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Single Sheet Tester Having Open Magnetic Path for Measurement of Magnetostriction of Electrical Steel Sheet

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***Abstract* — A single sheet tester having closed magnetic path (a closed type of SST) has a problem that measurement accuracy of magnetostriction is considerably affected by electromagnetic force between specimen and yoke. Therefore, an open type has been developed. In order to get uniform flux distribution in sufficiently large region, a compensating magnetizing winding is installed, and a method of waveform control is investigated, in which applied voltages to main and compensating windings are adjusted individually. The effectiveness of the newly developed open type is demonstrated by measuring magnetostrictions of thin amorphous sheet as well as highly grain-oriented silicon steel sheet.**

***Index Terms* — amorphous metal, laser Doppler vibrometer, magnetostriction, silicon steel, single sheet tester**

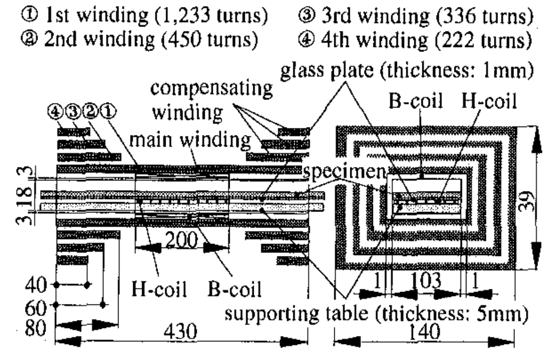
I. Introduction

A closed type of SST is widely used in the measurements of magnetic properties such as magnetostriction as well as magnetization curve and power losses of electrical steel sheets [1]-[3]. However, the measurement accuracy of magnetostriction is very sensitive to the electromagnetic force between specimen and yoke [3]. Although an open type of SST having a single magnetizing winding is proposed to overcome such a difficulty, the uniformity of flux distribution is not sufficient [4].

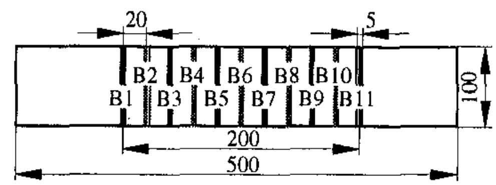
In this paper, an open type of SST having main and compensating windings, which are excited individually, is proposed. The construction and feature of the proposed open type are described, and a technique for making the flux distribution uniform by controlling the applied voltages of both windings is discussed. The magnetostriction measurements obtained from the open and closed types are compared.

II. Single Sheet Tester Having Open Magnetic Path

Figure 1 shows the newly developed open type. As shown in Fig. 1 (a), the compensating winding is wound at the edges of main winding to get the uniform flux distribution. The length (430mm) and width (103mm) of main winding are determined so that a specimen of 500mm×100mm shown in Fig. 1(b) can be used, which is also available for the JIS (Japanese Industrial Standards) SST [2]. The compensating winding is composed of three layers of different lengths (80, 60, 40mm) and they are connected in series. The configuration of windings is determined with the help of magnetic field analysis. As the main and compensating windings are excited individually, supplemental power amplifier, matching transformer and attenuator are added in an excitation part of the measuring system for the closed type [3] as shown in Fig. 2. In a data acquisition part, a scanning switch is also added, because flux densities at two positions in specimen are detected by using two of B-coils wound directly on specimen as shown in Fig. 1(b) for waveform control described below.



(a) magnetizing windings



(b) B-coils wound directly on a specimen

Fig. 1. Single sheet tester having open magnetic path.

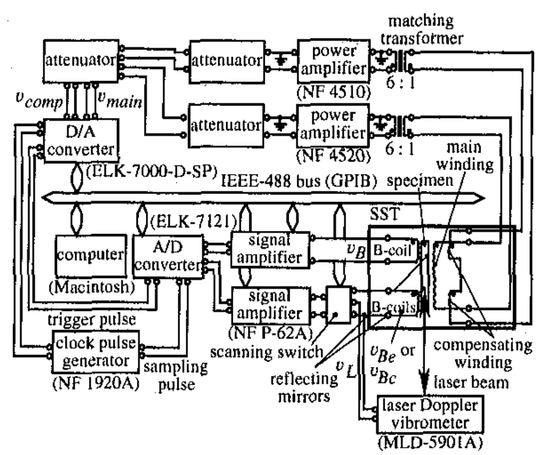


Fig. 2. Digital measuring system.

III. Method of Waveform Control

In order to establish a method of waveform control, the flux distribution in specimen is examined. Figure 3(a) shows the effects of the amplitude V_{main} of voltage v_{main} of main winding on the maximum value B_m and the phase angle θ_B of flux density when the amplitude V_{comp} of voltage v_{comp} of compensating winding and the phase difference φ_v between v_{main} and v_{comp} are fixed. Both B_m and θ_B increase with increase

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of V_{main}, and the change rates of both quantities at the center are larger than those at the edge. The effects of V_{comp} and φ_v are also measured as shown in Figs. 3(b) and (c). The tendency of obtained results can be summarized as shown in Table I. A method of waveform control is developed based on these results.

