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INVESTIGATION OF A MODEL TO VERIFY SOFTWARES FOR 3-D NONLINEAR EDDY CURRENT ANALYSIS

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ABSTRACT

The model for verifying software should be decided considering many viewpoints, for example, ease of experiment. Then, the general requirements of the most suitable model for 3-D nonlinear eddy current analysis are examined in this paper.

Some factors affecting the analysis and experiments are also investigated, in order to obtain accurate and reproducible results. For example, various types of elements are compared with each other.

A transient nonlinear model is proposed, and the flux and eddy current distributions obtained by using the finite element method are compared with experimental results.

1. INTRODUCTION

Several types of formulations for 3-D eddy current analysis were developed[1]. Recently, the verification of the software for 3-D linear eddy current analysis has been carried out by using Workshop models[2]. Models for verification of 3-D nonlinear eddy current analysis, however, were not proposed until quite recently[3], because of a long CPU time and difficulties in experiments.

In this paper, requirements in selecting the 3-D nonlinear eddy current model are investigated, and a simple model is proposed for analysis. The factors affecting experiments are also examined. Calculated results of the simple model are compared with measured ones.

2. MODEL FOR VERIFICATION

Because there is no analytical solution for the 3-D nonlinear eddy current problem, verification should be carried out by comparison with results obtained by other methods or by other groups or experimental results. In any case, we need a standard model for verification.

2.1 Necessary characteristics as the model

The model should be decided from the following viewpoints:

(1) Flux and eddy current should be distributed non-uniformly and three-dimensionally.
(2) Techniques to represent the following material characteristics can be investigated:
   (a) anisotropy, (b) saturation, (c) hysteresis.
(3) Rapid calculation techniques under the following conditions can be examined:
   (a) excitation by voltage sources[4],
   (b) time-periodic excitation[5],
   (c) various boundary conditions, such as the 3-D periodic boundary condition[6].
(4) Advantages and disadvantages of the following problems in 3-D magnetic field analysis can be discussed:
   (a) various methods, such as the $A-\phi$ and $T-\Omega$ methods[7] (which include problems of gauge condition[8], modelling of holes[9] and cancellation error[10], etc.),
   (b) various finite elements, such as nodal and edge elements, tetrahedral and brick types[11],
   (c) various solving techniques, such as the ICCG method, of large nonlinear equations.
(5) In order to simplify the mesh generation and to reduce the CPU time, the geometry should be simple. For example, the model is symmetric and has few curved parts.
(6) The experiment is easy.
   This condition can be satisfied, if the model has the following features:
   (a) The dimensions of the model are large enough to measure accurately the flux and eddy current distributions.
   (b) The model has enough space to insert sensors.
   (c) The amplitudes of fluxes and currents are sufficiently large enough to be measured accurately.
   (d) The exciting VA is not so large. It is recommended to use nearly closed magnetic circuits.
   (e) The model is not heated by eddy currents.

2.2 An elementary model

An ideal model which satisfies all requirements mentioned above cannot be easily found. The model shown in Fig.1 which partly satisfies the requirements is proposed for the TEAM Workshops[3] as a first step. In this model, the phenomenon is not steady state but transient, because the analysis of periodic phenomenon takes a long CPU time[5]. The exciting current increases with time from zero and there is no residual magnetism in the steel, so that the initial magnetization curve can be used instead of the hysteresis loops. The model composed of thin plates is chosen so that the skin effect is not remarkable, in order to reduce the number of elements near the surface of the conductor.

The number of turns of a coil is equal to 162. The conductivities of the channels and the plate are both 7.505×10^6S/m. The current Io in the coil increases exponentially with time as follows:

$$I_0 = I_m(1-e^{-t/\tau})\ (A) \qquad (1)$$

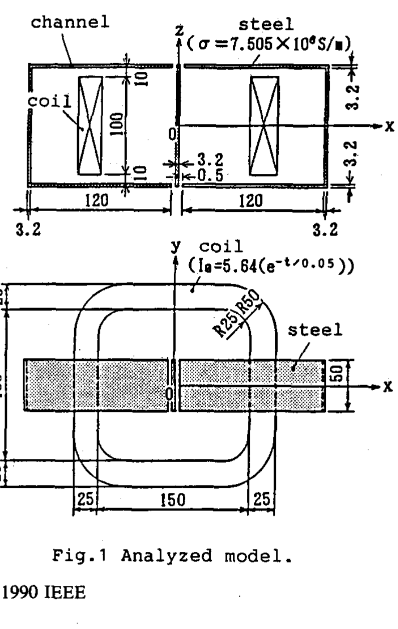

Fig.1 Analyzed model.

