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model (Problem 21)

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Nonlinear Analysis of Eddy Current and Hysteresis Losses of 3-D Stray Field Loss Model (Problem 21)

Norio Takahashi, *Fellow, IEEE*, Toshiomi Sakura, and Zhiguang Cheng

Abstract—The evaluation method of stray field loss of engineering oriented loss model (*TEAM Workshop Problem 21*) is investigated. It is shown that the nonlinear eddy current analysis is obligatory in order to investigate the eddy current loss in the steel plate, because the flux and eddy current in steel are affected by the permeability of the plate. The hysteresis loss in such a steel plate having a substantial skin effect is not negligible, even if the flux density in air is small.

Index Terms—Eddy current loss, finite element method, hysteresis loss, stray field loss.

I. INTRODUCTION

THE 3-D stray field loss model (Problem 21) [1], [2] is an engineering oriented problem to study eddy current loss distribution in steel plates. This model has been solved by many groups [3], but their calculations are almost linear ones, because the flux density in air is small. But there is large discrepancy between the iron loss in steel plate calculated by linear analysis and measured one [4]. Therefore, the behavior of magnetic field and iron loss in such a steel plate should be investigated in detail.

In this paper, the nonlinear eddy current analysis of Problem 21 is carried out using the 3-D finite element method. The necessity of nonlinear analysis of such eddy current loss in steel plate and the calculation of hysteresis loss is discussed. The calculated total loss is compared with measurement.

II. 3-D STRAY FIELD LOSS MODEL (PROBLEM 21) AND METHOD OF ANALYSIS

Fig. 1 shows the analyzed model. Model A consists of two coils of the same dimensions and two steel plates. In the center of one steel plate, there is a rectangular hole. Model B consists of two coils and one steel plate without hole. The direction of exciting current of one coil is different from that of the other coil. The ampere-turns of each coil is 3000 AT (rms, 50 Hz). The conductivity of steel plate is 6.484×10^6 S/m. Fig. 2 shows the B - H curve of steel plate, measured by a single sheet tester (SST) [5]. Fig. 3 shows the hysteresis loss curve (w_h - B_m curve) [6]. B_m is the maximum flux density. This curve is obtained by the following process: First, dc hysteresis loop of steel plate is measured using SST. Then, the area of hysteresis loop is calculated and this value is transformed to the value at 50 Hz. Fig. 4

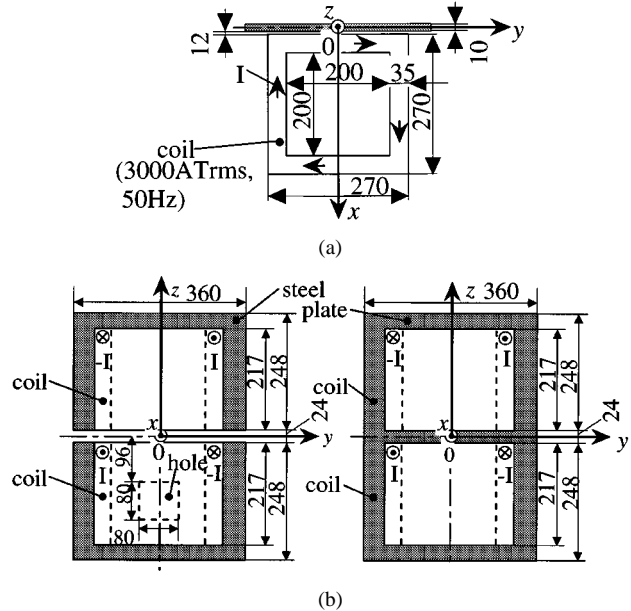


Fig. 1. Analyzed model (Problem 21). (a) x - y plane. (b) y - z plane.

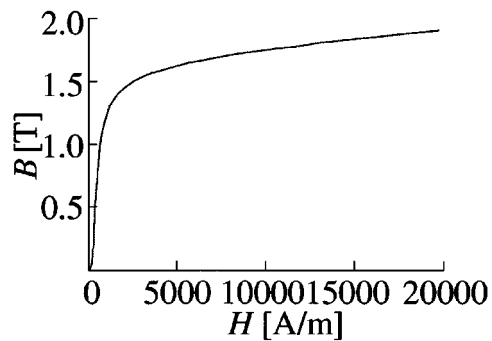


Fig. 2. B - H curve.

shows the schematic diagram of flux and eddy current distributions. The eddy current distribution is considerably different in models A and B.

