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Experimental Studies of Various Factors Affecting Minor Loop Hysteresis Loss

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Synopsis

When the distorted flux is induced in a magnetic circuit, the minor loops arise sometimes inside the major hysteresis loop. The area, accordingly the hysteresis loss of the minor loop, is affected by its amplitude and position, by the maximum flux density, by the quality of material, etc.. In this paper, we describe the experimental studies of the factors on the minor loop hysteresis loss.

A method of getting the displacement factor of a minor loop which is placed at arbitrary position and has any amplitude is developed from our experimental results. Using this method, the core losses caused by the distorted flux can be calculated within the error less than three percent, even if the amplitude of the minor loop becomes near to the amplitude of the major loop.

1. INTRODUCTION

A method to calculate the core losses which are produced by a hysteretic curve containing minor loops has been proposed by us.[1] But, this method is applicable only small amplitude factor, a ratio of the minor loop to the major one, which is less than 15%, because the hysteresis losses of the minor loops are calculated by using the function for calculating the hysteresis loss of the major loop. When the amplitude factor of the minor loop is large, the hysteresis loss of the minor loop is

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affected by its amplitude and position, by the maximum flux density of the major loop, and by the shape of the hysteresis loop, etc..

As described in the preceding paper,[1] in order to calculate accurately the core losses due to the distorted flux containing large minor loops, the hysteresis loss of any minor loop must be able to be accurately estimated. Ball[2] and other few investigators have studied about the unsymmetrical hysteresis loops on the magnetization curve, and also about the minor loops which appear at the special positions on the major loop. However, the hysteresis loss of a minor loop which arises at arbitrary position on the major loop has been little treated.

In this paper, the experimental studies of the factors on the minor loop hysteresis loss are described. A method to calculate the displacement factor of a minor loop which arises at arbitrary position is also described.

By using this new method, the core losses due to the distorted flux having the large amplitude factor of the minor loop can be calculated far more accurately than by any other method.

2. Experimental Results and Discussions

2.1 Conditions of the experiment

The factors that may affect the loss of a minor loop are as follows:

(1) The amplitude of the minor loop Bk.

(2) The position of the minor loop Bc.

(3) The maximum flux density of the major loop Bm.

(4) The "quadrant" of the minor loop.

(5) The shape of the hysteresis loop (the quality of material).

The Bm, Bk, Bc and the quadrant of the minor loop used in this paper are defined as in Fig.1. The quadrant of the minor loop which appears on the up-going part of the hysteresis curve is called the first quadrant, and that which appears on the down-going part is called the second quadrant.

It is ideal that the experiment will be made over all the combination of the various values of Bk, Bc, Bm and the quadrant. But, only the following experiments (I) through (IV) are made so that the tendency of the influences of the factors upon the hysteresis

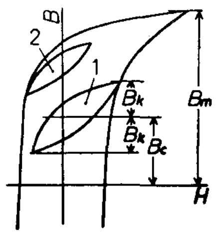


Fig.1. The definition of Bm, Bk, Bc and "quadrant".

loss of the minor loop may be qualitatively estimated by less experimental points.

(I) Influence of the major loop shapes.

In order to investigate the influence of the shapes of hysteresis loops, the experiment is made with Bm=10kG, Bk=2kG, with Bc set at intervals of 1kG from 0kG to (Bm-Bk)kG using G10 (Grain oriented silicon steel strip: JIS C 2553-1970 (Grade: AISI-68 M5)), S10 (Cold rolled silicon steel strip: JIS C 2552-1970 (Grade: AISI-68 M15)), and 50%NiFe.

The major hysteresis curves of these three materials at Bm=10kG are shown in Fig.2.

(II) Influence of the Bc.

The influence of the Bc upon losses and its variation by the maximum flux density Bm are investigated in this experiment.

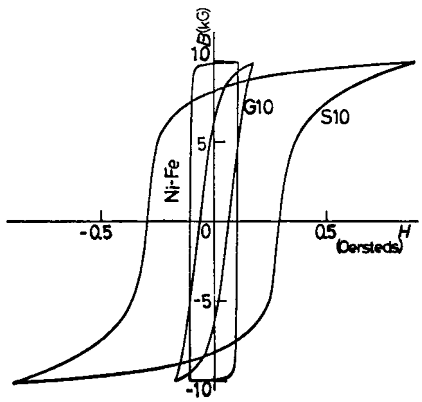


Fig.2. Hysteresis loops of various materials.

