

Iron Losses of Silicon Steel due to Rotating Fluxes (Inclined Rotating Flux and Distorted One)

Yoshiyuki ISHIHARA* and Norio TAKAHASHI*

(Received October 31, 1979)

Synopsis

Characteristics of iron losses in silicon steel due to inclined rotating fluxes and distorted ones are described. Iron losses due to rotating fluxes have been measured at various conditions for grain-oriented and non-oriented silicon steels by using an improved thermistor-bridge method.

Loss measurements indicate that the iron loss due to the inclined rotating flux is greater than that due to the non-inclined one. However, the iron loss due to the distorted rotating flux is not always greater than that due to the non-distorted one.

1. Introduction

It is well known that there exist rotating fluxes in the T-joints of three-phase transformer cores or the stator cores of rotary machines. The characteristics of the rotating fluxes in the former have been examined experimentally and analytically by using the finite element method [1,2,3]. The characteristics of those in the latter are being clarified lately [4,5].

Many studies show that the iron losses of silicon steel due to the rotating fluxes are very much different from those due to alternating fluxes [6,7]. Most of these studies are concerned with only the iron losses due to elliptically rotating fluxes whose major axes conform to the rolling directions of silicon steels. However, the

* Department of Electrical Engineering

directions of the major axes of actual rotating fluxes do not conform to the rolling directions or they contain harmonics. The iron losses due to these actual rotating fluxes have not been systematically investigated except for a few studies, such as the measurement of local iron losses at T-joints of model transformer cores by K. Narita et al. and A. J. Moses et al [1,8].

In this paper, conditions of producing the inclined elliptically rotating fluxes are investigated. Iron losses of grain-oriented silicon steel (Grade : AISI-68, M-5) and non-oriented silicon steel (Grade : AISI-68, M-15) due to the inclined rotating flux and distorted one are measured by using the thermometric method of measuring local iron losses. The effects of the axis ratio ($a = \text{minor axis/major axis}$), inclination angle, harmonic content, and phase angle of the harmonics on such iron losses are clarified.

2. Conditions of Producing the Inclined Elliptically Rotating Fluxes

By impressing two kinds of voltages, whose phase angles are different from each other, on the two coils which intersect at right angles, various kinds of rotating fluxes can be experimentally obtained. In order to produce an optional rotating flux, it is necessary to obtain a detailed knowledge of the relations among the amplitude and the phase angle of the impressed voltage, and the flux density and the inclination angle of the elliptically rotating flux. In this section, the relations among the axis ratio a , the inclination angle θ shown in Fig. 1, and the amplitudes B_{xm} and B_{ym} of alternating flux densities due to the two coils are investigated.

It is assumed that the inclined elliptically rotating flux is represented by the following equations in the X-Y coordinate system.

$$\left. \begin{aligned} b_x &= B_L \sin \omega t, \\ b_y &= B_S \cos \omega t. \end{aligned} \right\} \quad (1)$$

Where, B_L and B_S represent the maximum flux densities in the major and minor axis directions respectively. B_y transforming X and Y into x and y respectively, following equations are obtained.

$$\left. \begin{aligned} b_x &= B_{xm} \sin \omega t = \sqrt{B_L^2 \cos^2 \theta + B_S^2 \sin^2 \theta} \sin \omega t, \\ b_y &= B_{ym} \sin(\omega t + \alpha) = \sqrt{B_L^2 \sin^2 \theta + B_S^2 \cos^2 \theta} \sin(\omega t + \alpha). \end{aligned} \right\} \quad (2)$$

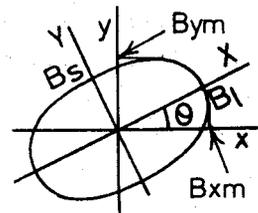


Fig. 1 Inclined elliptically rotating flux.

Where, θ is the angle between X and x axes. B_{xm} and B_{ym} are the maximum flux densities in the x and y directions respectively. The phase difference α between b_x and b_y is given by

$$\alpha = \tan^{-1}(B_g \cos \theta / B_l \sin \theta) + \tan^{-1}(B_g \sin \theta / B_l \cos \theta). \quad (3)$$

An optional elliptically rotating flux can be obtained by impressing the two kinds of fluxes whose amplitudes are B_{xm} and B_{ym} , and phase difference is α , which are determined by Eqs. (2) and (3) respectively, on the two coils. Let us define the following parameters:

$$\left. \begin{aligned} x_m &= B_{xm} / B_l, \\ y_m &= B_{ym} / B_l. \end{aligned} \right\} \quad (4)$$

B_l is normalized to 1.0, B_g is changed from 0.0 to 1.0 at 0.1 intervals in amplitude and θ from 0° to 45° at 5° intervals in angle.

Figure 2 shows the relations among the axis ratio a , the inclination angle θ , the parameters x_m , y_m , and the phase difference α . x_m and y_m are determined from Fig. 2 (a), and α from Fig. 2 (b). In the case of $45^\circ < \theta \leq 90^\circ$, x_m , y_m , and α are obtained by replacing θ with $90^\circ - \theta$ and by exchanging x_m for y_m and y_m for x_m in Eqs. (2)-(4).