Three kinds of methods, $j\omega$ method (linear), step-by-step method (nonlinear) and quasilinear method are used. In the quasilinear method, it is assumed that the flux and eddy current are sinusoidal [time harmonic ($j\omega$) method], but the change of permeability at each position in steel plate is considered. The permeability is assumed as the function of the maximum flux density B_m .

In the case of $j\omega$ method and step-by-step method, a half of the region of model A, and a quarter of model B are discretized into 1st order brick edge elements. Only the vector potential A is treated as unknown variable (A method). The skin depth δ is

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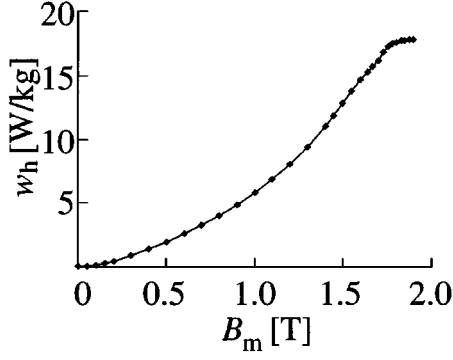
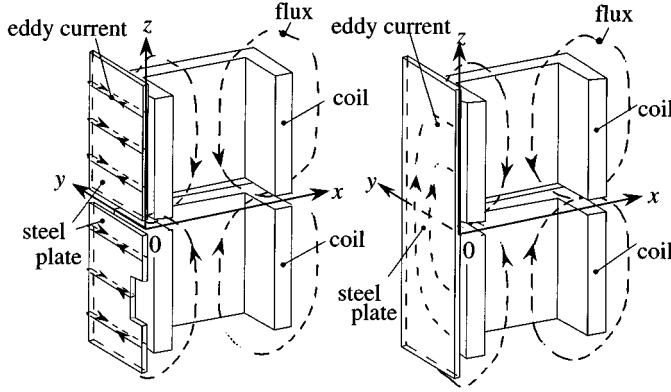
Fig. 3. w_h - B_m curve.

Fig. 4. Schematic diagram of flux and eddy current distributions.

TABLE I
DISCRETIZATION DATA AND CPU TIME

model	A (1/2region)			B (1/4region)		
	linear (j ω)	nonlinear		linear (j ω)	nonlinear	
analysis		step-by- step	quasi- nonlinear		step-by- step	quasi- nonlinear
element type	1-st order brick edge	1-st order brick nodal		1-st order brick edge	1-st order brick nodal	
no. of elements	60,060	33,800		33,024	11,700	
no. of nodes	65,178	37,206		36,300	13,338	
no. of unknowns	170,333	117,414		92,819	41,862	
no. of nonzeros	2,772,105	4,016,570		1,500,039	1,309,914	
memory [MB]	152	76	83	96.5	38	31
CPU time[h]	0.32 ^{#1}	54 ^{#1}	9.5 ^{#2}	0.19 ^{#1}	35 ^{#1}	2.4 ^{#3}

#1: Computer used: VT-Alpha 600 (SPECfp 95 : 27.0) convergence criterion of ICCG method: 1×10^{-5} , #2: Computer used: P586/300 MHz, #3: Computer used: P586/166 MHz.

0.884 mm. The region of skin depth is subdivided into 3 layers. As a result, the steel plate is subdivided into 9 layers. In the case of quasilinear method, the analysis region is subdivided into 1st order brick nodal elements, and the $\mathbf{A} - \phi$ method (ϕ : electric scalar potential) is used. The steel plate is subdivided into 5 layers. Table I shows the discretization data and CPU time.

