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3-D Nonlinear Eddy-Current Analysis of Alternating Magnetic Flux Leakage Testing—Analysis of One Crack and Two Cracks

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***Abstract*—The alternating magnetic flux leakage testing has been applied in the nondestructive inspection process for detecting cracks on the surface of steel. This paper describes numerical analysis using three-dimensional (3-D) edge-based hexahedral finite element method for this testing. The necessity of nonlinear analysis is clarified in comparison with the linear analysis ($j\omega$ method). The characteristic of leakage flux is confirmed by verification experiment. The possibility of distinguishing two cracks is examined by calculating the detailed distribution of leakage flux around cracks.**

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

I. Introduction

THE ALTERNATING magnetic flux leakage testing has been applied in the inspection process for detecting cracks on the surface of steel [1], [2]. This method detects the leakage flux from the cracks in ferromagnetic material magnetized by an ac electromagnet. High frequency should be used to detect very small cracks in steel surface. In order to develop a precise inspection method, the flux and eddy-current distributions should be investigated for various kinds of cracks.

In this paper, the property of leakage flux from the crack of steel under ac excitation is investigated using three-dimensional (3-D) edge-based hexahedral finite-element method. The necessity of nonlinear analysis taking account of nonlinear magnetizing characteristics (B–H curve) is investigated by comparing with the linear analysis ($j\omega$ method). The experimental verification is also carried out.

The effects of crack width and crack length on the leakage flux in a search coil are also investigated. The behavior of the perpendicular (Bz) and parallel (Bx) components of the leakage flux density is examined, and the possibility to distinguish one crack and two cracks using both Bz and Bx is discussed.

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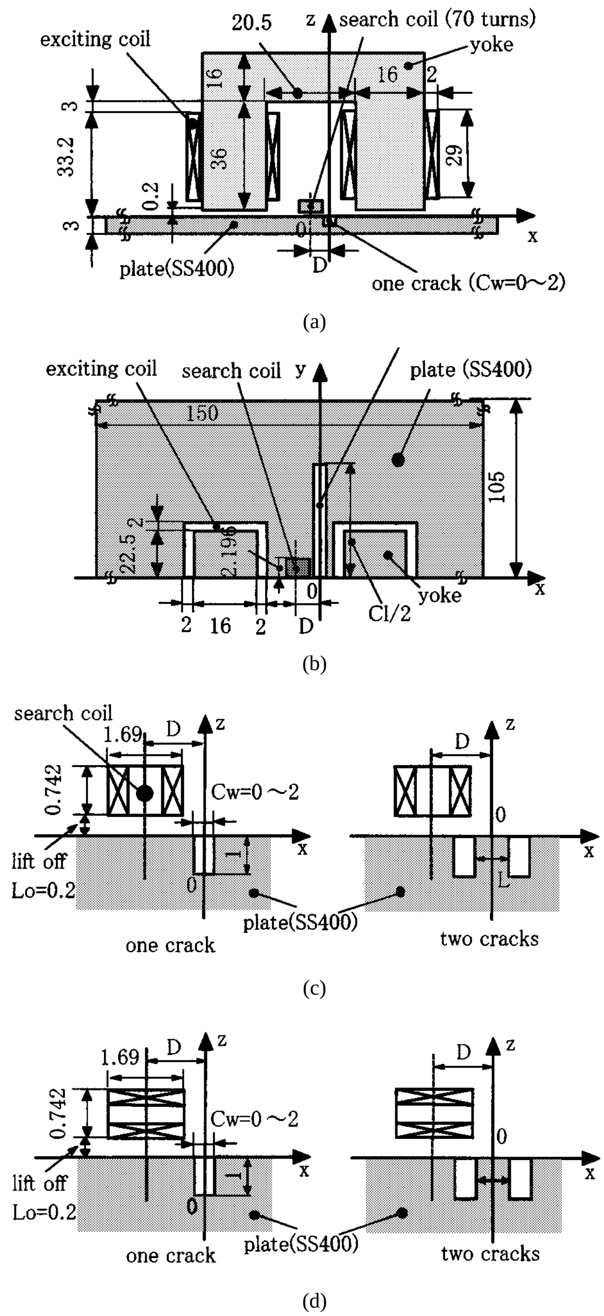


Fig. 1. Model of testing apparatus. (a) x-z plane. (b) x-y plane. (c) Search coil for measuring $|Bx|$ (x-z plane). (d) Search coil for measuring $|Bz|$ (x-z plane).

