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3-D Analysis of Eddy Current in Permanent Magnetof Interior Permanent Magnet Motors

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Abstract. Interior permanent magnet motors are widely used in various fields. However, in high-speed operations, it is important to decrease the eddy current loss in the permanent magnet. In order to decrease the eddy current loss, we propose to divide the permanent magnet. In this paper, we clarified the effect of division of permanent magnet on the eddy current loss using the 3-D finite element method.

1. Introduction

Recently, interior permanent magnet motors are widely used in various fields because of its high reliability. However, in high-speed operations, the eddy current loss in the permanent magnet becomes large. Therefore, it is important to decrease the loss. In order to decrease the eddy current loss, we propose to divide the permanent magnet. In this paper, we clarify the effect of division of the permanent magnet on the eddy current loss. Furthermore, we clarify the effect of the dividing direction of the permanent magnet on the eddy current loss.

2. Method of Analysis

2.1. *Fundamental equations*

The fundamental equation of the magnetic field using the 3-D finite element method with edge elements can be written using the magnetic vector potential A and the electric scalar potential ϕ as follows[1]:

$$\mathrm{rot}(\nu\,\mathrm{rot}A) = J_0 + \nu_0 \mathrm{rot}M - \sigma\left(\frac{\partial A}{\partial \mathrm{t}} + \mathrm{grad}\phi\right) \quad (1)$$

$$\mathrm{div}\left\{-\sigma\left(\frac{\partial A}{\partial \mathrm{t}} + \mathrm{grad}\phi\right)\right\} = 0\mathrm{s} \quad (2)$$

where ν is the reluctivity, J_0 is the current density, ν_0 is the reluctivity of the vacuum, M is the magnetization of the permanent magnet and σ is the conductivity.

The magnetic field can be obtained by calculating (1) and (2), simultaneously.

The 3-D region is divided into tetrahedral elements. The matrix of finite element method is solved by the ICCG method. The Newton-Raphson iteration technique is used for the nonlinear calculation of the cores.

2.2. *Double node technique*

In the conventional method, flat elements are needed for the slit region at the small air gap. The flat element causes the increasing of the number of ICCG iterations. Therefore, in order to reduce the flat elements, we use the double nodes for ϕ at only the slit[2].

2.3. *Calculation of eddy current loss*

The eddy current loss W_{ed} is given as follows[1]:

$$W_{ed} = \frac{1}{\tau/2}\int_{t}^{t+\tau/2}\left\{\int_{V_e}\frac{(J_e)^2}{\sigma}dV\right\}dt \tag{3}$$

where τ is the period of the eddy current waveform. V_e is the region of the conductor with the eddy current.

3. Analyzed Model

Fig.1 (a) shows an analyzed model[3]. The model is an interior permanent magnet motor that has 4 pairs of poles. Therefore, only 1/8 region is modeled because of the symmetry and periodicity. The rotation direction of the armature is counterclockwise. The permanent magnets are divided into n pieces in order to decrease the eddy current. Fig.1 (b) shows the divided permanent magnets (the number of division n is 5). Fig.1 (b)(i) shows the permanent magnet divided in axis direction. Fig.1 (b)(ii) shows permanent magnet divided in rotation direction. Fig.2 shows the 3-D finite element mesh.

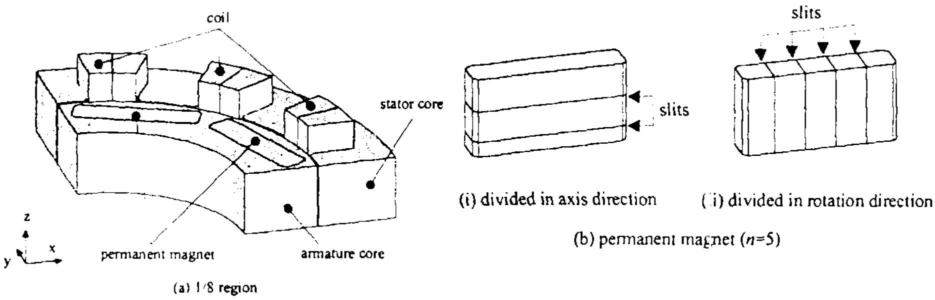

Figure 1: Analyzed model.

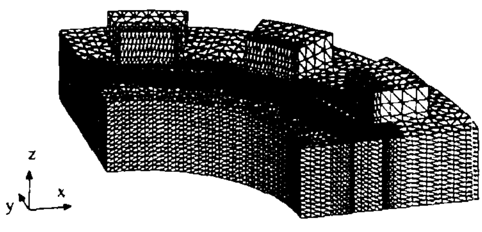

Figure 2: 3-D finite element mesh.

