Investigation of a model to verify software for 3-D static force calculation

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Abstract **- Requirements for a model to verify software for 3-D static force calculation are examined, and a 3-D model for static force calculation is proposed. Some factors affecting the analysis and experiments are investigated in order to obtain accurate and reproducible results.**

I. INTRODUCTION

It is necessary to evaluate the accuracies of various methods for calculating electromagnetic force, namely, the Maxwell stress tensor method, the advanced energy method[1,2], the magnetizing current method[3] etc. However, no systematic comparison of the accuracy of each method has been done previously.

In this paper, a suitable model for verification of 3-D software for calculating electromagnetic force is investigated. The factors affecting the accuracy, such as the calculation methods, number of elements, adjustment of gap etc. are investigated.

II. MODEL FOR VERIFICATION

As there is no analytical solution for the 3-D static force problem, the verification should be carried out by comparisons with results obtained by other methods, by other groups or experimental results. Therefore, we need a standard model for verification.

The model should be decided from the following viewpoints:

(1) The flux should be distributed non-uniformly and three-dimensionally.
(2) The influence of magnetic saturation on the flux distribution and electromagnetic force should be included.
(3) The flux density should be changed suddenly near the integration path for the Maxwell stress tensor method so that the integration path, the number of elements etc. can affect the results.
(4) The energy should not change linearly with the displacement of the movable body so that the influence of displacement on the accuracy of the conventional energy method can be investigated[2].
(5) In order to simplify the mesh generation and to reduce the CPU time, the geometry should be simple.
(6) The experiment should be easy, namely,
   (a) The dimensions of the model are large enough so as to make it accurately.
   (b) The amplitude of electromagnetic force is sufficiently large enough to be measured accurately.

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The 3-D model shown in Fig.1 which satisfies the above-mentioned requirements is proposed for verification of dc force calculation[4]. The center pole and yoke are made of steel. The coil has 381 turns and the ampere-turns (dc) are chosen to be 1000, 3000, 4500 and 5000 in order to investigate the saturation effect.

III. FACTORS AFFECTING ACCURACY OF CALCULATION

The flux distribution of the model is calculated by the finite element method using 1st-order brick elements[5]. The z-component Fz of the

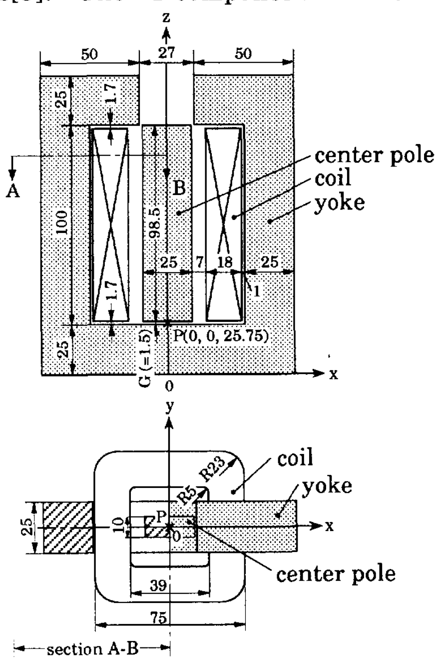

Fig.1 3-D model for verification of force calculation.

electromagnetic force of the center pole is calculated by using the Maxwell stress tensor method, the advanced energy method and the magnetizing current method.

A. Force Calculation Method

Fig.2 shows the z-components Fz of electromagnetic force calculated using the Maxwell stress tensor method, advanced energy method and magnetizing current method[6,7]. The number of elements, ne, is equal to 108864. The force calculated by the Maxwell stress tensor method using the edge element with ***A*** (magnetic vector potential) variable is the nearest to the measured value. The rate of increase of the force with current is reduced above 3000AT due to the saturation of the center pole.

B. Number of Elements

Fig.3 shows the effect of number of elements, ne, on the results calculated. Fig.4 shows the initial mesh (ne=4032). Each side of individual elements is subdivided into twice (ne=4032×2^3 =32256) and thrice (ne=4032 × 3^3 =108864).

The figure suggests that the force calculated by the Maxwell stress tensor method using the magnetic vector potential (***A***) converges to a constant value when ne is nearly equal to 30000. On the contrary, the forces calculated by the advanced energy method and the magnetizing current method change with ne. It is difficult to make a mesh which has extremely dense and sparse parts, unless the nonconforming element[8] is used. That is the reason why the convergence characteristic is so poor in Fig.3.

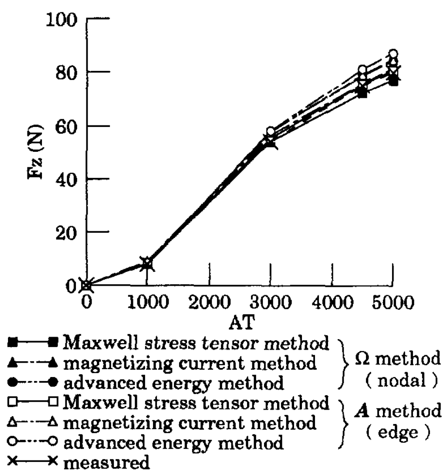

Fig.2 Z-component Fz of electromagnetic force (ne=108864).