First, the experiment is made at the parameter of Bm in the condition of Bk=2kG. If the value of Bk is too small, the error becomes too large in measuring the area of the minor loop, and if Bk is too large, the range of variation of Bc becomes too small. For this reason, the experiment is made at Bk=2kG where the error of measured area of the minor loop is less than 3%. Bm is set at intervals of 1kG from 10kG to 15kG in G10 and from 8kG to 14kG in S10.

Next, the experiment is made with Bm=13kG in G10 and Bm=12kG in S10 at the parameter of Bk. Bk is set at intervals of 1kG from 3kG to 5kG in both G10 and S10.

In these experiments, Bc is set at intervals of 1kG from 0kG to (Bm-Bk)kG.

(III) Influence of the Bk.

The influence of the Bk upon the losses and its variation by the maximum flux density Bm are investigated in this experiment. If the value of Bc is too large, it is impossible to vary Bk in a wide range. When Bc is set at 0kG, Bk can be varied in the widest range. In this experiment, Bk is set at intervals of 1kG from 2kG to (Bm-1)kG. Bm is set at the same values as adopted in the above experiment (II).

(IV) Influence of the quadrant.

The shape of the minor loop appearing on the first quadrant differs from that appearing on the second quadrant even if the other conditions are all the same; that is, Bm, Bk and Bc of the two minor loops are the same each other. There is a possibility that the hysteresis losses of these two minor loops are not identical. To investigate this point, we carry out an experiment which compares the core loss of the minor loop in the first quadrant with that in the second one. This experiment is impossible to carry out on D.C.. The experiment is performed by utilizing the following characteristic of the distorted waves.

The values of the Bm, Be (the nominal effective flux density)[3], Bk and Bc of the hysteresis loop arisen by a distorted flux are identical with those which occur by the inversed flux wave form[4], but only the quadrants of these minor loops differ each other. Since Bm and Be of each flux wave form have the same values, the major hysteresis loss and the eddy-current loss of these two hysteresis loops may be said to be identical. Therefore, the difference between these core losses, if exists, will be considered to be caused by the hysteresis losses of the minor loops.

From this point of view, a distorted flux wave which consists of the fundamental (50Hz) and the third harmonic waves and its inversed flux wave are adopted. The influence of the quadrant of the minor loop is investigated by comparing the core losses produced by these two distorted waves. This experiment is done at Bm=10kG using S10 which has the large percentage of the hysteresis loss to the total core losses. The conditions of the experiment are shown in Table 1. The phase angle in this table is defined by the phase angle Θ_3 of the following equation.

$$b=B_1\sin\omega t+B_3\sin 3(\omega t+\Theta_3), \qquad (1)$$

where, B_1 is the amplitude of the fundamental wave, and B_3 is the amplitude of the third harmonic. The in-phase means the condition where $0^\circ \leqq \Theta_3 < 60^\circ$, and the minor loop appears in the first quadrant. The anti-phase means the condition where $0^\circ > \Theta_3 \geqq -60^\circ$, and the minor loop appears in the second quadrant.

2.2 Measuring devices and experiment

The measurements are made by using a 25-cm Epstein tester for materials G10 and S10, and by using a wound toroidal core, of which inside diameter is 120mm, outside diameter is 140mm and height is 10mm, for material 50%NiFe. The thickness of former material is 0.35mm and that of latter is 0.1mm. A sample made of a wound toroidal core is also used for G10 and a sample made of a ring core is used for S10. The similar results to those on the Epstein tester are obtained.

The hysteresis loss of the minor loop is converted from the area of the D.C. hysteresis loop which is recorded on a X-Y recorder.

The circuit measuring the D.C. hysteresis loop is shown in Fig.3. A series of thirteen batteries (the unit is 2V and 210AH) is used as the power source. A integrating electronic flux meter is used as the integrator and its output is connected with the Y-axis input of the X-Y recorder. The voltage across the resistance Rs of 0.1Ω combined in series with the exciting winding is fed to the X-axis input of the X-Y recorder.

