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Measuring System for Magnetostriction of Silicon Steel Sheet under AC Excitation Using Optical Methods

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***Abstract* — A measuring system for magnetostriction of silicon steel sheet using optical methods and a single sheet tester has been developed to establish a standard test method for IEC and JIS. Various factors affecting measurement accuracy and reproducibility of the developed system are examined. Two optical instruments, such as a laser Doppler vibrometer and a heterodyne displacement meter, are compared. 3-D characteristics of magnetostriction under ac excitation in the rolling direction are measured up to 2.0 T.**

***Index Terms* — Acoustic noise of transformer, heterodyne displacement meter, laser Doppler vibrometer, magnetostriction, silicon steel, single sheet tester**

I. INTRODUCTION

It is fairly significant to measure magnetostriction of silicon steel to develop a method for reducing acoustic noise of electrical machines, especially transformers. In [1], a measuring system for magnetostriction under ac excitation using a laser Doppler vibrometer and single sheet tester (SST) [2]-[5] was reported. However, the effect of background vibration noise, which is very important, was not examined sufficiently, because a vibration eliminator could not be prepared. Moreover, investigation of measurement accuracy was not adequate. Namely, it was carried out at a specific flux density, because a robust waveform control method [6] was not developed. Some systems for measuring magnetostriction have already been reported [7]-[9]. However, they are not applicable to standardized silicon steel sheets, because they were specially designed for thin films.

In this paper, the accuracy of a measuring system is re-investigated by implementing the vibration eliminator and by realizing fully automatic measurements to establish a standard method of measurement of magnetostriction of silicon steel sheet using a SST for IEC and JIS. Various factors, such as background vibration noise, averaging, reset of reflecting mirror, and gap between specimen and yoke, affecting the measurement accuracy are examined. Reproducibility of the developed system is also validated. Furthermore, as optical instruments, a laser Doppler vibrometer (LDVM) and a heterodyne displacement meter (HDM) are compared. As an example, the magnetostriction in the rolling, transverse and thickness directions under ac excitation in the rolling direction are measured up to 2.0 T.

II. MEASURING SYSTEM USING OPTICAL METHODS

Fig. 1 shows the block diagram of the developed fully automatic digital measuring system [6]. A horizontal double-yoke type of SST [2]-[5] is adopted for the excitation of a specimen. Fig. 2 shows the cross section of the SST. The magnetizing winding is split so that the magnetostriction in the transverse direction can be measured under the condition that the rolling direction is excited. The distances between the two reflecting mirrors in the rolling and transverse directions are set at 170 and 90 mm respectively. A D/A converter, signal amplifiers and a A/D converter are all connected to a system controller through the IEEE-488 bus (GPIB). As optical instruments, the LDVM and the HDM are employed. The sensor part of the optical instrument and the SST are mounted on a phenol resin table (thickness: 36 mm) and they are put together on an air cushion type of vibration eliminator of which the natural frequencies in the vertical and horizontal directions are 1.5 and 1.8 Hz respectively. An induced voltage v_B of a secondary winding and the v_O corresponding to a velocity measured by the LDVM are amplified by the signal amplifiers to get an adequate voltage level for the input range of the programmable A/D converter. The LDVM requires two measurements, because it has only one beam. After these measurements, the displacement ΔL between the two mirrors on the specimen is calculated by integrating the velocity measured. The HDM has two beams and can evaluate ΔL at one measurement. It also has a GPIB interface internally and transfers ΔL directly to the system controller. The magnetostriction is calculated as the ratio of ΔL to a distance L between the two mirrors after removing the odd harmonics by FFT [1]. The flux density in the specimen is obtained by numerical integration of v_B. A control program is constructed by using the visual programming language LabVIEW, which enabled us to shorten the time for developing the program.

