

Topology Optimization of Rectangular Magnets and Iron Cores for Magnet Motors With Automatic Magnetization Direction Determination

Yuju SASABUCHI¹, Takahiro SATO¹, Shinya WATANABE¹ and Kazuhiro IZUI²

¹Muroran Institute of Technology, Muroran, Hokkaido, 050-8585, JAPAN

²Kyoto University, Kyoto, Kyotofu, 606-8501, JAPAN

Topology optimization of permanent magnet motors is one of the promising methods to find high performance designs. However, it is difficult to simultaneously optimize magnets and iron core geometries, because topology optimization often generates too complicated magnet shapes for manufacturing. To address this issue, this paper presents a new topology optimization method for permanent magnet motors that integrates image processing algorithm, which makes it possible to generate meaningful magnet shapes from the view of manufacturing and determines magnetization direction automatically.

Key Words : CMA-ES, Image processing, Permanent magnet motor, Topology optimization,

design domain according to the output of the NGnet. The output NGnet, y , is as follows:

$$y = \mathbf{w}^T \mathbf{b}(\mathbf{x}), \quad (1)$$

where $\mathbf{b}(\mathbf{x})$ is a vector consisting of N normalized Gaussian bases, and $\mathbf{w} = \{w_i | i = 1, \dots, N\}$, is a vector of connection weights. The on/off state V_e of element e is determined using the output of NGnet as:

$$V_e = \begin{cases} on & y(x_e) \geq 0 \\ off & y(x_e) < 0, \end{cases} \quad (2)$$

where $\mathbf{x}_e$ is the center of element e . As a result, topology optimizations of this method results in the parameter optimization of $\mathbf{w}$. Hence, any evolutionary algorithms for real-valued parameters can be used.

When using multiple NGnet, we can simultaneously optimize the magnets and iron core shapes [1]. However, in such approaches, magnet shapes generated by the optimization are quite complex as magnets, while such complexity is acceptable for the iron core. For this reason, conventional approaches are not suitable for optimizing magnet shapes from the view of manufacturing. For this reason, it has been reported that the magnet shapes are represented by some geometric parameters, while the iron cores are optimized using topology optimization [3].

B. Proposed method

In this work, to generate meaningful magnet shapes in high DoF, we propose to introduce shape modification process using image processing algorithms into NGnet-based method. Namely, magnet shapes generated by the NGnet-based method is modified to be rectangle shapes, which is suitable for manufacturing as magnets. As an example, a shape generated by the conventional method is shown in Fig. 1(a). This shape is acceptable as an iron-core, whereas is too complex as a magnet. Thus, a rectangle that covers the shape is derived by image processing algorithms, as shown in Fig. 1(b). Then, the shape, that is the on/off states of the cells, is modified to fit the rectangle, as shown in Fig. 1(c). Finally, the magnetization direction of the modified magnet shape can be set to the short axis of the rectangle derived. Consequently, the present method enables to obtain meaningful rectangle magnets, and their magnetization direction can automatically be determined, while

I. INTRODUCTION

Improving performance of permanent magnet motors (PM motors) is important to achieve carbon neutrality, and motor designs that can meet a wide variety of requirements are essential. However, it takes much effort for designers to find effective PM motor designs that satisfy given conditions. Thus, design automation techniques have aggressively been studied. For example, topology optimization, which can freely optimize the iron core shapes, have great attentions.

Among the shape representation methods in topology optimization, topology optimization using normalized Gaussian networks (NGnet) [1] has successively been applied to the core design of electric motors. Using topology optimizations, we can optimize iron cores of rotors in high degree of freedom (DoF). Since the cores are manufactured by the punching process, in general, there is little problems from the view of manufacturing when complicated core shapes are obtained. However, such complicated shapes are not so suitable as a shape of the magnets, because the manufacturing process of the magnets are restrictive. For this reason, there have been few cases in which the permanent magnets and iron cores of PM motors have been simultaneously optimized using topology optimization.[2]

In this work, to effectively optimize permanent magnets and rotor cores simultaneously, we propose a new topology optimization method that integrates image processing algorithms. As for the present method, the magnet shapes generated by the algorithm is modified to become rectangle shapes, which is suitable for manufacturing as magnets. The present method is applied to the rotor design problem of an PM motor. It is shown that the engineeringly meaningful magnet shapes can be obtained keeping high DoF as well as the iron core shapes.

II. TOPOLOGY OPTIMIZATION METHOD AND MAGNET SHAPE APPROXIMATION

A. Conventional method

In this work, NGnet is used as a base shape representation approach in topology optimization. As for this method, the shape is represented by assigning on/off states to each cell in

conventional methods must be manually set the magnetization directions [1].