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The amplitude Im(=5.64A) is chosen so that the steel parts can be saturated sufficiently. The time constant τ (=0.05) is chosen in order that the eddy current density is not so small, and the eddy current in the coil is neglected.

Figure 2 denotes the points recommended at which the results obtained by using various elements should be compared. It is favorable to choose points where a large error may occur due to the approximation of the potential in the element. As the active area of the search coil is not sufficiently small, the flux density cannot be measured accurately at the points where the amplitudes and the directions of flux density vectors change suddenly. Then, the points of small flux densities changes are chosen as the typical examined points to compare with experiments.

From the above-mentioned points, the following points are proposed for the comparison:

(1) When various numerical methods are compared with each other:
- (a) the points where the flux density or the eddy current density changes suddenly.. ①, ②, ③, ④
- (b) the point where the permeability or the conductivity changes suddenly .... ⑤
- (c) the point where the error due to the cancellation[10] may be large .... ⑥

(2) When calculated values are compared with measured ones:
- (a) the total flux .... ⑦, ⑧, ⑨
- (b) the points where the eddy current density is high and it does not change suddenly. ⑩, ⑪, ⑫

3. FINITE ELEMENT ANALYSIS

3.1 Method of analysis

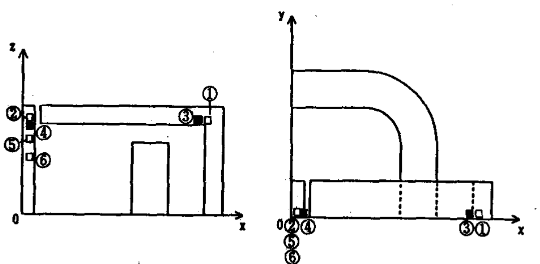
The A-ϕ method is used in the calculation. As the model is symmetric, 1/8 region is analyzed. The mesh is discretized into tetrahedral elements. Figure 3 shows the mesh. The numbers of elements and nodes are 29808 and 5776 respectively. The Newton-Raphson iteration technique is used in the nonlinear analysis. The time derivative term is replaced by the backward difference. The ICCG method is used to solve linear equations. Calculations are carried out on the NEC supercomputer SX-1E.

3.2 Factors affecting results of calculation

As the results calculated may be affected by the time interval Δt and the types of elements, these factors are examined here.

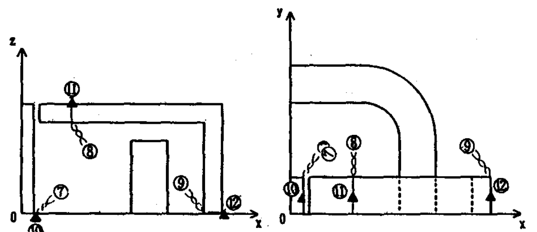
(1) Effects of Δt

Figure 4 shows the y-component of the eddy current density. The time interval Δt of the step-by-step method[12] in Fig.4(a) is 2.5ms for the first 50ms, 5ms for the next 50ms and 10ms for the next 50ms. The Δt in Fig.4(b) is 2.5ms for the first 25ms and 25ms for the next 125ms. The Figure denotes that the eddy current density is very much affected by the time



□ :flux density
■ :eddy current density

(a) Comparison of numerical methods



△ :flux density
▲ :eddy current density
∞ :total flux and total current

(b) Comparison of calculated and measured values

Fig.2 Points to be compared.

