論 文
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전기강판의 회전자계 하에서의 2차원 자계특성 측정

Measurement of Two Dimensional Magnetic Properties of Electrical Steel Sheets under Rotating Magnetic Fields

陰 泳 煥* · 洪 瑄 基** · 申 判 錫*** · 高 彰 燮†
(Young Hwan Eum · Sun-Ki Hong · Pan Seok Shin · Chang Seop Koh)

Abstract - It is necessary to measure precisely the magnetic characteristics of electrical steel sheets under rotating magnetic fields, to obtain an accurate numerical performance analysis of electric machines made of electrical steel sheets. In this paper, the two dimensional magnetic characteristics of an electrical steel sheet are measured and explained under rotating magnetic fields using a two-axes-excitation type single sheet tester (SST). Through experiments, the magnetic properties, under rotating magnetic fields, of a non-oriented and grain oriented electrical steel sheet were measured respectively. In addition, the iron losses due to not only the alternating magnetic fields, but also rotating magnetic fields were measured. These experimentally measured results can evidently be applied to the analysis of iron losses in electrical machines.

Key Words : two dimensional magnetic property, electrical steel sheet, iron loss, rotating field, single sheet tester

1. Introduction

For a precise design and iron loss analysis as well as performance analysis of rotating electric machines, it is essential to measure and apply the magnetic properties of ESSs(electrical steel sheets) under not only alternating magnetic fields, but also rotating magnetic fields. The authors had already developed a two-axes-excitation type SST, and reported it with the measured magnetic characteristics of an ESS when alternating magnetic fields are applied along the rolling and transverse directions, respectively [1]. The authors have also reported the two dimensional magnetic properties, such as phase difference between B and H vectors, of isotropic and anisotropic ESSs when alternating magnetic fields are applied along various directions [2].

In this paper, the two-dimensional magnetic properties of ESSs under rotating magnetic fields are measured. The measurements are carried out using the SST system developed in [1]. The system is designed to apply enough strong magnetic fields to saturate the specimen of ESS, along the rolling and transverse directions, independently. With the developed system, two dimensional magnetic properties of non-oriented and grain oriented ESSs are measured and compared with each other.

2. Two Dimensional Magnetic Properties of ESSs under Rotating Magnetic Fields

2.1 Two Dimensional Magnetic Properties

As is well known, there exists vector relationship between the magnetic flux density vector (B) and the magnetic field intensity vector (H), as shown in Fig. 1, in a magnetic material when rotating magnetic field is applied. As the exciting magnetic field rotates, the H and B vectors have phase difference. The phase differences are very non-linear and unpredictable with respect to both the magnitude and direction of the exciting magnetic field. Using a SST system with two-axes-excitation, the

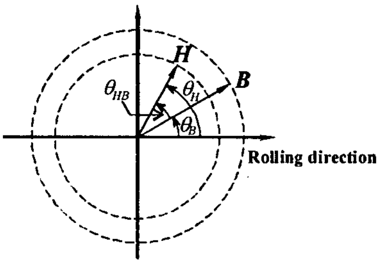

Fig. 1 Relationship between B and H vectors where ($\theta_{HB} = \theta_H - \theta_B$)

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* 學生會員 : 忠北大 電氣工學科 碩士課程

** 正 會 員 : 湖西大 電氣情報通信工學部 副敎授

*** 正 會 員 : 弘益大 電氣電子컴퓨터 工學部 敎授

† 교신저자, 正會員 : 忠北大 電氣電子컴퓨터 工學部 敎授
E-mail : kohcs@chungbuk.ac.kr

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phase differences can be measured for various magnitudes and directions of the exciting magnetic fields [3].

