The interaction efficiency evaluation between defect and eddy current induced by different exciting coils of planar eddy current probe

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Abstract
This paper presents a quantitative evaluation index efficiency of eddy current and defect interaction to evaluate the eddy current distribution induced by different planar eddy current probe. Efficiency's definition and its calculation method are presented. Eddy current induced by three different exciting coils interacting with defects having different lengths and different orientation angles is analyzed by the proposed method. Finally, the paper highlights strengths and weaknesses of the studied current probe inducers and an improving method is proposed.

Keywords
Non-destructive testing, efficiency, eddy current testing, fractal geometry, planar eddy current probe

Introduction
To ensure the integrity and reliability of key mechanical structures, regular non-destructive testing is required.\textsuperscript{1} Because of its advantages such as non-contact,\textsuperscript{2} rapidity, usability, and portability,\textsuperscript{3} eddy current (EC) testing method is one of the most suitable methods for detecting surface and sub-surface defects in conductive components.\textsuperscript{4} Moreover, EC method is widely used in composite materials detection.\textsuperscript{5,6}

To inspect the components with complex surface, flexible planar EC probes have been proposed. Usually, these kinds of probes are integrated on a printed circuit board and micro-electromechanical systems.\textsuperscript{7} Because the performances of EC probes strongly depend on the direction of defect, improving the EC distribution in space domain or in time domain are two effective ways to make probes more sensitive to defect in any direction. In space domain, many new shapes of the exciting coils such as meandering winding magnetometer (MWM),\textsuperscript{8,9} rosette-like,\textsuperscript{10} rectangular, and fractal Koch curve\textsuperscript{11} have been proposed. However, in time domain, only planar rotating field EC probes\textsuperscript{12–15} have been proposed.

All the aforementioned innovations aim to improve the EC distribution. However, except for the maximum and minimum, EC distribution can be only qualitatively analyzed. Guolong Chen and colleagues,\textsuperscript{16–18} proposed a novel method using information entropy to analyze quantitatively EC induced by different exciting coils, but this method could only quantitatively describe EC distribution in all directions by statistical analysis and not consider the sizes, positions, and directions of specific defects. To quantitatively analyze the EC distribution interaction with defects having a certain length and angle, because the EC is strongest disturbance by defect at the right angle of the EC and defect can only disturb the EC component which is perpendicular to the defect, interaction efficiency between EC distribution and virtual defect is proposed in this paper.

This work presents a quantitative index efficiency of the interaction between the EC and defect, and a method of how to calculate the index. Then, EC distribution induced by three different exciting coils is

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analyzed. The paper is organized as follows. Section “Introduction” gives a brief developing of planar EC probe and of the method of quantitative analysis of EC distribution. Section “Perturbation theory of defects detection by the EC method” describes the perturbation theory of defects detection by EC method. In section “EC transformation of coordinates,” EC transformation of coordinates is given and in section “Interaction efficiency between the EC and the defect,” the new method is introduced. In section “EC acquisition and calculation method of η(x) and η,” EC acquisition method is described. In section “Results and discussion,” the results are presented and analyzed. Conclusions and future works are addressed in the last section.

Perturbation theory of defects detection by the EC method

EC method in non-destructive testing is based on electromagnetic induction. Usually, an EC probe consists of an exciting coil, which may take various shapes, such as circular, MWM, rosette, cruciform, and fractal Koch curve, and a pickup element made up of coils or magnetic sensors, such as anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), and tunnel magnetoresistance (TMR). During testing, the coil is excited with alternating electric current that produces an alternating magnetic field (i.e. primary field), oscillating at the same frequency as the current running the coil. Because of Faraday’s electromagnetic induction principle, an EC, which oscillate at the same frequency as the exciting current, is induced in conductive test specimen and generates a magnetic field (i.e. secondary field). The combination of primary and secondary field is net magnetic field. Then, the pickup element feels the net field and generates an output signal. Defects in specimen disturb the EC distribution, causing a variation in the secondary and the net magnetic field allowing the defect to be recognized.

