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Abstract – **A new method for measuring the magnetostriction of silicon steel sheet using a laser doppler velocimeter has been developed. This method has the following advantages : (a) non-contact measurement, (b) better resolution (less than 4×10^{-8}m under the condition that the error is within 1%) than conventional methods, (c) measurement of magnetostriction in any direction of anisotropic material and (d) little operator skill required.**

I. INTRODUCTION

Magnetostriction, which contributes to the noise of electric machines (noticed remarkably as an environmental problem), has been measured using a differential transformer, a strain gauge, a needle with pick up coil or a Michelson interferometer[1]. These measuring methods have the disadvantages of requiring contact with the sample and operator skill. If a laser doppler velocimeter which has recently been developed for the measurement of very small displacements is applied, a non-contacting measurement of magnetostriction with high accuracy becomes possible.

In this paper, a new method for measuring magnetostriction of silicon steel sheet using the laser doppler velocimeter is introduced[2], and the factors affecting the accuracy are examined. Examples of measured results and improved reproducibility are shown.

II. MEASUREMENT SYSTEM

A. Principle of Measurement

Fig.1 shows the principle of measuring magnetostriction using the laser doppler velocimeter. The laser beam is divided in two directions (a_1 and a_2) by a half mirror (HM). The frequency of laser beam a_1 (① in Fig.1) is shifted by the frequency shifter by Δf (=80MHz) as follows:

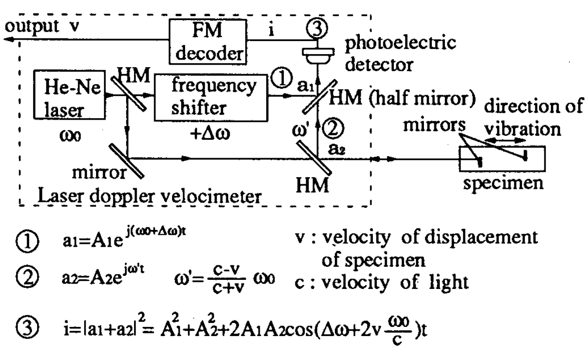

Fig.1 Principle of measurement.

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$$a_1=A_1\, e^{j(\omega_0+\Delta\omega)\, t} \qquad (1)$$

where A_1 is the amplitude, ω_0 is an angular frequency of the laser and $\Delta\omega$ is equal to $2\pi\Delta f$. The laser beam a_2 (② in Fig.1) of which the frequency is changed by the doppler effect is written as follows:

$$a_2=A_2\, e^{j\omega' t} \qquad (2)$$

where ω' is the angular frequency given by

$$\omega' =\omega_0\, (c-v) / (c+v) \fallingdotseq \omega_0\,(1-2v/c) \qquad (3)$$

where c and v are the light velocity and velocity of the specimen to be measured respectively. The output current i (③ in Fig.1) of photoelectric detector is given by

$$i = |a_1+a_2|^2 = A_1{}^2 + A_2{}^2 + 2A_1A_2 \cos (\Delta\omega+2v\omega_0 / c)\, t \qquad (4)$$

Equation (4) shows that the velocity v can be measured by decoding the output i of the FM signal.

B. Measuring Equipment and Method of Measurement

Fig.2 shows the construction of the measuring equipment. The yoke with lap joints is made of laminated grain-oriented silicon steel (AISI:M-5, thickness: 0.3mm). The whole equipment is placed on a car tire tube in order to reduce external vibration. The magnetostriction is measured using

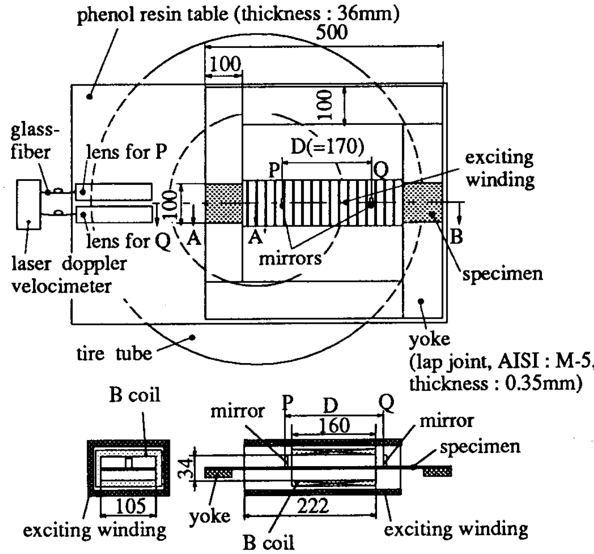

Fig.2 Experimental equipment.

the velocimeter which utilizes the laser doppler effect.

