Magnetic Property Evaluation of the High-Speed Motor Stator Core Under Sinusoidal and Pulse Width Modulation Wave Excitation Using the Stator Winding Excitation Method

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Development of a small, high-speed and high-power motor is necessary to improve the performance of machines such as robots, and drones. The motor is excited by a high frequency voltage when the motor rotates high-speed. Moreover, the motor is driven by the pulse width modulation (PWM) inverter because efficiency and controllability is good. The driving voltage of the PWM inverter contains many higher harmonics waves. In such a motor, generation of heat due to the loss is a major problem. The loss of the motor includes an iron loss, a copper loss, and a machine loss; here we focus on the iron loss. Eddy-current loss increases especially under a condition of high frequency excitation. To suppress the eddy-current loss, we produced the stator core for a small, high-speed and high-power motor using a 0.08-mm-thick ultrathin electrical steel sheet. Additionally, to evaluate the magnetic properties of this new stator core with complex shape, we also developed a stator winding excitation method using a dummy rotor made of the 0.08-mm-thick ultrathin electrical steel sheet. In this paper, the effectiveness of a small, high-speed, and high-power motor stator core made of the 0.08mm-thick ultrathin electrical steel sheet is shown using the stator winding excitation method when it is excited by the PWM wave.

Keywords: high-speed motor, ultrathin electrical steel sheet, PWM, carrier frequency, modulation signal frequency.

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1. Introduction

Recently, the development of equipment such as robots and drones that uses small, high-speed and high-power motors is active. However, an eddy-current loss increases in the motor during high-speed rotating. In the high power motor, the copper loss also increases. Moreover, a heat radiation problem occurs if the size of the motor is reduced. Therefore, the development of such a motor is not easy. We focus on the iron loss to solve this problem. One of possible solution is reduction of an eddy-current loss in stator core. When the motor rotates at a high-speed, an effective method of decreasing eddy-current loss is to thin the thickness of the electrical steel sheet that composes the stator core of the motor. [1-3]. Eddy-current loss in the stator core also increases when the motors are driven by PWM inverters [4-6]. To decrease eddy-current loss in the stator cores of small, high-speed high-power motors, we developed a 0.08-mm-thick ultrathin electrical steel sheet.

Additionally, we developed the evaluation methods for the iron loss in the actual stator core for a small motor. They are an inside excitation method and an outside excitation method. We also developed the stator winding excitation method with a dummy rotor to form the magnetic circuit.

We prepared two stator cores that used a 0.08-mm-thick ultrathin electrical steel sheet and a 0.35-mm-thick conventional electrical steel sheet. Moreover, we compared iron loss (W_{isin} [W/kg]) excited by sinusoidal waves with iron loss (W_{ipwm} [W/kg]) excited by PWM waves using the stator winding excitation method. Results revealed that W_{ipwm} was greater than W_{isin} and that the increasing rate of W_{ipwm} in the stator cores was especially low. We report measured iron losses excited by sinusoidal waves and PWM waves.

2. Iron loss and Specimens

2.1 Iron loss, hysteresis loss, and eddy-current loss

The iron loss (W_i [W/kg]) of the specimen can be calculated using (1). B_{ex} [T] and H_{ex} [A/m] are the magnetic flux density and magnetic field strength of the stator core, respectively. ρ [kg/m³] is the density of the core material, and T [s] is the period of the excitation current (I_{ex} [A]). Moreover, H_{ex} and B_{ex} can be evaluated using (2) and (3), respectively. In these equations, I_{ex} , N_e , L_e [m], N_s , and S [m²] represent the excitation current, the number of turns of the excitation coil, the effective magnetic path length, the number of turns of the search coil, and the sectional area of the search coil, respectively. B_{ex} was obtained using v_s [V], which is the induced voltage of the search coil, whereas H_{ex} is obtained from N_e , L_e , and the measured I_{ex} using v_r [V]. The value of v_r is the induced voltage of the shunt resistor. The values of K_h and K_e in (4) were calculated by the dual frequency separation method. Hysteresis loss (W_h [W/kg]) and eddy-current loss (W_e [W/kg]) were obtained using (5). In this case, anomalous eddy-current loss was not considered.