This non-linear relationships between the magnitudes and phases of B and H vectors are usually represented by using a tensor permeability. According to this method, the magnetic permeability tensor is represented:

$$\begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{bmatrix} \mu_{xx} & \mu_{xy} \\ \mu_{yx} & \mu_{yy} \end{bmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix} \qquad (1)$$

where the subscripts x and y denote the direction. Each element of the permeability tensor will be determined from the results of measurements for the case of various excitations. Equation (1), therefore, can express overall two dimensional magnetic properties of a EES [4, 5].

2.2 Calculation of Magnetic Power Loss

The following method has been used for the measurement of magnetic power loss under a rotating flux condition. This method, based on the measurements of the orthogonal components of both the magnetic field intensity and the flux density, provides the total magnetic power loss including the rotational power loss [6]. The total magnetic power loss is calculated:

$$P_t = \frac{1}{T} \int_T \left(H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) \qquad (2)$$

where H_x, B_x, H_y, *and* B_y are the measured components of the magnetic field intensity and the flux density in the x and y directions, respectively [7].

3. Measurement of Two Dimensional Magnetic Properties

3.1 Measuring System

The two-axes-excitation SST consists of a pair of double vertical yokes with exciting coils, H and B fields sensing units, and signal processing devices [1]. Magnetic circuits are designed so that the system has closed magnetic flux paths along both the x and y directions. The exciting coils are wound around each of the yoke poles as shown in Fig. 2. The B field sensing coils are directly wound on the sample sheet, and the H field sensing coil unit is placed under the sample sheet as closely as possible.

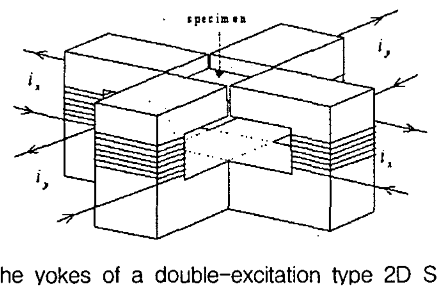


Fig. 2 The yokes of a double-excitation type 2D SST

Especially in the developed two-axes-excitation SST, nearly completely closed magnetic flux paths are achieved for both the rolling and the transverse directions. Then, the magnetic properties can be measured up to higher magnetic flux density under various conditions.

3.2 *B* Waveform Control

During the measurement of the magnetic properties, the sinusoidal waveform of B should be maintained. For instance, when the magnetic measurement is carried out under rotating magnetic fields, the magnetic flux densities along the rolling and transverse directions should be kept as follows:

$$B_{RD}(t) = B_m \cos(\omega t) \text{ [T]} \qquad (3)$$

$$B_{TD}(t) = B_m \sin(\omega t) \text{ [T]} \qquad (4)$$

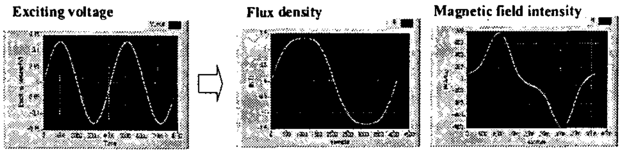
where the subscripts RD and TD represent the rolling and transverse directions, respectively, and B_m is the magnitude of the rotating magnetic flux density. Hence, the corresponding induced voltages should have the follow waveforms:

$$e_{RD}(t) = -(NA)_{RD}\, \omega B_m \sin(\omega t) \text{ [V]} \qquad (5)$$

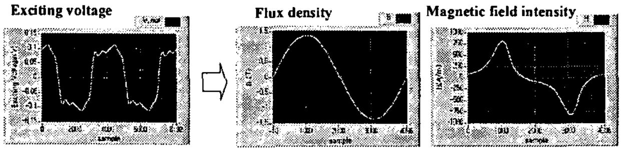
$$e_{TD}(t) = (NA)_{TD}\, \omega B_m \cos(\omega t) \text{ [V]} \qquad (6)$$