However, the strength of EC disturbance is different in defects with the same size and position but different orientation. In detail, when the direction is parallel to defect’s direction, the disturbance is the highest and the EC probe is most sensitive to defects. When defect and EC are perpendicular to each other, the disturbance is the lowest and the probe is insensitive to defects; as the angle between the same size defects and the same EC varies from 0° to 90°, the strength of disturbance will become stronger and stronger. That explains the different sensitivity of EC probe to defects.

When the angle between the defect and the EC becomes larger, the EC probe becomes more sensitive because the EC component in the direction at the right angle of defect becomes large. In other words, disturbance occurs between the defect and the EC component perpendicular to the direction of the defect, rather than the parallel component. It will be defined as vertical effective principle.

EC transformation of coordinates

As shown in Figure 1, an EC vector \( J(x, y) = (J_x(x, y), J_y(x, y)) \) is in a two dimensional plane, and the angle from positive \( x \)-axis is \( \theta \). The center of the virtual defect is at \( (x, y) \), and the angle from positive direction of the \( x \)-axis is \( \alpha \). The relationship between \( J(x, y) \) and \( J_x(x, y), J_y(x, y) \) is

\[
\begin{align*}
J_x(x, y) &= J(x, y) \cos \theta \\
J_y(x, y) &= J(x, y) \sin \theta
\end{align*}
\]

where \( J = \sqrt{J_x^2(x, y) + J_y^2(x, y)} \) is magnitude of the EC vector at point \( (x, y) \).

The angle between the EC and the virtual defect is \( \alpha - \theta \). Then, \( J(x, y) \) can be resolved in two directions, respectively, parallel and perpendicular to the direction of the defect

\[
\begin{align*}
J_{\text{parallel}}(x, y) &= J(x, y) \cos(\alpha - \theta) \\
J_{\text{vertical}}(x, y) &= J(x, y) \sin(\alpha - \theta)
\end{align*}
\]

where \( J_{\text{parallel}}(x, y) \) and \( J_{\text{vertical}}(x, y) \) are parallel and vertical component to the defect, respectively. \( J_{\text{vertical}}(x, y) \) is useful EC component interacting with defects, and \( J_{\text{parallel}}(x, y) \) is invalid component. Equation (3) describes the orthogonal decomposition of \( J \), as shown in Figure 1.

Figure 1. EC component at the right angle of the virtual defect.
Interaction efficiency between the EC and the defect

For the defect detection using EC method, the angle between of the EC and defect is a crucial factor to EC sensors. If the EC is perpendicular to defect, the EC can be easily disturbed by defect, and then the defect may be easily detected. Thus, in the detection procedure, the component of the EC vertical to the defect mainly affects the detectability of the EC method. To quantitatively calculate the useful component in the EC distribution, the proposed index imitated the efficiency in the classical physics. Specifically, the EC component vertical to defect and total EC were imitated to the useful work done and total work done, respectively. Efficiency is commonly defined as the ratio between the useful energy and the total energy, or the ratio of the useful power divided by the total power, in percent. The strict definition is as follows.

In practical application of EC testing, there is relative motion between the specimen and the probe. In this study, the probe is assumed to be stationary and the specimen moves along the x-axis; a virtual defect is tilted to x-axis with an angle of \( \alpha \). A parallelogram (width of \( D \), height of \( L \)) is the area swept by the virtual defect as interaction domain \( \Omega \) of EC and defect interaction; Figure 2 shows the area.