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$$W_i = \frac{1}{\rho T} \int H_{ex} \cdot \frac{dB_{ex}}{dt} dt \quad (1)$$

$$H_{ex} = \frac{N_e I_{ex}}{L_e} \quad (2)$$

$$B_{ex} = -\frac{1}{N_s S} \int v_s dt \quad (3)$$

$$\frac{W_i}{f_{ex}} = K_h + K_e f_{ex} \quad (4)$$

$$W_h = K_h f_{ex}, \quad W_e = K_e f_{ex}^2 \quad (5)$$

2.2 Specimens

Figure 1 shows stator core specimens with excitation coils. The cores were made of two kinds of electrical steel sheets including a 0.08-mm-thick ultrathin electrical steel sheet and a 0.35-mm-thick electrical steel sheet. Hereafter, the two stator cores were called the 0.08mm_Core and the 0.35mm_Core. The outer diameter, inner diameter, and thickness of the two cores were 28.4 mm, 12.6 mm, and 12.5 mm, respectively. The 0.35mm_Core had conventional specifications for comparison with the 0.08mm_Core. Only one piece was prepared for each of the cores. Figure 2(a) shows a dummy rotor made of the 0.08-mm-thick ultrathin electrical steel sheet used in this experiment. The outer diameter, inner diameter, and thickness of the dummy rotor were 12.4 mm, 3.2 mm, and 12.5 mm, respectively. Two cores and the dummy rotor were cut out using the wire electrical discharge machining method. The electrical steel sheets for the core and the dummy rotor were each laminated by a bonding agent.

In the case of the 0.08mm_Core, the diameter of excitation coils was 0.25 mm. Moreover, the diameter of excitation coils was 0.22 mm in the 0.35mm_Core. The number of turns of each excitation coil was 40 in both cores. The search coil for the magnetic flux density measurement was wound on the tooth of each stator core. The number of turns of the search coil was one in both cores. The diameter of the search coil was 0.2 mm. In the case of the 0.08mm_Core, the 7th and 8th excitation coils were used in this experiment, and connected with the series. In the case of the 0.35mm_Core, exciting coils were wound on two teeth as shown in Fig. 1(b). In this case, two excitation coils were connected with the series.

2.3 The stator winding excitation method

Figure 2(b) shows the arrangement of a stator core, the dummy rotor, the excitation coil, and the search coil for the stator winding excitation method. Figure 2(b) also shows the magnetic path of this method. Two excitation coils were connected so that the magnetic flux passed the magnetic path shown in Figure 2(b). In

this experiment, the magnetic properties of the stator core were measured using this method.

2.4 Finite element method analysis of the stator winding excitation method

We analyzed the magnetic flux distribution and the magnetic flux line of the stator winding excitation method using the 2 dimensional Finite element method (FEM). In this FEM analysis, we considers magnetic saturation, the eddy-current of the stator core. The material of the stator core used in this analysis was 50A1000, and the excitation frequency was 50 Hz. Fig. 3(a) and Fig. 3(b) show the magnetic flux density distribution and the magnetic flux line distribution in the stator core. From these two figures, it is understood that the magnetic flux passes two teeth and a back yoke and the dummy rotor.

3. Measurement system and conditions

3.1 Measurement system

The block diagram of the system used to evaluate the magnetic properties of the small, high-speed and high-power motor stator core is shown in Fig. 4. The excitation voltage outputted from the D/A converter, amplified with the power amplifier, was applied to two excitation coils. Values of v_s and v_r were inputted to a computer using the A/D converter. The excitation current was measured using the voltage generated in the shunt resistor (0.1 Ω).

(a) 0.08mm_Core

(b) 0.35mm_Core

Fig.1 Stator cores made of the 0.08-mm-thick ultrathin electrical steel sheet and the 0.35-mm-thick electrical steel sheet.

(a) Dummy rotor.

(b) Magnetic path length.

Fig.2 The dummy rotor and magnetic path in the stator core.

(a) Magnetic flux density.

(b) Magnetic flux line.

Fig.3 Magnetic flux density and magnetic flux line distribution analyzed by the 2D FEM.

Fig.4 Block diagram of the measurement system.

3.2 Measurement method

When the iron loss (W_{isin}) was measured under the sinusoidal wave excitation, the waveform of the excitation voltage was controlled by feedback so that the excitation magnetic flux density (B_{ex}) of the stator core became a sinusoidal wave. In this case, the iron loss (W_{isin}) was measured specifying the maximum excitation magnetic flux density (B_{exmax}). When the iron loss (W_{ipwm}) was measured under the PWM wave excitation, the excitation magnetic flux density controlled the maximum value of the fundamental wave of the measured magnetic flux density in the stator core. In this case, the fundamental wave was extracted using the Fast Fourier Transform method (FFT) from the measured B_{ex} .