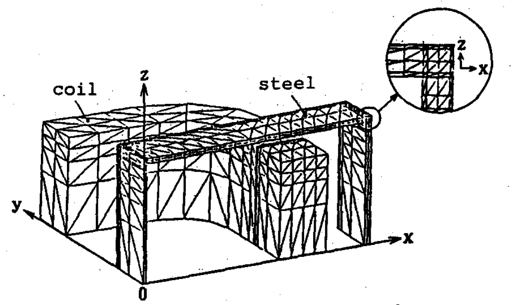
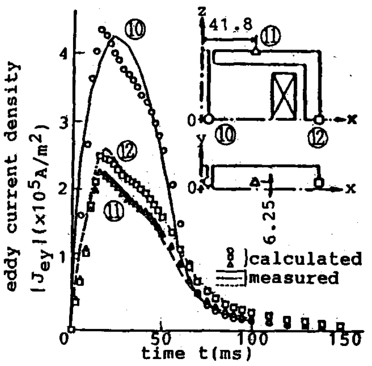
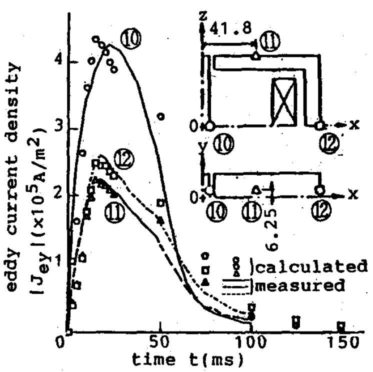


Fig.3 Meshes of steel and coil.



(a) Δt= 2.5ms(0<t≤50ms), 5ms(50<t≤100ms), 10ms(100<t≤150ms)



(b) Δt=2.5ms(0≤t≤25ms), 25ms(25<t≤150ms)

Fig.4 Time variations of eddy current density (Δt=2.5ms(0≤t≤25ms), 25ms(25<t≤150ms)).

interval Δt, because the phase difference between the true curve and the obtained curve is $\Delta t/2$[13].

Figure 5 shows the flux densities in the steel. The time interval Δt is the same as that in Fig.4(a). Even if the time interval Δt is changed like in Fig.4(b), the flux densities are scarcely changed. The total CPU times for Figs.4(a) and (b) are 14.0 and 8.6 hours respectively.

(2) Effects of types of elements

The effects of the types of elements(usual tetrahedral and brick nodal elements and the brick edge element[14,15]) on the accuracy of the flux density and the CPU time are investigated. In order to compare the brick element with other kinds of elements, the shape of the coil is modified so that the corner of the coil forms 90° edge. The numbers of elements and nodes for various types of elements are shown in Table 1. The CPU time for dc excitation which means the end of transient phenomena is also shown in Table 1. Table 2 shows the comparison of the average flux densities at the cross sections ⑦, ⑧ and ⑨ shown in Fig.2(b). The flux densities in Table 2 are the values at the steady state after transient phenomena(dc excitation). The figures in the parenthesis in the Table denote the error ε_B. The ε_B is defined by

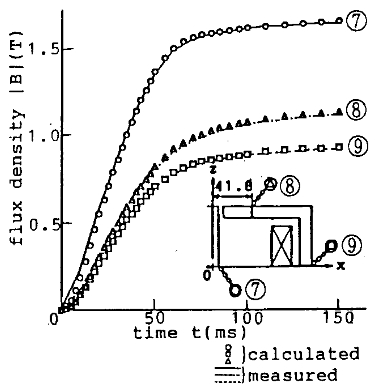


Fig.5 Time variations of flux density
(Δt= 2.5ms(0<t≤50ms), 5ms(50<t≤100ms), 10ms(100<t≤150ms)).

Table 1 Numbers of unknown variables and CPU time (dc excitation)

item	nodal		edge
	tetra.	brick	brick
number of elements	27720	4620	4620
number of nodes	5520	5520	5520
number of unknown variables	12522	12522	12795
number of iterations of ICCG method*	563	714	274
CPU time(s)	1717	3440	591

*:at the first step of the Newton-Raphson iteration

Table 2 Comparison of flux densities calculated and measured (dc excitation)

examined position	flux density (T)			
	calculated			measured
	nodal		edge	
	tetra.	brick	brick	
⑦	1.69 (1.2)	1.69 (1.2)	1.70 (1.8)	1.67
⑧	0.95 (1.0)	0.93 (-1.1)	0.96 (2.1)	0.94
⑨	1.15 (0.8)	1.13 (-0.9)	1.17 (2.6)	1.14

(figures in parenthesis show errors)

$$\varepsilon_B = \frac{B(cal)-B(mea)}{B(mea)} \times 100(\%) \qquad (2)$$

where B(cal) denotes the calculated average flux density in each cross section and B(mea) denotes the measured value. Although the number of unknown variables of the edge element is almost the same as that of the nodal element, the CPU time for the edge element is reduced to about 1/6 of the nodal element as shown in Table 1. This is because the number of iterations of the ICCG method for the edge element is decreased than that of the nodal element as shown in Table 1.

