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OPTIMAL DESIGN METHOD OF 3-D NONLINEAR MAGNETIC CIRCUIT
BY USING MAGNETIZATION INTEGRAL EQUATION METHOD

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ABSTRACT

A new method for determining the sizes of iron parts in a magnetic circuit, which preserves the requirement of prescribed flux densities, has been developed. In order to take into account the nonlinear characteristics of iron, the magnetization integral equation method is used in the analysis. The effectiveness of the method is examined by applying it to the design of pole shape of an electromagnet.

1. INTRODUCTION

It is required to develop an optimal design method for determining the sizes of iron parts, while preserving the requirement of prescribed flux densities. The optimal design method for determining the sizes of iron parts using the boundary element method has already been reported[1]. The nonlinearity of iron, however, cannot be taken into account by using such a method. Although, in order to take into account the nonlinearity, some studies of determining the sizes of permanent magnets[2] and iron parts[3,4] have been carried out using the finite element method, the sizes cannot be always determined successfully, especially in the complicated cases.

The optimal design method for determining the sizes of iron parts taking into account the nonlinearity of iron has been developed by using the nonlinear programming method[5] and the magnetization integral equation method[6]. As an example of application, the pole shape of an electromagnet which produces the uniform flux distribution is determined.

2. OPTIMAL DESIGN METHOD

2.1 Outline of the method

The method is explained by an example shown in Fig.1. No eddy current flows in the iron parts and the winding. The z-components of the flux densities at n points $P_1 \sim P_n$ shown in Fig.1 are specified. The iron parts are divided into m rectangular brick elements, of which the lengths are $L_1 \sim L_m$, and these are treated as unknown variables. The length L_j can be obtained by minimizing the following objective function[5]:

$$W = \sum_{i=1}^n \{ B_{zi} - \sum_{j=1}^m B_{zi}(L_j) \}^2 \quad (1)$$

where $B_{zi}(L_j)$ is the z-component of the flux

Fig.1 Analyzed model.

density at the point i. B_{zi} denotes the specified values of B_{zi} . As the obtained length should be within the maximum length L_{jmax} in the design of actual machines, for example, the following constraints should also be considered.

$$g(L_j) = L_j - L_{jmax} \leq 0 \quad (2)$$

As $B_{zi}(L_j)$ should be the function of the length L_j in the nonlinear programming method, the magnetization integral equation method is used to denote the nonlinear relationship between $B_{zi}(L_j)$ and L_j .

As $B_{zi}(L_j)$ is the nonlinear function of L_j , the objective function W becomes also a nonlinear one. The penalty function method[5], Marquardt's method[7], augmented Lagrangian method[5] etc. are used as nonlinear programming methods which can take into account the constraints in Eq.(2). As the convergence of the penalty function method is slow, and experiences are necessary for determining a weighting factor in the case of Marquardt's method, the augmented Lagrangian method is used here, because it does not have such disadvantages.

2.2 Formulation

In the augmented Lagrangian method, the following modified objective function should be minimized[5]:

$$Z = W + \frac{1}{4r} \sum_{j=1}^m \{ \max(0, 2rg(L_j) + \lambda_j) \}^2 - \lambda_j^2 \quad (3)$$

where, W is the objective function denoted in Eq.(1), and $g(L_j)$ is the constraint in Eq.(2). λ_j and r are the Lagrange multiplier and the penalty parameter respectively[5].

Equation(3) can be minimized by solving the following equation[5]:

$$\frac{\partial Z}{\partial L_j} = 0 \quad (4)$$

In the augmented Lagrangian method, the length L_j^{q+1} of the jth element at the (q+1)th iteration is given by

$$L_j^{q+1} = L_j^q + \alpha^q \cdot \delta L_j^q \quad (5)$$

α^q is a coefficient determined by a linear-search method[8]. δL_j^q is given by

$$\{ \delta L_j \} = - \left(\frac{\partial^2 Z}{\partial L_j \partial L_k} \right)^{-1} \left\{ \frac{\partial Z}{\partial L_j} \right\} \quad (6)$$

L_j and Z in Eq.(6) denote the values at the q-th iteration. The above equation can be solved by using the quasi-Newton method[5]. $\partial Z / \partial L_j$ can be written as follows using Eqs.(2) and (3):

$$\frac{\partial Z}{\partial L_j} = - \frac{\partial W}{\partial L_j} + \sum_{i=1}^n \{ \max(0, 2rg(L_j) + \lambda_i) \} \quad (7)$$

