Topological Optimization Using Basis Functions for Improvement of Rotating Machine Performances

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This paper presents a new topology optimization method based on basis functions by which the rotating machine performance is improved. In this method, the core shape of a given rotating machine is represented by the linear combination of the basis functions. The shape is then freely deformed by changing the weighting coefficients to the basis functions to find the optimal shape. It is shown that the average torque and iron loss of a test model are improved by 4.2 and 11 percent, respectively, using the present method.

Index Terms—Topology Optimization, Motors, Finite Element Method

I. INTRODUCTION

IN the topology optimization of rotating machines, the core shapes are freely deformed without introducing design parameters unlike the conventional parameter optimizations [1], [2]. It has been shown that simple optimal shapes which are suitable for manufacturing can be obtained by the topology optimization when the material shape is represented through the linear combination of basis functions [3]. The authors have shown that the Normalized Gaussian network (NGnet) is particularly suitable as the basis function for the topology optimization of rotating machines [4], [5].

The topology optimization has been carried out mainly aiming at finding novel shapes in the initial design phase. In the later design phases, on the other hand, it is often required to modify the *given* core shapes for further improvement of performance such as average torque and efficiency. The topology optimization would also be useful for this purpose because the optimal solution can be explored by flexibly deforming the original core shape.

In this paper, we introduce a new optimization method based on the basis functions which modifies the given core shapes of rotating machines. In this method, the material attribute {iron, air} in each finite element in the core is determined from the value of the linear combination of basis functions. The weighting coefficients are optimized so that the cost function is minimized under the given constraints. For the test of the proposed method, it is applied to shape optimization of the rotor an IPM motor.

II. OPTIMIZATION METHODS

A. Topology Optimization Using Basis Function

In this study, we employ NGnet as the basis function which is schematically shown in Fig.1. The core of a rotating machine is assumed to be subdivided into finite elements. The material attributes V_e of the elements in the design region are determined from the value of the shape function defined by

$$\phi(\boldsymbol{x}_{\mathrm{e}}) = \sum_{i=1}^{N_g} w_i b_i(\boldsymbol{x}_{\mathrm{e}}) \tag{1}$$

where w_i, $\boldsymbol{x}_e$ and N_g are the weighting coefficient, gravitation center of element e and number of Gaussian bases G_i, respec-
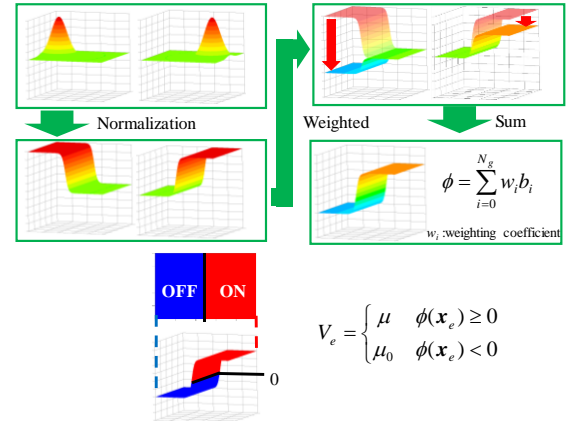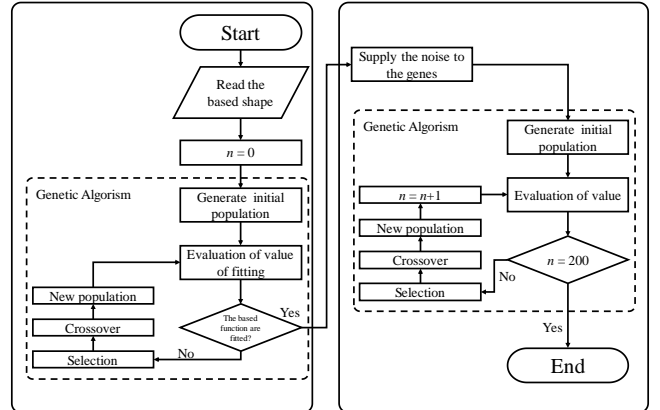

Fig.1 NGnet-based on/off method

Fig.2 Flow diagram of the present method

tively, and b_i denotes the normalized Gaussian function given by

$$b_i(\boldsymbol{x}_{\mathrm{e}}) = G_i(\boldsymbol{x}_{\mathrm{e}}) \bigg/ \sum_{j=1}^{N_g} G_j(\boldsymbol{x}_{\mathrm{e}}). \tag{2}$$

The material attribute is determined as follows: if $\phi \geq 0$ ($\phi < 0$) in an element, then "iron" ("air") is allocated there. We use Real-coaded Genetic Algorism (RGA) for optimization of w_i.

B. Shape fitting using NGnet

Fig.2 shows the flow diagram of the proposed method. First, we determine w_i by fitting ϕ to the base model by RGA. For this purpose, we solve the optimization problem defined by,

$$f = N_{air} \rightarrow \min. \tag{3}$$

where N_{air} is the number of air elements which are consistent with the base model.

On the second stage, we add random noises to the gene, $\boldsymbol{w}^{\mathrm{t}} = [w_1, w_2, ..., w_{N_g}]$, of the individuals in the initial population for free deformation. Then we start the RGA process for the shape optimization problem as described below.

