Shape Optimization of Flux Barriers in IPMSM
by using Polygon Model Method with GP

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Shape Optimization of Flux Barriers in IPMSM by using Polygon Model Method with GP

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Abstract—Recently, one of the problems is high efficiency for the electromagnetic machinery like a motor. This paper presents a new method of shape optimization. The target is flux barriers in the interior permanent magnetic synchronous motor (IPMSM) which is adopted as the benchmark model in IEE of Japan. Authors use the polygon model method with genetic programming (GP) by the two-dimensional finite element method (2D-FEM). The purpose is the investigation of shape design of flux barriers to improve the electromagnetic characteristics. In a conventional method as a size optimization, its design parameters are limited in most cases. However, the proposed method is the shape optimization by the tree structure. This method has more freedom for design parameters because the tree structure is possible to express every shape design.

Index Terms—Finite element method, Shape optimization, Polygon model method, Genetic programming, Interior permanent magnet synchronous motor

I. INTRODUCTION

RECENTLY, it is required the high efficiency for electromagnetic machinery like a motor. Therefore, this paper presents the shape optimization of the rotor in the interior permanent magnetic synchronous motor (IPMSM) which is adopted as the benchmark in IEE of Japan. IPMSM have been studied actively because it has a high degree of freedom of shape design [1]-[3]. In this case, researchers use the finite element method (FEM) and optimization algorithm [4]-[6]. However, these methods are often limited by using a size optimization method within a limited range and predetermined design parameters. For this reason, it has the disadvantage that depends on experiences and stereotypes of a developer. The mainstream is the researches of topology and shape optimization by using such as a level-set and on-off method recently [7]-[9].

In this paper, one of the approaches about these optimizations, authors present the polygon model method by operating tree structures. The tree structure of rotor in IPMSM is shown in Fig. 1. The analysis model like this structure is composed of some objects that have the data of some vertexes and materials. The proposed method is the structural optimization by operating these tree structures. The tree structure of this method is possible to express every form and shape design. Moreover, it is able to use the optimization algorithm together. As a result, the method has a more versatile optimization because it is possible to obtain the improvement of characteristics and simple form and shape by the setting of objective function and constraint conditions. This method uses the tree structure operation with genetic programming (GP) [10]. Additionally, this research uses the 3 phases 4 poles 24 slots IPMSM, and the search region is its rotor. The purpose of this paper is the investigation of this method from the optimized results of flux barriers and their characteristics.

II. METHOD OF OPTIMIZATION

The method of optimization is the polygon model method with GP. Moreover, an analysis model is evaluated by using 2D-FEM and parallel computing. Thus, the optimized shape is searched efficiently. These descriptions are shown in the section below.

A. Polygon Model

The region of a magnet and a flux barrier in IPMSM are regarded as a certain object. The object is a polygon that is composed of some vertexes. The shape design is optimized by operating objects and vertexes. As shown in Fig. 1, a flux barrier is composed of some vertexes. In addition, a magnet is composed of some vertexes, magnetization, and its direction. The analysis model has these objects. In a conventional method, the size optimization is based on the detailed design that is determined a limited range and predetermined design parameters. However, the polygon model method is possible to search the shape design within the entire region. Moreover, it has a high degree of freedom of shape design by optimization of tree structures because it is possible to express every shape design. In this method, the expression of holes in an object is not taken into consideration. Therefore, it is not the topology optimization, but the shape optimization. However, it is capable of the extension to topology optimization by applying this method.

Fig. 1. Tree structure of analysis model that is composed of objects like a flux barrier and magnet.

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B. Genetic Programming (GP)

Genetic programming (GP) is one of the metaheuristic algorithms in order to search an approximate solution. It is the extension of structural genotype about genetic algorithm (GA). In this method, it is regarded as a genotypic tree structure of the analysis model as shown in Fig. 1. Moreover, it searches the optimized shape by repeating a genetic operation such as the evaluation, selection, crossover, and mutation. The flowchart of this method is shown in Fig. 2.

