Study on problems in detecting plural cracks by alternating flux leakage testing using 3D nonlinear eddy current analysis

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Study on Problems in Detecting Plural Cracks by Alternating Flux Leakage Testing Using 3-D Nonlinear Eddy Current Analysis

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***Abstract*—The alternating magnetic flux leakage testing is used for the detection of cracks in a steel plate. A new technique of how to detect plural cracks, which are located at a very short distance from each other, using the parallel (x-) component of the leakage flux density is proposed. The behavior of leakage flux is examined using a three-dimensional edge-based hexahedral finite-element method. The effects of dimensions of search coils and cracks on the detection accuracy are illustrated.**

***Index Terms*—Alternating magnetic flux leakage testing, finite-element method, plural cracks, 3-D nondestructive inspection.**

I. Introduction

ALTERNATING magnetic flux leakage testing detects the leakage flux from cracks in ferromagnetic material magnetized by an ac electromagnet [1], [2]. High frequency should be used to detect very small cracks in a steel surface [3], [4]. Generally, the perpendicular (B_z) component of leakage flux is detected by this testing, because this component is not generated when there is no crack. However, when plural cracks are located at a very short distance, the distinction of the numbers of cracks cannot be performed by using the B_z component [5].

In this paper, a technique of how to detect plural cracks, which are located at very short distance, is investigated by a three-dimensional (3-D) edge-based hexahedral finite-element method (FEM) [6]. It is shown that the detection of the parallel (B_x) component of the leakage flux density is effective in inspecting plural cracks. The behavior of the parallel component B_x is examined, and the possibility to distinguish plural cracks using B_x is discussed. In order to detect B_x, a differential type of search coil is proposed. The required dimension of search coil for distinguishing plural cracks is given by investigating the relationship between the dimension of search coil and the obtained B_x. In addition, the experimental verification is also carried out.

II. Inspection Model and Method of Analysis

Fig. 1 shows a model of an alternating magnetic flux leakage testing that detects plural cracks. The search coils shown in Fig. 1(c) and (d) are used, and these detect the z component (B_z) and the x component (B_x) of leakage flux density near cracks. The height and width of the search coil are defined as S_h and S_w, respectively. The length of the search coil in the y direction is fixed at 10 mm. The distance [liftoff (L_o)] between the search coil and the surface of steel is 0.1 mm. The crack depth is defined as C_d. The amplitude of current is 1 A (rms) and the exciting frequency is 1 kHz.

The basic equation of the magnetic field with eddy current in the case of the $\boldsymbol{A}-\phi$ method is given by

$$\mathrm{rot}(v\mathrm{rot}\boldsymbol{A}) = \boldsymbol{J}_o - \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \mathrm{grad}\phi\right) \quad (1)$$

$$\mathrm{div}\left\{-\sigma\left(\frac{\partial \boldsymbol{A}}{\partial \mathrm{t}} + \mathrm{grad}\phi\right)\right\} = 0 \quad (2)$$

where $\boldsymbol{A}$ is the magnetic vector potential, v is the reluctivity, $\boldsymbol{J}_o$ is the current density, σ is the conductivity, and ϕ is the scalar potential.

The flux and eddy current are analyzed by the 3-D edge-based hexahedral FEM taking account of the nonlinearity of steel plate. In order to get the steady-state result, the calculation is carried out during 2.5 periods ($=40$ steps). The time interval Δt of the step-by-step method is chosen as 6.25×10^{-5} s. The condition of the calculation is shown in Table I. The yoke is assumed to be linear (relative permeability: $\mu s = 60\,000$) and the eddy current in it is neglected. The lamination of yoke is not taken into account.

III. Results and Discussion

A. Comparison of Parallel (B_x) and Perpendicular (B_z) Components of Leakage Flux

Fig. 2 shows the x component $|B_x|$ and the z component $|B_z|$ of the average flux density in the search coil calculated and measured by changing the position D. After 35–step calculations (about two periods), an almost steady-state result can be obtained. The dimensions of the search coils and cracks are shown in Table II. The figure also shows the comparison between the calculation and measurement when one and two cracks exist. The figure denotes that the calculated and measured peak values of $|B_x|$ and $|B_z|$ are in good agreement of about 4% accuracy.

