FE Analysis of Hybrid Stepping Motor (HSM)

Ki-Bong Jang* and Ju Lee†

Abstract - Though full 3D analysis is the proper method to analyze the hybrid stepping motor (HSM), it has weak points in the areas of computation time and complexity. This paper introduces 2D FEA using a virtual magnetic barrier for the axial cross section to save computation time. For the purpose of 2D FEA, the virtual magnetic barrier and equivalent permanent magnet model of HSM are proposed. This result is compared with that of experimental and 3D analysis, considered as a reference result.

Keywords: Cogging torque, Finite Element Analysis, Hybrid stepping motor

1. Introduction

Generally stepping motors are used widely in OA and FA applications. Among the various types of stepping motors, the type containing a permanent magnet rotor and many teeth both on the stator and rotor poles is called the hybrid stepping motor (HSM). HSMs are most commonly used in the industry because they have high torque and resolution advantages compared with other types of stepping motors.

The HSM was originally designed as an ac two phase synchronous motor for low-speed applications. Theoretically, the motor can be considered as a multi-pole synchronous motor. Recent demand for a low-speed, high-torque motor makes the HSM more attractive compared to the conventional ac motors such as induction motors and synchronous motors.

However, unlike the conventional ac motors, the HSM does not have a clear equivalent circuit for analysis, which makes it difficult to design an appropriate system and to estimate the corresponding characteristics.

Since the HSM has a great number of small-teeth on the stator and rotor surface and very small air gap, the magnetic saturation in the teeth becomes severe when the flux density is increased in the air gap. In addition, both radial and axial flux is produced because of the axially magnetized permanent magnet and geometric characteristics [1-3]. These make the analysis of the HSM more difficult. 3D Finite Element Analysis (FEA) is one of the solutions for the non-linear analysis of the HSM under these circumstances, but a large amount of computation time is necessary.

FEA is used extensively for the design and performance prediction of all types and topologies of the permanent magnet type machine and for calculating field distributions, winding inductances, back-emf waveforms, torque and force, and demagnetization withstand of magnets. Usually, FEA complements analytical techniques, which can provide a rapid and reliable means of design optimization [4].

This paper introduces the virtual magnetic barrier and the virtual equivalent permanent magnet magnetized in the radial direction for the 2D FEA of the HSM.

2. HSM model and Analysis

Fig. 1 shows the basic construction of a 2-phase HSM having 8 stator poles with 6 teeth per pole and 50 teeth on the rotor. The permanent magnet is magnetized in the z-direction. The step angle of this motor is 1.8°, the period of cogging torque is 3.6°and the airgap length is 0.05mm. Further details are presented in Table 1.

2D FE analysis of the HSM is essentially impossible because of its geometrical characteristic. To analyze the HSM by 2D method, various techniques must be considered. In order to calculate the torque of the HSM with 2D analysis, the permanent magnet in the HSM is replaced to an equivalent virtual magnet that is axially magnetized and the virtual magnetic barrier on both sides cause the magnetic flux to be oriented in the radial direction. This produces correct flux distribution.

2.1 Equivalent Permanent Magnets

The permanent magnet of the HSM is magnetized in the axial direction, but this paper assumes that the permanent magnet is magnetized in the radial direction without the change of size, and calculates the equivalent value of the remanence Br and recoil permeability μr in the simplified

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circuit of the permanent magnet shown in Fig. 2.

The demagnetization segment of the BH curve and equivalent circuit are shown in Fig. 2 (a). It illustrates that a simplified circuit model in Fig. 2 (b) of a permanent magnet in use is really equivalent.

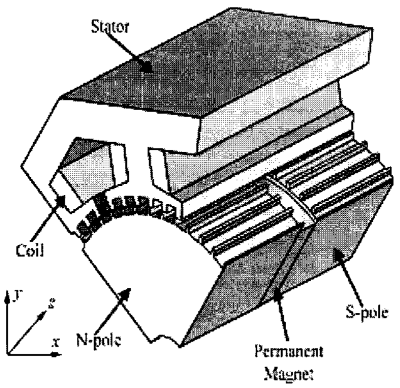
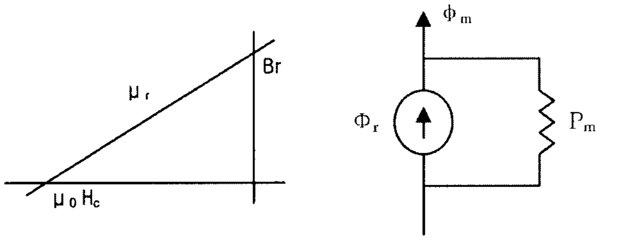


Fig. 1 The basic construction of a 2-phase HSM



(a) (b)

Fig. 2 (a) demagnetization segment. (b) simplified equivalent circuit

Table 1 The specifications of HSM.