The mirrors are made of a special thin sheet (thickness: 0.21mm) which reflects only parallel beam to the incident beam. Each mirror is pasted on an aluminum plate which is very small(4×3mm), thin(1.2mm) and light (about 0.05g). The distance D (=170mm) between the two mirrors is determined on the basis of sufficient output of magnetostriction, uniformity of flux distribution in the exciting winding and elimination of the effect of irregularity of the flux distribution due to grain boundaries.

In order to measure the magnetostriction between the two mirrors which are fixed on the specimen, firstly, the velocities of both mirrors shown in Fig.2 are measured at the same time, and the difference are stored in a microcomputer through a low pass filter (LPF) and an A/D converter as shown in Fig.3. The trigger pulse is derived from the voltage waveform which is applied to the exciting winding. Secondly, the magnetostriction difference between the two mirrors is obtained by integrating the difference of the measured velocities of the two mirrors.

The harmonic components of the measured waveforms are calculated by FFT. As the odd components do not exist theoretically, they are eliminated as noise. The final waveform is obtained by reconstructing each of the remaining harmonic component.

III. Factors affecting accuracy of measurement

Various factors affecting the accuracy are examined experimentally using a specimen of silicon steel (AISI : M-0H, thickness : 0.23mm). The applied flux density Bm is equal to 1.7T and the frequency is 50Hz.

A. Gap between Specimen and Yoke

The reproducibility of measurement may be reduced due to the vibration by the electromagnetic force between the specimen and the yoke. Then, the effect of the gap between the specimen and the yoke is investigated by inserting a glass-epoxy plate (thickness : 1mm) as shown in Fig.4.

Fig.5 shows the effect of the gap between the specimen and the yoke. The error ε is defined by the following equation:

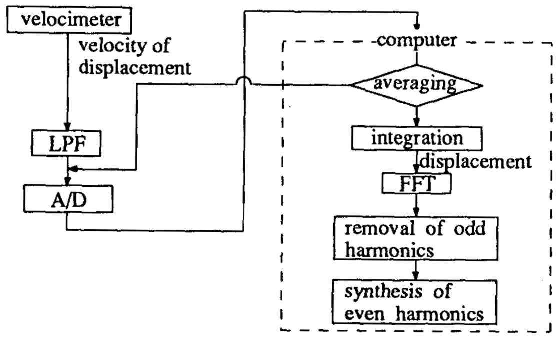

Fig.3 Flow chart of measurement.

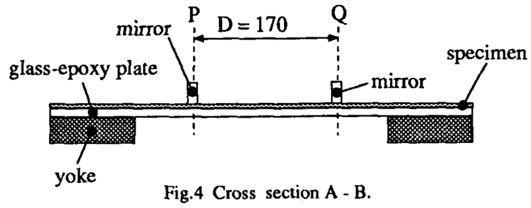

Fig.4 Cross section A - B.

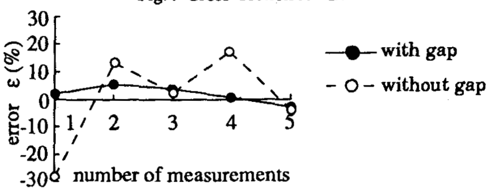

Fig.5 Effects of gap on reproducibility.

$$\varepsilon = \frac{\lambda - \lambda_{ave}}{\lambda_{ave}} \times 100\ (\%) \qquad (5)$$

where λ is the peak to peak value of measured magnetostriction and λ_{ave} is an average value of five results.

The reproducibility is improved by introducing a gap of 1mm between the specimen and the yoke. When there is no gap, the maximum error ε is about 30%. On the contrary, the reproducibility can be improved considerably (ε < 6%) by introducing a gap. The reason why the reproducibility is improved may be that: (a) If there is a gap, the flux distribution is uniform in the gap. Therefore, the total attractive force at the gap is less than that in the case of irregular flux distribution. It means that the vibration of mirror which causes an error becomes small. (b) If the gap length is small, the contacting positions of the specimen and the yoke are changed every time. It means that the vibrating mode of the mirror changes every instant. Therefore, the reproducibility is worse. (c) The flatness of the specimen can easily be increased by putting it on the flat glass-epoxy plate.

In order to examine the effect of the concentration of flux, the overlap length L between the specimen and the yoke shown in Fig.6 is changed. If the length L is decreased, the electromagnetic force between the specimen and the yoke is increased because the flux density in the overlap region is increased. Fig.7 shows that the reproducibility is reduced when the flux is concentrated (L= 10mm).

B. Length between Two Mirrors

The effect of distance D between two mirrors on

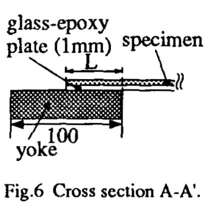

Fig.6 Cross section A-A'.

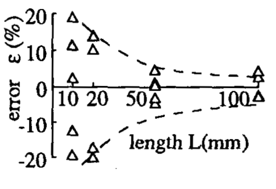

Fig.7 Effect of overlap length L on reproducibility.

reproducibility is shown in Fig.8. The reproducibility is reduced when D is small.