TABLE I
CONDITIONS OF ANALYSIS AND EXPERIMENT

Exciting coil	1kHz, 1A(rms), 30turns×2
Steel	SS400, σ =7.51×10^6 S/m
Nodes and elements	88095, 83232
Convergence criterion	N-R method 0.01T ICCG method 1.0×10^{-3}
CPU time	6.85 hours/1step, ($j\omega$ method: 3.54 hours) VT-Alpha5U-600MHz

TABLE II
NUMERICAL DATA OF B–H CURVE (SS400)

B (T)	H(A/m)	μs	B (T)	H(A/m)	μs	B (T)	H(A/m)	μs
0	0	0	0.80	230	2768	1.60	1310	972
0.05	101	394	0.90	249	2876	1.65	2120	619
0.10	138	577	1.00	267	2980	1.70	3490	388
0.20	162	982	1.10	295	2967	1.75	5490	254
0.30	177	1349	1.20	324	2947	1.80	8470	169
0.40	190	1675	1.30	384	2694	1.88	13200	113
0.50	199	1999	1.40	476	2341	1.94	18000	86
0.60	208	2296	1.50	676	1766			
0.70	218	2555	1.55	884	1395			

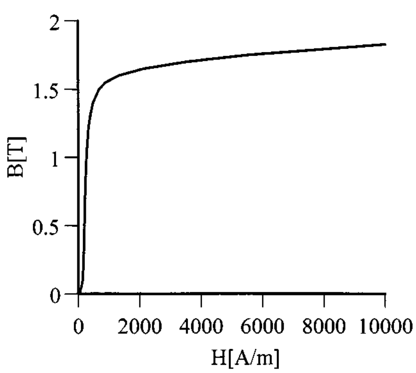


Fig. 2. B–H curve of steel plate (SS400).

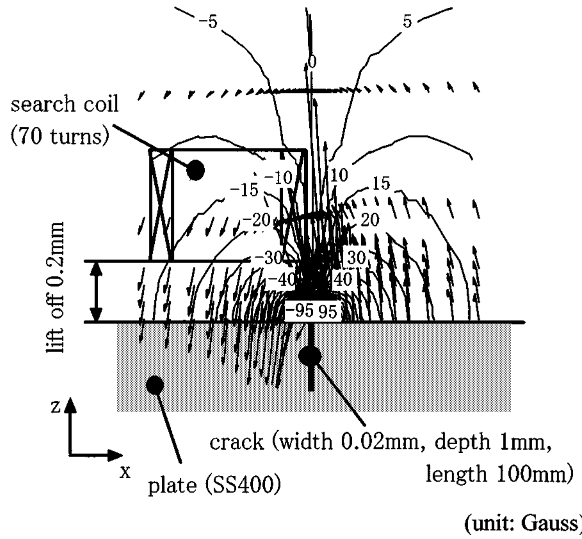


Fig. 3. Distribution of leakage flux (Cw = 0.02 mm, Cl = 100 mm).

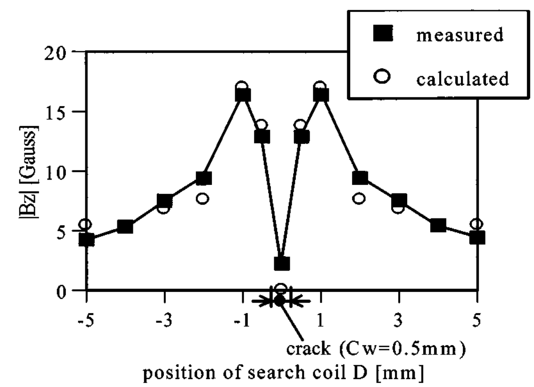


Fig. 4. Change of Bz by search coil position D (Cw = 0.5 mm, Cl = 100 mm).

