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Investigation of AC Loss of Permanent Magnet of SPM Motor Considering Hysteresis and Eddy-Current Losses

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NdFeB sintered magnets are widely used in rotating electrical machines. In order to develop an efficient rotating machine, it is important to estimate ac loss of the permanent magnet of rotor precisely. In this paper, the ac losses of the permanent magnet of IEEJ model (surface permanent-magnet motor model) are examined by using the three-dimensional finite-element method taking into account the newly measured hysteresis losses of permanent magnet. The result shows that we should consider not only the eddy-current loss but also the hysteresis loss, when the frequency of ac field due to a slot ripple is of the order of several hundred hertz.

***Index Terms*—Eddy-current loss, hysteresis loss, NdFeB magnet, SPM motor.**

I. Introduction

RECENTLY, NdFeB sintered magnets have been widely used in rotating electrical machines. It is considered that the major part of ac losses of the permanent magnet in motors with NdFeB magnets are eddy-current losses due to a slot ripple, inverter, etc. [1], as the conductivity of NdFeB magnet is fairly high compared to that of a ferrite magnet. If a large ac loss is produced in the NdFeB magnet, the temperature of magnet increases and it may cause the thermal demagnetization. In order to develop an efficient rotating machine, it is important to estimate the ac loss correctly. But, the calculation of eddy-current loss of permanent magnets in the rotor has not been verified by experiments until now.

In this paper, the ac loss of NeFeB sintered magnet is measured by using a newly developed closed-type measuring equipment, and compared to the calculated value. The behavior of the hysteresis loss of permanent magnet is investigated, and it is found that the hysteresis loss is larger than the eddy-current loss in the range of frequencies less than several hundreds hertz. Then, the ac losses of the permanent magnet of rotor of SPM motor model [2], which is proposed by IEE of Japan to investigate the estimation methods of iron losses, are examined considering the hysteresis and eddy-current losses.

II. Measurement of AC Loss of Permanent Magnets

A. Measurement System and Conditions

We measured ac loss of NdFeB magnets using the closed-type measuring equipment shown in Fig. 1. The measured specimen is an NdFeB magnet (NEOMAX-44H, NEOMAX Co. Ltd.) of 30 mm length, 10 mm width, and 10 mm thickness. The density ρ is 7500 kg/m^3 and the conductivity σ is 6.9 $\times$ 10^5 S/m. We measured the ac loss of a fully magnetized magnet. The ac loss of NdFeB magnet is measured from 30 to 150 Hz and 0.01 to 0.1 T. The ac loss is obtained by the flux density B measured using the search coil and the magnetic field strength H. H is measured using a coaxial double coil as shown in Fig. 2. This coil detects the magnetic field strength on the surface of a specimen by the difference of the inductive voltages of coil 1 and coil 2.

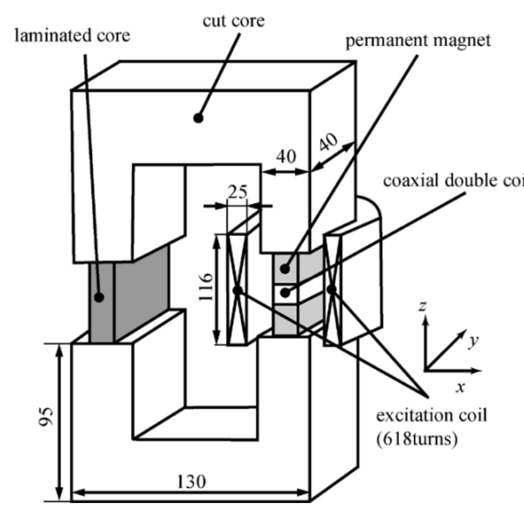

Fig. 1. Closed-type measuring equipment.