Fig. 2(a) suggests that the distinction of two cracks is possible by using $|B_x|$. On the contrary, the two cracks cannot be detected by using $|B_z|$ as shown in Fig.2(b). This is because two peaks are generated even when only one crack exists. But $|B_x|$ (about 68×10^{-4} T) of leakage flux is generated even when the

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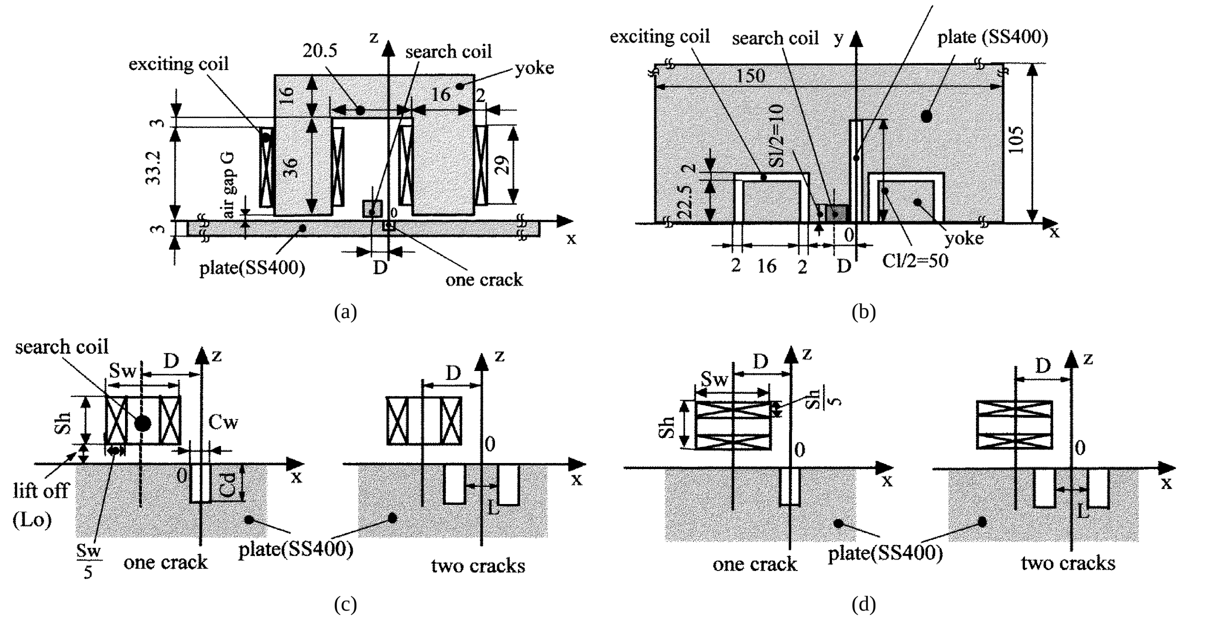

Fig. 1. Model for alternating flux leakage testing of plural cracks: (a) x–z plane; (b) x–y plane; (c) search coil for measuring $|B_z|$ (x–z plane); and (d) search coil for measuring $|B_x|$ (x–z plane).

TABLE I
CONDITION OF ANALYSIS AND EXPERIMENT

Exciting coil	1kHz, 1A(rms), 30turns × 2
Search coil	Length (Sl) in the y-direction=10mm, 20turns, Lift-off (Lo) = 0.1mm
Steel	SS400, $\sigma = 7.51 \times 10^6$ S/m Maximum relative permeability μ_s=3000 (xμ_0 H/m)
Cracks	Depth (Cd)=1mm, Length (Cl) in the y-direction=100mm
Nodes and elements	86400, 78540
Convergence criterion	N-R method: 1.0×10^{-3} T ICCG method: 1.0×10^{-5}

crack does not exist. On the other hand, $|B_z|$ of leakage flux is not generated when there is no crack.

Therefore, in order to distinguish plural cracks, a new detection method using differential search coils is proposed.

