1997年度 定期總會 및 秋季學術大會 論文集 1997.11.29

링내 회전자계를 고려한 히스테리시스 전동기의 유한요소해석 기법에 관한 연구

A Study for Finite Element Analysis of Hysteresis Motor Considering the Rotational Hysteresis in the Ring

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Abstract : This paper presents finite element analysis algorithm combined with vector hysteresis model for accurate analysis of the hysteresis motor. Magnetization-dependent vector model is adapted to calculate the vector magnetization. That is to say, from the magnitude and direction of the magnetic field intensity, the magnetization of each ring element is computed by the vector model. By comparing the simulation results with the experimental ones, it is found that good results are obtained`

.1. Introduction

Hysteresis motor is a self-starting synchronous motor that takes use of the hysteresis characteristics of magnetic materials. It is known that the motor could be easily affected by space harmonics due to the effects of the slot, current and winding distributions. To consider those effects, it would be desirable to adopt the finite element method(FEM) in analyzing the motor.

The hysteresis ring is affected by the rotational magnetic field caused by the stator winding so the direction of the magnetization of each ring element is different from that of the magnet field or magnetic flux density. Hence for an accurate analysis of the motor , the vector hysteresis model is required.

With respect to the hysteresis model, the Preisach model is one of the most powerful tools to describe the hysteresis behavior[1]. But the classical Preisach model has some problems and to overcome these problems many Preisach-based hysteresis models were proposed[1,2,3]. Moreover to explain the rotational hysteresis character-istics, many vector models have been presented. One of those models is Hong's model[4,5] which can calculate vector hysteresis for any vector fields with the magnitude varying or not.

In this paper, a finite element analysis(FEA) algorithm is proposed to calculate the magnetic state on the hysteresis ring of the hysteresis motor. In the FEA routine, the magnetic flux density of each ring element is calculated using the magnetization obtained from the vector hysteresis model. And in the vector model, the magnetization is computed from the magnitude and the direction of the magnetic field intensity.

2. Hysteresis Motor

Hysteresis motor consists of stator and hysteresis ring which is a part of the rotor. The structure of the stator is similar to that of general AC motors like induction or syncronous motors. The hysteresis ring is usually semi-hard magnetic material. Fig.1 shows the basic structure of a hysteresis motor. As shown in the figure, the rotor has just a cylindrical structure so that a merit of this motor is low speed regulation. The motor has self-starting ability without special starting device and it rotates synchronously according to the input frequency.

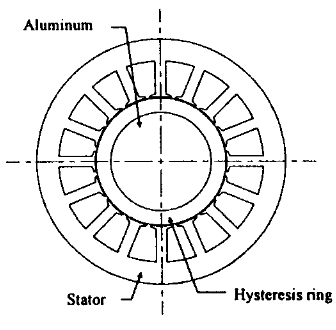


Fig.1 Structure of hysteresis motor

The hysteresis ring is affected by the rotational magnetic field caused by the stator winding so the direction of the magnetization of each ring element is different from that of the magnet field or magnetic flux density. Therefore, in order to get the informations of magnetic states on each part of the ring, it is necessary to develop an algorithm combined FEM with the vector hysteresis model.

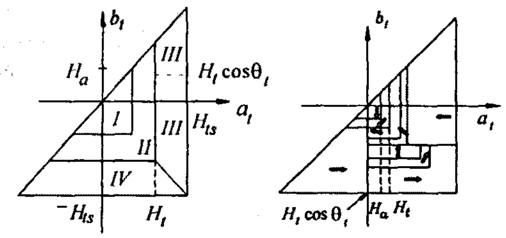
3. Vector Hysteresis Model

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 spatial distribution of the magnetization according to the field variation. One of such vector models is the vector magnetization-dependent Preisach model[4,5]. In the model, the magnetization is expressed as follows:

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

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

Fig. 2(a) shows the vector Preisach plane configuration for H_t when the applied field increases from the demagnetization state to H_a and the applied field rotates with constant magnitude. Let a_t and b_t be the upper and lower switching fields and θ_t be the phase angle of H_t.



(a) (b)

Fig. 2 The Preisach plane configuration for the total field.
(a) when the applied field increases from the demagnetization state to H_a
(b) after the applied field rotates subsequently.