C. Shape optimization of IPM motor

We optimize the rotor shape of the IPM motor shown in Fig.3, in which (a) and (b) show the base model [6] and corresponding motor shape resulted by solving fitting problem (3). For test of the proposed method, we consider here two different optimization problems given by

$$F = \frac{T_{ave}}{T_{\mathrm{ref}}} \rightarrow \max. \text{ sub to } \sigma_{\max} < \sigma_0, N_{\mathrm{area}} < 2, \quad (4)$$

$$F = \frac{W_{\mathrm{total}}}{W_{\mathrm{ref}}} \rightarrow \min. \text{ sub to } T_{\mathrm{ave}} > T_{\mathrm{ref}}, \sigma_{\max} < \sigma_0, N_{\mathrm{area}} < 2, \quad (5)$$

where, T_{ave} and W_{total} are the average torque and iron loss, respectively, and T_{ref} and W_{ref} are the corresponding values of the IPM motor shown in Fig. 3(a). Moreover, $\sigma_{\max}$ and $\sigma_0 =$ 304.0MPa are the maximum stress and stress of the base model, respectively, and N_{area} is the number of separated rotor cores. The optimization setting is summarized in Table.1. In this study, we employ the 1-D method [7] to compute the iron loss in the post-processing. The FE analysis of magnetic fields by fine angular interval $\Delta\theta$ gives rise to long computational time. For this reason, we set $\Delta\theta$=5 degrees for the optimization. Because the algorithm almost converges at 200 generations, we stop the RGA process at this point. After the optimization, the performance is evaluated by setting $\Delta\theta$=1 degree.

III. OPTIMIZATION RESULTS AND CONCLUSIONS

Fig.4 (a) and (b) show the results for optimization problems (4) and (5), respectively. The black and red lines show the optimized and original material boundaries. In Fig.4 (a), the flux barrier expands in the radial direction. This structure effectively blocks the local circulation of the magnetic fluxes near the magnet tips. As a result, the fluxes into the stator increase. The average torque is improved from 2.08Nm to 2.16Nm by the optimization. On the other hand, in Fig.4 (b), the flux barrier shrinks in the radial direction. Thus the fluxes toward the stator decrease. The iron loss is reduced from 7.25W to 6.57W by the optimization, whereas the average torque decreases. Fig.5 (a) and (b) show the magnetic fluxes in the optimized cores. Because of the trade-offs observed in these results, it is concluded that problems (4) and (5) should be solved simultaneously, e.g., using the vector optimization algorithms such as NSGAII and SPEAII.

In this paper, we have proposed a topology optimization method starting from a given core shape. This method can be used for improvement of existing machine models. In the full paper, we will report the result of the vector optimization problems considering the torque performance and efficiency simultaneously.

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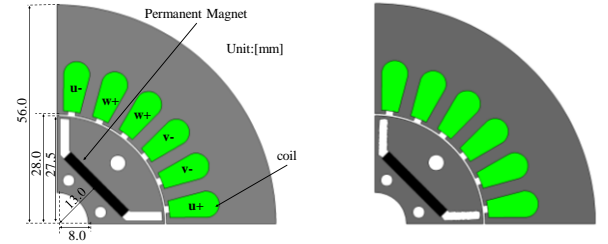
T_{ref} = 2.08Nm, W_{total}= 7.38W
(a) Base model

T_{ave} = 2.07Nm, W_{total}= 7.25W
(b) Base model represented by ϕ.

Fig.3 Representation of the core shape using the present metod

TABLE I.
SETTING OF OPTIMIZATION.

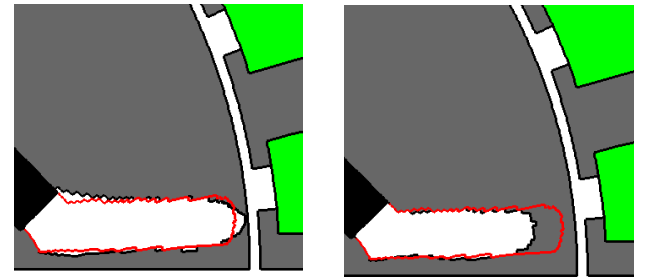|	
Current phase angle [degree]	30
Current effective value [A]	4.2425
Number of turns [turn]	35
Residual flux density [T]	1.25
Rotation speed (iron loss evaluation) [rpm]	1500
Rotation speed (stress evaluation) [rpm]	3000
The number of individual	840
The number of children	240

T_{ave} = 2.16Nm, W_{total}= 9.11W
(a)Maximization of average torque

T_{ave} = 1.68Nm, W_{total}= 6.57W
(b) Minimization of iron loss

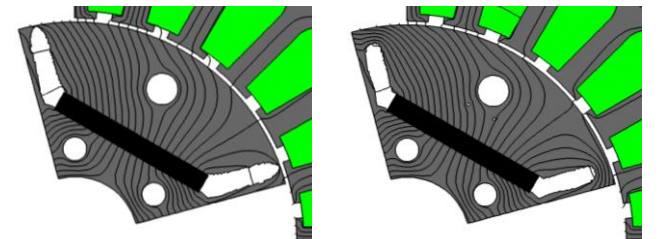Fig.4 Optimized rotor shapes

(a) Maximization of average torque

(b) Minimization of iron loss

Fig.5 Flux in the optimized cores