B. Proposal of Differential Search Coil

Fig. 3 shows the proposed differential search coils. The leakage flux $|B_x|$, which is uniformly distributed over the steel surface, is measured using the search coil β. The local leakage flux $|B_x|$ from the cracks is measured using the search coil α. The x length $(S_l - \alpha)$, y length $(S_w - \alpha)$, and z length $(S_h - \alpha)$ of the search coil α are 0.38, 5, and 0.1 mm, respectively. The x length $(S_l - \beta)$, y length $(S_w - \beta)$, and z length $(S_h - \beta)$ of the search coil β are 5, 4.8, and 0.22 mm, respectively.

The difference of B_x measured using the differential search coil, when two cracks exist, is shown in Fig. 4. The width (C_w), depth (C_d), and length (C_l) of both two cracks are 0.5, 1, and 100 mm, respectively. The figure suggests that the numbers of cracks can be recognized by using the proposed method. The output of $|B_x|$ is zero, when there is no crack. The figure denotes that the calculated and measured peak values of $|B_x|$ are in good agreement of about 4% accuracy.

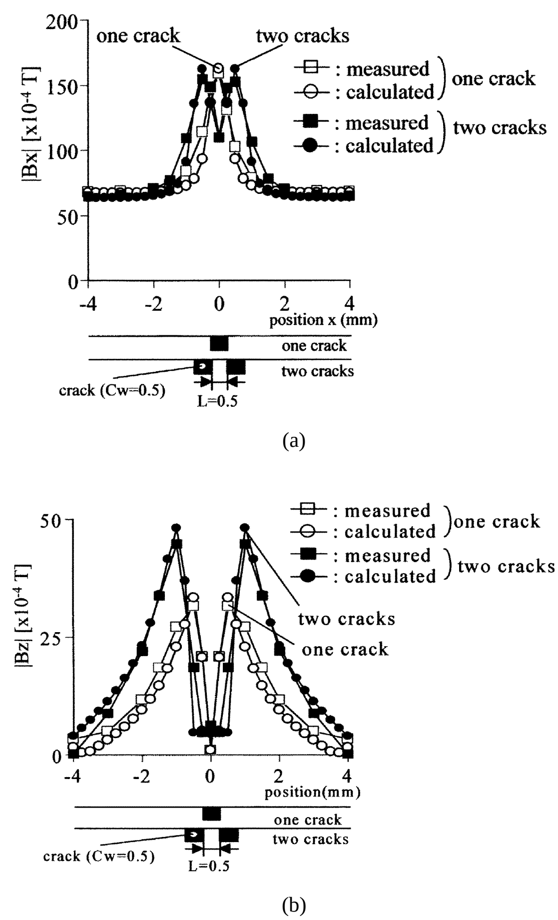

Fig. 2. Waveforms of $|B_x|$ and $|B_z|$ ($C_w = 0.5$ mm): (a) $|B_x|$ and (b) $|B_z|$.

Fig. 5 shows the calculated $|B_x|$ when there are one, two, and four cracks. The dimensions of search coils α and β are different from those of Fig. 3 (see Fig. 5). The figure suggests that the proposed method is useful in detecting plural cracks.

TABLE II
DIMENSIONS OF SEARCH COILS AND CRACKS USED IN EXPERIMENT

Search coil (20turns)	Bx	Width (Sw)=0.38mm, Height (Sh)=0.1mm
	Bz	Width (Sw)=0.18mm, Height (Sh)=0.5mm
Crack	Crack width (Cw)=0.5mm, Distance between two cracks (L)=0.5mm	

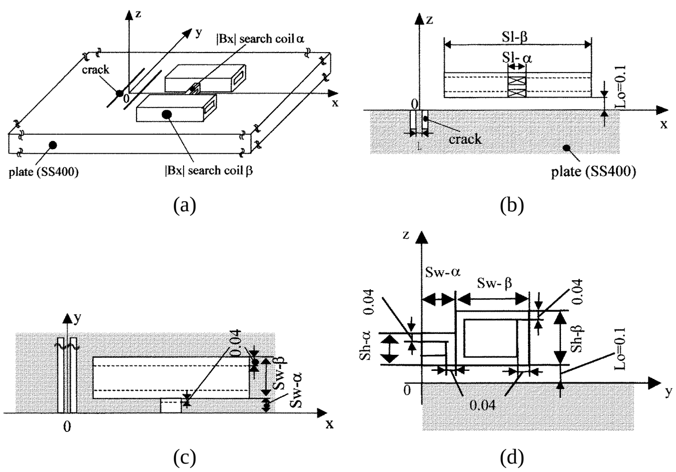

Fig. 3. Differential search coils for detecting leakage flux $|B_x|$ used in experiment and analysis: (a) bird's eye view; (b) x–z plane; (c) x–y plane; and (d) y–z plane.

