Torque Calculation of Hysteresis Motor Using Vector Hysteresis Model

Sun-Ki Hong, Hong-Kyu Kim, Hyeong-Seok Kim, and Hyun-Kyo Jung

***Abstract*—This paper presents how to determine the thickness of hysteresis ring of hysteresis motor using the 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 the vector hysteresis model and the torque can be obtained from the vector sum of each torque of each element or from the area of hysteresis loop. From these calculations, it is found that the motor torque is not proportional to the thickness of the ring. As a result, an optimum thickness of the hysteresis ring exists and it can be determined by the proposed method.**

***Index Terms*—Hysteresis motor, hysteresis ring, Preisach model, Vector hysteresis model.**

I. INTRODUCTION

HYSTERESIS motor is a self-starting synchronous motor that uses the hysteresis characteristics of the semi-hard magnetic materials. So far, it is not easy problem to determine the adequate thickness of the hysteresis ring in the hysteresis motor, and most cases depend on experimental results [2]. The motor torque was 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 experiment ones except for the case when the thickness of the ring is very thin [3]. 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 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 to make matters worse, 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, the 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 [1], [4] which can calculate vector hysteresis for any vector fields with the magnitude varying or not is adopted. And 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 each torque of each element. In the previous study [5], this method could calculate the motor torque with acceptable precision. Therefore the simulation results show that there exists the optimum thickness of the hysteresis ring and it can be calculated analytically.

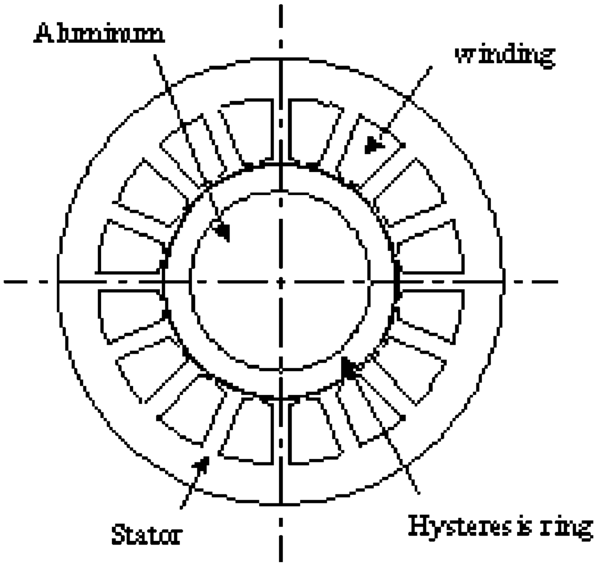

Fig. 1. Structure of hysteresis motor.

II. HYSTERESIS MOTOR CHARACTERISTICS

Hysteresis motor consists of polyphase stator and rotor which contains hysteresis ring. Most of cases, 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 fields 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 proportional to the volume of the ring. From the experimental results [3], however, the torque may decrease although the thickness becomes thicker when the thickness is relatively thick.

It is known [5] that there exists rotational hysteresis in the hysteresis ring and 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

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Manuscript received October 25, 1999.

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Publisher Item Identifier S 0018-9464(00)07191-0.

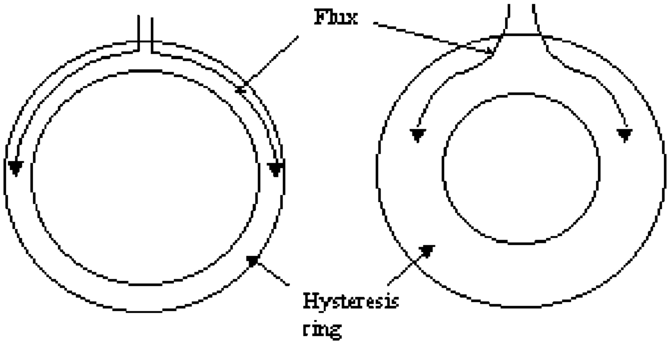

Fig. 2. Flux patterns in the hysteresis ring.

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 ring volume. Fig. 2(a) shows this case which can ignore the rotational hysteresis.

If the thickness becomes thicker, the rotational hysteresis can not be ignored and the direction of the magnetization is no more aligned to that of the field and both circumferential and radial components of the flux exist as shown in Fig. 2(b).

III. VECTOR HYSTERESIS MODEL

The directions of the magnetic field and magnetization are same in the scalar hysteresis models and these kinds of hysteresis models can not consider the rotational hysteresis. In order to design the hysteresis motor, the determination of the thickness of hysteresis ring is a very important problem due to the rotational hysteresis. Therefore, for the description of 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

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

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 the follow equation.

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

$\vec{\gamma}_{a_t b_t}$: 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 the dipoles of the Preisach elements have not only the density but also the rotating ability caused by the applied field.

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

IV. TORQUE CALCULATION

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

$$\vec{B} = \mu_0\vec{H} + \vec{M} \tag{3}$$

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

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

By using Galerkin's weighted residual method, after assembling system matrix, a set of nonlinear equations to be solved is obtained. That is, from (3) and (4) the magnetization $\boldsymbol{M}$ is related to the magnetic flux density and also to the unknown magnetic vector potential $\boldsymbol{A}$, so a set of nonlinear equations for the unknown variables $\boldsymbol{A}$ is composed. Such a system of equations can be solved by an iterative method.

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

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

Equation (5) reveals that small variation of the magnetization results in the large change of $\boldsymbol{H}$. 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 $\boldsymbol{M}$ in (4) are replaced by $\mu_0(1+\mu_{sp})$ and $\boldsymbol{M}_{sp}$ respectively and these are the input of the finite element analysis.

Fig. 3 shows the flowchart for the calculation. Here convergence criterion is the relative error of the magnetic field intensity $\boldsymbol{H}$.

If the finite element solution was obtained, the torque of the motor can be calculated by two methods.

A. Area of Hysteresis Loop

The maximum flux density $B_{\max}$ 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