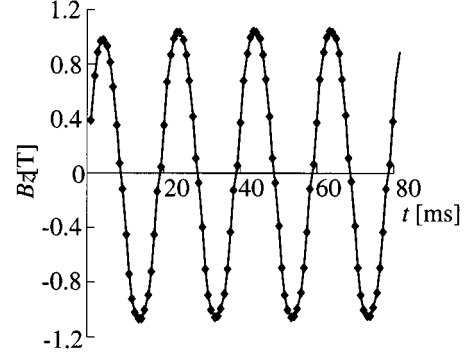
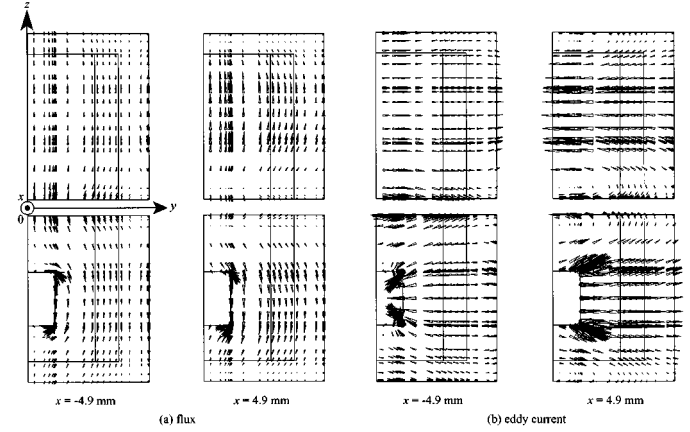
Fig. 5. Flux waveform in steel plate ($x = 4.9$ mm, $y = 20$ mm, $z = 100$ mm).

Fig. 6. Flux and eddy current distributions of model A.

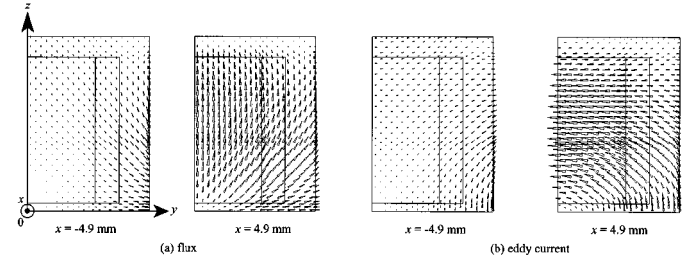


Fig. 7. Flux and eddy current distributions of model B.

III. RESULTS AND DISCUSSION

Fig. 5 shows the flux waveform at the point ($x = 4.9$ mm, $y = 20$ mm, $z = 100$ mm) in steel which is obtained by the step-by-step method. The time interval is chosen as 0.833 ms. The figure denotes that nearly steady state result can be obtained by the calculation of two periods (48 steps).

Figs. 6 and 7 show the flux and eddy current distributions at the instant when the exciting current becomes maximum. The right side figure shows the distribution near the surface ($x = 4.9$ mm) of the steel plate on the coil side. The left side figure shows the distribution near the surface ($x = -4.9$ mm) of the plate on the opposite side of the coil. The direction of eddy current on the coil side is different from that on the opposite side.

Fig. 8 shows the comparison of the flux densities near the steel plates obtained from the linear and nonlinear analyses. The results measured using a search coil are also shown. $x = 5.76$ mm corresponds to the position in the air near the surface

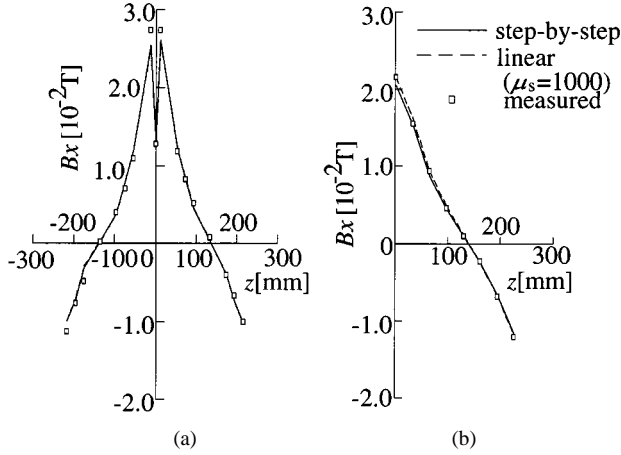


Fig. 8. Flux distributions ($x = 5.76$ mm, $y = 0$ mm). (a) Model A. (b) Model B.