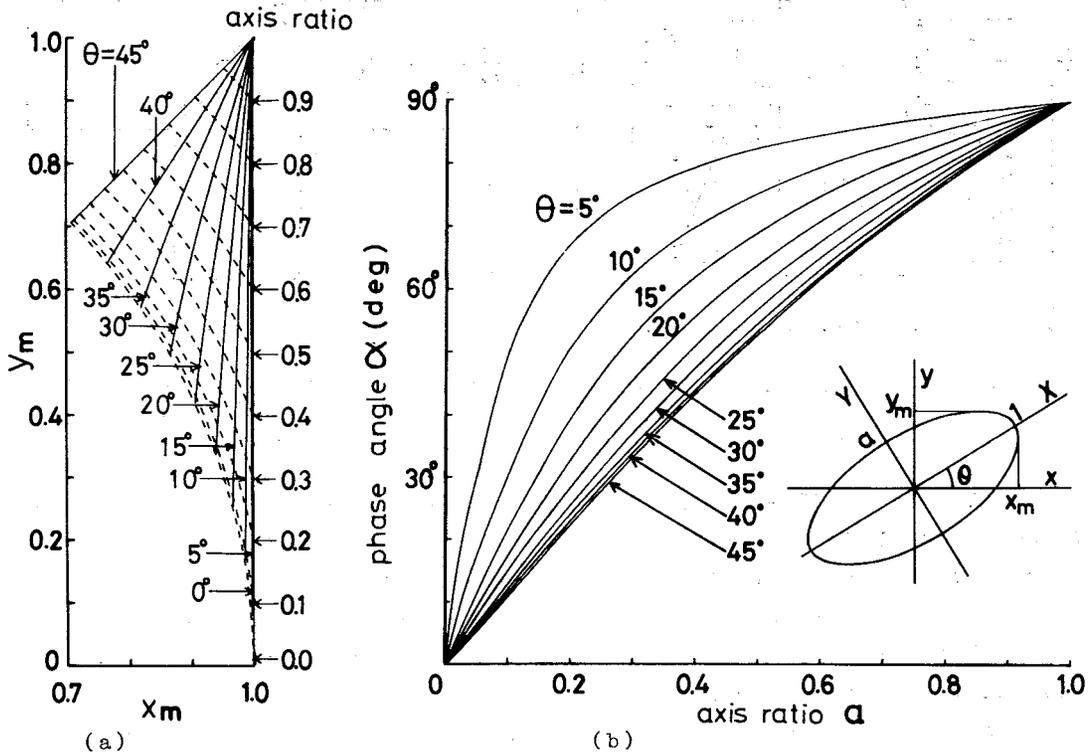


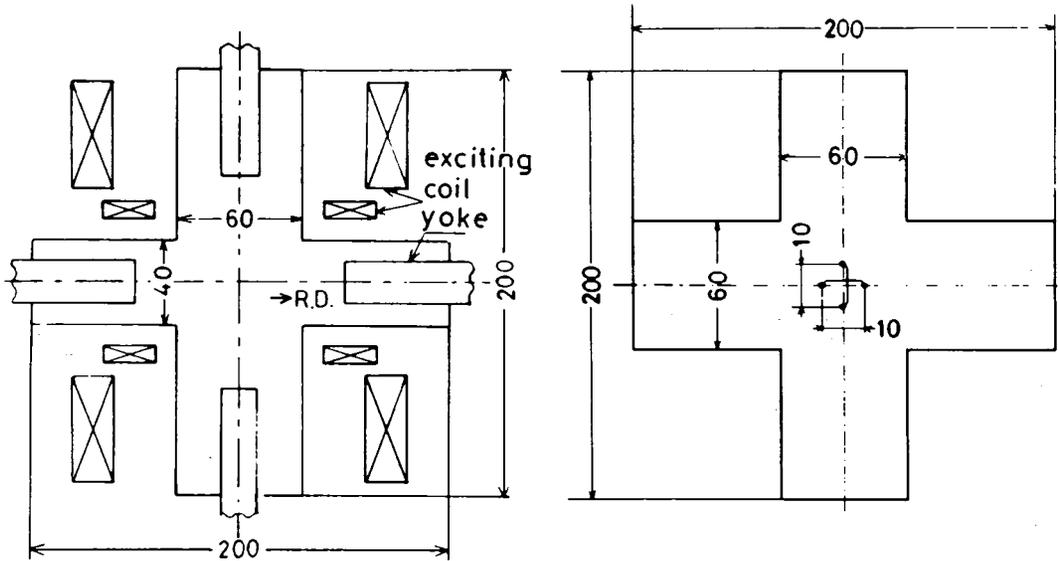
Fig. 2 Conditions of producing inclined elliptically rotating fluxes.

For example, x_m , y_m , and α at $\theta = 55^\circ$ can be obtained from those at $\theta = 35^\circ$.

It is obvious that the optional rotating flux with major axis B_l , minor axis $a \cdot B_l$, and inclination angle θ can be produced by composing the two alternating fluxes whose amplitudes are $B_l \cdot x_m$ and $B_l \cdot y_m$.

3. Samples and Exciting Apparatus

Figure 3 shows samples used in the experiment. The cross shaped samples are made of 0.35mm thick grain-oriented and non-oriented silicon steels. Four holes of diameter 0.16mm are made at 10mm intervals in these samples as shown in this figure. The measured point of the local iron loss is the center of them.



(a) grain-oriented silicon steel (b) non-oriented silicon steel

Fig. 3 Samples and arrangement of exciting coils.

Figure 4 shows the block diagram of the exciting apparatus. The source is composed of the low distortion CR oscillator and the audio stereo power amplifier (the maximum output : 300W + 300W). The distorted wave source is used in order to produce the distorted rotating flux. The circuit of the exciting source in Fig. 4 is the same with that enclosed with a broken line.

In order to avoid the magnetizing inrush current, soft start method is adopted, and accordingly, the voltage is increased from zero to the prescribed value in about 1 second.

The exciting coils are composed of four coils. Enamelled copper wire is wound on a bakelite frame. Two 750 turns coils are set in the rolling direction and two 1000 turns coils are set in the transverse direction as shown in Fig. 3 (a).