This definition was simulated, and EC-defect interaction efficiency was defined as the ratio between the useful energy and the total energy, or the ratio of the useful work done and total work done, respectively. Efficiency is given by

\[
\eta(x) = \frac{\int J_{\text{vertical}}(x,y)\,dL}{\int J(x,y)\,d\Omega}
\]

where \( \eta(x) \) is efficiency along x-axis; \( dL \) is infinitesimal virtual defect; \( \int J_{\text{vertical}}(x,y)\,dL \) indicates the energy of useful component of EC when the center of virtual defect is moving at the position \( (x,y) \); \( d\Omega \) is the infinitesimal interaction domain; \( \int J(x,y)\,d\Omega \) is the total energy of EC in the interaction domain. \( \eta(x) \) gives a quantitative description of EC-defect interaction when the defect is moving along x-axis which represents the scanning direction. However, the efficiency \( \eta \) in whole interaction is given by

\[
\eta = \frac{\int J_{\text{vertical}}(x,y)\,dx\,dy}{\int J(x,y)\,d\Omega}
\]

where \( \int J_{\text{vertical}}(x,y)\,dx\,dy \) indicates total useful energy of vertical component in the interaction domain. According to equation (4) and (5), we get

\[
\eta = \int \eta(x)\,dx
\]

where \( \eta \) is the area lying above the curve \( \eta(x) \) and the x-axis, \( \eta(x) \) is the distribution of total efficiency along x-axis.

![Figure 2. Interaction domain of EC and defect.](image)

EC acquisition and calculation method of \( \eta(x) \) and \( \eta \)

EC distribution was acquired by three finite element models which are identical with the models in the literature. The studied excitation currents were a line, a circle, and a second-order Koch curve, respectively, the centers of which were located in the origin of coordinates and the line was along y-axis. In the length direction of defects, EC vector was acquired in 64 points equally arranged. In the scanning direction, vector was acquired in the range –26 mm to 26 mm with certain step length of 0.5 mm. Defects were 5-, 10-, 20-, 25-, and 40-mm long, and the orientation angle \( \alpha \) of the defects was 0°, 15°, 30°, 45°, 60°, 75°, and 90°.

In actual calculation, integral operator is replaced by a summation. \( \int J(x,y)\,d\Omega \) is the sum of \( J(x,y) \) of all data points acquired in the whole interaction domain. \( \int J_{\text{vertical}}(x,y)\,dL \) is the sum of \( J_{\text{vertical}}(x,y) \) of all data points acquired in virtual defect at a certain position. In the same way, \( \int J_{\text{vertical}}(x,y)\,dx\,dy \) is the sum of \( J_{\text{vertical}}(x,y) \) of all data points acquired in virtual defect at a certain position.

Results and discussion

Efficiency \( \eta(x) \)

Efficiency \( \eta(x) \) of virtual defects with different lengths and different orientations interacting with EC induced by three different exciting coils is presented in Figure 3. Total efficiency \( \eta \) of all kind of defects is shown in Figures 4 and 5.

As detailed in Figure 3(a), the efficiency curves about linear inducer have one flat top, and the different lengths and orientations of a virtual defect result in different widths and heights of the flat top. In detail, width increases as the orientation angle \( \alpha \) increases, suggesting that the time of virtual defect-EC interaction increases because the projection length of the defect on the x-axis increases. For the same reason, width of flat top about defects with same orientation angle increases as the length of virtual defect increases. Furthermore, in case of defects with the same length,
the maximum value of \( \eta(x) \) increases as \( \alpha \) decreases. \( \eta(x) \) about EC induced by linear coil reaches its maximum value at \( x = 0 \) because the EC is concentrated on the specimen below exciting coils. Moreover, more remarkable, when the orientation angle \( \alpha = 90^\circ \), \( \eta(x = 0) = 0 \) because the induced EC is almost distributed along 90\(^\circ\) direction and is parallel to the direction of virtual defect.