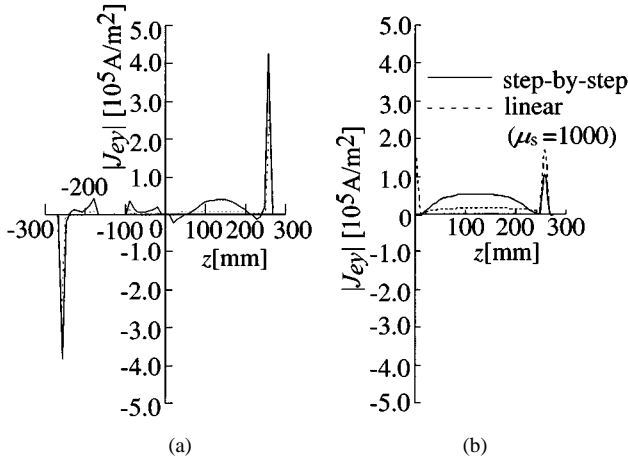


Fig. 9. y -component of eddy current density ($x = 2$ mm, $y = 0$ mm). (a) Model A. (b) Model B.

of the steel plate. The discrepancies between the linear and non-linear analyses and measurement are small.

Fig. 9 shows the comparison between the eddy current density in the steel plate obtained from the linear and nonlinear analyses.

In order to investigate the discrepancy between the eddy currents obtained from the linear and nonlinear analyses, the effect of the permeability of the steel plate on the flux and eddy current distributions in the steel plate is investigated. Figs. 10 and 11 show the results obtained. The flux and eddy current distributions in the steel plates are affected by the permeability (the skin depth is changed by the permeability).

Fig. 12 shows the instantaneous value of the eddy current loss w_e in the steel plate obtained using the nonlinear analysis. The eddy current loss w_e is calculated by the following equation:

$$w_e = \sum_{e=1}^{ne} \frac{|j_e^{(e)}|}{\sigma} V^{(e)} \quad (1)$$

where

j_e is the eddy current density at the instant of t ,
 ne is the number of elements in the steel plate, and
 $V^{(e)}$ is the volume of the element e .

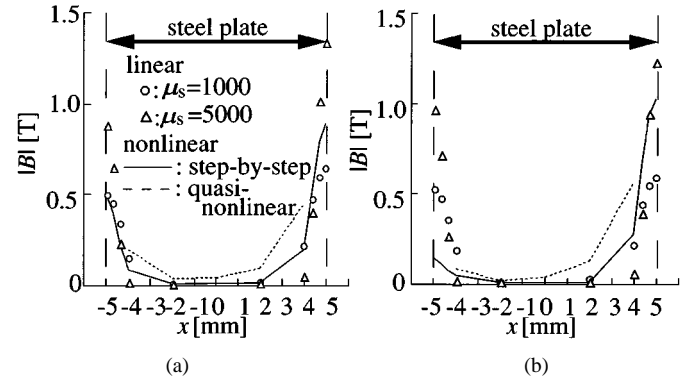


Fig. 10. Flux distributions ($y = 0$ mm, $z = 140$ mm). (a) Model A. (b) Model B.

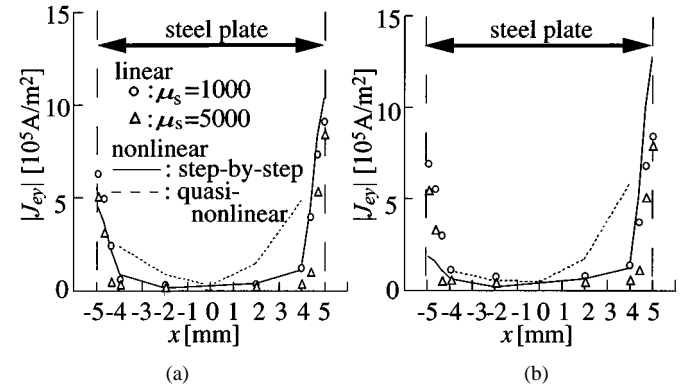


Fig. 11. Eddy current distributions ($y = 0$ mm, $z = 140$ mm). (a) Model A. (b) Model B.