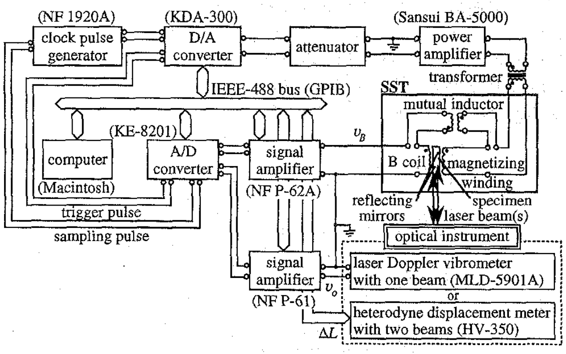

Fig.1 Digital measuring system for magnetostriction under ac excitation.

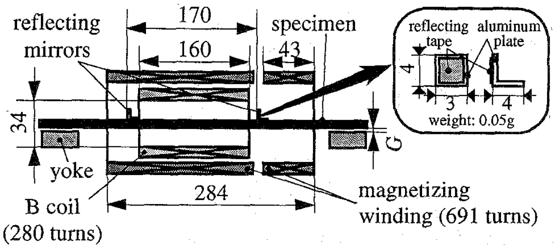

Fig.2 Single sheet tester.

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III. MEASUREMENT ACCURACY

A. Factor Affecting Measurement Accuracy

Various factors affecting measurement accuracy are examined using grain-oriented silicon steel sheets of JIS highest grade 27P100 (thickness: 0.27 mm, $W_{17/50} \le 1$ W/kg, $B_8 \ge 1.85$ T). The rolling direction is excited. The applied voltage is controlled so that the flux waveform in the specimen is sinusoidal. Waveform control is terminated, when absolute values of errors $|\varepsilon_{FF}|$ of the form factor FF and $|\varepsilon_{Bm}|$ of the amplitude B_m of flux density are both within 0.1 %. $|\varepsilon_{FF}|$ and $|\varepsilon_{Bm}|$ are defined as the deviations from the form factor of a sinusoidal wave (=1.111) and the required flux density respectively. B_m is varied from 0.6 to 1.9 T at a frequency of 50 Hz, which is made different from the commercial frequency (60 Hz), to reduce the noise due to electromagnetic induction from power source.

1) Environmental noise: Environmental noise is measured with no excitation. Namely, all instruments shown in Fig. 1 are switched on, but the output of the power amplifier is set at zero. Fig. 3 shows the displacement waveforms with and without the vibration eliminator. When averaging is not carried out, the effectiveness of the eliminator can be clearly seen. When the eliminator is used and averaging is carried out, environmental noise is removed considerably, but a periodic noise remains. As its principal harmonics have frequencies of 60 and 120 Hz, this periodic noise results from electromagnetic induction.

Fig. 4 shows the effect of the number of averages on the environmental noise converted into magnetostriction λ_{err}. Solid lines with triangle marks mean the average values of five individual measurements shown by circles at each number of averages. Comparing the two optical instruments at the lower number of averages, it can be seen that the HDM is stabler than the LDVM. At the higher number of averages, it is more difficult to judge what is superior between the two instruments, because their measure quantities are different from each other. From the standpoint of measuring time, it was decided that the number of averages should be thirty. At that number, the minimum magnetostrictions of the LDVM and HDM to be measured within error of 1 % are 3.11×10^{-7} and 3.64×10^{-7} respectively. As the distance between the two mirrors in the rolling direction is 170 mm as shown in Fig. 2, these minimum magnetostrictions correspond to displacements of 52.9 and 61.9 nm.

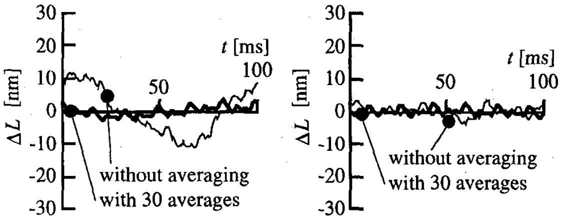
2) Gap between specimen and yoke: Fig. 5 shows the effect of the gap between the specimen and the yoke. The gap length G shown in Fig. 2 is changed by inserting glass plates. The error ε is defined as follows:

$$\varepsilon = (\lambda - \lambda_{ave}) \,/\, \lambda_{ave} \times 100\ [\%]\ , \qquad (1)$$

where λ is the peak-to-peak value of magnetostriction. λ_{ave} is an average value of five measurements at each flux density. The specimen is reset mechanically (remove and install again) every measurement and is neutralized.