Figure 5 shows two examples of produced rotating flux. Figure 5 (a) denotes the inclined elliptically rotating flux of $B_l = 1.2$ T, $B_s = 0.4$ T, and $\theta = 30^\circ$. This rotating flux is composed of the two kinds of sinusoidally alternating fluxes set to $B_{xm} = 1.25$ T, $B_{ym} =$

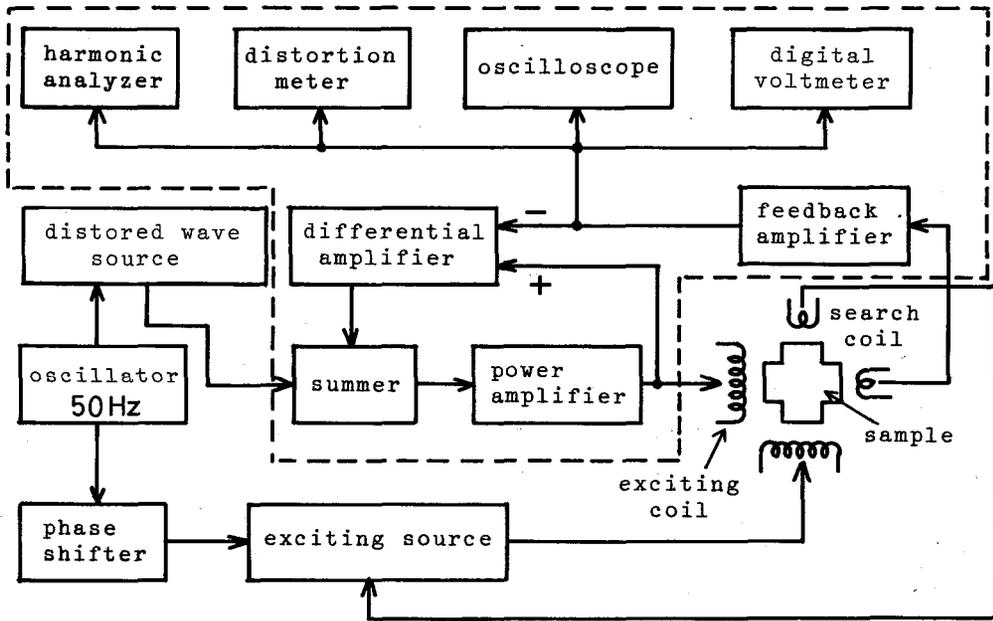


Fig. 4 Block diagram of exciting apparatus.

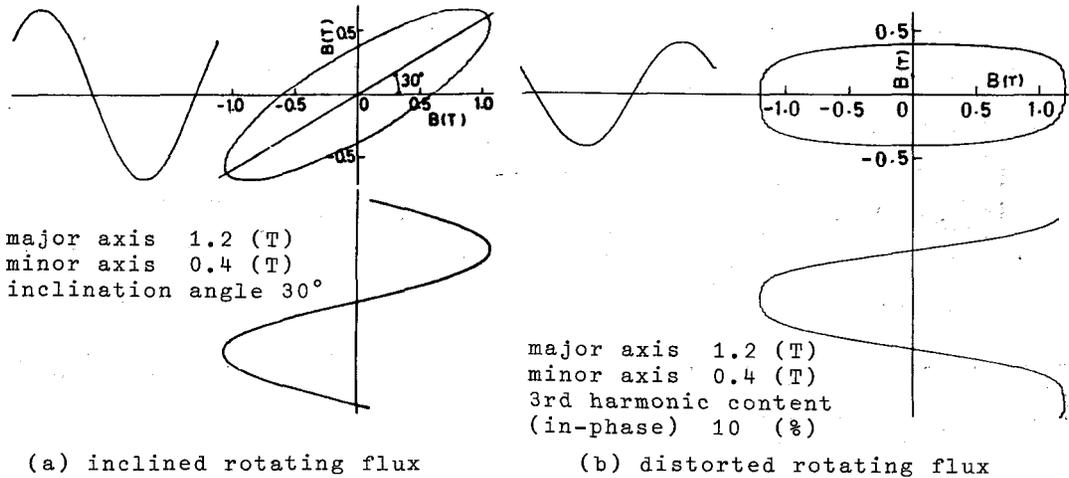


Fig. 5 Examples of rotating fluxes

0.69 T, and $\alpha = 40.9^\circ$. Where, B_{xm} and B_{ym} are the maximum flux densities in the rolling and transverse directions respectively. These values of B_{xm} , B_{ym} , and α can be easily obtained from Fig. 2 and Eq.(4). Figure 5 (b) denotes the distorted rotating flux of $B_l = 1.2$ T, $B_g = 0.4$ T, and $\theta = 0^\circ$. This flux is composed of the distorted flux in the rolling direction and the sinusoidal one in the transverse direction. The distorted flux contains the in-phase third harmonic component whose content K_3 is 10%. Where K_3 is defined by

$$K_3 = \frac{\text{3rd harmonic flux density}}{\text{fundamental flux density}} \times 100 (\%) \quad (5)$$

4. Method of Iron Loss Measurement

Local iron losses are measured by using an thermistor-bridge method. Figure 6 shows the block diagram of the measuring circuit. This circuit is composed of the detecting element, the lock-in amplifier, the differentiator, X-Y recorder etc..

The thermistor for measurement is a chip-shape one (plane contact type, 0.5mm square, and 0.25mm thick) whose B constant is 3876°K and resistance 17.55k Ω at 298°K. The thermistor which has the same characteristics as those of the thermistor mentioned above is used for the compensating one. In order to avoid induction, the 25Hz reference signal of the lock-in amplifier, whose frequency is different from the exciting one, is used as the source of the bridge. The value of the bridge voltage E is set to about 0.2V, which is enough to neglect errors caused by self-heating of the thermistor during measurement. The unbalanced voltage of the bridge is about 3.4 μ V/sec (at 25°C) per 1W/kg

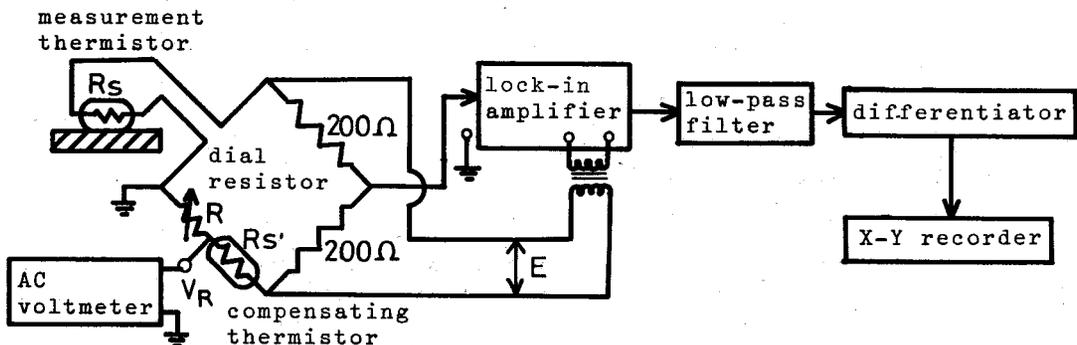


Fig. 6 Block diagram of circuit of iron loss measurement.

iron loss. This voltage is amplified by the lock-in amplifier. The output of the lock-in amplifier is recorded on the X-Y recorder through the low-pass filter and the differentiator. The low-pass filter is used in order to remove ripples contained in the d.c. output of the lock-in amplifier. The cut-off frequency of the filter is set to 0.4 Hz.