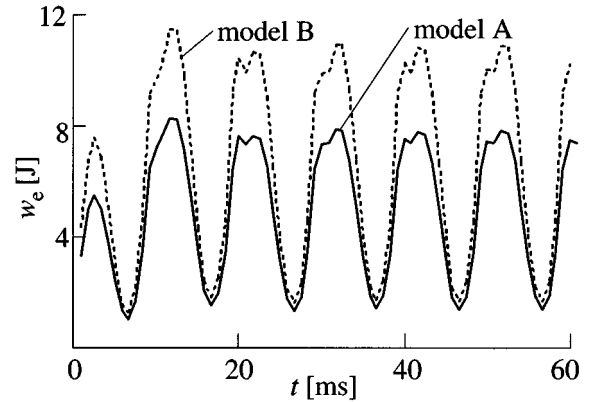


Fig. 12. Instantaneous value of eddy current loss.

The eddy current loss under nonlinear analysis (step-by-step method) is obtained as the average value during last one period ($t = 40 \sim 60$ ms).

The hysteresis loss W_h is calculated by assuming that W_h is the function of the maximum flux density B_m as follows:

$$W_h = \sum_{e=1}^{ne} w_h^{(e)}(B_m^{(e)}) \rho V^{(e)} \quad (2)$$

where w_h is the dc hysteresis loss (W/kg) shown in Fig. 3. ρ is the density of the steel plate.

TABLE II
CALCULATED AND MEASURED LOSSES [W]

model	analysis		calculated			measured W_t
			eddy current loss W_e	hysteresis loss W_h	total loss W_t	
A	linear (j ω)	$\mu_s = 1000$	5.92	0.29	6.21	9.28
		$\mu_s = 5000$	3.26	4.16	7.42	
	non- linear	step-by-step	5.32	2.92	8.24	
		quasi- nonlinear	6.87	2.24	9.11	
B	linear (j ω)	$\mu_s = 1000$	6.19	1.25	7.44	12.56
		$\mu_s = 5000$	1.55	2.46	4.01	
	non- linear	step-by-step	7.24	3.54	10.78	
		quasi- nonlinear	10.19	3.26	13.45	

Table II shows the calculated values of eddy current loss W_e and hysteresis loss W_h . The total iron loss W_t in the steel plate measured using a watt meter is also shown.

The eddy current loss in the steel plate obtained using the linear analysis is decreased with the permeability. This is, because the eddy current in the steel plate is reduced due to the increase of the opposing field produced by eddy current when the permeability is increased. As the permeability of the steel plate, which is the function of the flux density, is not known beforehand, the nonlinear analysis is necessary.

The evaluation of the results of quasinonlinear method is not easy [7]. The permeability of the steel, of which the B - H curve is shown in Fig. 2, becomes maximum at nearly 0.9 T. As it is assumed that the permeability is the function of the maximum flux density B_m in the time harmonic method, the permeability is overestimated compared with the real one. Then, the flux density obtained by quasinonlinear method is overestimated as shown in Fig. 10. The eddy current is also overestimated as shown in Fig. 11 due to the number of subdivisions (5 layers). As a result, the eddy current loss is overestimated as shown in Table II.

Table II suggests that the hysteresis loss is not negligible even if the flux density in air is small as shown in Fig. 8. This is, because the flux density near the surface of the steel plate is up to about 1 T as shown in Fig. 10.

IV. CONCLUSIONS

The analysis of Problem 21 is carried out by using the step-by-step method and the quasinonlinear method. The calculated results are compared with measured ones. The obtained results can be summarized as follows:

- The flux and eddy current distributions in steel plate are affected by the permeability of the plate. Therefore, the nonlinear analysis is obligatory to investigate the eddy current loss in the steel plate.
- The hysteresis loss in such a steel plate having the remarkable skin effect is not negligible, even if the flux density in air is small.

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