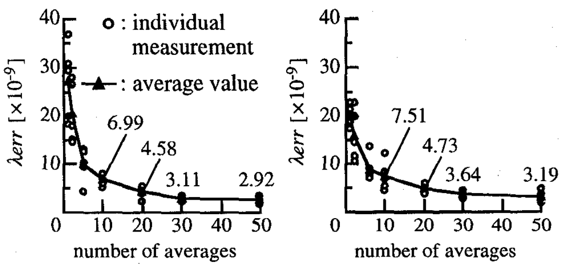
The amount of scatter for G = 1.2 mm is slightly smaller than that for G = 0 mm. In the case of G = 2.4 mm, which is not in Fig. 5, it is larger than the others. Therefore, some gap can make the flux distribution in the gap uniform and can reduce the electromagnetic force between the specimen and yoke. The larger gap, however, is not appropriate, because it causes a non-uniform flux distribution in the specimen.

3) Reset of reflecting mirrors and specimen: Fig. 6 shows the effect of removal and installation of the reflecting mirrors and specimen. Fifteen measurements are carried out at each flux density. The specimen is reset every time. The mirrors are reset every five measurements. The error ε is calculated using (1) after changing λ_{ave} into the average value of fifteen measurements. The amount of scatter is within ± 20 %. As the reset of mirrors is followed by that of specimen, the amount of scatter for the reset of mirrors cannot be separated directly. However, it is estimated to be within a few percent from the comparison of Figs. 5 (b) and 6 considering the reproducibility of the system shown later in Fig. 7.



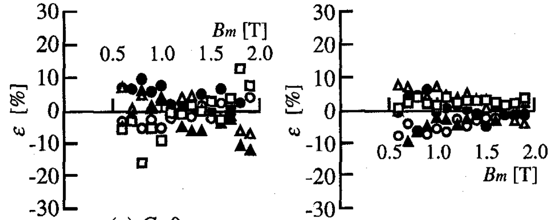
(a) without vibration eliminator (b) with vibration eliminator

Fig.3 Effect of vibration eliminator (G=1.2mm).



(a) LDVM (b) HDM

Fig.4 Effect of averaging.



(a) G=0mm (b) G=1.2mm

Fig.5 Effect of gap between specimen and yoke (with vibration eliminator).

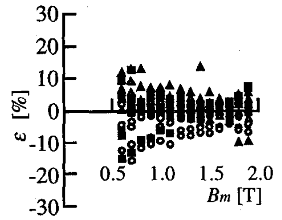


Fig.6 Effect of reset of reflecting mirrors and specimen (with vibration eliminator, G=1.2mm).

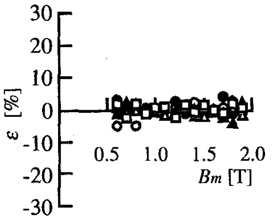


Fig.7 Continuous measurement (with vibration eliminator, G=1.2mm).

B. Reproducibility

In order to validate the reproducibility of the developed system, measurements are carried out continuously without reset of the specimen and mirrors. Five measurements are done at each flux density. Fig. 7 shows the scatter of the continuous measurements. The amount of scatter is within ± 5 %. Therefore, the reproducibility of the system may be good enough.