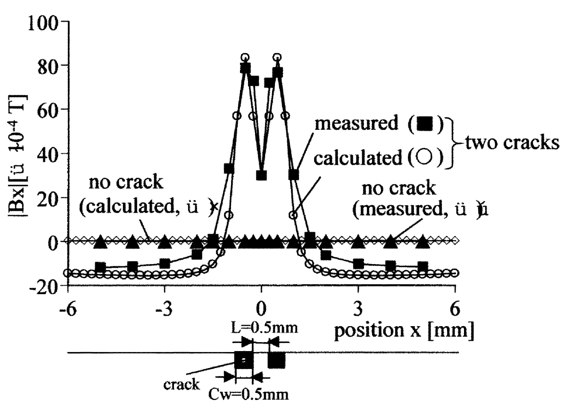

Fig. 4. Waveform of leakage flux $|B_x|$ detected using differential type coils (two cracks, $C_w = 0.5$ mm, $L = 0.5$ mm, $L_o = 0.1$ mm).

C. Effect of Dimensions of Search Coils and Cracks

In order to distinguish plural cracks, the distance L of which is very short, using the x-component B_x, the dimension of search coil α should be small. Then, the required dimension of search coil α is examined when two cracks exist. The depth (C_d) and length (C_l) of both two cracks are 1 and 100 mm, respectively. The height $(S_h - \alpha)$ and the length $(S_l - \alpha)$ of a search coil α, and the height $(S_h - \beta)$ of a search coil β are assumed as the same.

Fig. 6 shows the effect of the dimensions ($S_h - \alpha$, $S_l - \alpha$, and $S_h - \beta$) of the search coil α and β on output waveform of $|B_x|$, when the interval L and the width (C_w) of two cracks are changed. In Fig. 6(a) and (b), the widths (C_w) of both two cracks are 0.5 mm, and the intervals L are 0.2 and 0.5 mm, respectively. Fig. 6(a) and (b) suggests that the dimensions ($S_h - \alpha$, $S_l - \alpha$, and $S_h - \beta$) of search coils should be less than the interval L.

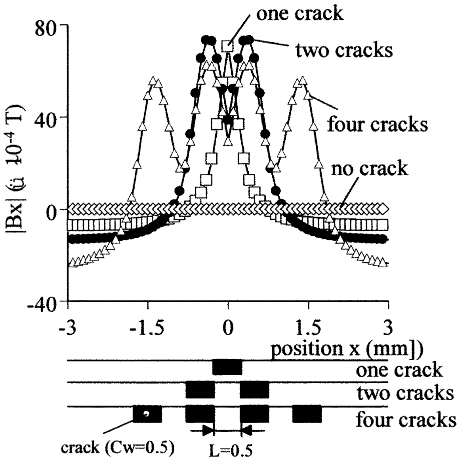

Fig. 5. Inspection of plural cracks using differential type coils ($C_w = 0.5$ mm, $L = 0.5$ mm, $L_o = 0.1$ mm, $S_l - \alpha = 0.3$ mm, $S_w - \alpha = 5$ mm, $S_h - \alpha = 0.3$ mm, $S_l - \beta = 14$ mm, $S_w - \beta = 10$ mm, $S_h - \beta = 0.3$ mm).