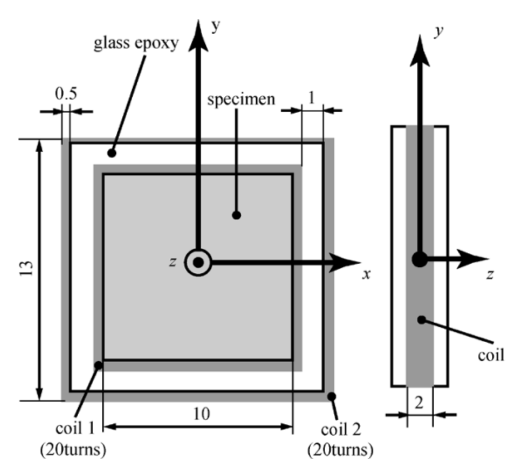

Fig. 2. Coaxial double coil.

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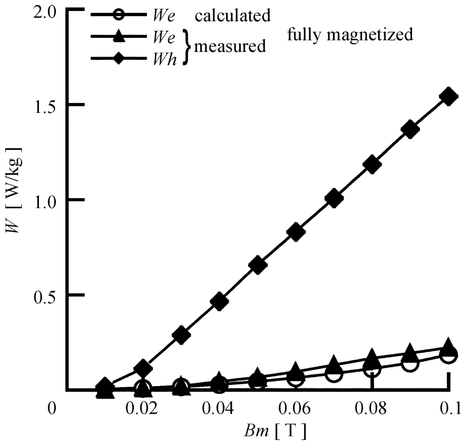

Fig. 3. Hysteresis loss W_{h} and eddy-current loss W_{e} (fully magnetized, 50 Hz).

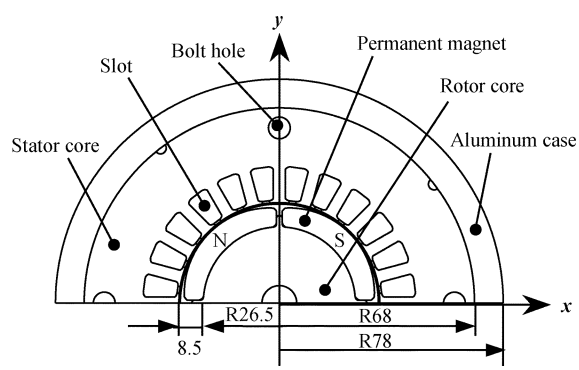

Fig. 4. Analyzed model.

B. Measured Results

The ac loss W was separated into the eddy-current loss W_{e} and the hysteresis loss W_{h} by using the two frequency method. The W–B curve at frequency $f = 50$ Hz is shown in Fig. 3. In order to verify the validity of measurement, we analyzed the eddy-current loss of NdFeB magnet by using the 3-D FEM. The relative permeability of magnet is considered 1.05 (fully magnetized). The calculated results are also shown in Fig. 3. The hysteresis loss is greater than the eddy-current loss.

As the eddy-current loss W_{e} is proportional to f^2, W_{e} is dominant at high frequencies (for example, more than 1 kHz). However, the hysteresis loss W_{h} cannot be neglected at low frequencies. Therefore, the hysteresis loss may need to be considered in the analysis of the ac loss of widely used motors (normal speed motor).

III. SPM Motor Model

Fig. 4 shows a 4-pole SPM motor model [2]. The motor consists of the rotor core, the permanent magnet, the stator core, and the aluminum case. The stator and rotor cores are made of nonoriented silicon steel (grade: 50A1300). The core length is 40 mm. The permanent magnet is Nd–Fe–B magnet and the magnetization is 1.26 T (parallel orientation). The rotor is rotated at no excitation to investigate the iron loss of stator core due to the flux produced by the permanent magnet of rotor. The rotating speed is 1500 rpm. The iron loss of stator core is measured by using a torque meter and by driving the permanent magnet rotor by another motor.

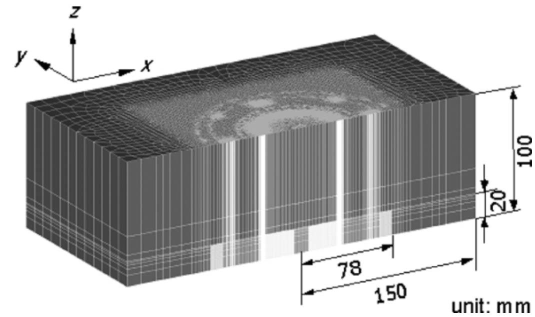

Fig. 5. 3-D finite-element mesh (1/4 region).