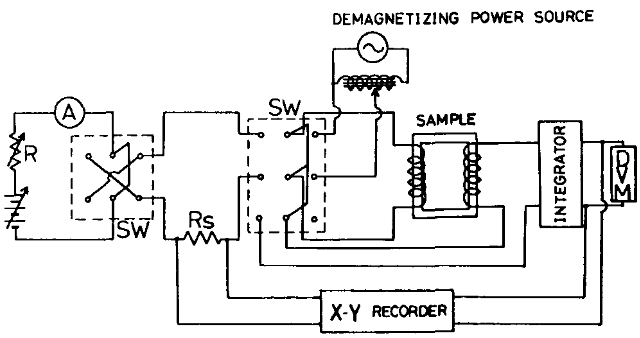


Fig.3. Measuring circuit.

The experiment in the item (IV) is made on A.C.. The constitution of the distorted source for this experiment is identical with that in the reference (1). Thus, the explanation of this circuit is omitted.

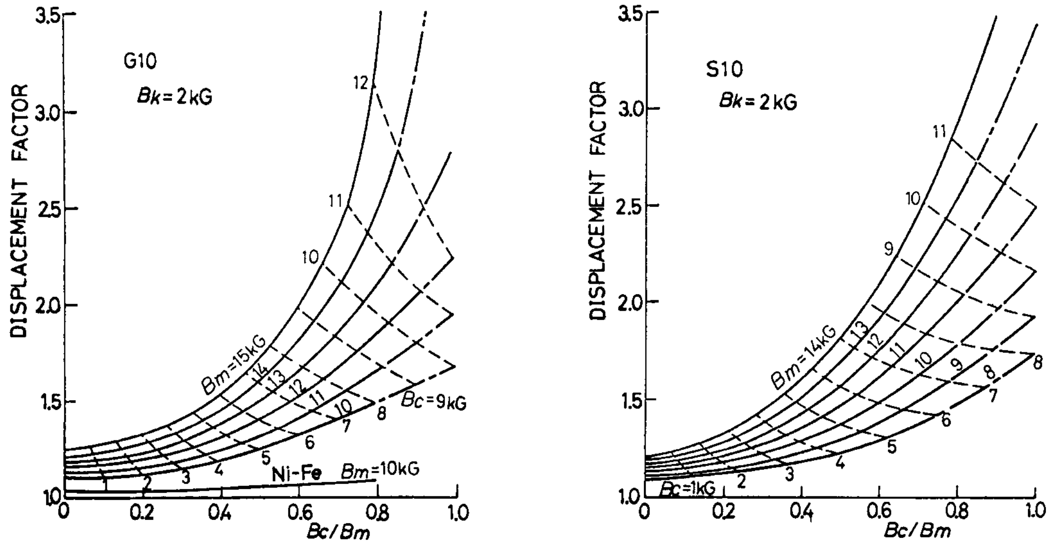
2.3 EXPERIMENTAL RESULTS

The experimental results are shown in Figs.4,5 and 6. Figures (a) denote the results about material G10, and Figs.(b) about S10. In Fig.4(a), the result for 50%NiFe at Bm=10kG is also shown. For better understanding, the results are shown by using the displacement factor. The displacement factor η is defined by the following equation:

