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Analysis of the Thickness Effect for Hysteresis Ring of Hysteresis Motor with Vector Hysteresis Model

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Abstract

This paper presents the thickness effect of hysteresis ring of hysteresis motor using finite element method combined with a vector hysteresis model. From the magnitude and direction of the magnetic field intensity, the magnetization of each ring element is calculated by a vector hysteresis model. The developed torque can be obtained with the vector sum of individual torque of each element on the hysteresis ring. From these calculations, it can be found that the motor torque is not in proportion to the thickness of the ring. As a result, there exists a proper point of thickness and that can be determined using the proposed metho○ in this paper.

Key Words : Hysteresis motor, Vector hysteresis mode, Rotational hysteresis, Finite element method

1. Introduction

Hysteresis motor is a kind of self-starting synchronous motor that uses the hysteresis characteristics of the semi-hard magnetic materials. So far, it has not been an easy problem to determine the adequate thickness of the hysteresis ring in the hysteresis motor, and in most cases it has been depending on experimental results[1]. The motor torque has been calculated by the area of hysteresis loop determined by the field intensity in the ring. However, these values are not always in accordance with the experimental ones, except the fact that only the thickness of the ring is very thin[2]. It means that the hysteresis ring which is a part of the rotor is affected by the rotational hysteresis caused by the stator windings, and that the direction of the magnetization of each element of the ring is different from that of the magnetic field or magnetic flux density. That is to say, the thicker the hysteresis ring becomes, the larger the rotational hysteresis increases and what is worse is that the output of the thicker ring motor becomes less than that of thin rotor motor. The reason of these phenomena seems to come from the existence of rotating hysteresis in the hysteresis ring. Hence for an accurate analysis of the motor, a vector hysteresis model which can consider the vector magnetization according to the history of the applied field is required.

In this study, a vector model[3, 4] which can calculate vector hysteresis for any vector fields

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with the magnitude either varying or not is adopted. Besides, a finite element analysis(FEA) employing vector hysteresis model is used to calculate the magnetic state on the hysteresis ring. From this process, the motor torque can be calculated by the hysteresis loop considering the vector hysteresis or the vector sum of individual torque of each element. In the previous study[5], this method could calculate the motor torque with acceptable precision. The simulation results in this study show that there exists an optimum thickness of the hysteresis ring and it can be calculated analytically.

2. Hysteresis motor

Hysteresis motor consists of a polyphase stator and a rotor which contains hysteresis ring. In most of the cases, a semi-hard magnetic material is used for the hysteresis ring. Fig. 1 shows the basic structure of the motor. The performance of the motor is determined by the hysteresis characteristics of this ring. In analytical methods, it is assumed that the directions of magnetic field and flux in the ring are only circumferential. That means, the directions of magnetic field and magnetization in the ring are aligned. In this condition, the motor torque is in proportion to the volume of the ring. From the experimental results[3], however, it can be seen that the torque may decrease even though the thickness becomes relatively larger.

It is well known[5] that there exists rotational hysteresis in the hysteresis ring and that the direction of the magnetization of each ring element is different from that of the magnetic field or magnetic flux density. However, if the scalar hysteresis model or the conventional analytical methods are used to analyze the motor performance, it is assumed that only the circumferential component of the flux exists. This is true on the condition that the thickness of the ring is very thin and the torque of the motor is just proportional to the volume of the ring. Fig. 2(a) shows the case which can ignore the rotational hysteresis.

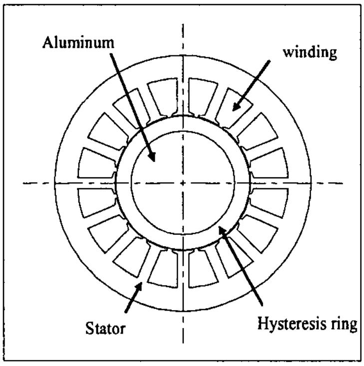
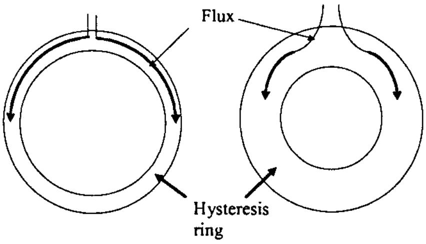