First of all, this method generates analysis models of the number of population randomly. This generation of initial population is necessary to specify the values of number of population, objects, nodes, and search radius. It uses the mersenne twister (MT) to generate random numbers. In the parallel processing, it uses master-slave method for GP. Thus, the analysis models distribute to slaves, and they analyze the electromagnetic characteristics such as the steady torque and cogging torque by using 2D-FEM. Furthermore, automatic mesh generation is the bubble mesh method [11].

The description of genetic operation is shown below. It uses the evaluation, selection, crossover, and mutation for the genetic operation. In the evaluation, it calculates the fitness value by the predetermined fitness functions of characteristics. In the selection, individuals of high fitness value are likely to be selected. It selects the number of population for the next generation. An example of crossover is shown in Fig. 3. In the crossover, it selects two parental models from the population. The models cross each other by the crossover probability. It has two crossover methods. These are crossover of objects and nodes. The positions of crossover for nodes and objects in the parental models are selected randomly. Moreover, it performs a movement and exchange of values. Apart from the crossover probability of parents, it is necessary to set the crossover probabilities of nodes and objects. The total number of candidates for crossover of object and node is the number of the smaller model of those. Moreover, the number of candidates is decreased by the crossover probability of object and node. They are divided into the method of exchange and movement. In addition, they are divided into the method to send and receive in the movement by a probability of 0.5. It is possible to give the child models without losing the genetic information of shape design in the parental model by crossing only a part of object and node. The reason is because it has not only the value of nodes but also the order of nodes. In the mutation, the operations are the addition, delete, and movement of objects. Similarly, nodes are operated by the addition, delete, and movement. These operation methods are selected by probability. It returns to the parallel processing after the genetic operation. These processing repeat until the termination condition is satisfied. Authors search the global optimal shape design of flux barriers in IPMSM by using this proposed method.

These are possibility that it generates the unanalyzable model. For example, it is the model having a self-intersection. It is necessary to prevent the generation for these models in the initial generation and genetic operation. In addition, the models having the same nodes of an object and the overlap of region of objects are also prevented in this method. The problem is resolved by checking the model when each item of initial generation and genetic operation. Its operation is repeated until acceptable model is generated. Thus, the models can be generated without impossible models.

C. Parallel Processing

In the optimization, it is necessary to evaluate many analysis models. The computing time becomes enormous. By the parallel processing, it is able to analyze the impossible large scale optimization analysis by a single PC.
In this paper, they are calculated by 4 PCs. It is possible to evaluate the individuals by the total 16 CPU cores because each PC has 4 CPU cores. GP is necessary to perform the global processing every generation. It is not possible to evaluate individuals about next generation until CPUs are ended all of the present evaluations. In this method, an analysis time per individual is not long by using 2D-FEM. It analyses an individual that has not been analyzed yet in order after an analysis by CPU has been completed. This reason is because they have time difference for each individual. In the parallel calculation method, it uses the master-slave method as shown in Fig. 4. In the master side, it performs the genetic operation and control of entire analysis. On the other hand, in the slave side, it calculates the fitness value by using 2D-FEM. It uses the text files with information like a fitness value between master and slave by using TCP/IP in order to exchange genetic informations.

III. ANALYSIS CONDITION

The necessary specifications by the optimization method are shown in the section below. For example, they are the specifications of initial model, equations of fitness value, and parameters of GP.

A. Analysis Model

The mesh model of analysis model is shown in Fig. 5. The analysis model is the IPMSM which is adopted as the benchmark model in IEE of Japan [12]. This is the 3 phases 4 poles 24 slots IPMSM. The analysis range is 0-90 degrees from the cycle of its model. The counterclockwise is plus for the direction of rotation. The currents of each phase are expressed by the following equations.