$$\eta = Whi(Bk)/Wh(Bk), \qquad (2)$$

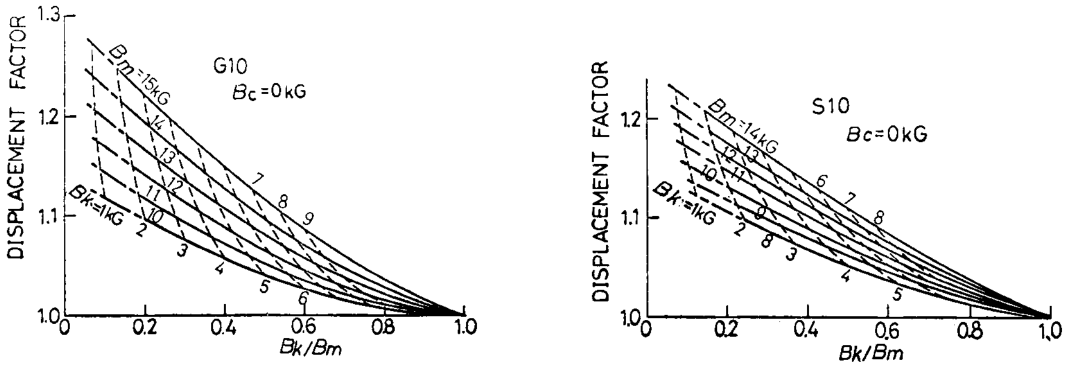
where, *Whi*(Bk) denotes the hysteresis loss of the minor loop with the amplitude Bk, and *Wh*(Bk) denotes the hysteresis loss of the major loop with the same amplitude.

The displacement factors of G10 and S10 vary tolerably by the value of Bc. But, that of 50%NiFe varies little. This is caused by the characteristic of the square hysteresis loop of 50%NiFe. Therefore,



(a) (b)

Fig.4. Relations between Bc/Bm and displacement factor at Bk=2kG.



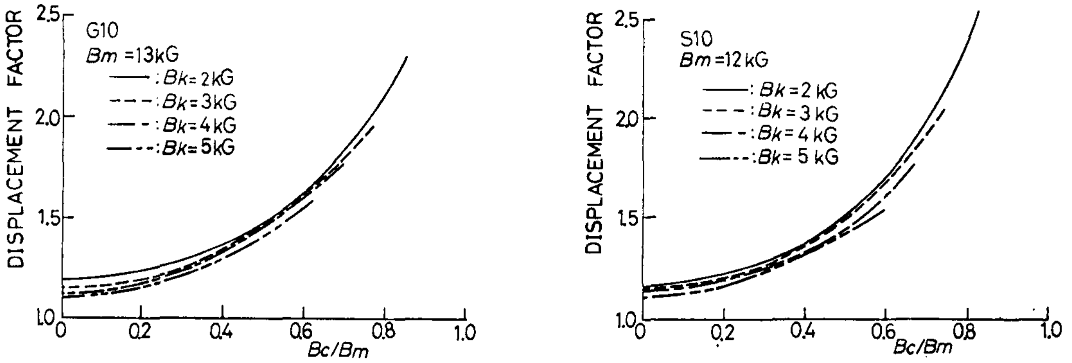
(a) (b)

Fig.5. Relations between Bk/Bm and displacement factor at Bc=0kG.

in 50%NiFe, only the experiment of the item (I) in Section 2.1 has been made.

Figure 5 shows the relation between Bk/Bm and the displacement factor at Bc=0kG. When Bk/Bm is equal to the unity, the displacement factor is also equal to the unity.

As the measured points in Figs.4,5 and 6 are so numerous, the figures become indistinct if all points are plotted. Therefore, only the presumed curves are drawn, but the error between the measured points and



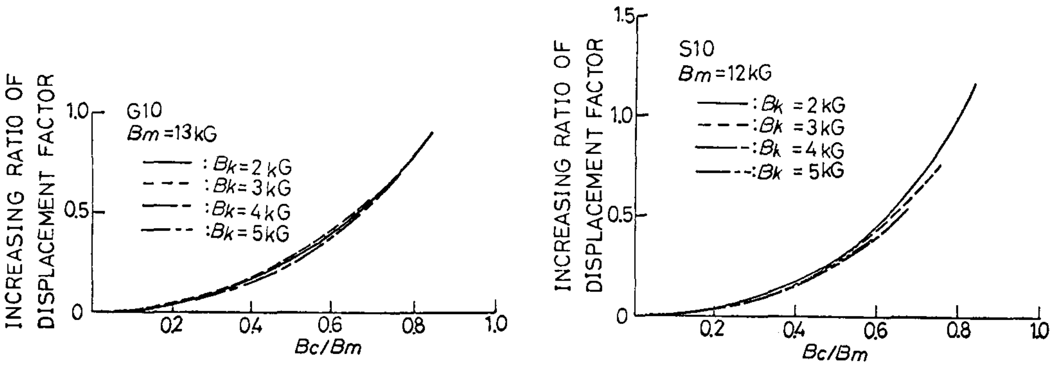
(a) (b)

Fig.6. Relations between Bc/Bm and displacement factor at a constant Bm.

the presumed curve remains less than 3%.