The error ε_B of the brick edge element is not so much different from that of the brick nodal element as shown in Table 2. On the contrary, the CPU time of the edge element is considerably reduced compared with that of the nodal element. Therefore, it may be concluded that the edge element is to be preferred.

3.3 Comparison with 2-D analysis

As the flux density vector is nearly parallel to the x-z plane, and the y-component of the eddy current density is much larger than the x- and z-components, fairly accurate results may be obtained by a 2-D analysis. Then, the result of 2-D analysis is compared with that of 3-D analysis.

Figure 6 shows the eddy current densities obtained by 2-D analysis. Although the eddy current density at the point ⑪ is different from that at the point ⑫ in 3-D analysis, the eddy current densities at these points ⑪ and ⑫ are almost the same each other in 2-D analysis. Therefore, a 3-D analysis is necessary even for such a simple model shown in Fig.1.

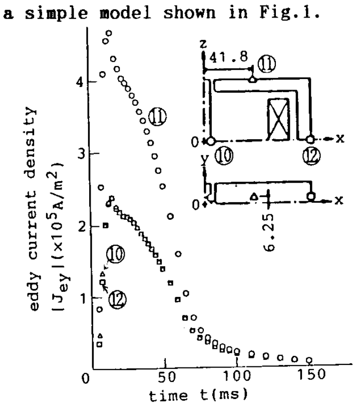


Fig.6 Time variations of eddy current density in 2-D analysis Δt=2.5ms).

4. EXPERIMENTS

4.1 Factors affecting experiments

The effects of the residual magnetism and the annealing of steel are examined, because these factors give fairly big influence in the measured results.

(1) Residual magnetism

An example of the average flux density in the cross section of the plate at z=0 is shown in Fig.7. Figure 7 shows that the model should be demagnetized. The demagnetization is carried out in a gradually reduced alternating field of very low frequency (1Hz) so that the flux can penetrate the steel.

(2) Annealing

In spite of the symmetric magnetic circuit, the flux distribution is not symmetric before annealing. The flux distribution, however, becomes symmetric after annealing(640℃, 1hour). Then, the effect of the annealing is examined for two kinds of specimens A and B. The specimen A is obtained by welding two channels each other, of which the quality is the same as the channels used in Fig.1. The specimen B is a 3.2mm thick steel ring stamped out from the same material of the channel. Figure 8 shows the B-H curves before and after annealing. The Figure illustrates that the B-H curves of the specimens A and B approach the real B-H curve of the material, if they are annealed.

4.2 Experimental verification

The comparisons of the calculated and measured results of flux densities and eddy current densities are shown in Figs.4 and 5. The eddy current density is measured using an improved probe method[16]. Table 3 denotes the comparison of the calculated and measured results of eddy current densities at the points ⑩, ⑪ and ⑫ in Fig.2(b). These are the values at the instant(t=25ms) when the eddy current density becomes nearly the maximum. The error ε_{Je} is also shown in the Table 3. ε_{Je} is defined by

$$\varepsilon_{Je}=\frac{Je(cal)-Je(mea)}{Je(mea)}\times 100(\%) \qquad (3)$$

where Je(cal) denotes the calculated eddy current density and Je(mea) denotes the measured one.

The calculated curve of the eddy current density at the point ⑩ is very much different from the measured curve as shown in Fig.4.

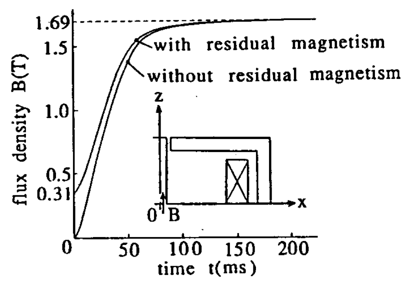


Fig.7 Effect of residual magnetism on flux density(measured).

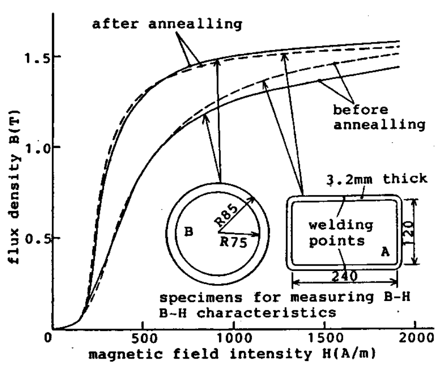


Fig.8 Comparison of B-H curves before and after annealing.