where (NA) is the effective area-turn of the B-coil. The B waveform control, therefore, is actually accomplished by controlling the exciting voltages for the rolling and transverse directions so that the induced voltages along the rolling and transverse directions in (5) and (6) may be obtained, respectively. The overall process of the B waveform control using digital feedback method is summarized as follows:

i) Sinusoidal exciting voltage, v_c, is generated.
ii) The induced voltage, e, is measured from the B field sensing coil,
iii) At the i-th iteration, the fundamental components, v_{c1} and e_1, of the exciting and induced voltages, $v_c^{(i)}$ and $e^{(i)}$, are obtained by using Fourier transformation,
iv) At the $(i+1)$-th iteration, the waveform of the exciting voltage, $v_c^{(i+1)}$, is determined as follows:



(a) Before B waveform control



(b) After B waveform control

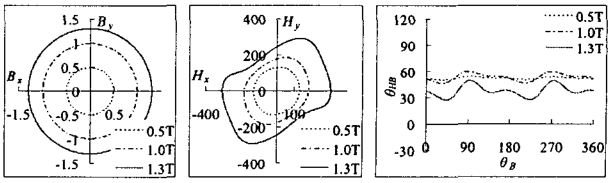
Fig. 3 Comparison of the exciting voltages before and after waveform control

$$v_c^{(i+1)} = v_c^{(i)} - K\frac{v_{c1}^{(i)}}{e_1^{(i)}}\left(v_b^{(i)} - e\right) \tag{7}$$

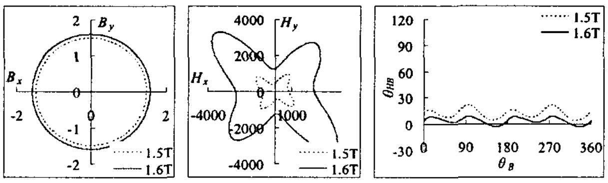
where K is the feedback coefficient and e is the required induced voltage given from (5) and (6) [8]. Fig. 3 shows a comparison of the waveforms of the exciting voltage, magnetic flux density and magnetic field intensity before and after the waveform control.

3.3 Result and Discussion

As specimens non-oriented and grain oriented ESSs are selected. The measuring frequency is fixed at the power frequency of 50Hz. When a ESS is placed in an uniform rotating magnetic field, the magnetic flux density B is, in general, not parallel to the field strength H. Therefore B_x and B_y are measured from the B flux sensing coils, respectively, and H_x and H_y are measured form the H field sensing coil units, respectively, and, finally, the B and H vector are determined. And, then, the phase difference, θ_{HB}, between B and H vectors are computed. The phase difference, θ_{HB}, is usually positive because of the rotational hysteresis losses.

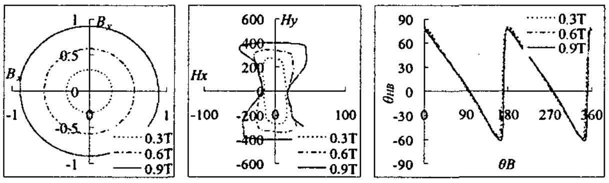


(a) Before saturation

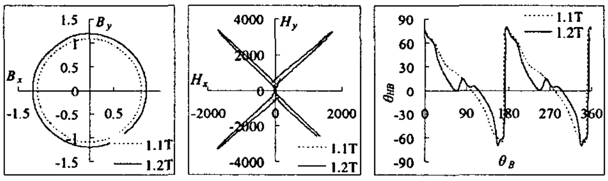


(b) After saturation

Fig. 4 Magnetic properties of a non-oriented ESS under pure rotating magnetic flux condition