The actually measured points in Fig.4 exist below (Bm-2)/Bm on the abscissa. For the convenience of the utilization to the estimating method described later, the presumed curves are extended to the points where Bc/Bm is equal to the unity. The stretched curves are denoted by the chain lines. For the same reason, the curves in Fig.5 are extended to the neighborhood of the ordinate. The dotted lines in Figs.4 and 5 give constant Bk and Bc curves.

The curves of the increasing ratio of the displacement factor obtained from Fig.6 are shown in Fig.7. The increasing ratio of the displacement



(a) (b)

Fig.7. Relations between Bc/Bm and increasing ratio of displacement factor at a constant Bm.

factor is defined as the ratio of the displacement factor at a certain Bc to that at Bc=0 in the same Bm and Bk.

The experimental results to investigate the influence of the quadrant of the minor loop described in the item (IV) of the preceding section are shown in Table 1.

Table 1. Comparison of the hysteresis losses of various minor loops arisen on the two quadrants.

Phase Angle (degree)	Bk(kG)	Bc(kG)	B_1(kG)	B_3(kG)	Core Losses (W/kg)	
					In-phase	Anti-phase
4	2.06	6.97	9.15	4.21	1.33	1.33
14	2.00	5.10	7.69	4.31	1.27	1.26
29	2.00	3.04	6.39	4.41	1.23	1.23
49	2.00	0.99	5.64	4.45	1.21	1.21
5	3.00	5.90	7.95	5.01	1.44	1.44
17	3.01	3.97	6.41	5.13	1.38	1.37
35	3.02	2.02	5.25	5.20	1.35	1.34
5	4.00	5.02	6.83	5.80	1.66	1.65
20	4.01	3.03	5.25	5.88	1.60	1.60
44	4.01	1.05	4.23	5.92	1.58	1.57

Material : S10 , Fundamental freq.: 50Hz

2.4 SUMMARY OF EXPERIMENTAL RESULTS

The summary of our experimental results in Section 2.3 is as follows.

(1) The displacement factor is greater than the unity. In other words, the hysteresis loss of a minor loop is greater than that of the major loop at the same amplitude.

(2) With increasing Bc/Bm, the displacement factor also increases at a constant Bk. With increased Bm, the displacement factor increases at a constant Bc/Bm. In other words, the displacement factor of the minor loop appearing in the saturated region is greater than other displacement factors.

(3) When Bk increases, the displacement factor decreases at a constant Bc. And if Bc is equal to zero, it decreases down to the unity.

(4) When Bm increases, the displacement factor also increases at a constant Bk and a constant Bc.

(5) The curve of the increasing ratio of the displacement factor is hardly affected by Bk at a constant Bm.

(6) The influence of the parameter Bc on the displacement factor is greater than those of other parameters Bm, Bk and quadrant.

(7) The displacement factor is influenced by the shape of the hysteresis curve, i.e. the quality of material. When the shape of the hysteresis curve approaches a rectangle, the displacement factor decreases and approaches the unity.

(8) The displacement factor is hardly affected by the quadrant.

3. Simple Estimating Method of the Displacement Factor

The displacement factor varies with Bm, Bk and Bc as described in Chapter 2. Therefore, numerous data are need to know the displacement factor of an optional minor loop. In this chapter, a simple method to estimate the displacement factor of a minor loop in an optional condition is described by utilizing the experimental curves in Chapter 2.

Item (5) of Section 2.4 means that the ratio of the displacement factor η_1 to η_3 is equal to that of η_2 to η_4. The η_1 through η_4 are the displacement factors of the minor loops 1 through 4 in Fig.8. The amplitudes of the minor loops 1 and 3 are the same (Bk_1) and those of 2 and 4 are also the same (Bk_2), and the positions of the minor loops 1 and 2 are the same (0kG) and those of 3 and 4 are Bco.