Table 3 Comparison of calculated and measured results (t=25ms)

examined point	coordinate (mm)			eddy current density ($\times 10^5 A/m^2$)		error ε_{Je}(%)
	x	y	z	calculated	measured	
⑩	1.6	0	0	3.89	4.20	-7.38
⑪	41.8	0	63.2	2.02	2.07	-2.42
⑫	125.3	0	0	2.80	2.37	-2.95

5. CONCLUSIONS

The necessary characteristics for the most suitable model and some factors affecting the calculated and experimental results are examined using a proposed model.

It is shown that the model for verification should be determined from many points of view mentioned in this paper. The experimental verification of the calculation using a simple model is shown. Demagnetization and annealing are important in the experimental evaluation of the nonlinear model.

As a very long CPU time is necessary in a 3-D nonlinear eddy current analysis, a new 3-D nonlinear model is proposed[17].

REFERENCES

[1] C.W.Trowbridge: "Low Frequency Electromagnetic Field Computation in Three Dimensions", Computer Methods in Applied Mechanics and Engineering, 52, 653 (1985).

[2] COMPEL, 7, 1-2 (1988) Boole Press.

[3] TEAM Workshop: Test Problems (1988-4).

[4] T.Nakata, N.Takahashi, K.Fujiwara & A.Ahagon: "3-D Finite Element Method for Analyzing Magnetic Fields in Electrical Machines Excited from Voltage Sources", IEEE Trans. Magnetics, MAG-24, 6, 2582 (1988).

[5] T.Nakata, N.Takahashi, K.Fujiwara & A.Ahagon: "3-D Non-linear Eddy Current Analysis Using the Time-periodic Finite Element Method", ibid., MAG-25, 5 (1989).

[6] T.Nakata, N.Takahashi, K.Fujiwara & A.Ahagon: "Periodic Boundary Condition for 3-D Magnetic Field Analysis and Its Applications to Electrical Machines", ibid., MAG-24, 6, 2694 (1988).

[7] T.Nakata, N.Takahashi, K.Fujiwara & K.Muramatsu: "Comparison of Various Methods for 3-D Eddy Current Analysis", ibid., MAG-24, 6, 3159 (1988).

[8] Z.J.Cendes, J.Weiss & S.R.H.Hoole: "Alternative Vector Potential Formulations of 3-D Magnetostatic Field Problems", ibid., MAG-18, 2, 367 (1982).

[9] T.Nakata, N.Takahashi, K.Fujiwara and Y.Okada : "Improvements of the $\mathbb{T}-\Omega$ Method for 3-D Eddy Current Analysis", ibid., MAG-24, 1, 94 (1988).

[10] T.Nakata, N.Takahashi, K.Fujiwara & T.Imai: "Effects of Permeability of Magnetic Materials on Errors of the $\mathbb{T}-\Omega$ Method", Compumag Conference, Tokyo (1989).

[11] T.Nakata, N.Takahashi, K.Fujiwara & Y.Shiraki: "Comparison of Different Finite Elements for 3-D Eddy Current Analysis", ibid. (1989).

[12] T.Nakata and Y.Kawase : "Numerical Analysis of Nonlinear Transient Magnetic Field by Using the Finite Element Method", J.IEE, Japan, 104-B, 6, 81 (1984).

[13] T.Nakata and Y.Kawase : "Errors in Phases of Waveforms in the Time-Periodic Finite Element Method", Papers of National Convention, IEE of Japan, 633 (1984).

[14] M.L.Barton and Z.J.Cendes : "New Vector Finite Elements for Three-Dimensional Magnetic Field Computation", J. Appl. Phys., 61, 8, 3919 (1987).

[15] A.Kameari : "Three Dimensional Eddy Current Calculation Using Edge Elements for Magnetic Vector Potentional", Apllid Electromagnetics in Materials(book), 225 (1989) Pergamon Press.

[16] T.Nakata, K.Fujiwara, M.Nakano & T.Kayada : "Effects of the Construction of Yokes on the Accuracy of a Single Sheet Tester", Proceedings of Soft Magnetic Materials 9 Conference, El Escorial (1989).

[17] T.Nakata, N.Takahashi, K.Fujiwara, K.Muramatsu, T.Imai and Y.Shiraki: "3-D Non-linear Magnetostatic Model", COMPEL, Special Issue (1990).