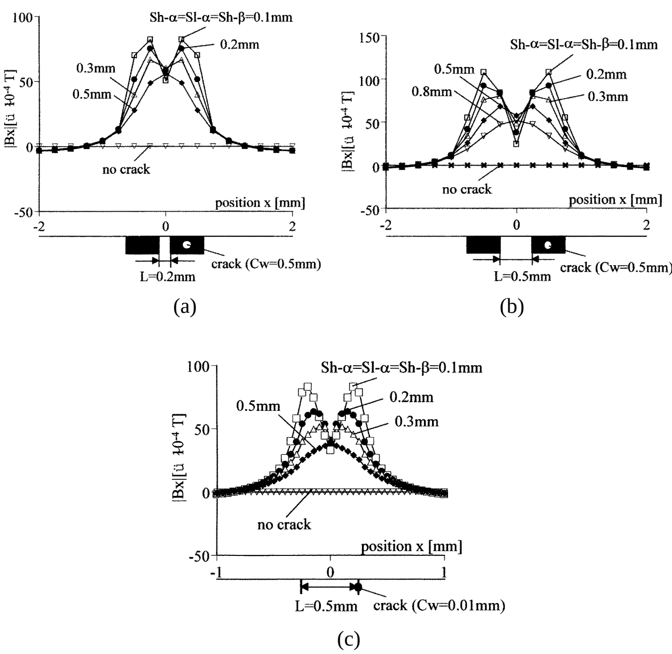

Fig. 6. Effect of interval L between two cracks and width C_w ($L_o = 0.1$ mm): (a) $L = 0.2$ mm and $C_w = 0.5$ mm; (b) $L = 0.5$ mm and $C_w = 0.5$ mm; and (c) $L = 0.5$ mm and $C_w = 0.01$ mm.

In Fig. 6(b) and (c), the intervals L are 0.5 mm, and the widths (C_w) of both two cracks are 0.5 and 0.01 mm, respectively. These figures show that the dimensions $(S_h - \alpha = S_l - \alpha = S_h - \beta)$ should be further reduced when the crack width C_w becomes smaller. But, it is possible to detect two cracks by the search coil of $S_h - \alpha = S_l - \alpha = S_h - \beta = 0.3$ mm, even when C_w is 0.01 mm.

Fig. 7 shows the distribution of $|B_x|$ when the depths of two cracks are different. The depths (C_d) of a left-side crack and a right-side crack are 0.5 mm and 1 mm, respectively. The width (C_w) and length (C_l) of both two cracks are 0.01 and 100 mm, respectively. The figure denotes that two cracks can be detected by the search coil of $S_h - \alpha = S_l - \alpha = S_h - \beta = 0.3$ mm. Moreover, the figure illustrates that the information about the difference of the crack depth is also obtained using the differential search coil.

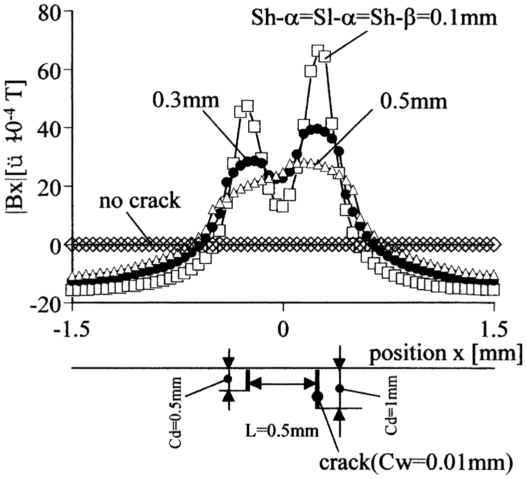

Fig. 7. Effect of imbalance of crack depth ($C_w = 0.01$ mm, $L = 0.5$ mm, $L_o = 0.1$ mm).

IV. Conclusion

The results obtained are summarized as follows.

1) The 3-D nonlinear edge-based hexahedral FEM is useful for investigating the alternating magnetic flux leakage testing with the plural cracks. Moreover, the validity of the calculation is illustrated by experiment.
2) A new technique using differential search coil for detecting plural cracks, which are located at very short distance, is proposed. It is proved that the plural cracks can be detected using the parallel (B_x) component of leakage flux.
3) The effects of dimensions of search coils and cracks on the detection accuracy are investigated, and the appropriate dimensions of search coils for respective intervals between cracks and crack widths and depths are also illustrated.

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