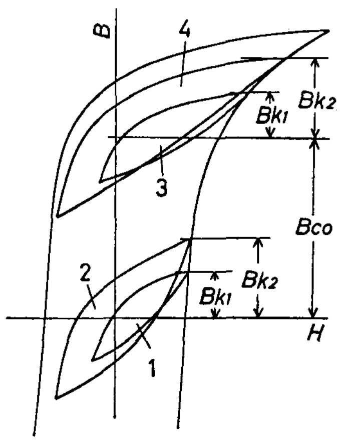


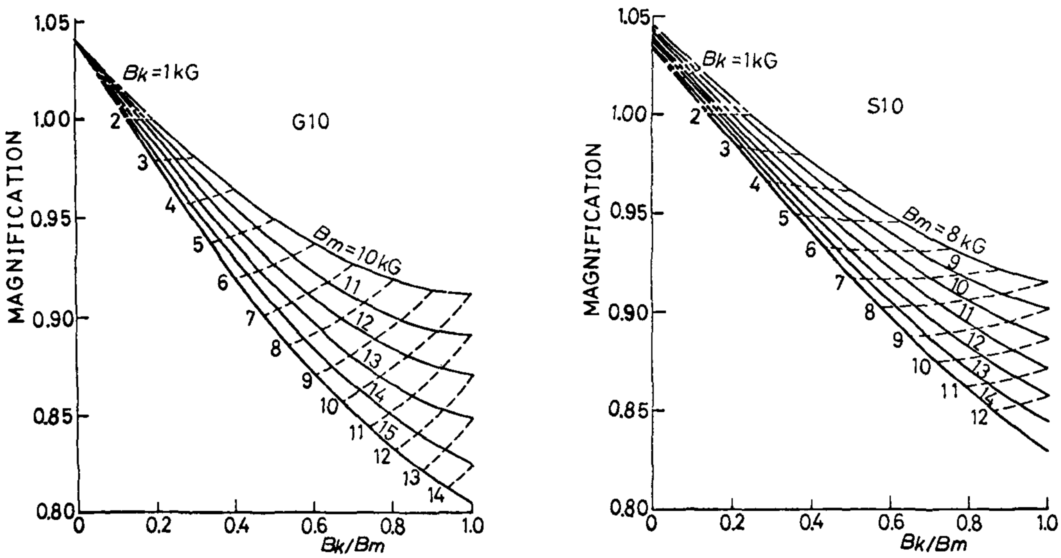
Fig.8. Schematic diagram of minor loops.

Hence, if optional three displacement factors among the η_1 through η_4 are known, the remainder can be calculated by using the relation described above. Now let us assume that η_4 is unknown. Taking the amplitude and position of the basic minor loop 1 at 2kG and 0kG, η_1 and η_3 at Bk_1=2kG can be obtained from Fig.4. The η_1 and η_2 at Bc=0kG can be obtained from Fig.5. Therefore, by utilizing Figs.4 and 5, the unknown displacement factor η_4 can be calculated by the following equation.

$$\eta_4=\eta_3 . \eta_2/\eta_1 . \qquad (3)$$

The displacement factor η_3 of the minor loop at Bk=2kG is known from

Fig.4. Therefore, if the value of η_2/η_1 at Bk_1=2kG is known, the displacement factor η_4 is easily calculated from Eq.(3). From this point of view, Fig.9 is obtained by using Fig.5. In Fig.9, the



(a) (b)

Fig.9. Relations between Bk/Bm and magnification.

Table 2. Comparison of calculated and measured displacement factors.