Elements in region I have $a_t < H_a$ and their magnetization rotates reversibly with the same orientation as the field. Elements in region II have $H_a < b_t < a_t < H_t$, and rotate irreversibly with an lagging angle θ for the applied field. Elements in region III and IV with $H_t < b_t$ maintain their previous orientation, but the border between region III and IV moves as the total field component parallel to that orientation changes. It means that the variations of the border in the region III and IV is followed by the scalar magnetization-dependent model.

When the applied field rotates in the materials, the Preisach elements also rotate. If the magnitude of the field changes, new regions are formed and the elements out of the affection of the total field maintain their previous states. Fig. 2(b) shows the variations of Preisach diagram followed by $\vec{H}_a$ when $\vec{H}_a$ rotates as $H_1(1 + k \sin 6)$ where 6 is the phase angle of the applied field and H_1 is an arbitrary positive value, and k is a value of $0 < k < 1$, where 6 varies from 0° to 270°. In conclusion, the magnetization can be represented as follows whether the applied field is elliptical or not.

$$\vec{M} = \iint_{a_t \le b_t} \rho(a_t, b_t)\, \vec{\gamma}_{a_t b_t}\, \vec{H}_t \, da_t \, db_t \tag{2}$$

$\gamma_{a_t b_t}$: vector Preisach operator for the total field

Equation (2) means that the vector magnetization is the vector sum of the density functions $\rho(a_t, b_t)$ on the Preisach plane. Though the magnetization in (2) is the function of the total field, the magnetization which is the function of the applied field can be calculated using (1) and iterative method[5].

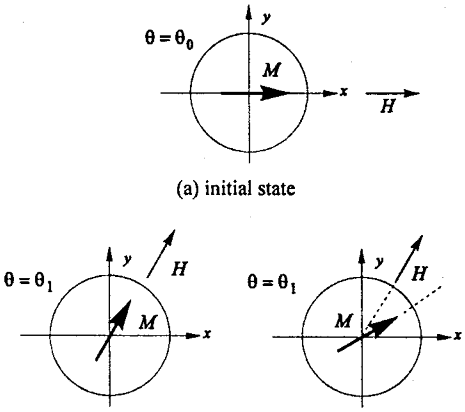
4. Proposed Algorithm

A. Magnetization Characteristics

If the rotational component of the magnetic field exists, the direction of the magnetization generally differs from that of the magnetic field in the magnetic materials because of the presence of rotational hysteresis. Obviously hysteresis motor undergoes the rotational hysteresis in the hysteresis ring. Hence, for the accurate analysis of the motor characteristics the magnetization is to be computed vectorially.

In the meanwhile, most of FEM did not take into account the hysteresis phenomena. Conventional FEM just considers the saturation effect only by using the initial magnetization curve of the magnetic materials. Some papers proposed the calculation method of the magnetization considering the effect of the hysteresis with a scalar model or a vector model that ignores the rotational hysteresis[6,7]. When the applied field rotates, although the lagging of the magnetization for the field exists like Fig. 3(c), the conventional methods could not explain these phenomena and the result becomes Fig. 3(b). Thus to get the exact magnetic state of the magnetic material was difficult.

Therefore, to obtain the accurate magnetization state of the hysteresis ring and to analyze the motor performance, an appropriate vector hysteresis model should be combined with FEM. The used vector model in this study[4,5] showed that it could calculate vector hysteresis when the magnetic field with varying magnitude rotates.



(a) initial state

(b) the state by conventional method (c) real state

Fig. 3 Magnetization characteristics

B. Finite Element Implementation

The constitutive relationship of the magnetic material is expressed by (3).

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

From this equation, the governing equation to be solved becomes (4).

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

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

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

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

(5) reveals that it is possible that small variation of M makes H change seriously and eventually convergence process becomes unstable. To avoid the unstability, pseudo- permeability is introduced and (3) is changed as follows:

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

where $\vec{M}_{sp} = \vec{M} - \mu \vec{H}$, μ_{sp} : pseudo-permeability

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

Fig.4 shows the flow chart for the proposed method. Here convergence criteria is checked using H.