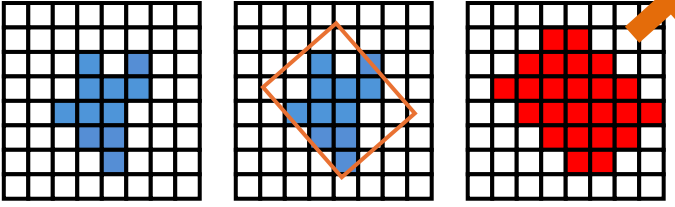


Fig.1. Magnet shape modification process, (a): original shapes generated, (b): rectangle shape for generated magnet, (c): modified magnet shapes through rectangle.

III. NUMERICAL EXPERIMENTS

To test the present method, a rotor shape of an interior permanent magnet motor shown in Fig. 2 is optimized. In this optimization, we consider the distributions of permanent magnet, the iron core, and the air. To represent three materials, thus, two NGnets, y_1 and y_2 , are prepared, and the state attributed to the cells are determined as:

$$V_e = \begin{cases} \text{air} & y_1(\mathbf{x}_i) < 0 \text{ and } y_2(\mathbf{x}_i) < 0 \\ \text{core} & y_1(\mathbf{x}_i) \geq 0 \text{ and } y_2(\mathbf{x}_i) < 0 \\ \text{magnet} & y_2(\mathbf{x}_i) \geq 0, \end{cases} \quad (3)$$

The objective of this optimization is to maximize the average torque and minimize the torque ripple keeping the magnet area of the original model as follows:

$$f_1 = -\frac{T_{ave}}{T_0} + 0.1 \frac{T_{rp}}{T_1} \rightarrow \min, \quad (4)$$

subject to

$$S_{mag} \geq S_T, \quad (5)$$

$$\rho \leq \theta_{th}, \quad (6)$$

where T_{ave} and T_{rp} are the average torque and torque ripple, respectively. In addition, $T_0 = 21.7$ Nm, $T_1 = 54.4\%$, and $S_T = 52.5$ mm² are the average torque, torque ripple, and magnet area of the original model, respectively. Moreover, ρ is the maximum von Mises stress of the iron core at a rotation speed of 10000min⁻¹, and $\theta_{th} = 200$ MPa, is the threshold.

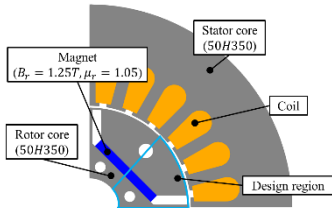


Fig.2 Original motor model.

To optimize w , CMA-ES is used [4]. The optimization is performed over 300 th algorithmic iterations. The number of bases in two NGnets are set to 196 and 194, respectively. respectively, i.e., total number of design variables is 390. The number of candidate solutions in each iteration is set to 112.

Fig. 3 shows the changes in fitness against the algorithmic iterations. We can see that the fitness is effectively improved with increasing the iteration. Fig. 4 shows the shapes obtained by the optimization for 1st and 300th iterations. The red arrows in this figure show the magnetization direction of each permanent magnet. As is clear from this figure, all the resultant

magnet shapes are almost rectangle, which is suitable for the manufacturing. In addition, it can be seen that many magnets are generated in the early stages of optimization, however, as the optimization progresses, two magnets are placed in appropriate positions. From this result, we can conclude that the present method can find meaningful magnet shapes in high DoF without determining magnetization directions, keeping DoF of the iron core.

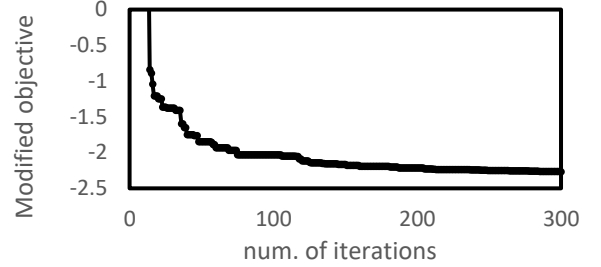
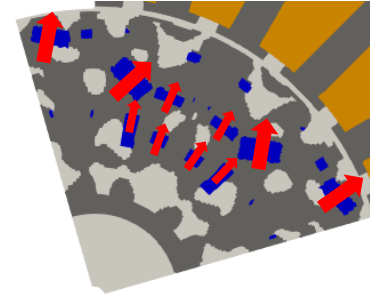
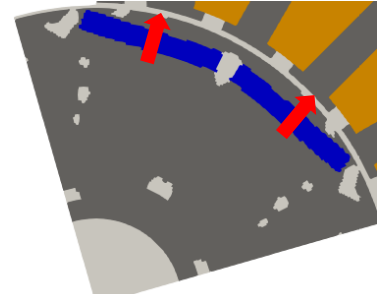


Fig.3 Changes in fitness.



(a) 1th iteration



(b) 300th iteration

Fig.4 Resultant rotor shapes.

In the fullpaper, we will mention the present process in detail, and more numerical results will be presented.

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