Fig. 1. Structure of hysteresis motor

If the thickness becomes larger, the rotational hysteresis can not be ignored and the direction of the magnetization is no more aligned to that of the field and that both circumferential and radial components of the flux exist as shown in Fig. 2 (b). Therefore, for an accurate analysis or proper design of the motor, it is necessary to use the vector hysteresis model which can consider the rotational hysteresis in the hysteresis ring and that this model also needs to be combined with FEM for accurate calculation.



(a) thin ring (b) thick ring

Fig. 2. Flux patterns in the hysteresis ring.

3. Vector hysteresis model

The directions of the magnetic field and the magnetization are same in the scalar hysteresis models and these kind of hysteresis models can not consider the rotational hysteresis. To design a hysteresis motor, one of the very important tasks is to determine the thickness of hysteresis ring caused by the rotational hysteresis. Therefore to describe the relationship between the rotational magnetic field and the magnetization, vectorially, the hysteresis model should be able to calculate not only the magnitude but also the direction of the magnetization according to the field variation. One of such vector models is the vector magnetization-dependent model[4]. In this model, the magnetization is expressed as

$$\vec{M} = f(\vec{H}_t) = f(\vec{H}_a + \zeta\vec{M}) \qquad (1)$$

where $\vec{M}$: magnetization, $\vec{H}_t$: total field, $\vec{H}_a$: applied field, ζ : magnetization-dependent constant.

Because this model is originally expanded from the Preisach model[6], it has Preisach density function $\rho(a_t, b_t)$ which is the function of the upper and lower switching fields a_t and b_t for total field H_t. The density function is integrated vectorially for the plane under $b_t = a_t$ to get the vector magnetization. This is expressed as in the follow equation.

$$\vec{M} = dint_{a_t \le b_t} \rho(a_t, b_t)\vec{r}_{a_t b_t}\vec{H}_t da_t db_t \qquad (2)$$

$\vec{r}_{a_t b_t}$: vector Preisach operator for the total field.

In the classical Preisach model, the Preisach operator has just a sign to represent the + or - direction of the dipole. In the vector model, the vector Preisach operator can have any direction, which means that the dipoles of the Preisach elements have not only the density but also the rotating ability caused from the applied field.

Though the magnetization in (2) is a function of the total magnetic field, the magnetization which can be assumed as a function of the applied magnetic field can be calculated using (1) and by an iterative method[4].

4. Torque calculation

The constitutive equation for the magnetic material is expressed as follows:

$$\vec{B} = \mu_0\vec{H} + \vec{M} \qquad (3)$$

From equation (3), the governing equation to be solved becomes

$$\nabla\times(\nabla\times\vec{A}) = \mu_0\vec{J} + \nabla\times\vec{M} \qquad (4)$$

Using Galerkin's weighted residual method, after assembling the system matrix, a set of non-linear equations to be solved is obtained. That is, from (3) and (4) the magnetization M is related to the magnetic flux density and also to the unknown magnetic vector potential A. Therefore a set of non-linear equations for the unknown variable, A, is composed. Such a system of equations can be solved by an iterative method.

Using the initial magnetization and the flux density calculated by the FEM, the magnetic field intensity is calculated from (5).

$$\vec{H} = \frac{1}{\mu_0}(\vec{B} - \vec{M}) \qquad (5)$$

Equation (5) reveals that a small variation in the magnetization results in a large change in H. To overcome this problem a, pseudo - permeability is introduced and (3) is changed as follows:

$$\vec{B}=\mu_0(1+\mu_{sp})\vec{H}+\vec{M}_{sp} \tag{6}$$

$$\mu_{sp}=M_s/(\mu_0 H_s) \tag{7}$$

where $\vec{M}_{sp}=\vec{M}-\mu_0\mu_{sp}\vec{H}$, μ_{sp} : pseudo permeability, M_s : saturation magnetization, H_s : saturation field intensity.