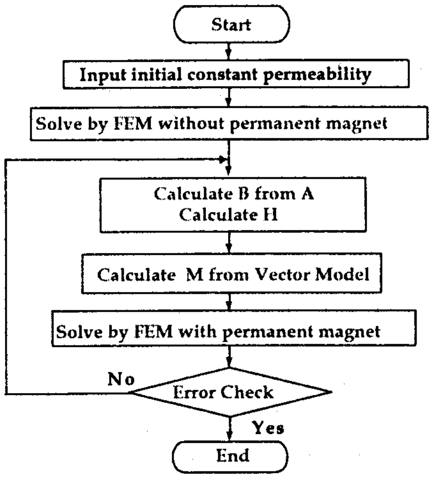


Fig.4 Flow chart for the proposed method

5. Simulation and Results

Table I and II show the specification of the tested motor. Because the number of poles is 4, the ring has two major hysteresis loops.

TABLE 1
STATOR SPECIFICATION (2 phase 4 poles)

no. of phase	2	no. of poles	4
no. of winding	2280	winding factor	0.8536
no. of slot	16	inner diameter	30[mm]
effective thickness	28 [mm]		

TABLE 2
ROTOR SPECIFICATION

outer diameter	29.6 [mm]	thickness	3.5 [mm]
axial length	28.1 [mm]	air gap	0.2 [mm]

Fig.5 shows the mesh diagram of the sample motor. a half of the motor is analyzed because of the symmetry. At first stage of analysis, the permeability of each element on the ring is the same and initial M is zero. At the next step, magnetization of each element is calculated from previous and present H using vector hysteresis model. In the analysis procedure, convergence is checked using (7). So iteration calculation stops when both x and y component of H are satisfied with (7).

$$\frac{H_i(n+1) - H_i(n)}{H_i(n+1)} < e \qquad (7)$$

where, n is iteration step, $i = x$ or y, e: convergence criteria

Fig.6 shows the equi-potential lines when the amplitude of the current is 103 [mA] and 131[mA] and the phase angle is 0 degree. As shown in the figure, the results are for a half of the motor and the flux makes 2 poles because the motor has 4 poles.

From the calculation results, the torque is computed by the virtual work method. Fig.7 shows the average torque obtained by the simulation and experiment. It is found that the simulation result shows very good agreement with the experimental one.

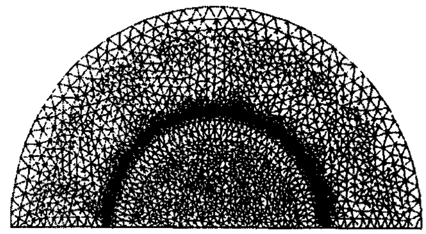
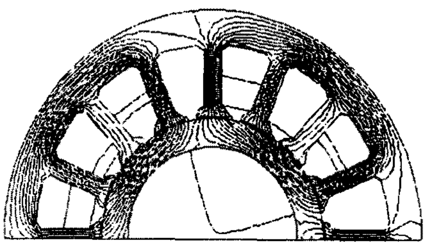
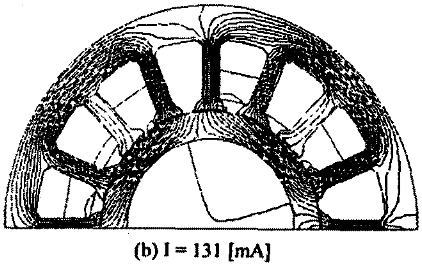


Fig.5 Mesh diagram of the motor



(a) I = 103 [mA]



(b) I = 131 [mA]

Fig.6 Equi-potential lines of hysteresis motor

6. Conclusion

In this paper, finite element analysis algorithm combined with vector hysteresis model is presented for accurate analysis of the hysteresis motor. Magnetization-dependent vector model is adapted to calculate the vector magnetization. That is, from the magnitude and direction of the magnetic field intensity, magnetization of each ring element is computed by the vector model. Therefore, the method can consider the rotational hysteresis effects which scalar hysteresis model cannot calculate.

By comparing the simulation results with the experimental ones, it is verified that very reasonable results are obtained. The proposed method can be applied to other magnetic systems where the rotational hysteresis characteristics must be considered.

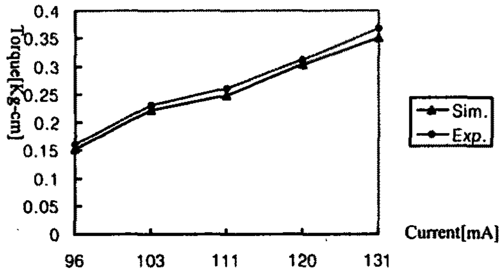


Fig. 7. Comparison of the average torque

7. References

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