IV. MAGNETOSTRICTIONS UNDER AC EXCITATION

Figs. 8-10 shows the waveforms, the butterfly loops and the peak-to-peak values of magnetostriction of the grain-oriented silicon steel sheet of 27P100 respectively. The rolling direction is excited at 50 Hz. By improvement of waveform control [6], the magnetostriction can be measured easily even at 2.0 T. λ_r, λ_w, λ_t mean the magnetostriction in the rolling, transverse and thickness directions. λ_t is calculated by assuming that the volume of specimen is not changed by the deformation as follows:

$$(1+\lambda_r)(1+\lambda_w)(1+\lambda_t)=1\ . \qquad (2)$$

The magnetostriction in the transverse and thickness directions show a similar tendency.

Fig. 11 shows a comparison of the LDVM and the HDM. The difference is within ± 5 %, when it is normalized by the results of the HDM.

V. CONCLUSIONS

The results obtained are summarized as follows:

1. Environmental noise can be removed considerably by implementing a vibration eliminator and by averaging several measurements.
2. Some gap is required between specimen and yoke.
3. The minimum magnetostriction to be measured within error of 1 % at a mirror distance of 170 mm is about 4×10^{-7}.
4. The amounts of scatter for reset of mirror and specimen, and continuous measurements are within ± 20 and 5 % respectively.
5. The difference of prepared optical instruments is within ± 5 %.
6. The 3-D characteristics of magnetostriction can be evaluated up to 2.0 T.

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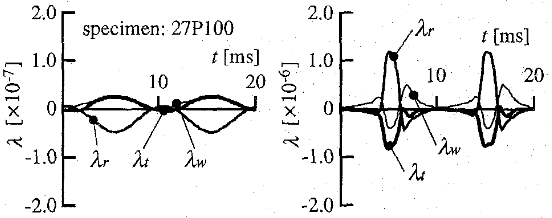
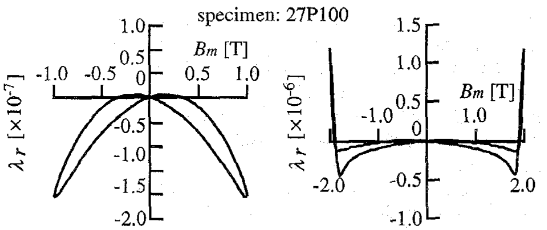
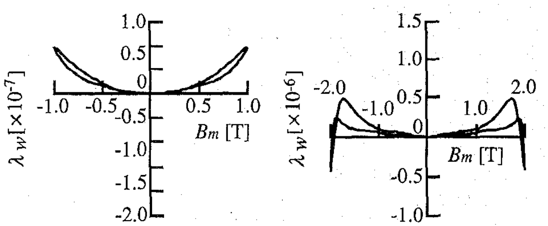


(a) $B_m = 0.5$T (b) $B_m = 2.0$T

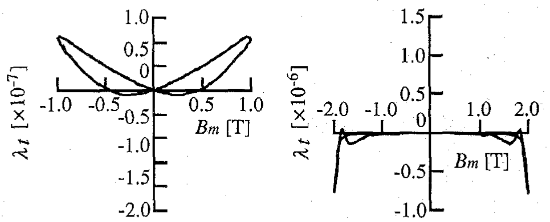
Fig.8 Waveforms of magnetostriction (with vibration eliminator, G=1.2mm).



(a) rolling direction



(b) transverse direction



(c) thickness direction

$B_m = 1.0$T $B_m = 2.0$T

Fig.9 Butterfly loops (with vibration eliminator, G =1.2mm).

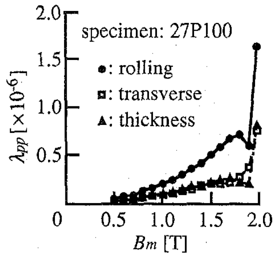


Fig.10 Peak-to-peak values of magnetostriction (with vibration eliminator, G=1.2mm).

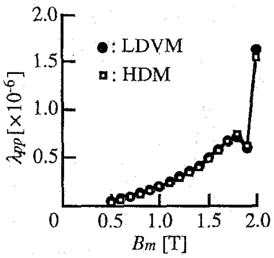


Fig.11 Comparison of LDVM and HDM (with vibration eliminator, G=1.2mm).