The iron loss is calculated by using an initial rate of rise of temperature [9]. The initial rate of rise of temperature is obtained from the gradient of the increasing voltage. When the differentiator is not inserted, the gradient of the increasing voltage should be read off the recorded voltage on the X-Y recorder. As the next measurement should be waited till the temperature of the sample becomes constant after one measurement, very long time is necessary for each measurement. On the contrary, the gradient of the increasing voltage can be directly obtained by inserting the differentiator. Moreover, the time for measurement can be reduced. Because the next measurement is possible when the rate of the variation of the temperature becomes constant, even if the temperature is not constant.

5. Experimental Results

Figure 7 shows the iron loss characteristics of inclined ellipti-

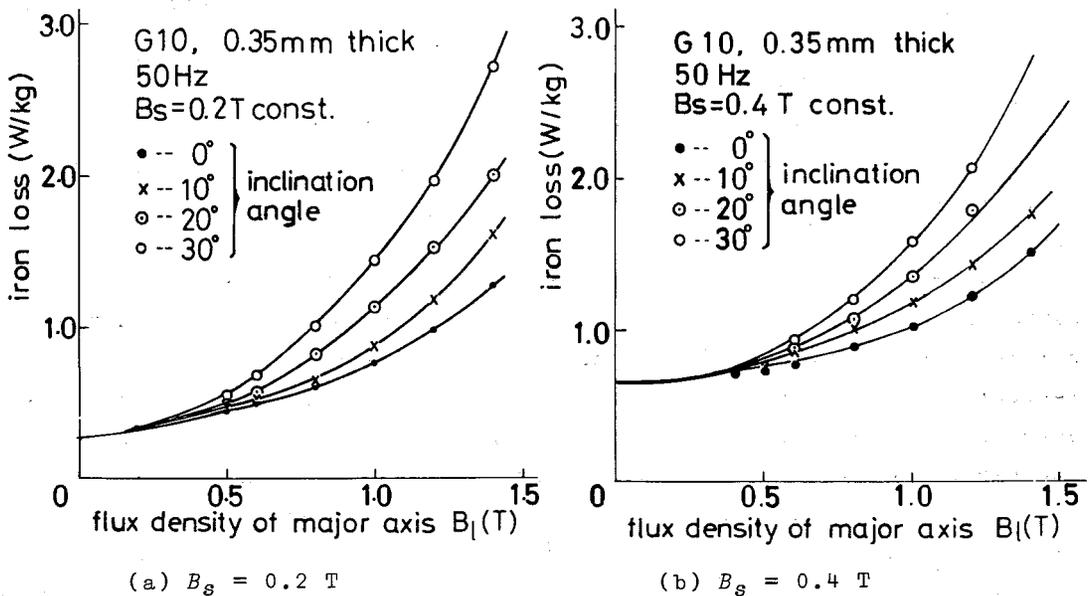


Fig. 7 Iron losses of grain-oriented silicon steel due to inclined elliptically flux.

cally rotating flux in the grain-oriented silicon steel. B_s of Figs. 7 (a) and (b) are 0.2 T and 0.4 T respectively. Therefore, when B_l of Figs. 7 (a) and (b) are 0.2 T and 0.4 T respectively, these rotating fluxes become circularly rotating ones, and accordingly, the iron losses are not changed by the inclination angle θ . The iron loss at $B_s = 0.2$ T is much more affected by the inclination angle θ than that at $B_s = 0.4$ T.

Figure 8 shows the relation among the iron loss, the flux density B_s of the minor axis, and the inclination angle θ at $B_l = 1.0$ T. B_s is changed from 0.0 T to 0.8 T at 0.2 T intervals in amplitude and θ from 0° to 90° at 10° intervals in angle. $B_s = 0.0$ T corresponds to the alternating flux. The iron loss is the maximum at $\theta = 60^\circ - 70^\circ$ independent of B_s . As B_s decreases, the rate of change of iron loss with θ increases, and the characteristics of the iron loss approach to those of alternating fluxes. The iron loss due to the circularly rotating flux is represented by the chain line. This is not affected by θ .

Figure 9 shows the iron loss characteristics of inclined elliptically rotating flux in the non-oriented silicon steel. The characteristics of the iron loss are the same with those of the grain-oriented silicon steel, but the iron loss is not so affected with θ as that of the grain-oriented one.

