}(u, v) \tilde{H}(u, v) e^{jus} e^{-j(u(x_{0}cosφ + ssinφ) + vscosφ)} du dv|
\]

III. EXPERIMENT

In Fig. 3, experiments have been carried out on the voltage measurement of the triple-coil probe scanning over surface slots with different rotary angles. As shown in Fig. 3 (a), the specimen is placed on a rotatory mount with an angle increment of 5 degrees. The voltage is measured by the custom apparatus – EM instrument fabricated by the SISP group at EEE, University of Manchester [44,45]. Moreover, the EC probe is controlled by a scanning stage with a custom board. The
scanning step of the EC sensor is set at 0.25 mm.

As listed in Table 1, to achieve a relatively high scanning resolution, the coils are wound with a small mean radius of 1 mm (which is much smaller than the crack length). In Table 2, to further test the effect of different depths on the crack orientation retrieval, the test piece (carbon steel) is machined with ideal surface slots of different depths (Fig. 3 b). To ensure that the EC thin-skin regime is valid for surface slots of different depths (where the length and depth of surface crack are 3 to 4 times of the skin depth calculated in 1), the working frequency of the excitation current is 40 kHz. The skin depth is 0.12 mm for the test piece (benchmark sample) under 40 kHz.

### TABLE I
PARAMETERS OF THE TRIPLE-COIL DRIVE-PICKUP EDDY-CURRENT SENSOR AND MEASUREMENT SETUP

<table>
<thead>
<tr>
<th>Parameter of coils (T, R₁, R₂)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius r₁ (mm)</td>
<td>0.75</td>
</tr>
<tr>
<td>Outer radius r₂ (mm)</td>
<td>1.25</td>
</tr>
<tr>
<td>Number of turns N</td>
<td>300</td>
</tr>
<tr>
<td>Coil spacing s (mm)</td>
<td>2.0</td>
</tr>
<tr>
<td>Coil height h (mm)</td>
<td>3.0</td>
</tr>
<tr>
<td>Lift-off l₀ (mm)</td>
<td>2.0</td>
</tr>
<tr>
<td>Working frequency f (kHz)</td>
<td>40</td>
</tr>
<tr>
<td>Displacement along scanning direction x₀ (mm)</td>
<td>-5.0:0.25:5.0</td>
</tr>
</tbody>
</table>

### IV. RESULTS AND DISCUSSIONS

A. **Scanned voltage for different crack depths**

Fig. 4 and Fig. 5 show the comparison of analytical (solid lines) and scanned results (markers) for the difference and sum of the normalised voltage change (from T − R₁ and T − R₂ sensing pairs) versus scanning displacement, respectively. The result is for the crack slot with the same angle of 45 degrees but different depths. It can be observed that the normalised voltage difference in Fig. 4 is centrosymmetric whereas the normalised voltage sum in Fig. 5 is y – axially symmetric. 

![Fig. 4 Normalised voltage difference](image)

![Fig. 5 Normalised voltage sum](image)
The magnitude of both the sum and difference of the normalised voltage increases with the slot depth. For the case of the displacement $x_0 = 0$ mm (the transmitter $T$ is above the centre of the crack), two receivers are spatially centrosymmetric at the crack centre, which results in an identical signal from two receivers. Overall, both the real part and imaginary part of the analytical normalised voltage sum (or difference) fit that of the experimental result for a fixed crack angle of 45 degrees, with the error controlled within 3.0%. The maximum percentage error occurs at the minimum crack depth (0.4 mm), which should substantially larger than the skin depth (0.12 under 40 kHz) (considering the valid criterion of the EC thin-skin regime).

### B. Scanned voltage for different crack orientations

Fig. 6 illustrates the comparison of analytical (solid lines) and experimental (markers) results for the difference and sum of the normalised voltage change (from $T - R_1$ and $T - R_2$ sensing pairs) versus scanning displacement for the crack slot with the same depth of 0.8 mm but different angles. Similar to the trend in Fig. 4 and Fig. 5, the normalised voltage (change) difference (in Fig. 6 a and b) and sum (in Fig. 6 c and d) is centrosymmetric and $\gamma$ - axially symmetric respectively. As the crack angle increases from 0 to 180 degrees, the real part (or imaginary part) of the normalised voltage difference gradually changes from left-lobe (or right-lobe) positive to right-lobe (or left-lobe) positive. The discrepancy between the analytical and experimental result is caused by the approximation of the thin-skin regime, the precision of the scanning system, the distance between the coil windings and crack (a larger distance could lead to a low Signal-to-noise ratio (SNR) due to the weakly coupled effect), and the impedance sensitivity to crack angles and depths. Considering the magnitude of both the normalised voltage sum and difference, the result at the displacement $x_0 = -1$ mm is used for the further effect analysis of crack orientations.

