Recent Development in Grain-Oriented Electrical Steel with Low Magnetostriction

M. Yabumoto, S. Arai, R. Kawamata, M. Mizokami, and T. Kubota

For precise evaluations of magnetostriction properties, a new magnetostriction measuring system using a laser vibrometer was developed. Frequency analysis of magnetostriction under non-sinusoidal magnetization revealed a nonlinear relation between harmonics in flux and those in magnetostriction. Transformer core vibration was investigated in order to clarify the relations between magnetostriction and transformer noise and to realize low-noise transformers. Resonance was proved to have an important role for core vibration. Domain-refined, grain-oriented electrical steel, which fulfills low loss and low magnetostriction properties simultaneously, is also explained.

Keywords grain-oriented electrical steel, magnetics, magnetostriction, noise, resonance, silicon steel, transformer core, vibration

1. Introduction

In the past, the key required property for transformer materials was low watt loss, and watt loss reduction has been a principal target in the improvement of grain-oriented electrical steel (Ref 1). Recently, low-noise transformers have been sought (Ref 2, 3). Low magnetostriction is required, as well as low watt loss, in order to produce low-noise transformers without decreasing core flux density or attaching complex noise-damping devices.

Grain orientation improvement was one of the most effective means of loss reduction (Ref 4) until domain refining techniques were developed (Ref 5). At present, domain-refined materials with low magnetostriction are the candidate core materials for best-performance transformers with low watt loss and noise.

In order to develop low-magnetostriction materials, it is necessary to measure magnetostrictive deformation accurately. Conventional measuring methods using a strain gage, differential transformer, capacitance manometer, or record pickup are not sufficient in accuracy, reproducibility, or convenience. In addition, it is necessary to clarify the relation between material magnetostriction and core vibration in order to reduce transformer noise by using low-magnetostriction materials.

This paper reviews a new magnetostriction measuring system, low-magnetostriction materials, frequency analysis of magnetostriction, and model transformer experiment results.

2. Analysis of Magnetostriction

2.1 *Origin of Magnetostriction*

Test specimens were prepared from commercial products which contained about 3% Si.

M. Yabumoto, S. Arai, R. Kawamata, M. Mizokami, and **T. Kubota,** Nippon Steel Corp., Steel Research Laboratory, 20-1 Shintomi, Futtsu, Chiba 293, Japan.

Figure 1 shows magnetic domain patterns on grain oriented electric steel sheet. The grains are highly oriented to (110)[001], and magnetization directions are almost parallel to the rolling directions, constructing the 180°domains shown in these figures. The most decisive factors in magnetostriction in grain-oriented electrical steel are small supplementary domains called "lancet" appearing in 180° domains (Ref 6, 7). The subsurface structures of lancet are shown in Fig. 2. There are 90° domains having magnetization components at right angles to those of the main 180° domains. These domains are elongated to the transverse and vertical directions, in contrast to the 180° domains, elongated to the rolling direction.

Magnetostriction is a size change that occurs when a magnetization direction is changed. Magnetostrictive deformation in actual materials occurs because of the volume change of 90° domains under ac magnetization. Magnetostrictive deformation in grain-oriented electrical steel is of 10^{-6} order.

Figure 3 shows calculated 90° domain volume as a function of [001]-axis misorientation angle out of the sheet plane. The calculations were based on a model by Bär et al. (Ref 8). The 90° domain volume is found to be decreased with the smaller misorientation angle or the higher external tension. Magnetostrictive deformation can be minimized almost to zero by decreasing deviations from (110)[001] and strengthening coating stress.

2.2 *Magnetostriction Measurement*

Magnetostrictive deformations of advanced grain-oriented electrical steel sheet with a high degree of (110)[001] texture, named HI-B, are small, on the order of 10^{-6}. Accuracy to detect submicron length change is required to measure these deformations. Therefore, magnetostriction was not routinely measured before a new method using a laser Doppler vibrometer was developed in our laboratory (Ref 9, 10).

Figure 4 is a block diagram of the new measuring system. The measuring equipment is placed on an insulator frame set on a vibration-free stage. Sample sheet size is 100 × 500 mm. Change of 270 mm length between the clamp fixed on the frame and a small reflector pasted on the sample is measured. The reflector weighs less than 0.1 g and hardly affects magnetostrictive oscillation.

Magnetizing signals are supplied from a two-channel arbitrary function generator. Non-sinusoidal magnetization con-