Figure 3. \( \eta(x) \) of different exciting coils and different length and orientation angle defect: (a) linear exciting coils; (b) circular exciting coils; (c) Koch curve exciting coils; 1: \( L = 5 \) mm; 2: \( L = 10 \) mm; 3: \( L = 20 \) mm; 4: \( L = 25 \) mm; 5: \( L = 40 \) mm (\( L \) is the height of the interaction domain).
Figure 3(b) details $\eta(x)$ of EC induced by circular exciting coils. Some of the curves show one peak, while the other has two peaks. The number of peaks equals the number of times on the continuous EC-defect interaction. From Figure 3(b-1) to Figure 3(b-3), it can be found that every curve $\eta(x)$ has two peaks. There are two continuous interactions when the virtual defect approaches to and is far away from exciting coils, because the defect is shorter than the size of the diameter of circular coils. However, one peak appears in Figure 2(b-4) and Figure 2(b-5) because defect is continuously disturbing the EC when near and far away from the exciting coils. Consistent with the case in line, width of the peak or the flat top increases with length but decreases as the orientation angle of virtual defects, and when the length of 5-mm-long defect angle is $0^\circ$ the maximum value of $\eta(x)$ is near zero. However, unlike the $\eta(x)$ of linear exciting coils, for $\alpha = 90^\circ$, $\eta(x)=0$ for any length of virtual defect; for circular exciting coils, $\eta(x) \neq 0$ when virtual defect is 10-mm long. The maximum value of $\eta(x)$ is 13%, and the one of $\eta(x)$ for the same orientation angle increases with the length of virtual defect. Thus, from the perspective of short defect, the circular likes the line, so it is difficult to detect short defect for same linear or circular exciting coils EC probe.

For the Koch curve exciting coils, $\eta(x)$ curves exhibit one or two peaks, whose width roughly increases with the length of virtual defects but decreases with the orientation angle, according to the cases of linear and circular exciting coil. However, as shown in Figure 3(c-1), for a 5-mm-long defect, the maximum value of $\eta(x)$ is near zero. However, unlike the $\eta(x)$ of linear exciting coils, for $\alpha = 90^\circ$, $\eta(x)=0$ for any length of virtual defect; for circular exciting coils, $\eta(x) \neq 0$ when virtual defect is 10-mm long. The maximum value of $\eta(x)$ is 13%, and the one of $\eta(x)$ for the same orientation angle increases with the length of virtual defect. Thus, from the perspective of short defect, the circular likes the line, so it is difficult to detect short defect for same linear or circular exciting coils EC probe.

Figure 4. $\eta$ for different exciting coils: (a) line, (b) circle, and (c) Koch curve.

Figure 5. $\eta$ for different length of virtual defects: (a) 5 mm, (b) 10 mm, (c) 20 mm, (d) 25 mm, and (e) 40 mm.
value of $\eta(x)$ at $\alpha = 90^\circ$ is almost equal to that of the case $\alpha = 0^\circ$, and differs from values of the aforementioned coils. Then, the maximum values of $\eta(x)$ for other lengths at orientation angle $\alpha = 0^\circ$ are greater than that of other angles. Here again, values are different from the aforementioned coils. For linear exciting coils, the maximum value of $\eta(x)$ at orientation angle $\alpha = 90^\circ$ is almost distributed for different lengths of virtual defect overlap because the EC induced by the linear and circular curves exciting coils have a multi-radius property, due to the similarity of fractal geometry.

**Total efficiency of the same exciting coil varying lengths and orientation angles of virtual defects**

The total efficiency $\eta$ against orientation angle for different lengths of the virtual defect is shown in Figure 4. For linear exciting coils, the total efficiencies at same orientation angle but different lengths are the same. In other words, the curves of $\eta$ against orientation angle for different lengths of virtual defect overlap because EC induced by the linear coil is almost distributed in one certain direction.

For circular exciting coils, when the orientation angle is less than $45^\circ$, total efficiency of the whole interaction domain decreases as the orientation angle increases. However, when the angle is bigger than $45^\circ$, the decrease in total efficiency is different for different lengths of virtual defects. In this region, with the increasing of the length of virtual defect, total efficiency decreases with the angle for defects $5,$, $10,$, and $20$-mm long, but the total efficiency is about $50\%$ for all angles of defects $25$- and $40$-mm long. The slope of $\eta$ against angle decreases as the length of virtual defect increases. For $5$-mm- and $10$-mm-long virtual defects (orientation angle $90^\circ$), total efficiency is less than $10\%$. Thus, short defects are difficult to be detected when their orientation is parallel to the one of the EC. Note that total efficiency is $50\%$ for orientation angle $\alpha = 45^\circ$ for any length of virtual defect.