\[
I_U = \sqrt{2} I_{rms} \sin(\omega t + \beta) \\
I_V = \sqrt{2} I_{rms} \sin(\omega t - \frac{2}{3} \pi + \beta) \\
I_W = \sqrt{2} I_{rms} \sin(\omega t + \frac{2}{3} \pi + \beta)
\]

where \( I_{rms} \) is the effective value of current, \( \omega \) is the angular frequency, \( \beta \) is the phase of current. The cycle of steady torque is 30 degrees in the mechanical angle from the numbers of poles and shape geometry. Similarly, that of cogging torque is 15 degrees in the mechanical angle. Therefore, the number of steps of steady torque analysis is 31 and cogging torque analysis is 16. The specifications of the model are shown in Table I. The material of stator and rotor core is M-36. This is an electromagnetic steel sheet. The material of shaft is s45c. This is a carbon steel for machine structural use. The magnetization is 1.25 T, and it is a neodymium magnet. This model is the initial model. The optimization of this method is started without flux barriers of initial model.

B. Method of Evaluation

GP is necessary to express the fitness value for each individual because it decides the superior individuals for next generation in the selection. In this paper, it calculates the average steady torque, its ripple, and peak-to-peak of cogging torque by using 2D-FEM. These value is used the calculation of fitness value. The calculation of fitness value is expressed by the following equations.

\[
f = T_{ave} \cdot w_1 + T_{rp} \cdot w_2 + T_{cog} \cdot w_3 + C \cdot w_4
\]

\[
T_{ave} = \frac{T_{ave\_opt}}{T_{ave\_ini}}
\]

\[
T_{rp} = \frac{T_{rp\_ini}}{T_{rp\_ini} + T_{rp\_opt}}
\]
where \( T_{\text{ave}} \) is the average steady torque, \( T_{\text{rp}} \) is its ripple, \( T_{\text{cog}} \) is the peak-to-peak of cogging torque, and \( C \) is the worst complexity of all object. Additionally, the \( \text{opt} \) of subscript is the value of optimized model, and the \( \text{ini} \) of subscript is that of initial model. \( f \) is the circumference of object. \( S \) is the area of object. It calculates \( T_{\text{ave}}, T_{\text{rp}}, T_{\text{cog}}, \) and \( C \) of the value by above functions. It multiplies these values by each weighting factor. \( f \) is the fitness value. It is the sum of these values. The value of \( w_1 \) is 10, \( w_2 \) is 3, and \( w_3 \) is 3. The fitness value is set to increase by increasing the average steady torque, decreasing the ripple, cogging torque, and complexity of object. The complexity of object plays a filtering role of object.

In this paper, the initial model has bolt holes. However, the optimized model is ignored them in this method because the influence of presence or absence of bolt holes is small. The fitness value of its presence without the value of complexity is higher than that of its absence by only 0.004%.

C. Parameters

In this method, it is necessary to decide the parameters of GP, and the range of parameters in the model creation. The parameters of GP are shown in Table II, that of crossover is shown in Table III, and that of mutation is shown in Table IV. As shown in Table II, the population size is 1000. It is necessary to prepare much size as possible because this method by the GP deals with the huge number of solutions. The selection method is tournament and elite method. Moreover, the method finishes this program after the termination condition is satisfied by the number of continuous generation. Table III shows the crossover probability of object and node after the decision of crossover for parental models. Additionally, it shows the probability of crossover method as the exchange and movement. As shown in Table IV, It selects the target and method. The target is an object or node, and the method is addition, delete, or movement.

The parameter range of model creation is shown in Table V, and the search region is shown in Fig. 6. It is necessary to set the parameters of generation of initial population and mutation. The initial number of nodes must be at least 3 in order to have a region of object. The search radius is up to 27.0 mm because it has the necessary room of 0.5 mm from a structural problem. Additionally, the minimum value is 8.0 mm because the shaft is not included in the search region. The search region is a half of a rotor of quarter model as shown in Fig. 6. It generates flux barriers so as to be symmetrical.