II. MODEL AND METHOD OF ANALYSIS

Fig. 1 shows a model of alternating magnetic flux leakage testing. The search coil shown in Fig. 1(c) is used, and this detects the z component (Bz) of the leakage flux near cracks. The distance [(liftoff Lo)] between the search coil and the surface of steel is 0.2 mm. The crack depth is 1 mm. The amplitude of current is 1 A(rms) and the exciting frequency is 1 kHz. The time interval Δt of the step-by-step method is chosen as 6.25 $\times$ 10^{-5} s. In order to get the steady-state periodic result, the calculation is carried out during 2.5 period (=40 steps). The yoke is assumed to be linear (relative permeability: μs = 60 000) and eddy current in it is neglected. The linear analysis ($j\omega$ method) is also carried out under the same condition for comparison. The lamination of yoke is not taken into account in calculation. The conditions of analysis and experiment are shown in Table I. The B–H curve of the steel plate (SS400) used by this research is shown in Table II and Fig. 2, respectively.

III. RESULTS AND DISCUSSION

A. Distribution of Leakage Flux

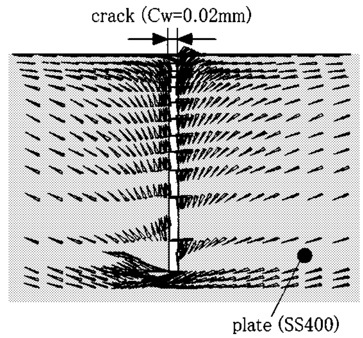
Fig. 3 shows the flux distribution in the air near the search coil when the exciting current is maximum. The crack width (Cw) and crack length (Cl) are 0.02 and 100 mm, respectively. The contour lines of the z component Bz of flux density are also shown in Fig. 3. The flux density measured by the search coil becomes maximum at the edge of crack.

Fig. 4 shows the z component Bz of the average flux density in the search coil that is measured by changing the position D. Bz calculated by nonlinear analysis is also shown. After 35 steps calculations (about 2 period), almost steady state result can be obtained. Fig. 4 denotes that the measured and calculated values are in good agreement of about 3.5% accuracy.

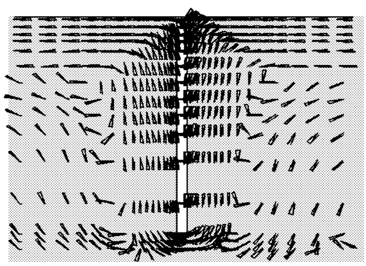
B. Comparison of Linear and Nonlinear Analyses

In order to confirm the necessity of 3-D alternating nonlinear analysis, the result by linear analysis is compared with that by nonlinear analysis.

The comparison of flux distribution inside steel plate is shown in Fig. 5. The relative permeability used in the linear analysis is chosen as the maximum relative permeability (μs = 3000) of the steel plate (SS400). In the linear analysis, the result at $\omega t = 0$ degree when the exciting current becomes the maximum (real value) is shown. In the nonlinear analysis, the result at 36 steps (when the exciting current becomes the maximum) of 2.25 cycles is shown. In the linear analysis, the maximum flux



(a)



(b)

Fig. 5. Comparison of flux distributions at linear and nonlinear analyses (Cw = 0.02 mm, I = 1 A(rms)). (a) Linear analysis (μs = 3000, $|B|\max$ = 21.2T). (b) Nonlinear analysis [(2.25ms(36 steps), $|B|\max$ = 1.69T].

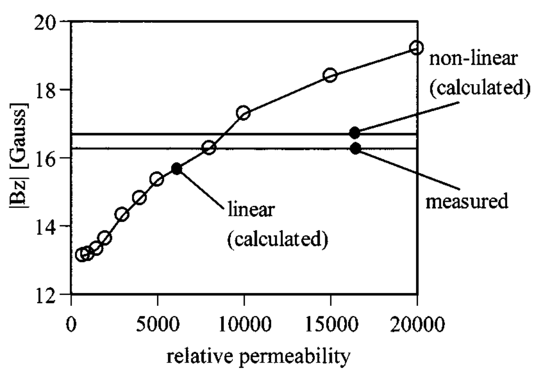


Fig. 6. Comparison of linear and nonlinear analyses (Cw = 0.5 mm, Cl = 100 mm, D = 1 mm).

density inside steel plate is 21.2 T, and this value is unreal. On the other hand, in the nonlinear analysis, the flux is concentrated near the steel surface and the maximum flux density is 1.69 T.