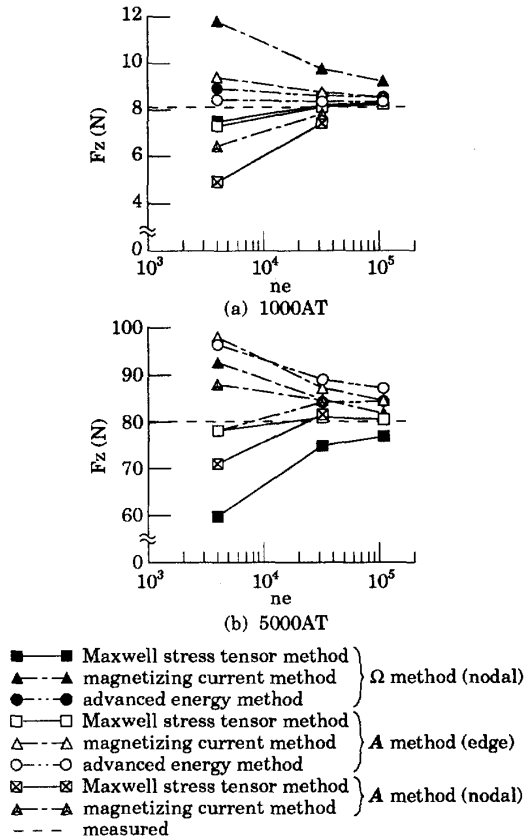

Fig.3 Effect of number of elements ne.

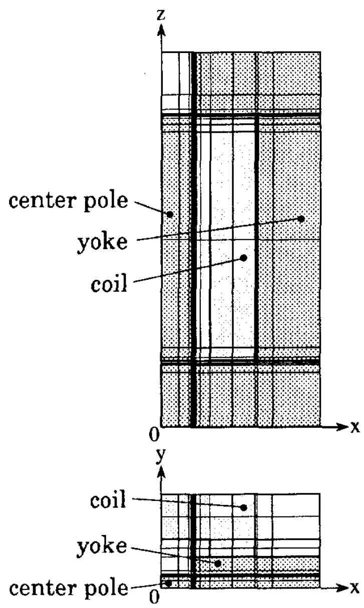

Fig.4 Initial mesh (ne=4032).

C. Unknown Variable and Element Type

Fig.5 shows the z-component Bz of flux density for ne=32256 at the point P(0,0,25.75) in the gap under the center pole. Table 1 shows the discretization data and CPU time. From the viewpoint of accuracy, roughly speaking, Figs. 3 and 5 show that the result of ***A*** method may be better than that of Ω method. From the viewpoint of CPU time for ***A*** method, Table 1 denotes that the edge element is better than the nodal element.

The influence of the integration path for the Maxwell stress tensor method on the force calculated is investigated in the reference[8].

IV. Experimental Equipment and Factors Affecting Accuracy

Fig.6 shows the experimental equipment. The z-component of electromagnetic force is measured by a load cell which is located at the top of a supporting rod made of nonmagnetic stainless steel which is connected directly to the center pole. The displacement of the center pole is measured using an eddy current type displacement sensor.

As the model is made by machining process, the residual mechanical stress affects the shape of B-H curve about 10%[6]. The effect of stress is removed by annealing (650°C, 1 hour).

In order to remove the effect of the residual magnetism on the measured result, the measurements under positive and negative excitations are repeated until the difference between them becomes within 1%.

The gap length G in Fig.2 is changed with the ampere-turns, because the sensor part of the load cell moves about 0.5mm in maximum by the electromagnetic force. As the positioning of the center pole is not easy, firstly, G is adjusted to 1.5mm(① in Fig.7) under no excitation. Then, Fz is measured at 1000 AT excitation(②). After repeating these processes(③ ~⑬), Fz at 1.5mm can be obtained by interpolation. Fig.8 shows the reproducibility of measurement. The error ε_1 is defined by

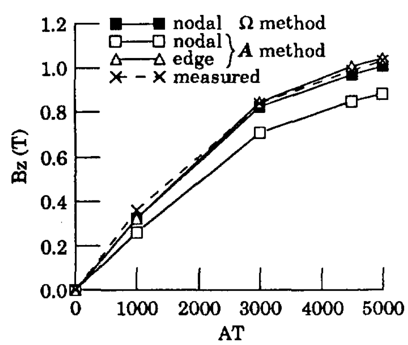

Fig.5 Z-component Bz of flux density at point P (ne=32256).