In this case μ_0 and M in (4) are replaced by $\mu_0(1+\mu_{sp})$ and M_{sp}, respectively, and these are the input to the finite element analysis.

Fig. 3 shows the flowchart for the calculation. Here, the convergence criterion is checked by the relative error of the magnetic field intensity H. If the finite element solution is obtained, the torque of the motor can be calculated by two methods; the area of hysteresis loop and the summation of each element's torque.

4.1 Area of hysteresis loop

The maximum flux density Bmax of the circumferential flux component on the ring can be obtained from the calculation results. From this datum and by the hysteresis model, such as the Preisach model, the hysteresis loop whose maximum flux density is $B_{\max}$ can be made. Because the torque of hysteresis motor is proportioned to the area of the loop, the torque of the motor can be simply calculated by [5]

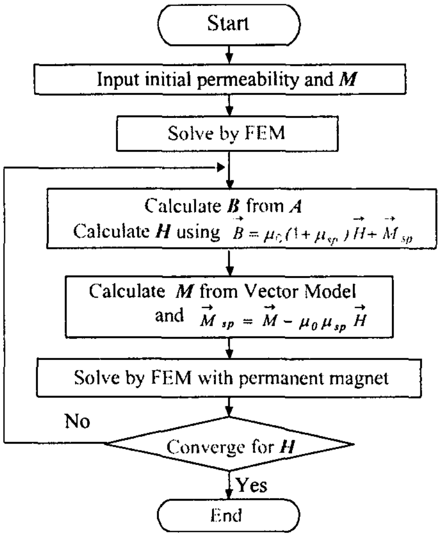


Fig.3. Flowchart for the proposed method

$$\tau=\frac{1}{2\pi}V_r E_h \tag{8}$$

where TAU : number of pole pairs, V_r : volume of hysteresis ring, E_h : area of the hysteresis loop.

4.2 Summation of each element torque

The torque of i-th element can be calculated by the follow equation[7],

$$\vec{\tau}_i=\vec{B}_i\times\vec{H}_i \tag{9}$$

where $\vec{B}_i$ and $\vec{H}_i$ is the flux density and magnetic field of i-th element. These values can also be obtained from the results of the FEA and the vector sum of these torques for the circumferential direction means the mechanical torque of the hysteresis motor.

5. Simulation and results

Table I and II show the specifications of the tested motor. The rated output was 3[W], the voltage was adjusted to 110[V] at the current of 0.12[A]. In this case, the inner diameter was 22.6[mm] and the thickness of rotor was 3.5[mm] with the thickness rate of 1.31.

Table 1. Stator specification(2phase 4 poles)

No. of phase	2	No. of poles	4
No. of winding	2280	winding factor	0.85
No. of slot	16	inner diameter	30 [mm]
Axial length	28 [mm]		

Table 2. Rotor specification

Inner diameter	22.6[mm]	Thickness	3.5[mm]
Axial length	28.1[mm]	Air gap	0.2[mm]

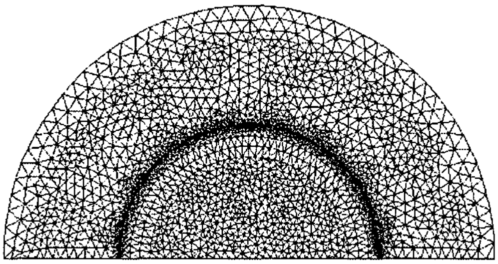


Fig. 4. Mesh diagram of the motor

Fig. 4 shows the mesh diagram of the motor. A half of the motor is analyzed because the number of poles of the tested motor is 4 and there is symmetry. The number of elements is 5669 with that of the nodes being 2893. At the first stage of the analysis, it was assumed that the permeability of each element on the ring was identical and the initial magnetization M was zero. At the next step, the magnetization of each element was calculated from the previous and present H using the vector hysteresis model. In the analysis flow, the convergence to the solution was checked using the following equation.

$$\frac{H_i^{(n+1)} - H_i^{(n)}}{H_i^{(n+1)}} < \varepsilon \qquad (10)$$

where n is the iteration step, i is either x or y component, and ε is the convergence criterion.