IV. RESULT OF OPTIMIZATION

In this paper, authors investigate the 3 analyses by changing the value of \( w_f \). It is the complexity of object, and it plays a filtering role of object. The optimized shapes and these characteristics by using this method of shape optimization are shown in the section below.
A. Evaluation Process

The evaluation processes by the proposed method are shown in Fig. 7. These total computing times are shown in Table VI. The fitness value of initial model in Fig. 7(a) is 13.00. Similarly, its value in Fig. 7(b) is 14.00 and its value in Fig. 7(c) is 15.00. The end values of evaluation processes are higher than the values of initial model. Moreover, the evaluation process of Fig. 7(a) is slower than the others. This reason is because it has no complexity. It is no limitation for searching global optimal shape design.

B. Optimized Shape and Characteristics

The optimized shapes are shown in Fig. 8. Fig. 8(a) has the complicated shape of flux barriers because it is no filtering when the value of \( w_4 \) is 0. By contrast, Fig. 8(b) and Fig. 8(c) have the simple shapes because the value of \( w_4 \) is 1 and 2, respectively.

![Fig. 7. Evaluation process: (a) \( w_4 = 0 \), (b) \( w_4 = 1 \), and (c) \( w_4 = 2 \).](image)

![Fig. 8. Optimized shape by using proposed method: (a) \( w_4 = 0 \), (b) \( w_4 = 1 \), and (c) \( w_4 = 2 \).](image)

![Fig. 9. Steady torque of optimized shapes.](image)

![Fig. 10. Cogging torque of optimized shapes.](image)

<table>
<thead>
<tr>
<th>Weight ( w_4 )</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total computing time [hour]</td>
<td>161.98</td>
<td>126.89</td>
<td>125.54</td>
</tr>
</tbody>
</table>

TABLE VI

TOTAL COMPUTING TIME
TABLE VII
SUMMARY OF CHARACTERISTICS

<table>
<thead>
<tr>
<th>Weight (w_z)</th>
<th>initial</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average steady torque [Nm]</td>
<td>1.833</td>
<td>2.057 (12.2%)</td>
<td>2.081 (13.5%)</td>
<td>2.117 (15.5%)</td>
</tr>
<tr>
<td>P-P of cogging torque [Nm]</td>
<td>0.0751</td>
<td>0.0054 (92.9%)</td>
<td>0.0062 (91.7%)</td>
<td>0.0156 (79.3%)</td>
</tr>
<tr>
<td>Ripple of steady torque</td>
<td>0.434</td>
<td>0.164 (62.1%)</td>
<td>0.199 (54.1%)</td>
<td>0.317 (26.8%)</td>
</tr>
<tr>
<td>Fitness value without complexity</td>
<td>13.00</td>
<td>16.20 (24.6%)</td>
<td>16.18 (24.5%)</td>
<td>15.77 (21.3%)</td>
</tr>
</tbody>
</table>

\(w_z\) is 1 and 2. The steady torque is shown in Fig. 9, and the cogging torque is shown in Fig. 10. Moreover, the summary of these characteristics is shown in Table VII. In the fitness values of Table VII, the complexities are ignored. The average steady torques of these models are higher than that of initial model. Additionally, the ripples of steady torque of these models are lower than that of initial model. The higher a value of \(w_z\) tends to be increased an average steady torque and its ripple. Meanwhile, the peak-to-peaks of cogging torque of these models are lower than that of initial model. The higher a value of \(w_z\) tends to be increased cogging torque. According to the fitness values in Table VII, it is difficult to search the global optimal solution when the value of \(w_z\) is high. This is because it is limited by the filtering of complexity of object.

V. CONCLUSION

This paper presents a new method of shape optimization by the polygon model method with GP. This method is high degree of freedom of shape design because a tree structure is possible to express every shape design. The purpose is optimization of shape design of flux barriers in order to improve the electromagnetic characteristics. Moreover, the complexity of object is taken into consideration. As a result of this method, the characteristics of average steady torque, its ripple, and cogging torque were improved. Simultaneously, it was possible to obtain simple shape designs of flux barriers.

In the future works, Authors will investigate the parameter identification, filtering of shape design, and simultaneous optimization. The proposed method has many parameters. Therefore, it is necessary to search the best parameters. In this paper, Authors optimized the flux barriers only. However, the position and shape design of magnets are also important. Authors will research the simultaneous optimization.

VI. REFERENCES