Figures 10 and 11 show the iron loss characteristics due to distorted rotating fluxes which contain the third harmonic only in the rolling and transverse directions of the grain-oriented silicon steel respectively. Figure 10 (a) and Fig. 11 (a) show the iron loss characteristics due to distorted alternating fluxes. The iron loss due to the distorted flux with in-phase third harmonic is larger than that due to the sinusoidal one. The iron loss due to the distorted flux with anti-phase third harmonic is smaller than that due to the sinusoidal one when K_3 is less than 25%. On the contrary, the characteristic of the iron loss is opposite to that mentioned above when K_3 is equal to 30%. The change of iron loss due to the distorted alternating

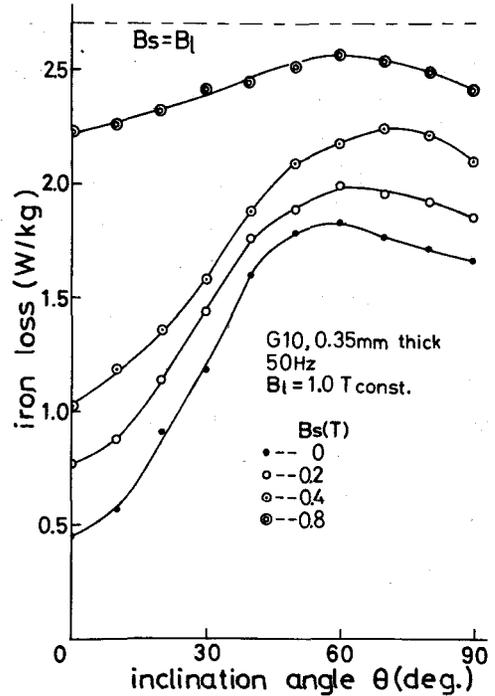


Fig. 8 Relation among iron loss, θ , and B_s .

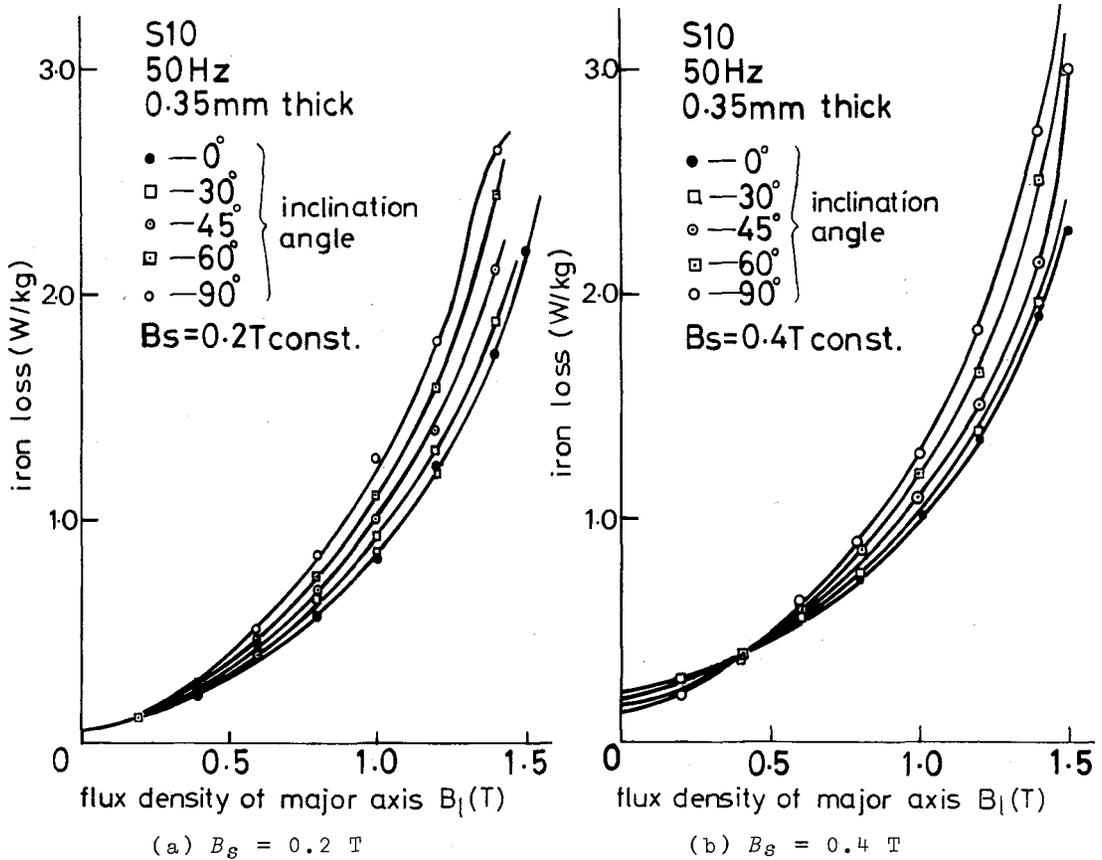


Fig. 9 Iron losses of non-oriented silicon steel due to inclined elliptically rotating flux.

flux in the rolling direction with K_3 and the phase angle is larger than that in the transverse direction. The iron loss characteristics due to distorted rotating fluxes shown in Figs. (b) and (c) are the same with those due to distorted alternating fluxes. The change of iron loss of Fig. (c) with the third harmonic flux is larger than that of Fig. (b). Namely, the effect of the harmonic flux on the iron loss becomes remarkable with the increase of the sinusoidal flux.

Figures 12 and 13 show the iron loss characteristics due to distorted rotating fluxes which contain the third harmonic only in the rolling and transverse directions of the non-oriented silicon steel respectively. The iron loss characteristics are almost the same with those of the grain-oriented silicon steel, except that the iron loss due to the distorted rotating flux which contains the anti-phase third harmonic only in the transverse direction is always smaller than that due to the non-distorted rotating one.