Fig. 5 shows the equi-potential lines when the amplitude of the current is 103 mA and the phase angle is 0 degree. As shown in the figure, the results are just for the half of the motor and that the flux makes only 2 poles because the motor has a total of 4 poles.

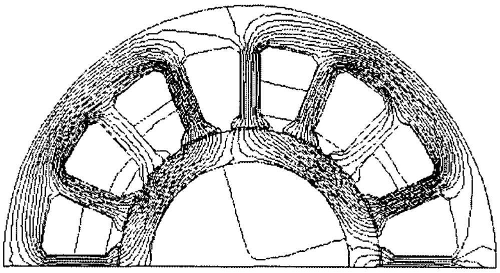


Fig. 5. Equi-potential lines of hysteresis motor

From these results, the direction and amplitude of the flux density and magnetization for each element can be obtained, and the torque can be calculated with equation (8) or (9). Fig. 6 shows a comparison of the average torque obtained by simulation and by experiment. It is found that the simulation results show a very good agreement with the experimental ones.

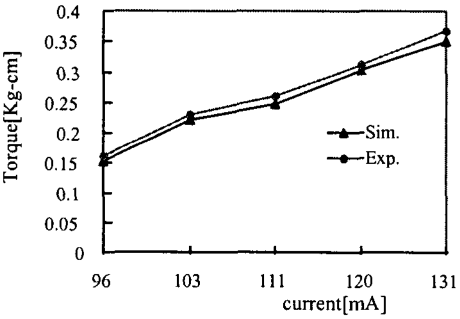


Fig. 6. Comparison of the average torque

Because the used method can explain the hysteresis phenomena well, we can simulate the hysteresis motor torque for the thickness of the hysteresis ring with confidence. Fig. 7 shows the motor torque as calculated by the proposed method. In the classical methods, if the volume increases, the output also increases. However from Fig. 7, it can be seen that if the ring is too thin, the torque will be very small because the volume of the ring also becomes small, and although the volume of the ring increases, the torque can decrease according to the ring thickness.

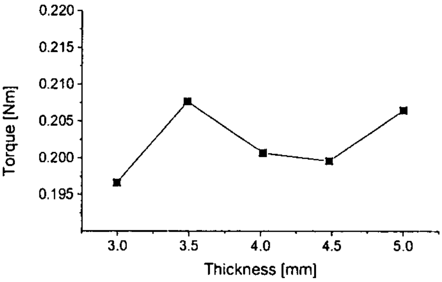


Fig. 7. Torque for current=100[mA]

6. Conclusions

In this paper, the thickness effect of hysteresis ring has been analyzed. Because of the rotational hysteresis, the hysteresis motor torque is not in proportion to the ring volume and it is needed to determine the proper thickness of the hysteresis ring. This problem can be solved by using a finite element analysis combined with vector hysteresis model for accurate analysis of the hysteresis motor. The method can consider the rotational hysteresis effects which the scalar hysteresis model cannot deal with. Comparing the simulation results with the experimental ones for a given thickness, it has been found that the FEA is very reasonable. So from these results, it was confirmed that there exists a proper rate for inner and outer radii of hysteresis ring and that can be calculated with the finite element method coupled with a vector hysteresis model. The proposed method can be applied to other magnetic systems where the rotational hysteresis characteristics must be considered.

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Biography

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Sun-Ki Hong was born in Seoul, Korea, on January 24, 1965. He graduated from the Department of Electrical Engineering, Seoul National University in 1987. He received his M.S. and the Ph.D in electrical engineering from Seoul National University in 1989 and 1993, respectively. He became a Member of IEEE in 1993 and worked as a researcher at REX industrial Co., Ltd. from 1993 to 1995. He has been teaching at the School of Electrical Engineering, Hoseo University since 1995. His special interests is the modeling and computation of hysteresis. His present interests include the fields of design and analysis of electric and field analysis of magnetic field system with finite element method considering hysteresis.