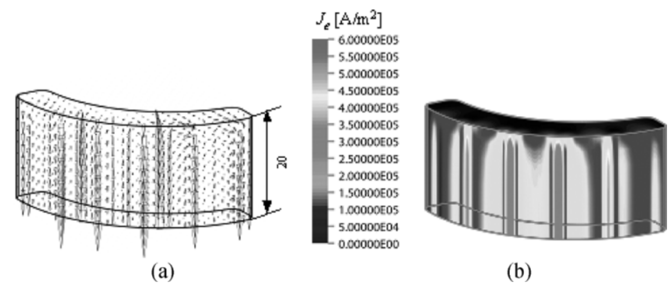

Fig. 6. Eddy-current distribution in magnet. (a) Distribution of eddy-current vectors. (b) Distribution of eddy-current density.

IV. Calculation of AC Loss of SPM Motors

A. AC Loss of Permanent Magnets

1) Distribution of Flux and Eddy-Current Density in Permanent Magnet: We analyzed the flux and eddy-current distribution in the magnets of the rotor by using the 3-D edge-based hexahedral finite-element method [3]. Fig. 5 shows the region analyzed (1/4 of the whole region). The number of elements is 247 696 and the number of nodes is 283 050. Eddy currents are considered only in the magnets. Fig. 6(a) shows the eddy-current vector in the permanent magnet at the mechanical angle 30°. Fig. 6(b) shows the eddy-current density in the magnet. It is 1/2 of the magnet. The eddy current shows small loops according to the slot ripple.

The waveform of flux density ($B_{\|}$, $B_{\perp}$, B_z) at two points in the permanent magnet of rotor is shown in Fig. 7. $B_{\|}$ is the component which is parallel to the magnetization and $B_{\perp}$ is that perpendicular to the magnetization. The flux density changes periodically due to the slot ripple at point a on the surface of magnet. The flux density is almost constant at point b inside the magnet. The fundamental frequency of flux waveform is 600 Hz.

2) Calculation of AC Loss: The eddy-current loss W_{e} was calculated directly by using the eddy-current density J_{e} in the permanent magnet obtained by using the 3-D FEM as follows:

$$W_e = \frac{1}{T}\int_T \left(\int_{V_e} \frac{|J_e|^2}{\sigma} dV \right) dt \tag{1}$$

where σ is the conductivity. V_{e} is the volume of permanent magnet, and T is a period.

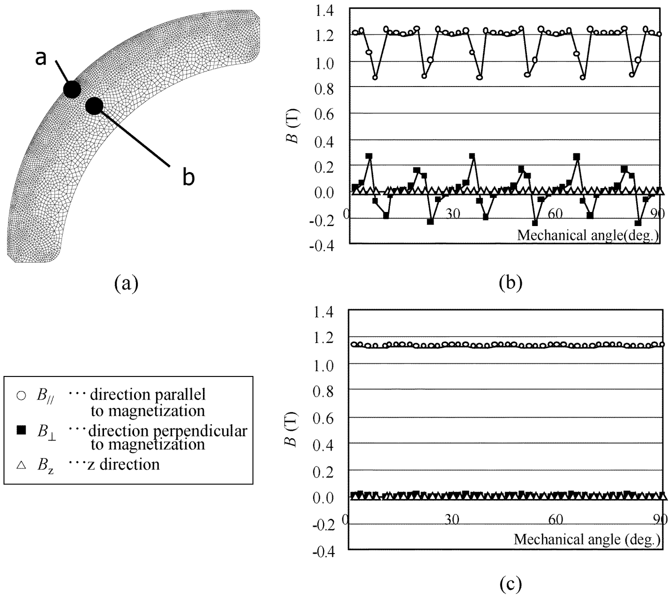

Fig. 7. Waveforms at each point of magnet. (a) Points in magnet. (b) Waveform of flux density at point a. (c) Waveform of flux density at point b.