The change of iron loss of the non-oriented silicon steel due to

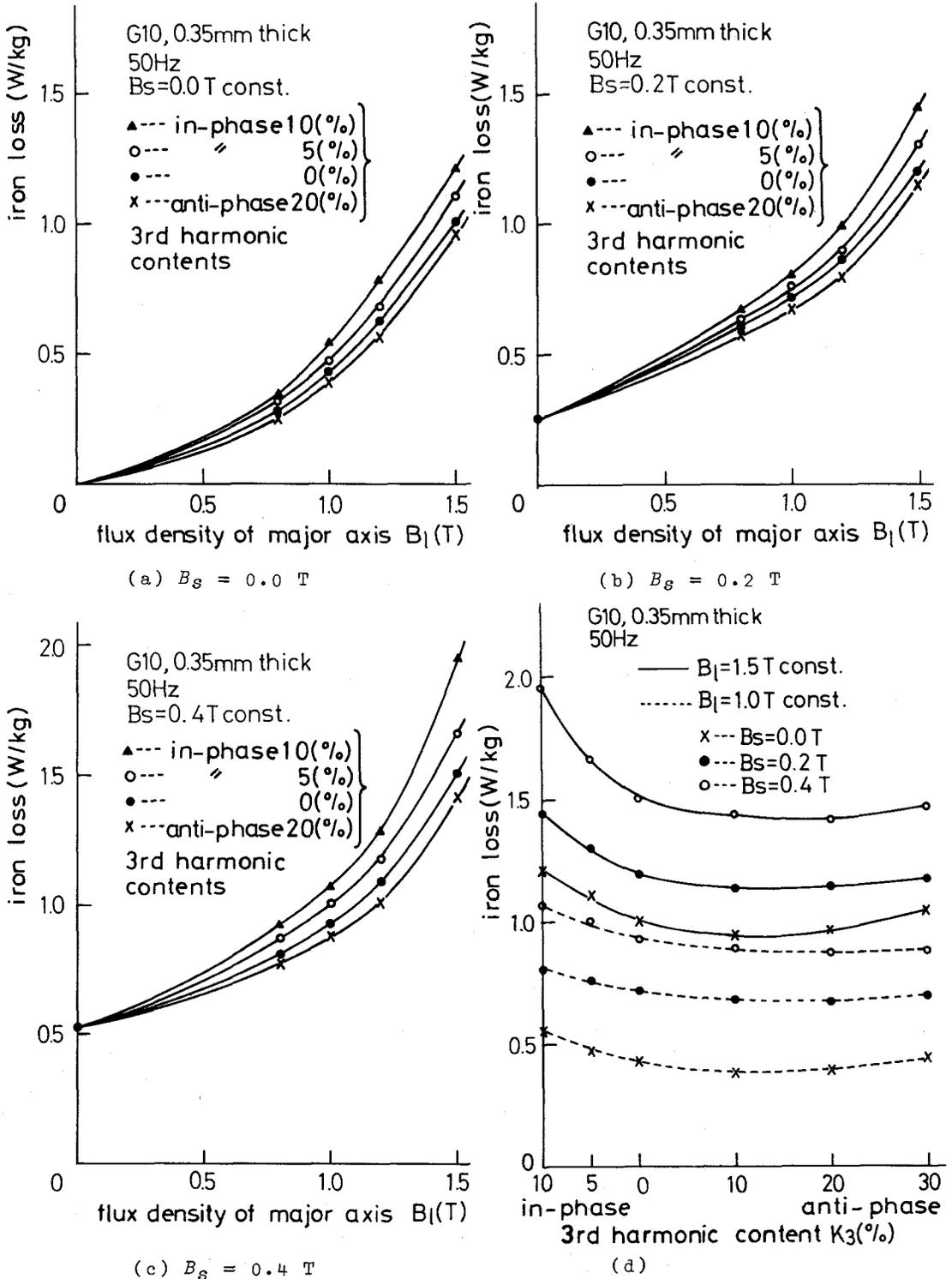


Fig. 10 Iron losses due to distorted rotating fluxes(3rd harmonic in the rolling direction, grain-oriented).