(a) Before saturation

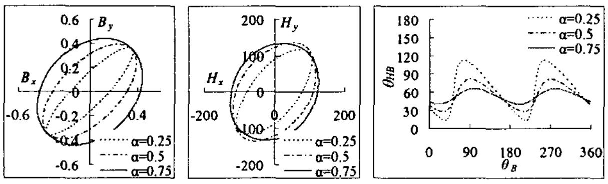


(b) After saturation

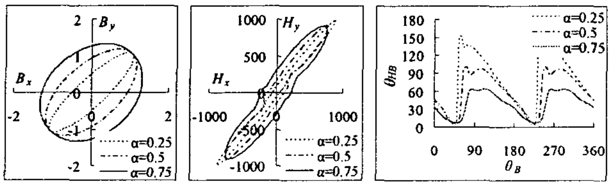
Fig. 5 Magnetic properties of a grain oriented ESS under pure rotating magnetic flux condition

Fig. 4 shows the relationships between H_x-H_y and θ_{HB} under a pure rotating magnetic flux condition for a non-oriented material. As shown in this figure, θ_{HB} has a maximum value about of 0.5[T] and decreases with increasing magnetic flux density. Fig. 5 shows the same contents for a grain oriented material. From these results, it is shown that θ_{HB} is not always positive because of the anisotropic energy of the material. In the case of non-oriented material, the anisotropy is small (ideally 0) and the fluctuation of θ_{HB} is small. However, in the case of the grain oriented sheet, the fluctuation of θ_{HB} is much larger than that of the non-oriented material. Because the anisotropic energy caused from the lattice structure does not dissipate any effective energy, as can be seen in Fig. 5, the fluctuation of θ_{HB} becomes more symmetrical for the x-axis when the flux density approaches to the saturation. This means the hysteresis loss becomes zero without decreasing the fluctuation of θ_{HB} [9].

The two dimensional magnetic properties under a mixed magnetic field condition of a pure rotating and a pure alternating magnetic fields are also measured. The mixed magnetic field is often called elliptically rotating magnetic fields. Fig. 6 shows the B, H and θ_{HB} relationships of a non-oriented EES under an elliptically rotating magnetic field condition as α varies from 0.25 to 0.75. At the figure α is defined as $\alpha = B_{\min}/B_{\max}$ where $B_{\min}$ and $B_{\max}$ are the minimum and maximum values of the magnetic flux density, respectively. As α varies from 1 to 0 ($\alpha = 1$ means a pure rotating magnetic field and $\alpha = 0$ means a pure alternating magnetic field), the

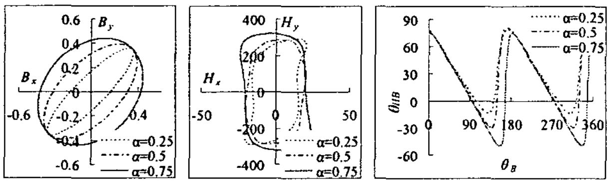


(a) Before saturation (B_{max} = 0.5T)

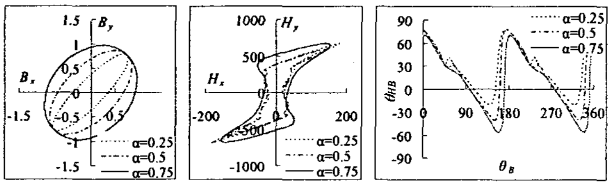


(b) After saturation (B_{max} = 1.5T)

Fig. 6 Magnetic properties of a non-oriented ESS versus α when $\theta_B = 45°$.



(a) Before saturation (B_{max} = 0.5T)



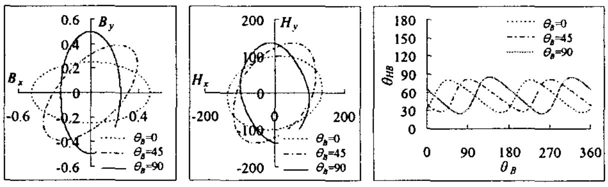
(b) After saturation (B_{max} = 1.1T)

Fig. 7 Magnetic properties of a grain oriented ESS versus α when $\theta_B = 45°$.