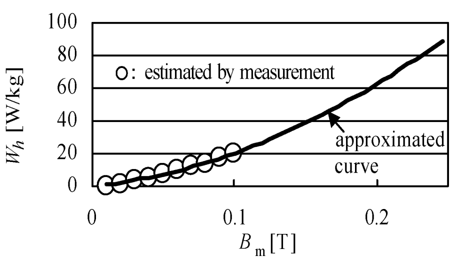

Fig. 8. Hysteresis loss of permanent magnet (600 Hz).

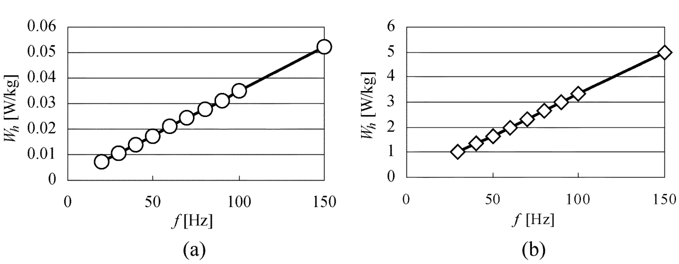

Fig. 9. $W_{\rm h}$–f characteristics. (a) $B = 0.01$ T. (b) $B = 0.1$ T.

The hysteresis loss $W_{\rm h}$ was calculated by using the approximated curve obtained from the measured values as shown in Fig. 8. In a first step, a $W_{\rm h}$–B curve at 600 Hz was extrapolated by using the measured $W_{\rm h}$ at 150 Hz and 0.01–0.1 T shown in Fig. 9 (The frequency and flux density are limited due to the capacity of power source). Next, the $W_{\rm h}$–B curve is approximated by assuming that the hysteresis loss is proportional to the square of flux density. The hysteresis loss $W_{\rm h}$ was calculated by using the approximated curve and by assuming that $W_{\rm h}$ is the function of the maximum flux density at 600 Hz in each part of the permanent magnet.

B. AC Loss of Stator Core

Fig. 10 shows the loci of flux density vectors. Distorted elliptical rotating flux can be observed at the back of teeth and slot, and also at the tip of teeth. In order to estimate the iron loss precisely, it is necessary to take into account the iron loss under rotating flux as shown in Fig. 10 [2]. The iron loss under distorted elliptical rotating flux is estimated by using the iron losses measured under elliptical rotating fluxes having various axis ratios.

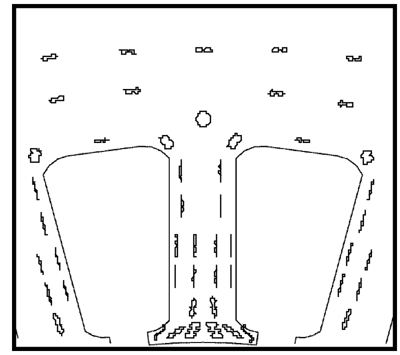

Fig. 10. Loci of flux density vectors.

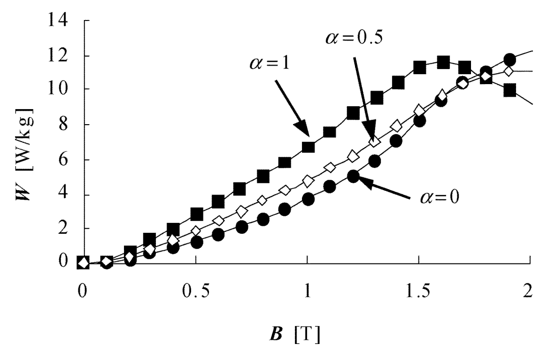

Fig. 11. W–B curve under rotating flux (50A1300, 50 Hz, measured).

Fig. 11 shows iron losses under rotating flux of nonoriented silicon steel (50A1300, 50 Hz) measured by using the 2-D SST [4]. The axis ratio α of the rotating flux of fundamental component is defined as follows:

$$\alpha = \frac{B_{\rm min}}{B_{\rm max}} \tag{2}$$

where $B_{\rm max}$ and $B_{\rm min}$ are the major and minor axes, respectively.