Figure 4 shows the flow chart of proposed method of waveform control. At the process ①, v_{main} is adjusted so that B_c and B_e can be equal to each other, where B_c and B_e are the maximum flux densities at the center and the edge, respectively. At the process ②, the waveform b_e of flux density at the edge, which is less sensitive, is controlled so as to be sinusoidal by adjusting v_{main}. When v_{main} is adjusted, the waveform of flux density approaches to the sinusoidal one in wide region as well as the specified position. At the process ③, the waveform b_c at the center, which is more sensitive, is controlled so as to be sinusoidal by adjusting v_{comp}. These processes are iterated until specified convergence criteria shown in Table II are satisfied at each process. ε_B and ε_{FF} are the errors of the maximum flux density and form factor FF of induced voltage, respectively. $\Delta\theta_B$ is the phase difference between b_c and b_e. By using the proposed method of waveform control, the sufficient uniformity can be realized in the range of 200 mm in terms of the maximum flux density and the phase.

Figure 5 shows the initially and finally applied waveforms of v_{main} and v_{comp}. B1 and B6 coils shown in Fig. 1(b) are adopted to control the flux waveforms. A highly-oriented silicon steel sheet (JIS 27P100, thickness: 0.27 mm, $W_{17/50}$: ≤1.00 W/kg) is used as a specimen. B_m and frequency f are set at 1.9 T and 50 Hz, respectively. There is a large difference between the final waveforms of v_{main} and v_{comp}. Although another measurement is also carried out by using B8 in stead of B6, the similar results are obtained. It is understood that the maximum flux density of the open type is large enough compared with the closed type.

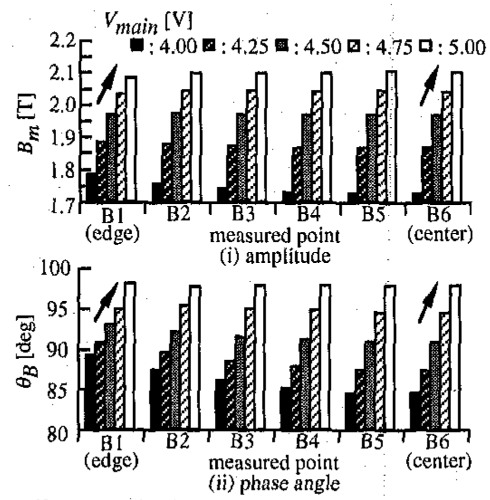
IV. Results and Discussion

Figure 6(a) shows the comparison of magnetostrictions of silicon steel sheet (27P100) obtained from the open and closed types with various conditions. The frequency is 50 Hz. The magnetostrictions are measured by means of a laser Doppler vibrometer [3]. It is understood that the measurement accuracy of magnetostriction obtained from the open type is comparable to that from the closed type with a glass plate [3] inserted between specimen and yoke. When there is no glass plate and B-coils are wound directly on specimen, the closed type gives the extremely large error. Figure 6 (b) shows the comparison for the thin amorphous sheet (METGLAS 2605S-2, thickness: about 30 μm), which is annealed at 350 °C for 10 min applying magnetic field of 1.2 kA/m. In the case of silicon steel sheet, the difference between the result obtained from the open type and that from the closed type with gap is within a few percents. In the case of thin amorphous sheet, however, the difference is about several ten percents. Especially, the closed type without gap is not applicable to the magnetostriction measurements of thin amorphous sheet. It is demonstrated that the magnetostriction of amorphous metal is about ten times as large as that of silicon steel.

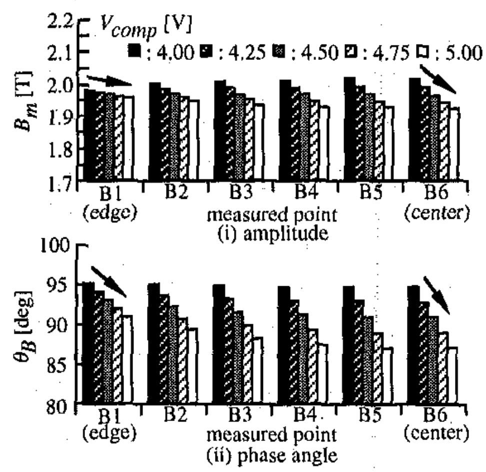
V. Conclusions

The results obtained are summarized as follows:

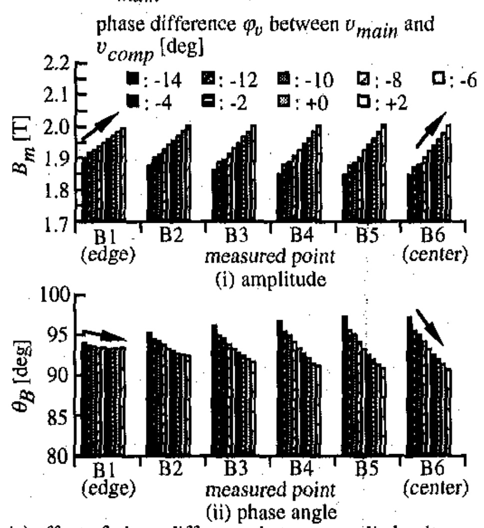
(1) By exciting the main and compensating windings individually, the flux distribution can be uniform enough compared with the closed type. The maximum flux density is also sufficiently large.