### C. Voltage for different crack orientations

Fig. 7 (a) exhibits the comparison of analytical (solid lines) and experimental (markers) results for the normalised voltage difference and sum (at the displacement $x_0 = -1$ mm) versus crack angles with different crack depths. Similar to the trend in Fig. 4 and Fig. 5, an increased crack depth results in a larger signal magnitude (for both normalised voltage difference and sum). The discrepancy between the experimental and analytical reaches the peak value (less than 3.0 %) at the crack angle of 90 degrees, which is caused by the largest distance between the receiver and crack centre. Consequently, at the crack angle of 90 degrees, the sensor scans along with the crack orientation; and two receiver coil windings never skim over the surface.
In Fig. 7, the normalised voltage (change due to the crack) sum, \( \Delta V_{t-r1}(x_0) + \Delta V_{t-r2}(x_0) \), is monotonic to the crack angle (\( \phi \)) in the ranges from 0 to 90 degrees and from 90 to 180 degrees. Therefore, the crack angle can be retrieved from both ranges (0°~90° and 90°~180°), but not the whole angle domain (0°~180°). Thus, an additional feature is required for judging which range (0°~90° or 90°~180°) the crack angle distributes in. It can be found in Fig. 7 (a) and (b) that the normalised voltage difference \( \frac{\Delta V_{t-r1}(x_0) - \Delta V_{t-r2}(x_0)}{V_0} \) is centrosymmetric at \( \phi = 90° \). Therefore, the crack angle can be retrieved by combining both the normalised voltage sum and difference.

D. Retrieval of surface crack orientation

Fig. 8 depicts the comparison of analytical (solid lines) and experimental (markers) diagram for the normalised voltage (change due to the crack) sum \( \frac{\Delta V_{t-r1}(x_0) + \Delta V_{t-r2}(x_0)}{V_0} \) versus difference \( \frac{\Delta V_{t-r1}(x_0) - \Delta V_{t-r2}(x_0)}{V_0} \) with different crack angles (\( \phi \)) and depths.

In Fig. 7, the normalised voltage (change due to the crack) sum, \( \frac{\Delta V_{t-r1}(x_0) + \Delta V_{t-r2}(x_0)}{V_0} \), is monotonic to the crack angle (\( \phi \)) in the ranges from 0 to 90 degrees and from 90 to 180 degrees. Therefore, the crack angle can be retrieved from both ranges (0°~90° and 90°~180°), but not the whole angle domain (0°~180°). Thus, an additional feature is required for judging which range (0°~90° or 90°~180°) the crack angle distributes in. It can be found in Fig. 7 (a) and (b) that the normalised voltage difference \( \frac{\Delta V_{t-r1}(x_0) - \Delta V_{t-r2}(x_0)}{V_0} \) is centrosymmetric at \( \phi = 90° \). Therefore, the crack angle can be retrieved by combining both the normalised voltage sum and difference.

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90°. Overall, the error of the crack orientation retrieval can be controlled within 3.5 %. As the curves of different depth intersect, the depth of surface defect is set as a prior for the proposed method, which can be evaluated by rotating field eddy-current techniques [34,35].

V. CONCLUSION

Based on the EC thin-skin regime, a revised analytical algorithm is proposed for the mutual impedance of the driver-pickup coil winding scanning over long surface crack slots with different angles. For the retrieval of crack orientation, instead of spatially rotating a single driver-pickup coil winding, an additional sensing coil is included in the designed triple-coil driver-pickup EC sensor. Considering the reversibility of the signal-angle function, a monotonic behaviour is found between the normalised voltage diagram and crack angles. Results show that by referring to the voltage diagram of the normalised voltage difference versus sum, the error of the crack orientation retrieval is controlled within 3.5 % for different crack depths. In the practical measurement, both the length, depth, and orientation of surface defects affect eddy-current signals. The length and depth of surface defects can be determined or classified by other techniques including the ACFM [32,33] (for defect length retrieval), and rotating-field eddy current sensor [34,35] (for defect depth retrieval). The proposed method aims to incorporate those existing techniques for the further determination of crack orientations. Therefore, high-frequency signals are commonly used so that a relatively thin skin depth satisfies.

Besides, to ensure that the proposed method is less affected by the border of the defect (when the sensor pass near the defect border), it is suggested to use sensor arrays (particularly in a line and perpendicular to the scanning direction) with relatively small coil diameter to inspect surface crack. The defect orientation is retrieved from the sensor with the most significant voltage change (among arrays) when using the proposed method (based on eddy-current thin-skin regime). Moreover, the scanning position of \( x_0 = -1 \text{ mm} \) can be identified from sensor arrays (along scanning direction) with a spacing of 1 mm by comparing their signals.

The defect clusters are commonly located using the ultrasonic sensor. Besides, eddy current sensors are used to incorporate with ultrasonic sensors to quantity the dimension of defects. Due to the skin effect, where the eddy current is confined near the surface of test piece, the eddy current testing only applies to surface or near-surface defects. Moreover, the defect may be irregular (asymmetric) in practical measurement (particularly for small defect compared to the sensor diameter). Further investigations on the inspections of sub-surface defects and even asymmetric defects will be carried out in the future.

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