No.	Bm(kG)	Bk(kG)	Bc(kG)	Displacement Factors		
				Calculated	Measured	Error (%)
1	10.0	3.0	1.0	1.08	1.07	0.9
2	10.0	6.0	1.0	1.03	1.05	-1.9
3	10.0	6.0	3.0	1.08	1.10	-1.8
4	14.0	3.0	1.0	1.17	1.16	0.9
5	14.0	3.0	5.0	1.37	1.36	0.7
6	14.0	3.0	9.0	1.87	1.85	1.1
7	14.0	3.0	3.0	1.26	1.24	1.6
8	14.0	6.0	3.0	1.18	1.15	2.6
9	14.0	9.0	3.0	1.12	1.14	-1.8
10	8.0	3.0	1.0	1.09	1.07	1.9
11	8.0	6.0	1.0	1.03	1.02	1.0
12	8.0	4.0	3.0	1.12	1.14	-1.8
13	13.0	3.0	1.0	1.19	1.17	1.7
14	13.0	3.0	5.0	1.46	1.43	2.1
15	13.0	3.0	9.0	2.14	2.19	-2.3
16	13.0	3.0	3.0	1.28	1.27	0.8
17	13.0	6.0	3.0	1.21	1.18	2.5
18	13.0	9.0	3.0	1.16	1.13	2.6

No.1-No.9: G10, No.10-No.18: S10
Error={(calculated)-(measured)}×100/(measured)

magnification is a ratio of the displacement factor η_2 of the minor loop of which parameters are equal to Bm, Bk and Bc=0kG to the displacement factor η_1 of the minor loop of which parameters are equal to Bm, Bk=2kG and Bc=0kG. Hence, the magnification is identical with η_2/η_1 of Eq.(3). The dotted lines in Fig.9 give a constant Bk.

The comparison between the displacement factor calculated with Figs.4 and 9 and that actually measured is shown in Table 2. The experimental points in Table 2 are so selected as to investigate in the wide range of Bm, Bk and Bc for both G10 and S10.

Let us explain concretely how to presume the displacement factor about the case of No.1 in Table 2. As the displacement factor at Bm=10kG and Bc=1kG, the value 1.10 is obtained from Fig.4(a). As the magnification at Bm=10kG and Bk=3kG, the value 0.98 is obtained from Fig.9(a). Hence, the displacement factor 1.08 at Bm=10kG, Bk=3kG and Bc=1kG is obtained by multiplying the displacement factor 1.10 by the magnification 0.98.

According to Table 2, the error of the displacement factor obtained by our method is less than 3%.

4. Calculation of Core Losses Produced by the Highly Distorted Flux

In this chapter, the application of the method proposed in Chapter 3 to the calculation of the core losses caused by the highly distorted flux is described.

Let us assume that the core losses W can be estimated by the following equation.

$$W = Wh(Bm) + We(Be) + 2\Sigma\eta Wh(Bk), \qquad (4)$$

where, $Wh(Bm)$= the hysteresis loss at the maximum flux density Bm(W/kg),
$We(Be)$= the eddy current loss at the nominal effective flux density Be(W/kg).

The method of calculating the eddy current loss $We(Be)$ has already been explained in the preceding paper.[1]

Many experimental results of the core losses are compared with those calculated from Eq.(4). Table 3 shows these losses and parameters of the distorted wave forms used in experiment. In Table 3, No.1 through 4 show the distorted wave forms containing the optional odd harmonics. The values of Bm, Bk and Bc of these waves are read from the wave form drawn on the X-Y recorder as shown in Fig.10. The Be is calculated from the figure by the harmonic analysis. No.5 through 10 show the distorted

Table 3. Comparison of calculated and measured core losses produced by highly distorted flux.

No.	Bm(kG)	Be(kG)	Bk(kG)	Bc(kG)	Measured Displacement Factor	Minor Loop Hysteresis Loss (W/kg)	Total Core Losses Calculated (W/kg)	Total Core Losses Measured (W/kg)	Total Core Losses Error (%)
1	13.6	29.1	6.4	2.8	1.22	0.63	3.68	3.73	-1.3
2	13.9	27.5	5.2	5.2	1.42	0.53	3.52	3.49	0.9
3	14.6	34.9	10.0	0.9	1.06	0.25	3.17	3.25	-2.5
4	14.7	27.0	6.3	6.7	1.45	0.15	2.18	2.24	-2.9
5	10.0	14.9	1.0	4.3	1.33	0.06	1.23	1.22	0.8
6	10.0	18.9	2.1	3.7	1.26	0.20	1.67	1.65	1.8
7	10.0	22.2	3.0	3.2	1.21	0.35	2.13	2.11	0.9
8	10.0	13.4	1.1	8.9	1.99	0.05	1.12	1.13	-0.9
9	10.0	16.4	2.0	8.0	1.78	0.16	1.44	1.43	0.7
			0.6	0.0	1.16				
10	10.0	20.4	3.1	6.9	1.57	0.32	1.94	1.92	1.0
			1.7	0.0	1.14				

Notes: 1. No.1 to 4 are by the optional distorted wave, No.5 to 7 are by the wave in which the fifth harmonic wave is in-phase with the fundamental wave and No.8 to 10 are by that of anti-phase.