C. Sensitivity

The output (noise) of the measuring equipment exists, even if there is no magnetostriction. These components are removed by averaging the measured results. Fig.9 shows the effect of number of averaging on the noise λ_{err} of the magnetostriction. The output after averaging thirty measurements is 0.228×10^{-8} as shown in the figure. The amplitude of magnetostriction is $0.228 \times 10^{-8} \times 0.17$m $= 3.88 \times 10^{-10}$m. Therefore, the minimum value to be measured within 1% error using this equipment(D=170mm) is less than 4×10^{-8}m.

IV. Measured Results

Fig.10 shows the waveforms of applied flux density B and magnetostriction λ, and butterfly loop for low magnetostriction material (6.5% silicon, thickness:0.35mm). Bm is the maximum value of the applied flux density. The smoothly butterfly loop is obtained using this method.

Fig.11 shows the waveforms of applied flux density B and magnetostriction λ which are measured for various specimens having arbitrary cut angles θ. The specimen is highly-oriented silicon steel (AISI M-0H, thickness: 0.3mm). The amplitude of magnetostriction λ is negative when $\theta < 45°$, and λ is positive when $\theta > 60°$.

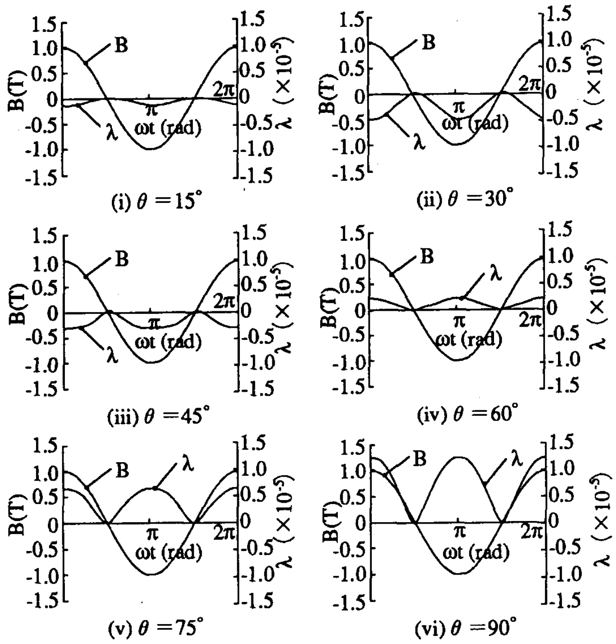

Fig.11 Waveforms of flux density and magnetostriction in various direction θ for highly-oriented silicon steel (M-0H, thickness : 0.3mm, Bm=1.0T, 50Hz).

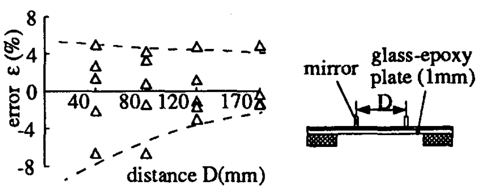

Fig.8 Effect of distance D between two mirrors on reproducibility.

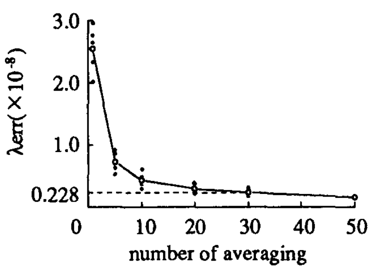

Fig. 9 Effect of averaging (D=170mm).

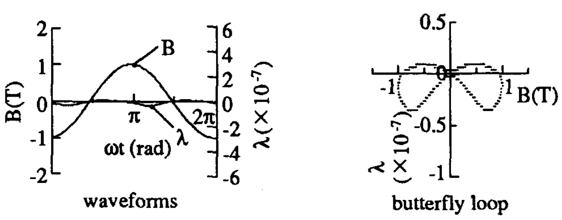

Fig.10 Waveforms of flux density B and magnetostriction λ and butterfly loop for low magnetostriction 6.5% silicon steel (thickness : 0.35mm, Bm=1.0T, 50Hz).

V. Conclusions

A new method for measuring the magnetostriction of silicon steel sheet has been developed. The results obtained can be summarized as follows :

(1) It is possible to measure very small displacement less than 4×10^{-8}m.

(2) The reproducibility is significantly improved (within 6%).

(3) The magnetostriction in arbitrary directions in anisotropic material is measured.

The magnetostriction under distorted wave excitation and the measurement of very thin specimen such as amorphous metal will be reported in another paper.

References

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[2] T. Nakata, N. Takahashi, M. Nakano and M. Miyake, "Measurement of magnetostriction using a laser doppler velocimeter with good reproducibility", *Abstracts of Softmag Conference 11* No.S4-16, Venezia, September 1993.