Stator		
	Pole number	8
	Teeth number per pole	6
	Phase number	2
	Turns per phase	38
	Inner diameter	13 (mm)
	Outer diameter	21 (mm)
Rotor		
	Teeth number	50
	Outer diameter	12.95 (mm)
	Residual flux density	1.2 (T)
	Airgap length	0.05 (mm)
Magnet		
	Outer radius	9.75 (mm)
	Inner radius	2.50 (mm)
	Thickness	2.0 (mm)

The shape of permanent magnet used in FEA is just as shown in Fig. 3, and the dimension is indicated in Table 1.

Where, the permeance and flux in the radial direction, and the axial direction are as follows [5];

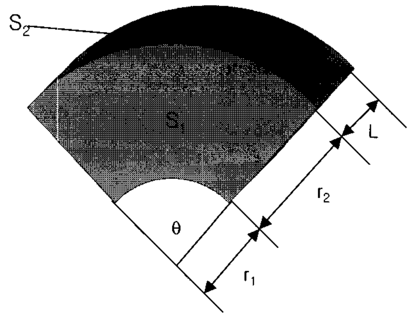


Fig. 3 The Shape of permanent magnet

$$P_{r\_radial} = \frac{\mu_0 \mu_r L\theta}{\ln(1 + r_2 / r_1)} \quad (1)$$

$$\phi_{r\_radial} = B_r L\theta \cdot r_1 \quad (2)$$

$$P_{r\_axial} = \frac{\mu_0 \mu_r S_1}{L} \quad (3)$$

$$\phi_{r\_axial} = B_r S_1 \quad (4)$$

Where, the two permanent magnets are equivalent under the condition of

$$P_{r\_radial} = P_{r\_axial}, \quad \phi_{r\_radial} = \phi_{r\_axial}.$$

So, the new equivalent remanence Br and recoil permeability μr can be achieved by solving the simultaneous equations of

$$P_{r\_radial} = P_{r\_axial}, \quad \phi_{r\_radial} = \phi_{r\_axial}.$$

The new equivalent values are used in 2D-FEA.

2.2 Virtual Magnetic Barrier

The actual flux flow is as follows; N pole of PM – N side of rotor tooth – airgap – stator tooth – stator – stator tooth – airgap – S side of rotor tooth – S pole of PM.

However, this paper adds the virtual magnetic barriers on both sides as shown in Fig. 4, and they cause the magnetic flux to be oriented in the radial direction. At this point, the following assumption is needed.

<assumption>

The permeability of the virtual thin magnetic barrier is so small that the flux scarcely passes the barrier.

2.3 2D-FEA

Most of the MMF drop is due to the airgap of the HSM and it is important to describe the flux distribution around the airgap when FEA is used. Fig. 4 shows the flux distribution in the pole of the HSM as a result of 2D FEA using the virtual magnet barrier. Although the flux route in the 2D model is different from that of the actual situation, the flux distribution in the airgap is very similar to that of the real one. That is due to the virtual magnetic barrier placed at both sides of the magnet and the virtual equivalent permanent magnet in the radial direction.

The calculation of detent torque, one of the static characteristics of the HSM, is based on the Maxwell stress tensor method. According to the rotor position angle, the detent torque is calculated by moving the rotor teeth region.