2. The material except for No.3 and 4 is S10 and that of No.3 and 4 is G10.
3. The frequency of the fundamental wave is 50Hz.
4. The error is the value of 100(Wc-Wm)/Wm, where Wc is the calculated value and Wm is the measured value.

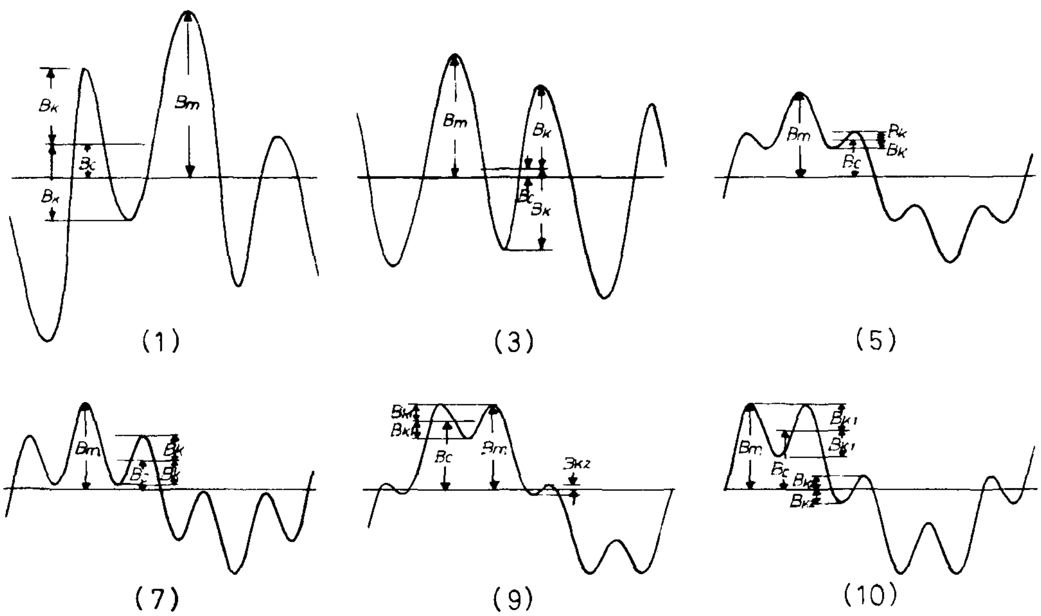


Fig.10. Measured flux waveforms.

waves composed of the fundamental wave and the fifth harmonic. Except No.8, No.5 through 10 have two pairs of minor loops. In No.5, 6 and 7, the fundamental wave and the fifth harmonic are in-phase, and in No.8, 9 and 10, they are anti-phase. In the former, two pairs of minor loops appear at the same position. And in the latter, the minor loops appear at the top and the side of the hysteresis loop. The values of Bm, Be, Bk and Bc of these waves are obtained from the calculation.

Figure 10 shows typical wave forms used in experiment. The numbers of the figures agree with numbers in Table 3.

Table 3 shows that the error of the calculated core losses is less than 3%. From this experiment, we find that the core losses produced by the highly distorted flux can be calculated with fairly good accuracy.

5. Conclusions

The factors affecting the hysteresis loss of the minor loop, i.e. the amplitude, position and quadrant of the minor loop, the maximum flux density of the major loop and the quality of material are investigated experimentally. The summary of these results are shown in Section 2.4.

Considering the experimental results, a simple calculating method of the displacement factor is proposed. The error of the displacement factor calculated with our method is less than 4%. Utilizing the displacement factor obtained by this method, the error of the core losses produced by the highly distorted flux is less than 3%.

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