Fig. 6 shows the flux density $|Bz|$ inside the search coil obtained by linear and nonlinear analyses. The measured value is also shown. The maximum relative permeability of steel plate (SS400), of which the B–H curve is shown in Fig. 2, is about 3000. In order to obtain the same result, the permeability of steel needs to be increased to about 8000 in the case of linear analysis (8000 is an unreal value). The reason can be explained as follows: As the permeability of the linear analysis is uniform in the steel plate, the flux density penetrate into a deep portion as shown in Fig. 5(a), therefore the permeability should be extremely large in order to increase the leakage flux. In the linear analysis, the leakage flux is greatly changed by the change of relative permeability in a steel plate. From these results, it can be concluded that the nonlinear analysis is indispensable for solving the phenomenon of this testing.

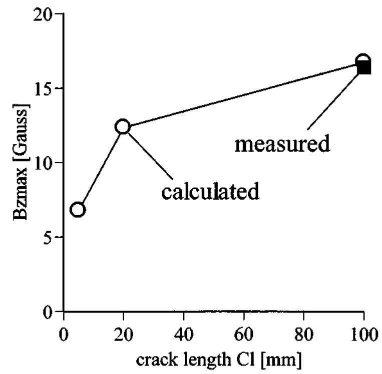


Fig. 7. Effect of crack length Cl on Bz (Cw = 0.02 mm, D = 1 mm).

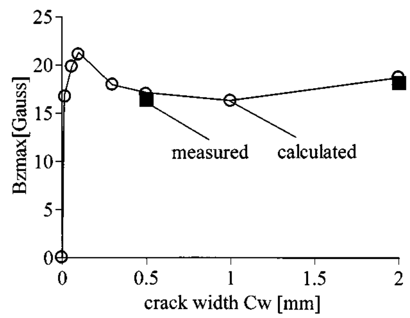
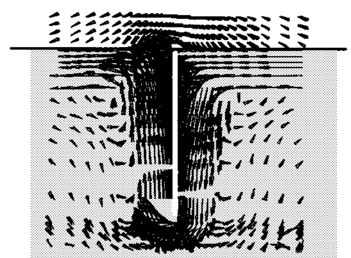
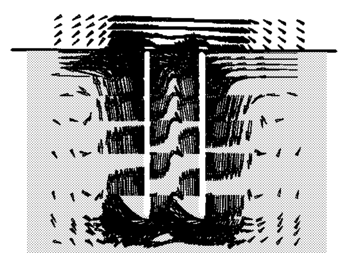


Fig. 8. Effect of crack width Cw on Bz (Cl = 100 mm, D = 1 mm).



(a)



(b)

Fig. 9. Flux distribution near one crack and two cracks (Cw = 0.02 mm, Cl = 1 mm). (a) One crack. (b) Two cracks (L= 0.2mm)

C. Effect of Crack Length and Width

Fig. 7 shows the effect of crack length Cl on the maximum flux density $Bz\max$ in the search coil. This $Bz\max$ shows one of the values of two peaks obtained when the search coil is measured by changing the position D. Bz is increased when Cl is increased.

Fig. 8 shows the effect of crack width Cw on $Bz\max$. The measured values are also shown. The discrepancy between the

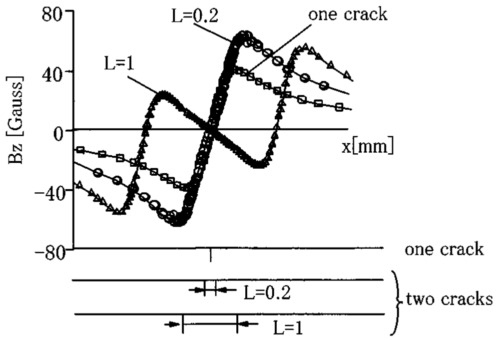


Fig. 10. Distribution of Bz (Cw = 0.02 mm).

measurement (two points) and calculation is about 3.5%. Bz is suddenly increased as the increase of Cw and it has a peak value near $Cw = 0.1$ mm, then Bz is reduced when Cw is more increased. The reason for appearing such a peak is as follows: When Cw is increased a little, Bz is increased, because the leakage flux from the crack reaches to the search coil. When Cw is increased to some extent, the magnetic resistance also becomes large, and then Bz is reduced in some range of Cw.