4. Results and Discussion

4.1. Effect of division of permanent magnet on eddy current

Fig.3 shows the distributions of eddy current density vectors in the permanent magnet. Fig.4 shows the positions of the permanent magnet that correspond to Fig.3. It is clarified that the divided magnet has large advantage to decrease the eddy current in comparison with the standard magnet. Fig.5 shows the rotation angle - eddy current density characteristics at the position of elements A and B shown in Fig.6. It is found that the eddy current of these motors changes on 30-degree cycle. Furthermore, it is found that the model divided in axis direction has advantage to decrease the eddy current in comparison with the model divided in rotation direction at the element A. However, at the element B, the effect of dividing direction of permanent magnet on the distribution of the eddy current is small.

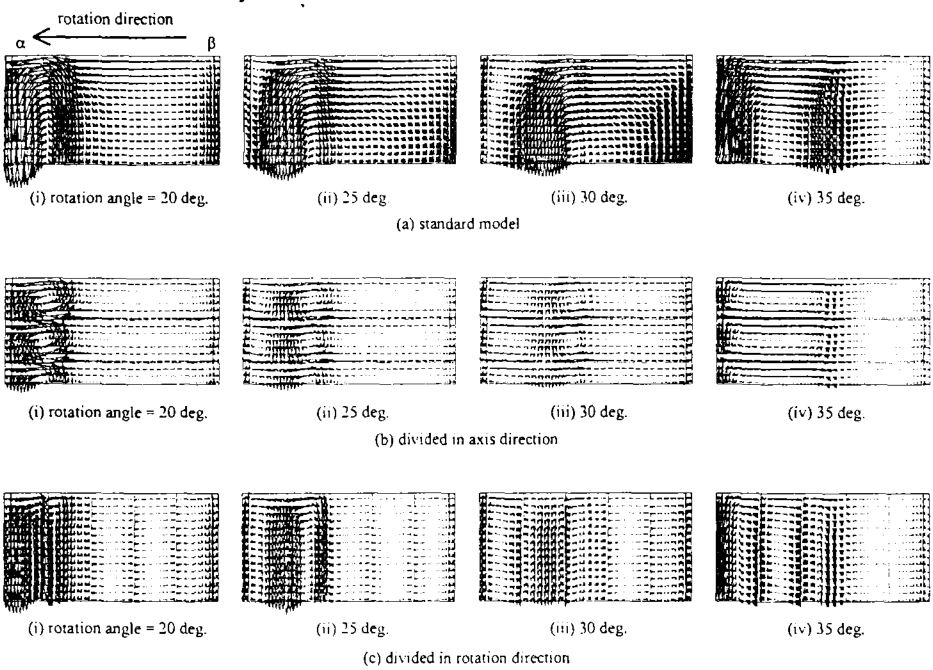

Figure 3: Distributions of eddy current density vectors.

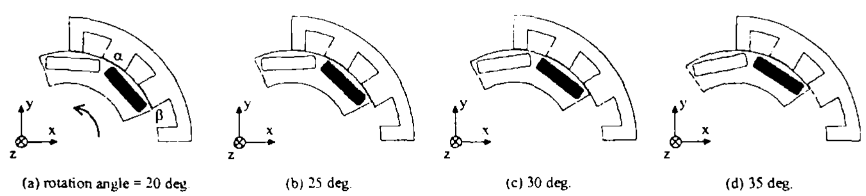

Figure 4: Position of permanent magnet.

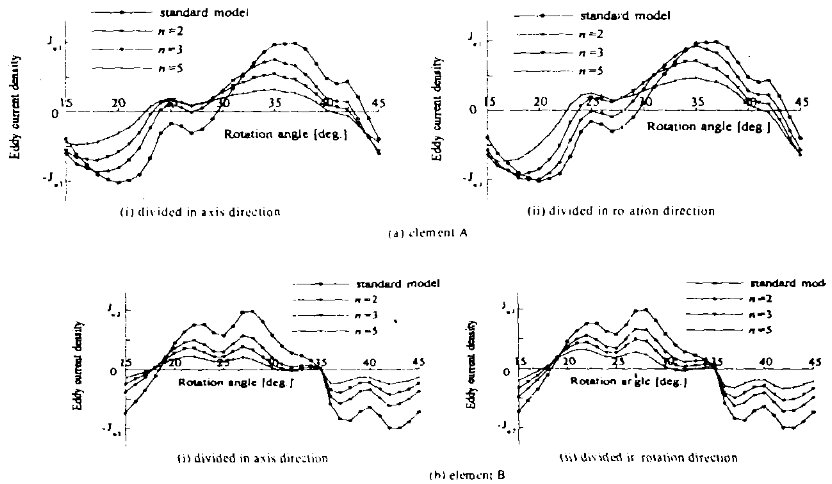

Figure 5: Rotation angle – eddy current density characteristics.

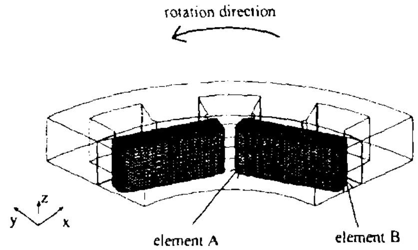

Figure 6: Position of element A and B of permanent magnet.