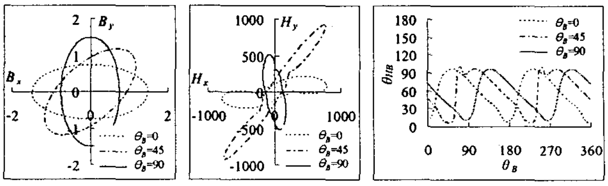
variation of θ_{HB} increases, because the effects to the material of the alternating field increase. Fig. 7 shows the same kinds of results for a grain oriented material. It shows that the variation of θ_{HB} is not severe because the effect of the anisotropy is larger than that of *a*.

Fig. 8 and Fig. 9 show the measured two dimensional properties of a non-oriented and grain oriented ESSs, respectively, as the phase angle, θ_B, of the maximum *B* varies from zero to 90°. In case of the non-oriented ESS, the phase difference, θ_{HB}, varies very consistently, as expected, with the θ_B. However, in case of the grain oriented ESS, the phase difference, θ_{HB}, is not much affected by θ_B. It is thought because the difference of the permeability between the rolling and transverse directions is very large [9, 10].

Fig. 10 shows the iron losses including rotational hysteresis loss and eddy current loss under pure rotating and elliptically rotating magnet fields conditions. In the

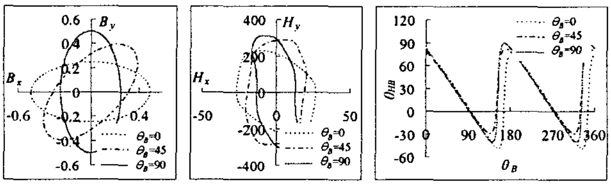


(a) Before saturation (B_{max} = 0.5T)

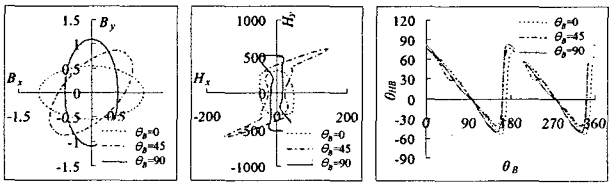


(b) After saturation (B_{max} = 1.5T)

Fig. 8 Magnetic properties of a non-oriented ESS versus θ_B when α = 0.5.

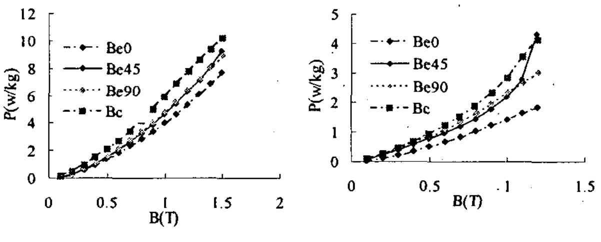


(a) Before saturation (B_{max} = 0.5T)

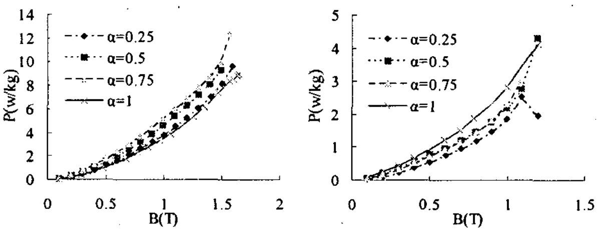


(b) After saturation (B_{max} = 1.1T)

Fig. 9 Magnetic properties of a grain oriented ESS versus θ_B when α = 0.5.



(a) Non-oriented (*a* = 0.5) (b) Grain oriented (*a* = 0.5)



(c) Non-oriented (θ_B = 45°) (d) Grain oriented (θ_B = 45°)

Fig. 10 Iron losses including rotational loss figure, B_c and B_e represent the pure rotating and elliptically rotating magnetic fields conditions, respectively, and α is fixed to 0.5 and the numbers 0, 45, 90 mean the phase angle θ_B

The rotational hysteresis loss, in general, is known dependent upon the area of the B-vector. However Fig. 10(b) shows that the loss for B_e45 (when phase angle is $45°$ in elliptically rotating magnetic field) is bigger than that for B_c (when a pure rotating magnetic field is applied). This is thought because the decreased transverse directional anisotropy increases H_{TD}, and it affects the amplitude of B_{RD}, where H_{TD} and B_{RD} are transverse directional magnetic field intensity and rolling directional magnetic flux density, respectively.

