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Hysteresis Torque Analysis of PM Motor Using Initial B-H curve and Tested Core Loss

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This paper presents the hysteresis torque analysis method for the permanent magnet motor using core loss without hysteresis loop. Core loss can be divided into hysteresis loss, eddy current loss, and abnormal loss. If the method of separation is used, hysteresis loss can be calculated by core loss. And, the hysteresis torque is calculated by divide hysteresis loss by speed. The result of hysteresis torque analysis is applied to electrical motor and then compared to result from the experiment.

***Index Terms*—cogging torque, core loss, friction torque, hysteresis torque**

I. Introduction

HYSTERESIS phenomenon is become important in many areas of science and technology, such as permanent magnets, hysteresis motor, magnetic recording and so forth. Many models are known in literatures about hysteresis modeling [1]-[2]. The Preisach model is provides precise prediction of magnetization in the various models for scalar hysteresis models [3]-[4]. Hysteresis phenomenon is inevitable in general electric machines and occurs even without electrical input in permanent magnet motor. Hysteresis loss produces opposite torque against rotation direction and these force called hysteresis torque .

Preisach model of hysteresis has been widely used because of its ability to reproduce the ferromagnetic behavior. Among its advantages there are the compact storage of the applied field history, a satisfactory mathematical formulation [5]

Recently, in order to analysis hysteresis motor hysteresis loop applied to FEM[6] . But the method is complicate to using Preisach model for FEM. In this paper, a simple calculation method of hysteresis loss torque is presented using hysteresis loss data separated from measured core loss data. Fig. 1 shows the cogging torque and hysteresis torque. The maximum of cogging is defined as break way torque, and torque average of total friction is defined as offset torque. Cogging torque means the peak to peak of a periodic. Hysteresis torque is defined as offset torque minus bearing friction torque. This hysteresis torque is generated by hysteresis loss as Fig. 2, which is shows the initial b-h model and hysteresis curve. The area of hysteresis loss is defined as hysteresis loss in magnetic core. In order to compute the hysteresis loss, finite element analysis is used. After calculation of magnetic flux density and their frequency in each element of core using FEA, hysteresis loss is calculated from material hysteresis loss data. The hysteresis loss data is separated from measured core loss by using Steinmets Equation.

In order to verify the simulation result, the experiment equipment is consisted. In order to verify the accuracy of simulation result, hysteresis torque is tested. The experimental method of electric motor of hysteresis torque is similar with cogging torque test. From the cogging torque result, the offset of dc-bias component is defined the sum of hysteresis torque and bearing friction torque. As a result, hysteresis torque is measurable considering cogging and bearing friction in shaft torque. At the result, analyzed results are compared to experimental results with low cogging designed for the electrical power steering (EPS).

Suggested method is more convenient than the method using Preisach model and easy to understand the theoretical background.

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II. Model and Analysis Method

A. Analysis Model

Fig. 3 and Table 1 shows the cross-section and brief specifications of the analysis model. The model is consist 6 pole and 27 slot. The material of stator and rotor is S60 grade.

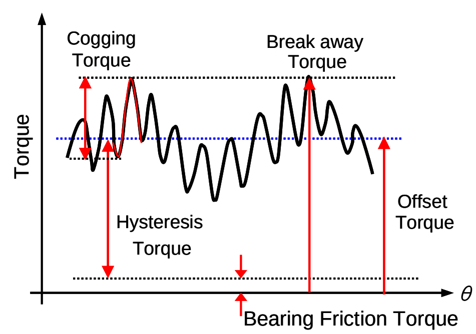

Fig. 1. Cogging torque and hysteresis torque

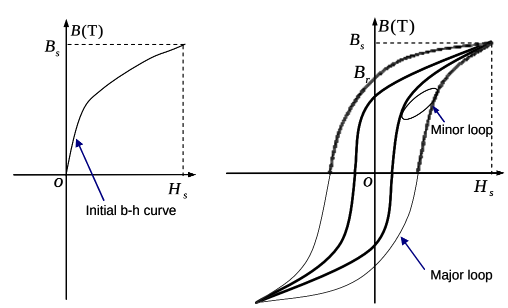

Fig. 2. Initial B-H curve and hysteresis curve

B. Analysis Process and Magnetic Field Analysis

Fig. 4 shows the process of hysteresis torque analysis. The static field FEM is used for the analysis of the magnetic field. The governing equation for 2-D FE analysis is given by (1).