From Eq.(1), $\partial W / \partial L_j$ can be given by

$$\frac{\partial W}{\partial L_j} = 2 \sum_{i=1}^n (B_{zi} - \sum_{j=1}^m B_{zi}(L_j)) \cdot \left(- \frac{\partial B_{zi}(L_j)}{\partial L_j} \right) \quad (8)$$

$B_{zi}(L_j)$ and $\partial B_{zi}(L_j) / \partial L_j$ can be given by the following equations[6]:

Fig.5 Prescribed points.

Fig.6 Subdivision.

Fig.7 Obtained shape.

Fig.8 Comparison of flux densities.

distribution approaches to a uniform one by optimizing the shape of the pole.

4. EXPERIMENTS

The verification of the developed software is carried out by comparing calculated results with measured ones. The flux distribution at the gap of the electromagnet in Fig.4(initial shape) is measured using a Hall probe. As the flux density is very much affected

by the annealing of the core and the residual magnetism[9], the core is annealed and demagnetized.

Table 1 denotes the comparison of the calculated and measured results of the z-directional component B_z of the flux density. The error ε of B_z is also shown in the table. ε is defined by

$$\varepsilon = \frac{\text{calculated} - \text{measured}}{\text{measured}} \times 100 \% \quad (15)$$

The discrepancies between the calculated and measured results may be due to the fact that the element used is not so accurate and the number ne of elements is insufficient.

Table 1 Comparison of calculated and measured results

Examined point	Coordinate(mm)			Flux density B_z (T)		Error(%)
	x	y	z	Calculated	Measured	
P ₁	0.0	-15.0	0.0	0.334	0.342	-2.3
P ₂	0.0	-5.0	0.0	0.318	0.343	-7.3
P ₃	0.0	10.0	0.0	0.312	0.343	-9.0
P ₄	12.5	-10.0	3.0	0.326	0.345	-5.5
P ₅	12.5	-5.0	3.0	0.315	0.347	-9.2
P ₆	12.5	15.0	3.0	0.312	0.346	-9.8

5. CONCLUSIONS

Although it became possible to determine the sizes of iron parts taking into account the nonlinearity, there are many problems to be investigated in future as follows:

- introduction of more accurate elements such as a high order element with an arbitrary shape,
- comparison with other optimization methods such as the conjugate gradient method[5],
- development of a method which can take into account eddy currents,
- verification (whether the sizes can be successfully obtained or not) of the optimal design method using typical models.

REFERENCES

- A.G.A.M.Armstrong, M.W.Fan, J.Simkin and C.W.Trowbridge: "Automated Optimization of Magnet Design Using The Boundary Integral Method", IEEE Trans. on Magnetics, MAG-18, 2, 620 (1982)
- T.Nakata and N.Takahashi: "New Design Method of Permanent Magnets by Using the Finite Element Method", ibid., MAG-19, 6, 2494 (1983)
- T.Nakata, N.Takahashi, Y.Kawase and K.Fujiwara: "Determination of Sizes of Electrical Machinery by Using Gap Elements", Papers of Technical Meeting on Rotating Machinery and Static Apparatus, RM-83-45, SA-83-35 (1983)
- S.J.Salon and B.Istfan: "Inverse Non-Linear Finite Element Problems", IEEE Trans. on Magnetics, MAG-22, 5, 817 (1986)
- M.Avriel, M.J.Rijckaert and D.J.Wilde: "Optimization and Design" (1973) Prentice-Hall
- N.J.Newman, C.W.Trowbridge and L.R.Turner: "GFUN: An Interactive Program as an Aid to Magnet Design", Rutherford Lab., RPP/A94 (1972)
- D.W.Marquardt: "An Algorithm for Least-Squares Estimation of Non-Linear Parameters", J. Soc. Indust. Appl. Math. 11, 2, 431 (1963)
- R.H.Gallagher and O.C.Zienkiewicz: "Optimum Structural Design -Theory and Applications- (1973) John Wiley & Sons
- T.Nakata, N.Takahashi and K.Fujiwara: "Investigation of A Model to Verify Softwares for 3-D Nonlinear Eddy Current Analysis", Compumag Conference, Tokyo (1989)