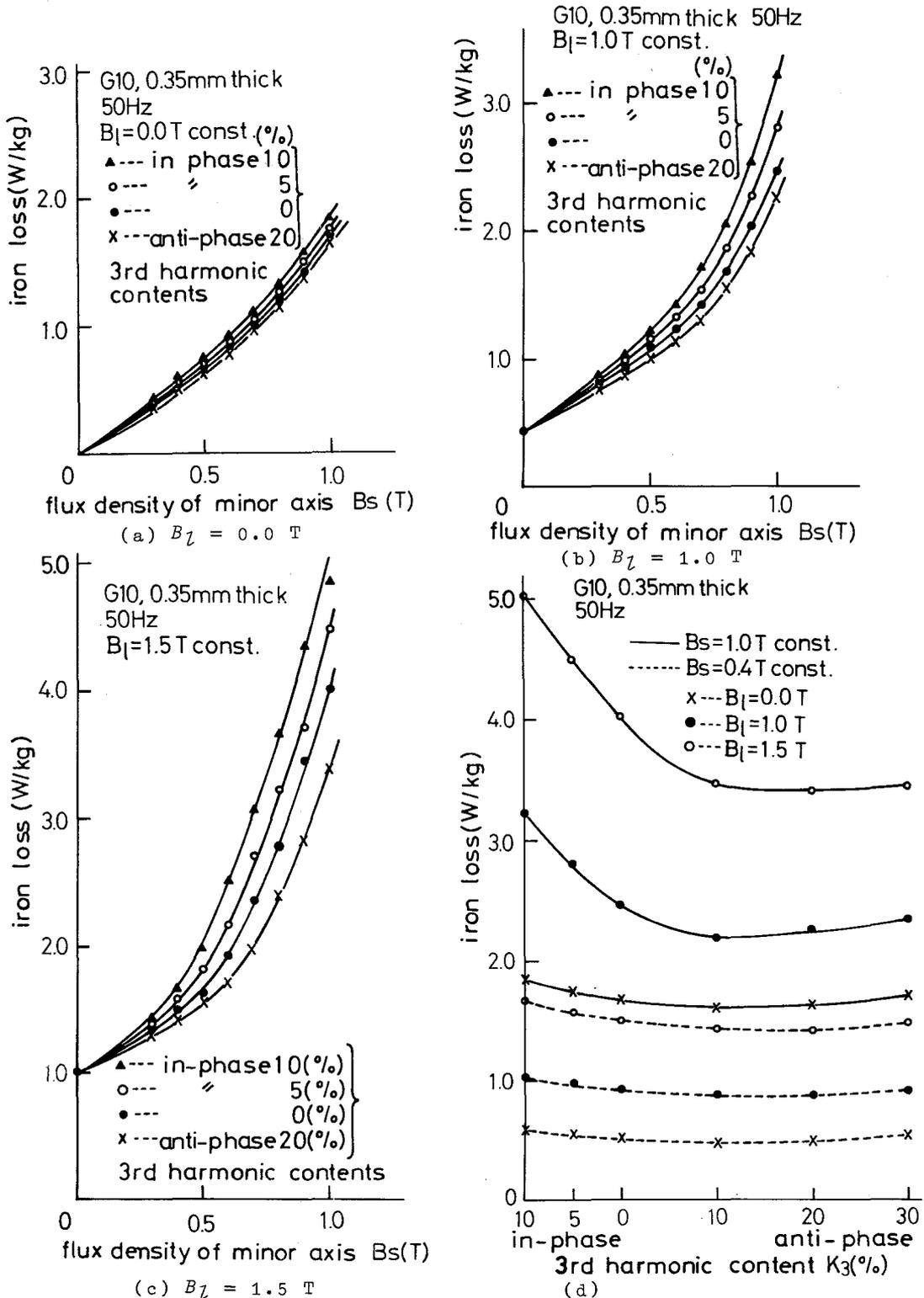
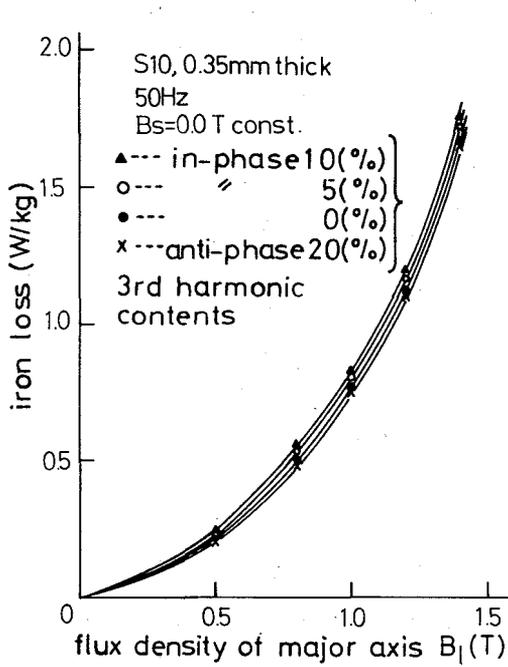
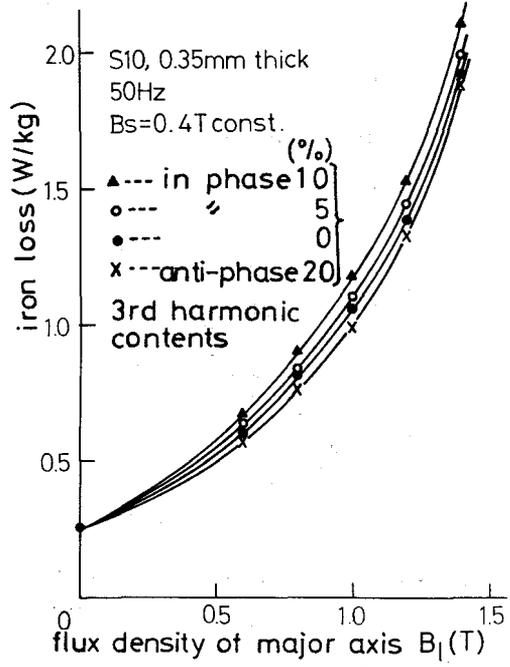


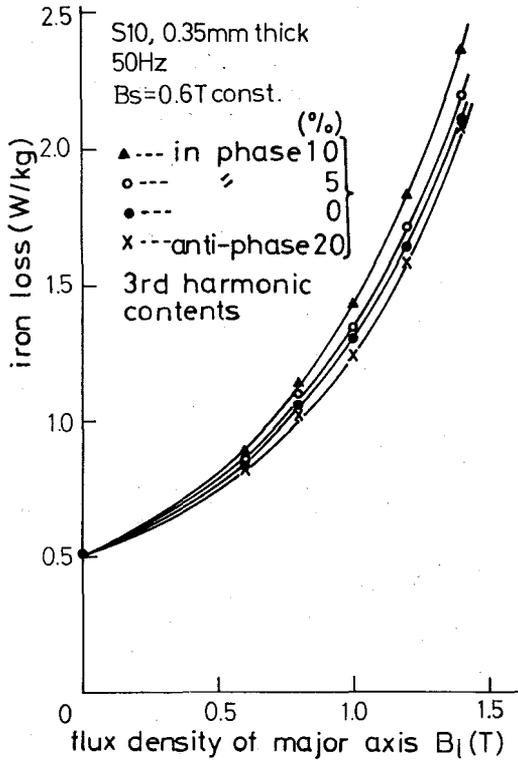
Fig. 11 Iron losses due to distorted rotating fluxes(3rd harmonic in the transverse direction, grain-oriented).



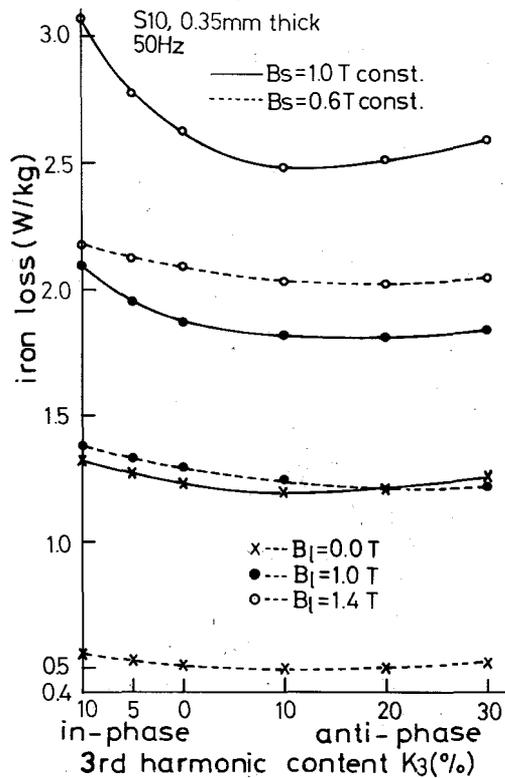
(a) $B_s = 0.0$ T



(b) $B_s = 0.4$ T



(c) $B_s = 0.6$ T



(d)

Fig. 12 Iron losses due to distorted rotating fluxes(3rd harmonic in the rolling direction, non-oriented).