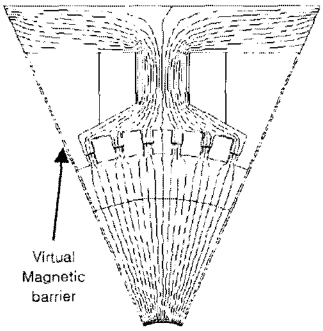


Fig. 4 Flux distribution by 2D FEA

2.4 Simulation Result

The analysis model has 4 pole pairs on the stator, and the mechanical angle between rotor teeth and stator teeth is 1.8 degrees. When one pair of poles is aligned with the rotor, the others are always positioned on the 1.8, 3.6, and 5.4 degree difference with the rotor, respectively. So, if the torque of one pole is calculated, then the others could be calculated by shifting them by 1.8, 3.6, and 5.4 degrees, respectively. The result of 2D-FEA is shown in Fig. 5. The strong line indicates total torque, which is the sum of torque at 0, 1.8, 3.6, and 5.4 degrees, respectively.

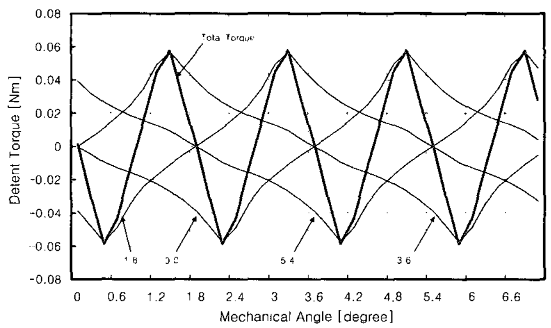


Fig. 5 Detent torque by 2D FEA

2.5 Experimental Result

In order to obtain the detent torque of the HSM, the experimental setup is composed of a pulley, a string, a weight, and a position detector with a DSP based measurement system as shown in Fig. 6.

The resolution of the position detector is 0.036°. Despite high resolution, only one fourth of the period can be successfully measured by the above shown equipment due to the nature of the detent torque. Detent torque is measured by the weight.

Due to the very small detent torque and step angle, the experimental result may have some tolerance. The results are an average value of several measurements.

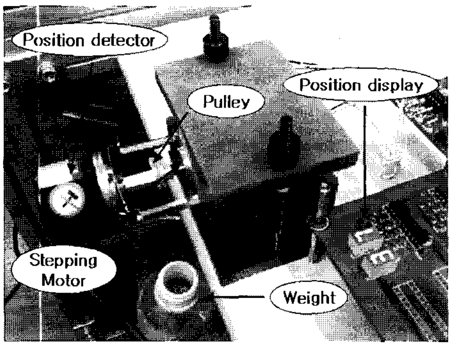


Fig. 6 Experimental setup

3. Conclusion

2D analysis studies only a cross section of the method, but on the other hand, 3D analysis must examine the entire model. Therefore, the number of nodes to be calculated is increased, and the computing quantity is dramatically increased as well. It is not possible to carry out 2D analysis for the HSM because of structural problems. However, this paper presents the 2D analysis method using a virtual magnet and barrier. The proposed method can reduce the computing time by about 1/30, in the case of the HSM.

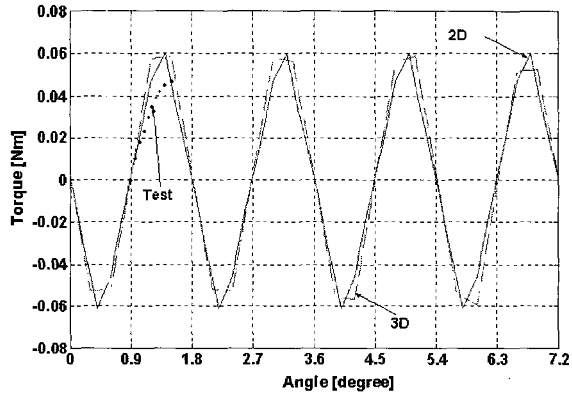


Fig. 7 Detent Torque of HSM

Fig. 7 indicates the detent torque of the HSM, which is calculated by 2D analysis. This result is compared with that of experimental and 3D analysis, considered as a reference result.

Accuracy is sufficient to assess that the suggested method, considering magnetic saturation, realizes a good compromise between simulation time and precision.

Acknowledgements

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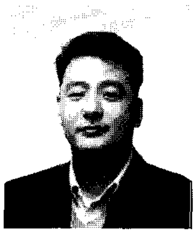

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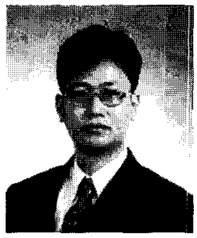

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