D. Behavior of Leakage Flux Near Two Cracks

The behavior of leakage flux when there is one crack or two cracks is examined. Fig. 9 shows the flux distributions near one crack and two cracks. The distance L between two cracks is 0.2 mm. Fig. 10 shows the distribution of Bz for various kinds of distance L between two cracks along the x axis ($y = 0$ mm, $z = 0.175$ mm). The result of one crack is also shown. When $L = 0.2$ mm, two cracks cannot be recognized by the distribution of Bz. Fig. 11(a) shows the average flux density in the search coil. Bz in the case of two cracks is larger than that in the case of one crack. The reason is as follows: Fig. 9(b) denotes that the flux inside steel plate makes a detour by the existence of two cracks compared with the case of one crack. As the equivalent resistance of the steel with two cracks becomes large, the leakage flux is increased. As the outer diameter (ϕ1.69 mm) of search coil is larger than the distance L, two cracks cannot be recognized when $L = 0.2$ mm and 1 mm.

In order to examine the possibility of distinguishing two cracks, the behavior of the x component Bx of flux density which is detected by the search coil shown in Fig. 1(d) is examined. Fig. 11(b) shows the distribution of $|Bx|$. $|Bx|$ is detected even when there is no crack. The figure suggests that it will be possible to distinguish two cracks by using Bx, even if the dimension (=1.69 mm) of search coil is larger than the distance ($L = 1$ mm). However, there is some limitation for the search coil of some dimension to distinguish the distance L. The detailed examination should be carried out in future.

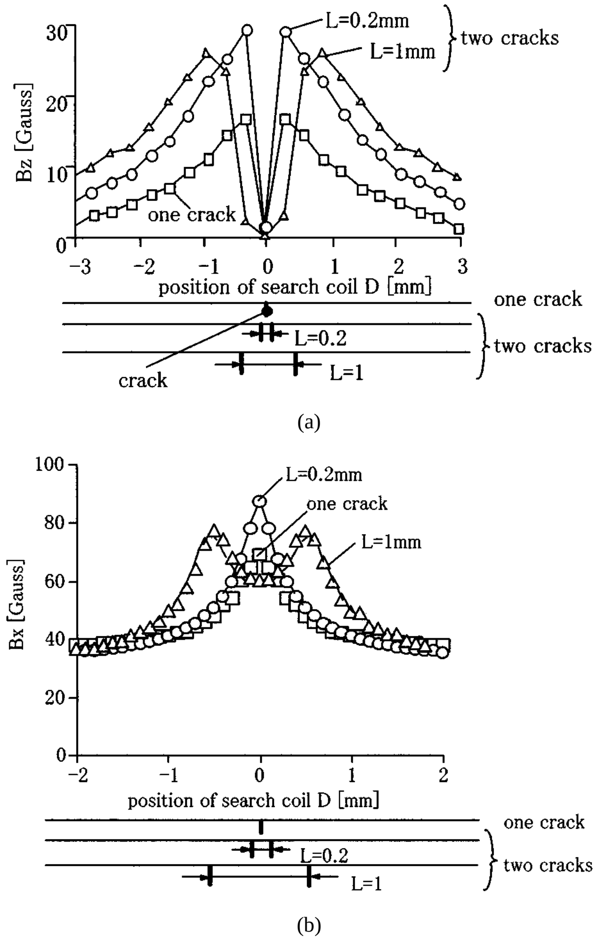


Fig. 11. Changes of (a) $|Bz|$ and (b) $|Bx|$ by search coil position (Cw = 0.02 mm, Cl = 100 mm).

IV. Conclusion

The results obtained by this research are summarized as follows.

1) In the linear analysis, the leakage flux changes considerably with the relative permeability in steel plate. It is shown that the nonlinear analysis is indispensable in alternating magnetic flux leakage testing.
2) The leakage flux has a peak value when the crack width is increased.
3) In order to distinguish two cracks, it is effective to evaluate the component of leakage flux parallel to steel plate.

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