4.2. Effect of division of permanent magnet on eddy current loss

Fig.7 shows the distributions of eddy current loss in the permanent magnets. It is found that the eddy current loss at the surface of the permanent magnet is large. Furthermore, the eddy current loss of the front position of the permanent magnet in the rotation direction is larger than that of the rear position. Fig.8 shows the eddy current loss of the permanent magnet divided in the rotation direction (n=5) as shown in Fig.9. It is found that the eddy current loss at the magnet 1 is about 50% of the total eddy current loss. Fig.10 shows the effect of division of the permanent magnet on the eddy current loss. It is clarified that the eddy current loss decreases in inverse proportion to the number of division of permanent magnet n. In this model, the eddy current loss of the model divided in the axis direction is smaller than that of the model divided in the rotation direction. Table I shows the discretization data and CPU time.

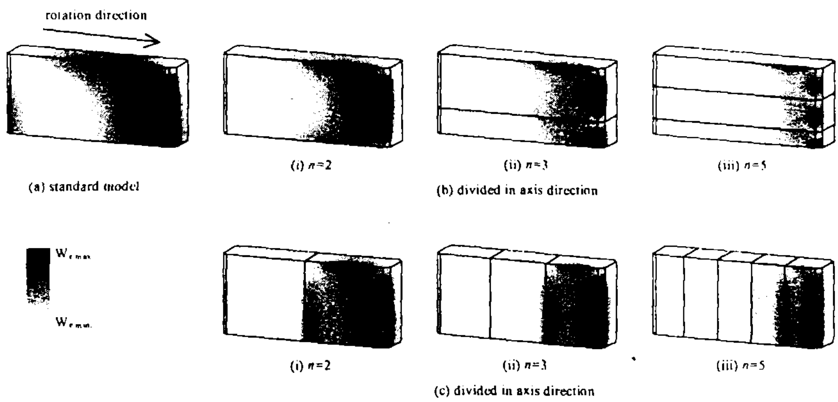

Figure 7: Distributions of eddy current loss in permanent magnet.

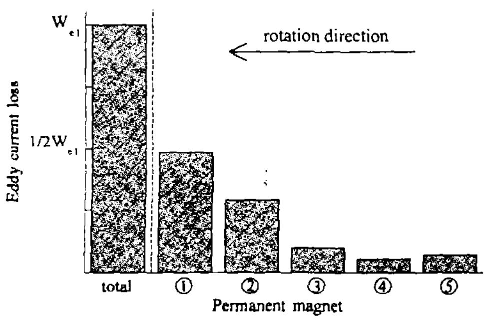

Figure 8: Eddy current loss of permanent magnet divided in rotation direction (n=5).

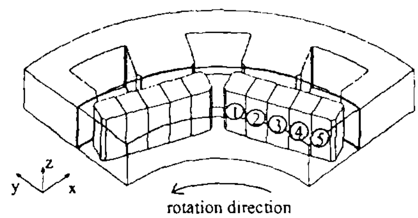

Figure 9: Position of permanent magnet.

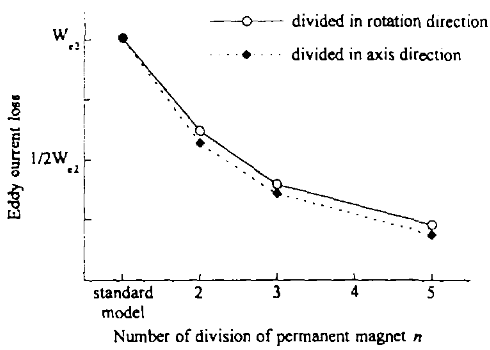

Figure 10: Effect of division of permanent magnet on eddy current loss.

Table I:Discretization data and CPU time.

Number of elements	207,792
Number of edges	253,439
Number of unknowns	245,048
Number of non-zero entries	2,445,202
Number of non-linear iterations	18
Number of time steps	46
Total CPU time [hours]	189

Computer used : Pentium III 700MHz PC

5. Conclusions

We propose to divide the permanent magnet in order to decrease the eddy current loss. It is clarified that the effect of division of the permanent magnet on the eddy current loss are very large. Furthermore, it is quantitatively clarified that the divided permanent magnet is very useful to decrease the eddy current loss in interior permanent magnet motors. The difference of effect of dividing direction of the permanent magnet on the eddy current loss is also clarified.

6. References

[1] *Y.Kawase and S. Ito, "New Practical Analysis of Electrical and Electronic Apparatus by 3-D Finite Element Method," Morikita Publishing Co.,1997.*

[2] *Y.Kamiya and T.Onuki, "3-D Eddy Current Analysis by the Finite Element Method Using Double Nodes Technique," IEEE Trans. Magn., vol. 32, no.3, pp 741-744, 1996.*

[3] *Y.Kawase, T.Ota and H.Fukunaga, "3-D Eddy Current Analysis in Permanent Magnet of Interior Permanent Magnet Motors" Conference Record of the 12th COMPUMAG Conference on the Computation of Electromagnetic Field, vol. 1, pp. 200-201, 1999.*