(a) effect of amplitude of applied voltage of main winding (v_{comp} = 4.5V, φ_v= 0deg)



(b) effect of amplitude of applied voltage of compensating winding (v_{main} = 4.5V, φ_v= 0deg)



(c) effect of phase difference between applied voltages (V_{main} = V_{comp} = 4.5V)

Fig. 3. Effect of applied voltages of main and compensating windings on flux distribution.

Table I. Effects of applied voltages

applied voltage			flux density edge ••• center	
V_{main}	↗	B_m, θ_B	↗ ••• ↗	increase
V_{comp}	↗	B_m, θ_B	→ ••• ↘	decrease
φ_v	(+) ↗ (-)	B_m	↗ ••• ↗	increase
		θ_B	↘ ••• ↘	decrease

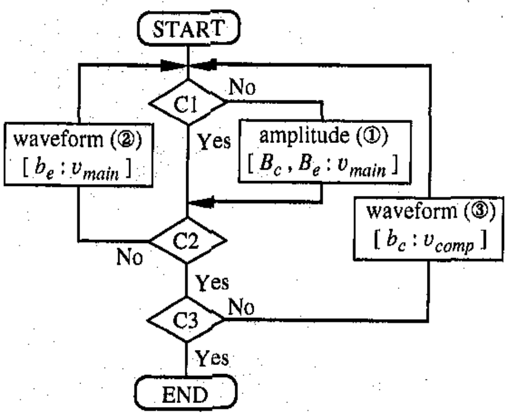


Fig. 4. Flow chart.

Table II. Convergence criteria

criteria	C1	C2	C3
$\lvert\varepsilon_{Bc}\rvert$ [%]	0.1	–	0.1
$\lvert\varepsilon_{Be}\rvert$ [%]	0.1	0.1	0.1
$\lvert\varepsilon_{Bc}-\varepsilon_{Be}\rvert$ [%]	0.15	–	0.15
$\lvert\Delta\theta_B\rvert$ [deg]	0.05	–	0.05
$\lvert\varepsilon_{FFc}\rvert$ [%]	–	–	0.1
$\lvert\varepsilon_{FFe}\rvert$ [%]	–	0.1	0.1

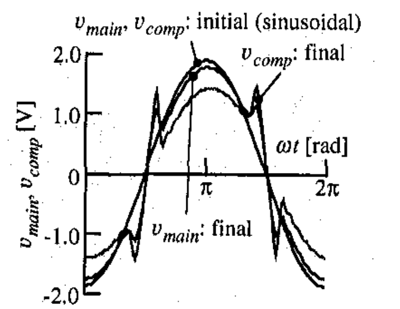
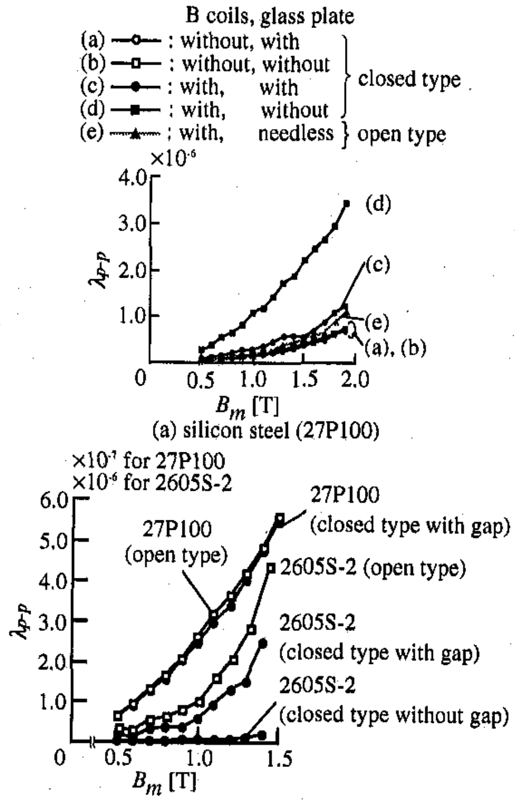


Fig. 5. Waveforms of applied voltages (JIS 27P100, B_m = 1.9T, f = 50Hz).



(b) amorphous metal (2605S-2)

Fig. 6. Comparison of magnetostrictions (f = 50Hz).

(2) The proposed method of waveform control is effective.
(3) The newly developed open type can be used for the magnetostriction measurements of thin amorphous sheet. However, the closed type is not applicable.
(4) In the case of silicon steel sheet, the closed type is sufficient. Then, the open type is not required.
(5) The magnetostriction of amorphous metal is about ten times as large as that of silicon steel.

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