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-J_0-J_m \qquad (1)$$

where, A is the z-component of magnetic vector potential, μ is the permeability, J_0 is electrical input current density and J_m is magnetizing current density. The input current J_0 is not exists in hysteresis torque analysis. Therefore, J_0 is equal to zero.

The loss of power P_{hys_loss} is area of fig. 1. And which value is same as hysteresis loss. The hysteresis torque T_{hys_loss} is can be computed according to

$$T_{hys\_loss}=\frac{P_{hys\_loss}}{\omega} \qquad (2)$$

where, ω is rotational mechanical speed.

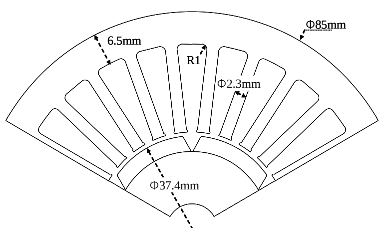

Fig. 3. Cross-section view of 3-phase brushless motor

TABLE I
BRIEF SPECIFICATIONS OF 3-PHASE BRUSHLESS MOTOR

Item	Value	Item	Value
Pole number	6	Magnet Br (T)	1.2
Slot number	27	Recoil Perm.	1.05
Stator outer dia. (mm)	85	Core-Material	S60 (0.5t)
Airgap (mm)	0.8	PM direction	Radial
Stack length (mm)	26	Voltage (Vdc)	12

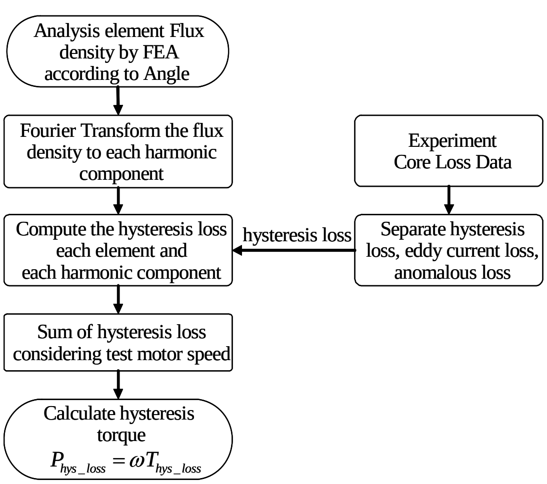

Fig. 4. Process of hysteresis torque analysis

C. Measurement of S60 core loss

Core loss date is provided by manufacturer generally. But, in order to apply to each frequency of harmonic order of flux density, many core loss of wild range is needed. In this paper, the core loss is measured by Epstein tester. Under no load conditions and depending on the motor, magnetic loading can be around 1.5 T, and increases with loading conditions. In this paper, hysteresis torque is measured at 1 rpm very low speed. Therefore, harmonic order is very small frequency range. In this paper, Epstein test method is used for sheet core loss according to magnetic flux density and frequency.

D. Hysteresis loss data

In traditional ac machine theory the core loss is viewed as being caused mainly by the fundamental frequency. Normally, under alternating flux conditions, the iron core is separated into a hysteresis loss, an eddy current component, anomalous loss. Therefore, the core loss is separated using Steinmetz equation as in (3).

$$P_{core}=k_h fB^2+k_e f^2B^2+k_a f^{1.5}B^{1.5}\ \ \text{[W/kg]} \qquad (3)$$

where k_h, k_e, k_a is coefficient of hysteresis loss, eddy current loss, anomalous loss respectively. In eq.(3) the coefficient of eddy current and anomalous is very small in low frequency. In test result, the core loss is proportion to frequency below 10Hz because the eddy current loss is small. Fig. 5 shows the hysteresis loss separated from core loss and fig. 6 shows flow chart for hysteresis computation.