As Figure 4(c) shows, for the Koch exciting coils the orientation angle is less than $45^\circ$, and the total efficiency of whole interaction domain decrease as the angle increases. Unlike the circular exciter, the rate of change of $\eta$ increases with the length of virtual defect when orientation angle is less than $45^\circ$. Consistent with that for circular exciting coils, the total efficiency is $50\%$ when orientation angle $\alpha = 45^\circ$. When $\alpha$ is bigger than $45^\circ$, the total efficiency is about $50\%$ for virtual defects the length of which is more than $20$ mm, but there is a slight variation of total efficiency for lengths of $5$ and $10$ mm. For such exciting coils, the total efficiency at each length and each orientation angle is higher than $30\%$, which is the advantage of the Koch exciting coil.

**$\eta$ for defects with same length but different orientation angles and different exciting coils**

Figure 5 compares the total efficiency of three different exciting coils. For all the lengths of virtual defect, when $\alpha$ is smaller than $45^\circ$, the total efficiency is more than $50\%$ and decreases as the orientation angle increases. Note that the total efficiency $\eta$ is $50\%$ when the orientation angle is $45\%$. When the angle is bigger than $45^\circ$ and the defect is $5$-mm long, the curve of $\eta$ for linear and circular coils are similar. When the orientation angle is bigger than $45^\circ$ and virtual defect is $25$- and $40$-mm long, $\eta$ for linear and Koch coils shows the same pattern. For length of $5$ mm and angle of $90^\circ$, total efficiency of Koch coil is $30\%$, obviously higher than that of linear and circular coils, that is about $0\%$.

**Suggestions for EC probe testing**

According to the foregoing discussion, the use of Koch curve exciting coils improves the interaction efficiency for short virtual defects. Koch curve can improve the EC distribution in space domain. However, in time domain, the method can be used as following:

1. Use the rotating field EC probe, which can induce a rotating EC flowing in the specimen. Thus, at the same time, the direction of EC can be perpendicular to the direction of defects.
2. It is similar to the rotating field EC probe, so the EC probe is rotating in mechanically.
3. Testing process can be improved. Based on the conclusions drawn from the previous analysis, the total efficiency is bigger than $50\%$ when the orientation angle is smaller than $45^\circ$. Thus, probe can scan in two directions, perpendicular to each other. In the first step, $0^\circ$-$45^\circ$ range is focused, but in the second step, $45^\circ$-$90^\circ$ range is focused. The total efficiency, which is greater than or equal to $50\%$ for all orientation angles and all lengths of virtual defects, can be obtained, as shown in Figure 6.

**Conclusion**

This paper first proposes the interaction efficiency between the EC and the virtual defect to evaluate EC distribution, giving a measurement of interaction strength between EC and defect. The advantage of this EC distribution evaluation method takes account into specific sizes and direction of defect. By evaluating $\eta(x)$ and $\eta$, the proposed method compares the EC distribution induced by three different exciting coils. Results highlight that when the orientation angle is $45^\circ$, the
efficiency for every exciting coils is equal to 50%. Then, for short defects, $\eta(x)$ and $\eta$ for Koch exciting coils has obvious advantages. However, based on efficiency, methods are proposed to cover the shortage of linear and circular EC exciting coils. Future works will focus on the investigation of the proposed efficiency in three-dimensional EC distribution and defect.

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**Appendix I**

**Notation**

- $J(x, y)$ vector of EC at point $(x, y)$
- $J_x(x, y)$ component of $J(x, y)$ in $x$ direction
- $J_y(x, y)$ component of $J(x, y)$ in $y$ direction
- $J$ magnitude of the vector $J(x, y)$
- $J_{\text{vertical}}(x, y)$ component of $J(x, y)$ in the direction which is perpendicular to defect direction
- $J_{\text{parallel}}(x, y)$ component of $J(x, y)$ in the direction which is parallel to defect direction
- $\eta$ interaction efficiency between the EC and the defect in the interaction domain
- $\eta(x)$ interaction efficiency between the EC and the defect at a certain $x$