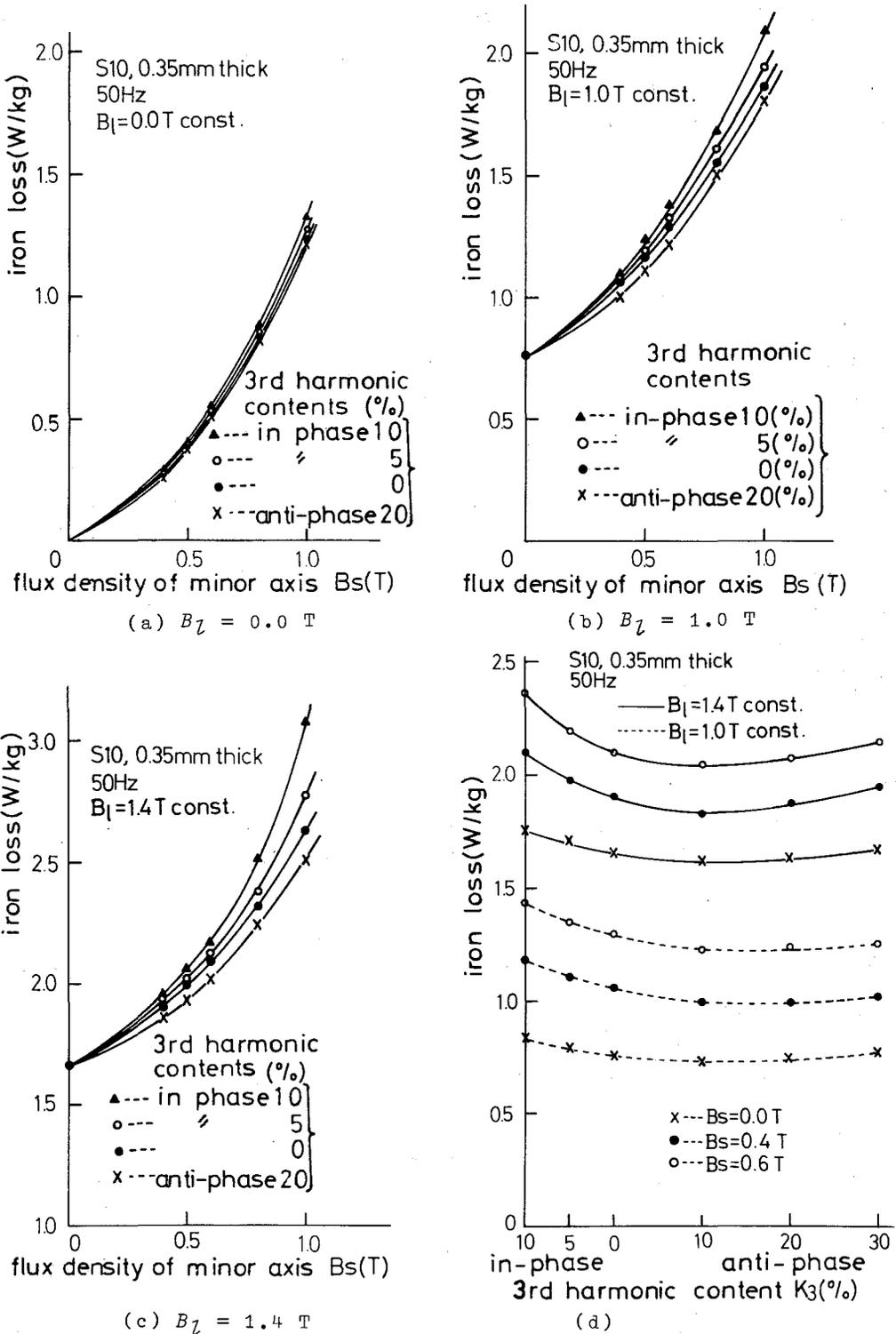


Fig. 13 Iron losses due to distorted rotating fluxes(3rd harmonic in the transverse direction, non-oriented).

the distortion of the flux is less than that of the grain-oriented silicon steel. Because, the ratio of the eddy current loss to the iron loss of the non-oriented silicon steel is less than that of the grain-oriented silicon steel.

6. Conclusions

Iron losses due to rotating fluxes are measured by using an improved thermistor-bridge method. The experimental results can be summarized as follows :

- (1) The iron loss due to the inclined rotating flux is greater than that due to the non-inclined one. As the axis ratio decreases, the rate of change of iron loss with the inclination angle increases.
- (2) The iron loss due to the distorted rotating flux is not always greater than that due to the non-distorted rotating flux which has the same major and minor axes with those of the distorted one. This fact suggests that the iron loss due to the distorted rotating flux is related to the effective flux density just like the iron loss due to the alternating one.

References

- (1) K. Narita, T. Yamaguchi et al., The Transactions of the Institute of Electrical Engineering of Japan, 95-B(1975), 9, 431.
- (2) T. Nakata, Y. Ishihara et al., Proceeding of EPS Soft Magnetic Materials 2 Conference, 4-5(1975), 57-62.
- (3) T. Nakata, Electrical Engineering in Japan, 95(1975), 3, 43-50.
- (4) T. Nakata, N. Takahashi et al., Chugoku Section Convention Record I.E.E.J., 40510(1977).
- (5) T. Yamaguchi et al., Papers of National Convention, IEE, Japan, 653(1975).
- (6) F. Baily, Trans. Roy. Soc., 187-A(1896), 715.
- (7) K. Narita and T. Yamaguchi, IEEE Trans. Magnetics, MAG-10(1974), 165.
- (8) A. J. Moses, B. Thomas et al., IEEE Trans. Magnetics, MAG-8(1972), 785.
- (9) K. Narita and M. Imamura, The Transactions of the Institute of Electrical Engineering of Japan, 94-A(1974), 4, 167.