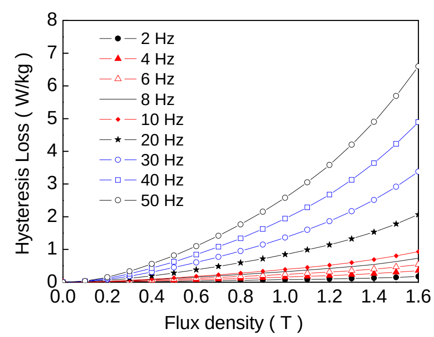

Fig. 5. Hysteresis data separated from core loss

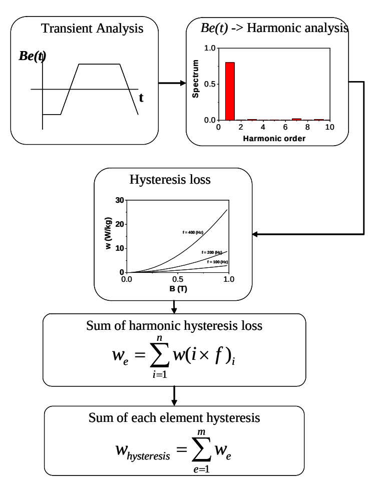

Fig. 6. Flow chart for hysteresis loss calculation

III. ANALYSIS RESULT

A. FEA element and magnetic circuit

In order to analysis using FEM, triangular mesh is used as shown in fig. 7. Total modeling angle is 120°. Fig. 8 shows the equi-potential line which state is no load for cogging torque analysis. Fig. 9 shows the flux density in P1, P2 position of Fig. 8. Fig. 10 shows the magnitude and harmonic order of flux density of Fig. 9.

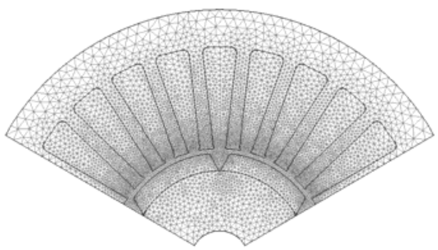

Fig. 7. Triangular mesh for analysis (element=12644, node=6516)

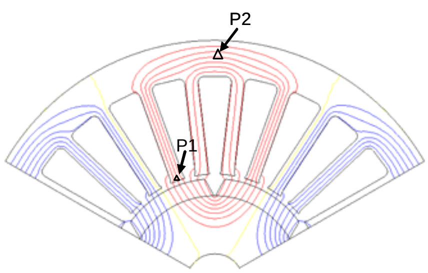

Fig. 8. Equi-potential line of analysis model

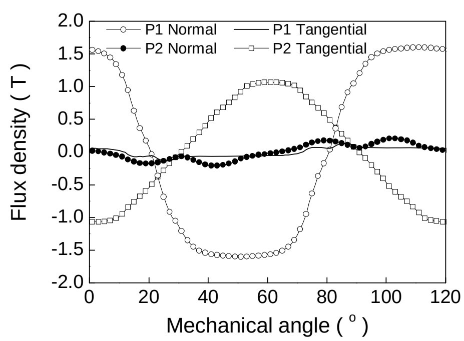

Fig. 9. Flux density of each direction of P1 and P2

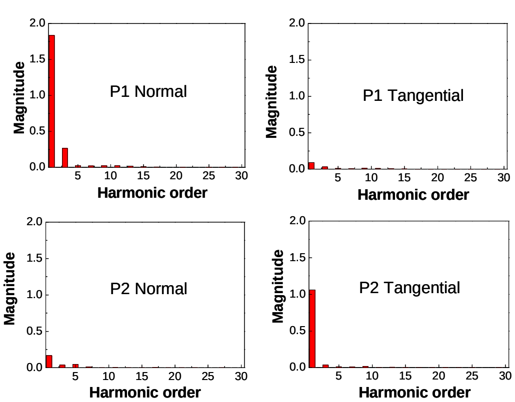

Fig. 10 Flux density of each direction of P1 and P2

Fig. 10 shows the tangential and normal components of the magnetic flux density waveforms at the stator yoke. It is shows the some slot effect and space harmonic component. In hysteresis point of view, this harmonic component is small magnitude and high frequency compared with high magnet rotational speed.

B. Hysteresis loss distribution

Fig. 11 shows the hysteresis loss density distribution of permanent magnet motor designed for EPS. The hysteresis loss of rotor is similar to zero. Almost hysteresis loss distribute in stator teeth and stator. The simulation is performed at 30 rpm because the minimum frequency of measured core loss data is 2Hz. Hysteresis loss is proportion to frequency, it is possible to neglect. Total hysteresis torque is 30rpm 2.4 mW.