In the proposal estimation method, the iron loss W under a distorted rotating flux is represented as a summation of the loss W_0 under an elliptical rotating flux of fundamental component and the iron loss $W_{\rm n}$ under alternating flux of harmonic components as follows:

$$\begin{aligned} W &= W_0 + W_{\rm n} \\ &= W_0(\alpha, B_{\rm m}) + \sum_{\rm n=2,3\ldots} W_{\rm n}(B_{\rm n}) \end{aligned} \tag{3}$$

where $W_0(\alpha, B_{\rm m})$ denotes that the iron loss under rotating flux is the function of axis ratio α and the maximum flux density (major axis) $B_{\rm m}$. $W_{\rm n}(B_{\rm n})$ is the iron loss due to alternating flux as a function of harmonic components $B_{\rm n}$.

The calculation is performed by using the following procedure: In a first step, the fundamental components in the r and θ components are obtained by using the harmonic analysis. Then,

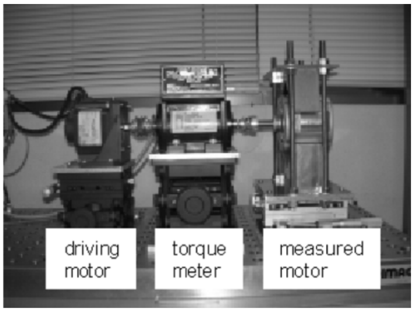

Fig. 12. Measuring equipment of torque.

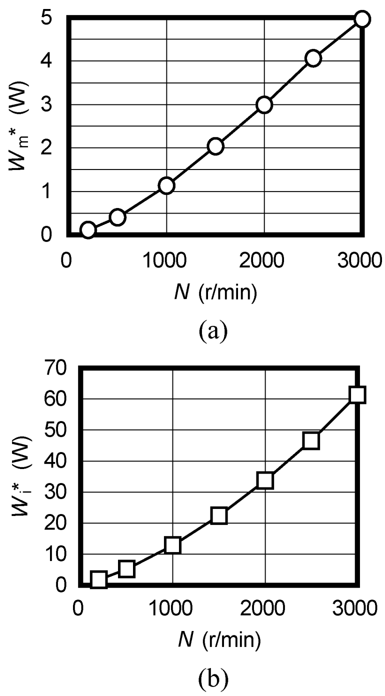

Fig. 13. Measured losses of IEEJ model. (a) Mechanical loss. (b) Iron loss.

the iron loss W_0 under the rotating flux of fundamental component at any axis ratios α and flux density B_{m} can be obtained by performing interpolation of the B–W curve. The iron loss due to harmonic component is obtained as a summation of the iron loss at each harmonics by using the B–W curves at various frequencies.

V. Results and Discussion

The torque of the SPM motor model (IEEJ model) shown in Fig. 4 is measured by a torque meter when the permanent magnet rotor is driven by another motor, as shown in Fig. 12 [3]. The iron loss of the stator is obtained by subtracting the torque (corresponding to the mechanical loss) measured by rotating a rotor having nonmagnetized permanent magnet from the torque when the permanent-magnet rotor is driven by another motor. Fig. 13(a) and (b) shows the mechanical losses W_{m}^* and iron losses W_{i}^* measured.

TABLE I
Comparison of Measured and Calculated Results of AC Loss of the IEEJ Model at 1500 rpm

	calculated [W]			measured [W]
rotor	eddy current loss		1.0	22.4
	hysteresis loss	$W_{//}$	0.9	
		$W_{\perp}$	1.3	
stator	iron loss		23.4	
total			26.6	

Table I shows the comparison of the calculated and measured ac losses of the IEEJ model. The hysteresis loss of magnets is greater than twice the eddy-current loss at 1500 rpm. The results show that we should consider not only the eddy-current loss but also the hysteresis loss, when the frequency of ac field due to a slot ripple is of the order of several hundred hertz (600 Hz for the model in Fig. 4).

VI. Conclusion

The ac losses of the permanent magnet of IEEJ model (SPM motor model) are examined by using the 3-D finite-element method taking into account the newly measured hysteresis losses of permanent magnet. Consequently, the hysteresis loss of magnets is greater than twice the eddy-current losses at 1500 rpm. The results show that we should consider not only the eddy-current loss but also the hysteresis loss in the analysis of iron loss of SPM motor, when the frequency of ac field due to a slot ripple is of the order of several hundred hertz.

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