The PWM excitation wave form that was the excitation voltage wave form shown in Fig. 5(b) was made with software using a sinusoidal modulation signal and a triangular carrier signal shown in Fig. 5(a). This PWM excitation wave was amplified with a linear power

amplifier, and supplied to the excitation coil. In both cases, the magnetic properties were measured three times and then averaged.

3.3 Measurement condition under the sinusoidal wave excitation

The value of B_{exmax} was applied from 0.4 T to 1.2 T in 0.1 T steps. The excitation frequencies (f_{ex} [Hz]) were 50 Hz, 100 Hz, 200 Hz, 500 Hz, 1 kHz, and 2 kHz.

3.4 Measurement condition under the PWM wave excitation

In this case, B_{exmax} was applied from 0.4 T to 1.2 T in 0.1 T steps. The modulation signal frequency (f_m [Hz]) was 50 Hz. Carrier frequencies (f_c [Hz]) were 1 kHz and 2 kHz. The iron loss was measured three times and then averaged. Moreover, when the peak to peak value of the carrier signal and the maximum value of the modulation signal were defined as E_c [V] and E_m [V], modulation index (m) could be written as (6). In this experiment, modulation indexes (m) were 0.4, 0.6, and 0.8.

$$m = \frac{E_m}{E_c} \quad (6)$$

4. Experimental results and discussions

4.1 H_c and B_r of the 0.08mm_Core and 0.35mm_Core under the sinusoidal wave excitation

Figure 6 shows the frequency characteristics of coercive force (H_c) and residual magnetic flux density (B_r) of the 0.08mm_Core and the 0.35mm_Core when B_{exmax} was 1.0 T. From these figures, H_c and B_r were greatly changed in the 0.35mm_Core according to an increase in the excitation frequency. Moreover, they were slightly changed in the 0.08mm_Core according to an increase in the excitation frequency. This shows that the eddy current of the 0.08mm_Core is smaller than that of the 0.35mm_Core.

4.2 B - H curves of the 0.08mm_Core under the PWM wave excitation

Figure 7 shows B - H curves of the 0.08mm_Core when f_{ex} , f_c , B_{exmax} , and m were 50 Hz, 2 kHz, 1.2 T, and 0.8, respectively. From this figure, the B - H curve is long and slender shape because there is a gap of 0.1 mm between the stator core and the dummy rotor. Moreover, the minor loop by the influence of PWM excitation is observed.

4.3 W_i , W_h , and W_e under the sinusoidal wave excitation

Figure 8 shows the relationship between W_i and excitation frequencies of two cores such as the 0.08mm_Core and the 0.35mm_Core. In this case, B_{exmax} was 1.0 T. Values of W_i of two stator cores

increased according to the increase in excitation frequencies. When f_{ex} was 2 kHz, W_i of the

(a) Carrier and modulation signal wave form. (b) PWM wave form.

Fig.5 The carrier signal wave form, the modulation signal wave form, and the PWM wave form.

(a) H_c

(b) B_r

Fig.6 H_c and B_r of the 0.08mm_Core and the 0.35mm_Core under the sinusoidal wave excitation ($B_{exmax}=1.0$ T).

Fig.7 B - H curves of the 0.08mm_Core under PWM wave excitation ($f_{ex}=50$ Hz, $f_c=2$ kHz, $B_{exmax}=1.2$ T, and $m=0.8$).

0.08mm_Core was about 42 % of W_i of the 0.35mm_Core. It is understood that W_i of the stator core made of the 0.08-mm-thick ultrathin electrical steel sheet was very small for a high excitation frequency of 2 kHz.

Figure 9 shows the relationship between W_h and W_e of two cores and excitation frequencies. There was no big difference into W_h of both cores even if the excitation frequency changed. However, there was big difference into W_e of both cores due to the excitation frequency. This phenomenon happened because of the difference of the thickness of both electrical steel sheet.

Figure 10 shows the relationship between W_i and B_{exmax} of two cores. When B_{exmax} was 1.2 T, W_i of the

Fig.8 Frequency characteristics of W_i under the sinusoidal wave excitation ($B_{exmax}=1.0$ T).

(a) W_h .

(b) W_e .

Fig.9 Frequency characteristics of W_h and W_e under the sinusoidal wave excitation ($B_{exmax}=1.0$ T).

0.08mm_Core was about 52 % of W_i of the 0.35mm_Core. Figure 11 shows the relationship between W_h and W_e of two cores and B_{exmax} as same as Fig. 10. There was no big difference into W_h of both cores even if B_{exmax} changed. However, there was big difference into W_e of both cores due to B_{exmax} .