IV. EXPERIMENT AND DISCUSSIONS

A. Measurement Equipment

Fig. 12 shows test equipment, the ATM-2 is cogging torque measurement equipment. This machine measure the cogging torque and bearing friction torque.

Fig. 4 shows the FEM result and FFT result of flux density in P1. Hysteresis loss distribution is shown in Fig. 5. High density hysteresis losses exist in tooth. And hysteresis loss of rotor is almost zero because there is few flux variation. Fig. 6 shows comparison between the experimental result and simulation result. In the test result, cogging torque is very small about 2.5mNm and the offset of torque is 13.8mNm, the mechanical friction is included in the offset. The simulated hysteresis torque is 13.4 mNm. The difference between simulation result and tested result are expected to the friction torque.

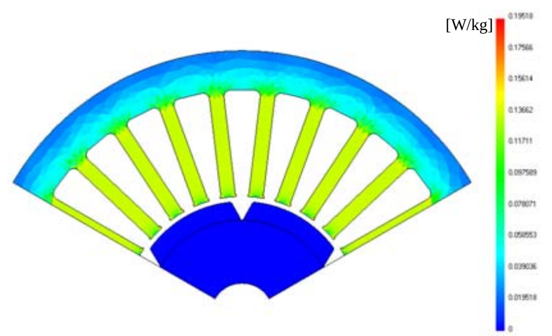

Fig. 11. Hysteresis loss distribution of permanent magnet motor

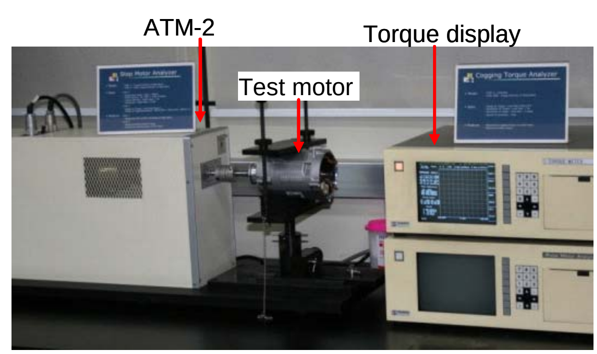

Fig. 12. Equipment for measure the cogging and bearing friction

B. Comparing Simulation and Test Result

Fig. 13 Table II shows comparison the simulation result and the tested result. In the test result, cogging torque is very small about 2mNm and the offset of torque is 13.9mNm, the measured mechanical friction is 1.1 mNm. The simulated hysteresis torque is 11.5mNm.

V. CONCLUSION

In this work, hysteresis torque is obtained from hysteresis loss which is separated from the core-loss experiment. This method is much simple than Preisach model and the result is similar experiment and analysis result.

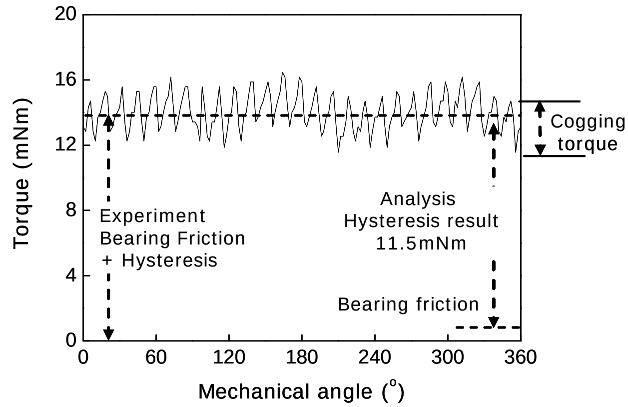

Fig. 13. Equipment for measure the cogging and bearing friction

TABLE II
COGGING TORQUE OFFSET AND HYSTERESIS TORQUE

Item	Unit	Simulation	Measurement
Cogging torque	mNm	3.2	3.6
Offset torque	mNm	-	13.9
Bearing friction torque	mNm	-	1.1
Hysteresis loss	mW	2.4	-
Speed	rpm	2	2
Hysteresis torque		11.5	12.8

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