Through the measurements, the non-oriented ESS is found to have almost isotropic characteristics until the magnetic flux density is around 1 [T]. However as the magnetic flux density becomes bigger than 1.2 [T], it has the characteristic of double grain oriented material, where the hard axes are 45 and 135 degrees. As the applied magnetic field increases, these phenomena become more conspicuous. For the grain oriented ESS, the same characteristics are observed even when the magnetic flux density is around 0.9 [T].

4. Conclusion

Many parts of electrical machine cores, such as transformer joints and the stator tooth roots of motors, have not only alternating iron loss but also rotational hysteresis loss. The B vector has a rotational as well as a linear component. The extra losses because of rotational loss have been widely studied. Especially in an anisotropic metal like grain oriented steel, the spatial variation in permeability makes it difficult to sustain and control a rotating flux vector of constant defined amplitude and waveform in a two dimensional SST. Certainly in actual devices, rotational flux is always associated with waveform distortion and amplitude variations. It may be expected that ESSs, which perform equally under alternating magnetic fields, may behave differently when they are exposed to a rotational field [11].

In this paper, many characteristics are measured with non-oriented and grain oriented ESSs. From the results, the relationships between B and H vectors are very nonlinear, and these kinds of measurements look essential to estimate precisely the effects of the iron loss characteristics of ESS on electrical machines.

In the future research, the directional permeability curves and loss versus B plots will be fed into a finite element analysis of electric machines to predict iron loss.

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저자소개

음 영 환 (陰 泳 煥)

1981년 2월 14일생. 2006년 충북대학교 전기공학과 졸업. 2006년~현재 동대학원 전기공학전공 석사과정.

Tel : 043-274-2426
Fax : 043-274-2426
E-mail : yh3701@chungbuk.ac.kr

홍 선 기 (洪 瑄 基)

1965년 1월 24일생. 1987년 서울대 공대 전기공학과 졸업. 1989년 동 대학원 전기공학과 졸업(석사). 1993년 동 대학원 전기공학과 졸업(공박). 1993년~1995년 렉스 산전(주) 선임 연구원. 1995년~현재 호서대 전기정보통신공학부 부교수.

Tel : 041-540-5674
Fax : 041-540-5693
E-mail : skhong@office.hoseo.ac.kr

신 판 석 (申 判 錫)

1977년 서울대 공대 전기공학과 졸업. 1986년 Rensselaer Polytechnic 대학원 전력공학과 졸업(석사), 1989년 동대학원 전력공학과 졸업(공박), 1980년~1993년 KERI 연구원. 1993년~현재 홍익대 전기공학과 교수.

Tel : 041-860-2593
Fax : 041-863-7605
E-mail : psshin@hongik.ac.kr

고 창 섭 (高 彰 燮)

1986년 서울대학교 전기공학과 졸업(학사). 1988년 동 대학원 전기공학과 졸업(석사). 1992년 동 대학원 전기공학과 졸업(공박). 1993~1994년 미국 Florida International University 전기 및 컴퓨터공학과 객원 연구원. 1994~1996년 삼성전기(주) 종합연구소 선임연구원. 2003년 2월-2004년 1월 미국 Texas A&M University, 전기컴퓨터공학과 객원 교수, 1996~현재 충북대학교 전기전자컴퓨터공학부 교수.

Tel : 043-261-2426
Fax : 043-274-2426
E-mail : Kohcs@chungbuk.ac.kr