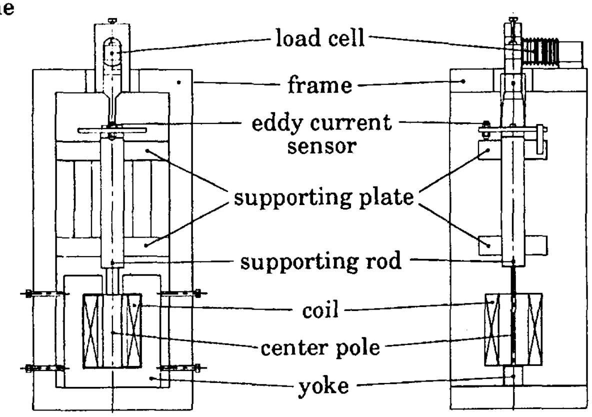

Fig.6 Measurement system of electromagnetic force.

Table 1 Discretization data and CPU time

method	***A*** method												Ω method					
unknown variable	edge						nodal						nodal					
type of subdivision	mesh-1		mesh-2		mesh-3		mesh-1		mesh-2		mesh-3		mesh-1		mesh-2		mesh-3	
ampere-turns (AT)	1,000	5,000	1,000	5,000	1,000	5,000	1,000	5,000	1,000	5,000	1,000	5,000	1,000	5,000	1,000	5,000	1,000	5,000
number of elements	4,032		32,256		108,864		4,032		32,256		108,864		4,032		32,256		108,864	
number of nodes	4,862		35,475		116,032		4,862		35,475		116,032		4,862		35,475		116,032	
number of unknown variables	10,585		90,626		312,699		9,900		87,699		-		4,862		35,475		116,032	
number of non-zero entries	161,957		1,464,166		5,140,359		352,863		3,363,666		-		60,447		467,381		1,559,491	
computer storage (MB)	4.2		37.2		129.5		8.4		76.7		-		3.5		25.8		85.4	
number of iterations for Newton-Raphson method	4	8	4	9	4	9	4	11	4	10	-	-	8	17	8	16	8	13
total number of iterations for ICCG method	316	598	619	1,212	901	1,832	849	1,764	2,683	5,199	-	-	316	598	619	1,212	901	1,832
CPU time (s)	84	162	1,381	2,772	6,611	13,567	467	1,027	14,288	23,061	-	-	69	141	840	1,515	3,973	6,329

computer used : HP735 workstation (40MFLOPS)
convergence criterion for Newton-Raphson method : 0.01T
convergence criterion for ICCG method : 10^{-5}

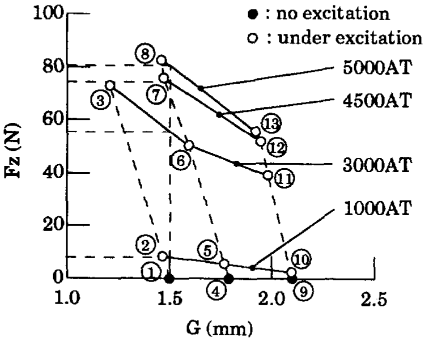

Fig.7 Interpolation of force.

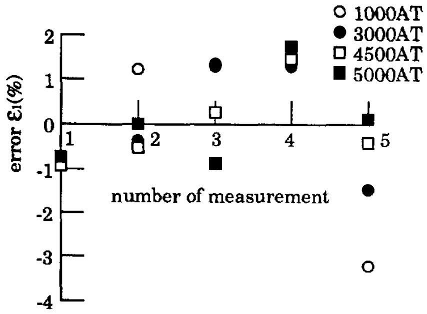

Fig.8 Reproducibility.

$$\varepsilon_1 = (Fz - Fz_{ave}) / Fz_{ave} \times 100(\%) \quad (1)$$

where Fz_{ave} is the average value of five results.

Fig.9 shows the influence of the deviation ΔG of gap length from the specified value(G=1.5mm) on the error ε_2 of measured electromagnetic force Fz. The error ε_2 is defined by

$$\varepsilon_2 = (Fz|_{\Delta G} - Fz|_{\Delta G=0}) / Fz|_{\Delta G=0} \times 100(\%) \quad (2)$$

The figure denotes that the gap should be adjusted within 20μm in order to measure the electromagnetic force within 2% error.

V. Conclusions

The obtained results can be summarized as follows:

(a) A suitable model (device) for verification of 3-D software for calculating electromagnetic force is proposed.
(b) The influence of the force calculation method, number of elements, unknown variable and element type on the accuracy of calculated forces are investigated. It is shown that the force calculated using the edge element is the nearest to the measured result.
(c) It is shown that the adjustment of gap length is especially important. The method for improving the reproducibility is also denoted.

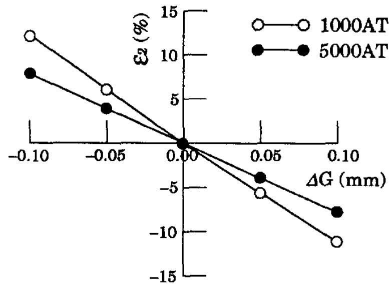

Fig.9 Influence of deviation ΔG of gap length on force Fz.

The following items should be investigated in the future:

(1) effect of order of interpolation function,
(2) introduction of 3-D adaptive refinement technique using nonconforming element[9],
(3) expansion of the model to ac steady state and transient problems,
(4) a model (device) in which the force has two- or three-components.

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