4.4 W_{ipwm} vs. m under the PWM wave excitation

When W_{ipwm} of the stator core under the PWM wave excitation was evaluated, modulation index (m) was an important parameter. We examined the relationship between W_{ipwm} and B_{exmax} of both cores as shown in Fig. 12(a) and Fig. 12(b) when f_c was 1 kHz. The value of m was changed to 0.4, 0.6, and 0.8. When m was 0.4, W_{ipwm} grew in both cores because the PWM excitation wave contained many higher harmonic waves. From Fig. 12(b), the tendency was especially clear in the 0.35mm_Core.

4.5 W_{isin} and W_{ipwm} under the sinusoidal wave excitation and the PWM wave excitation

Figure 13 shows the comparison between W_{isin} and W_{ipwm} of both cores when f_{ex} was 1 kHz and 2 kHz. In the case of Fig.13, f_m was 50 Hz and m was 0.4. The ratio of W_{isin} to W_{ipwm} ($W_{\text{ipwm}}/W_{\text{isin}}$) was 2.8 for the 0.08mm_Core and 6.7 for the 0.35mm_Core when B_{exmax} was 1.2 T and f_c was 1 kHz. When B_{exmax} was 1.2T and f_c was 2 kHz, they were 2.2 and 5.2. An

Fig.10 Maximum excitation magnetic flux density (B_{exmax}) characteristics of W_i under the sinusoidal wave excitation ($f_{\text{ex}}=1$ kHz).

Fig.11 B_{exmax} characteristics of W_h and W_e under the sinusoidal wave excitation ($f_{\text{ex}}=1$ kHz).

increase in the iron loss by PWM wave excitation of the 0.35mm_Core is obviously larger than that of the 0.08mm_Core. This phenomenon attributed to the higher harmonic waves of the excitation voltage increasing when f_c became high.

(a) 0.08mm_Core.

(b) 0.35mm_Core.

Fig.12 W_{ipwm} under the PWM wave excitation ($f_m=50$ Hz, $f_c=1$ kHz).

(a) $f_{\text{ex}}=1$ kHz.

(b) $f_{\text{ex}}=2$ kHz.

Fig.13 W_{isin} and W_{ipwm} under the sinusoidal wave excitation and the PWM wave excitation ($f_m=50$ Hz, $m=0.4$).

4.6 W_{ipwm} vs. f_c under the PWM wave excitation and the sinusoidal wave excitation

Figure 14 shows the comparison between W_{isin} and W_{ipwm} of both cores when m was 0.8. In both case, f_c was 1 kHz and 2 kHz, and f_m was 50 Hz. W_{ipwm} when f_c was 2 kHz became smaller than it at 1 kHz. Reactance of the excitation coil increases when f_c increases. Therefore, the higher harmonics waves of the excitation current decreases when f_c increases, and W_{ipwm} decreases.

5. Conclusion

To demonstrate the effectiveness of a stator core made of the 0.08-mm-thick ultrathin electrical steel sheet for a small, high-speed and high-power motor, we measured magnetic properties under the sinusoidal wave excitation and the PWM wave excitation using the stator winding excitation method. The magnetic properties in two cores such as the 0.08mm_Core and the 0.35mm_Core were compared. Consequently, we reached the following results.

- (1) The stator winding excitation method using the dummy rotor that was developed by us clearly detected the magnetic properties of the actual stator core.
- (2) The gap between the dummy rotor and teeth greatly influenced the B - H curve of the 0.08mm_Core under the PWM wave excitation. Moreover, many minor loops were observed in the B - H curve.
- (3) The frequency dependency of magnetic properties (H_c , B_r , W_i , W_h , W_c) of the 0.08mm_Core was smaller than that of the 0.35mm_Core. This shows that the eddy current of the 0.08mm_Core is smaller than the eddy current of the 0.35mm_Core.

(a) 0.08mm_Core.

(b) 0.35mm_Core.

Fig.14 W_{isin} and W_{ipwm} under the sinusoidal wave excitation and the PWM wave excitation ($f_m=50$ Hz, $f_c=1$ kHz and 2 kHz, $m=0.8$).

The stator core made of the 0.08-mm-thick ultrathin electrical steel sheet appears to be effective for decreasing the iron loss of a small, high-speed, high-power motor excited by the PWM wave. It is necessary to evaluate the iron loss of the stator core made of the ultrathin electrical steel sheet by using an actual inverter excitation system in the future.

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