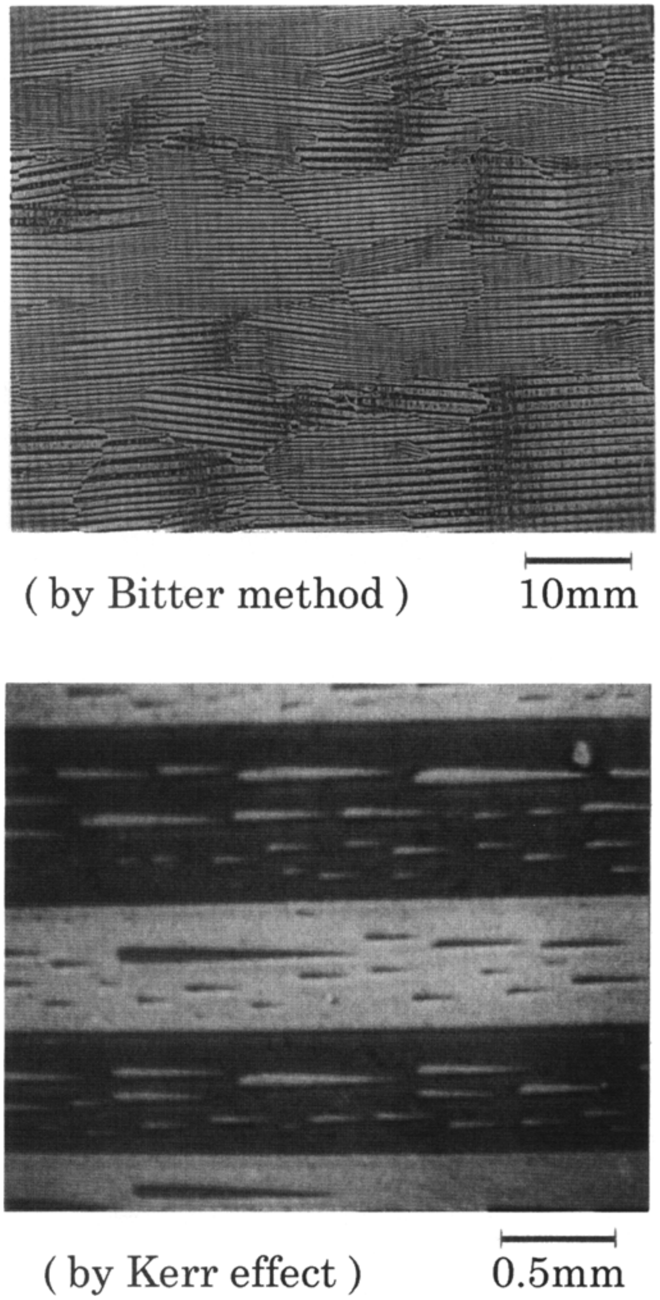


Fig. 1 Magnetic domain patterns on grain-oriented electrical steel sheet

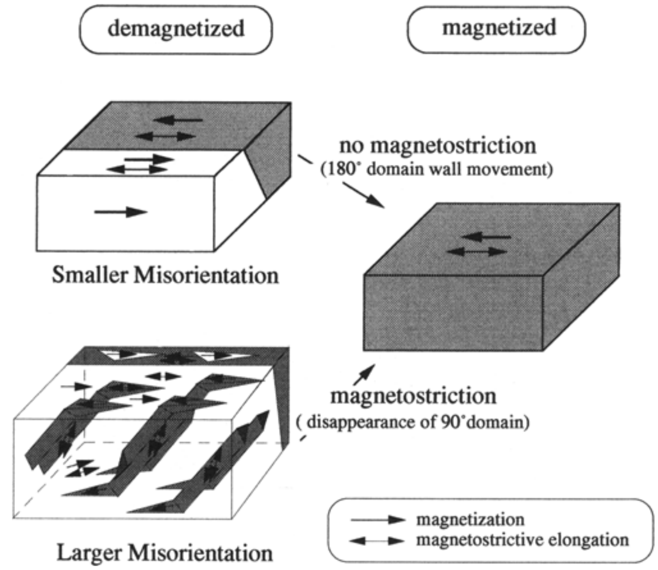


Fig. 2 Schematic diagram of magnetic domains and the magnetostriction of grain-oriented electrical steel

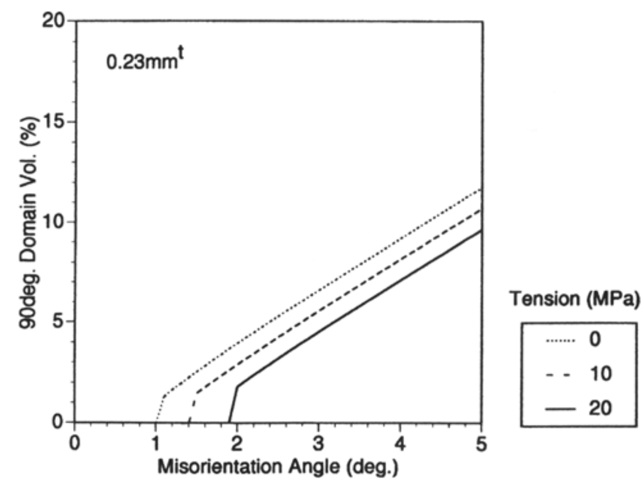


Fig. 3 Calculated 90° domain volume fraction as a function of <001>-axis misorientation angle from the surface plane, without external field

taining harmonics is possible besides sinusoidal magnetization (Ref 11).

Magnetostrictive vibration is measured using a two-beam laser Doppler vibrometer. One beam is reflected by the reflector on the sample and the other by the reflector fixed on the frame. By measuring relative movement between these two reflectors, vibration noise from the circumstance can be reduced. In order to improve the S/N ratio further, measured signals are input to the digital oscilloscope and averaged coincident with the external clock of the function generator. The most disruptive noise is out-of-plane vibration of the sheet sample. This noise is suppressed by a glass plate placed on the sample.

For the estimation of magnetostriction under stress introduced into materials during the core manufacturing process, compressive stress along the magnetization direction is applied to the sample using an air cylinder. The typical value of compressive stress is 3 MPa.

Not only accuracy, but also high reproducibility and convenience are provided by the new method.

Figure 5 shows an induction versus magnetostriction curve, namely a "butterfly curve," under ac magnetization of 50 Hz. Usually ac magnetostriction of grain-oriented electrical steel has been evaluated using the o-peak values and peak-to-peak values defined in Fig. 5. These values are not sufficient to evaluate magnetostriction behavior, because butterfly curves show complex hysteresis reflecting nonlinear change of magnetic domains during ac magnetization. Measured data were sent to a personal computer and frequency analysis was made using a fast fourier transform program.

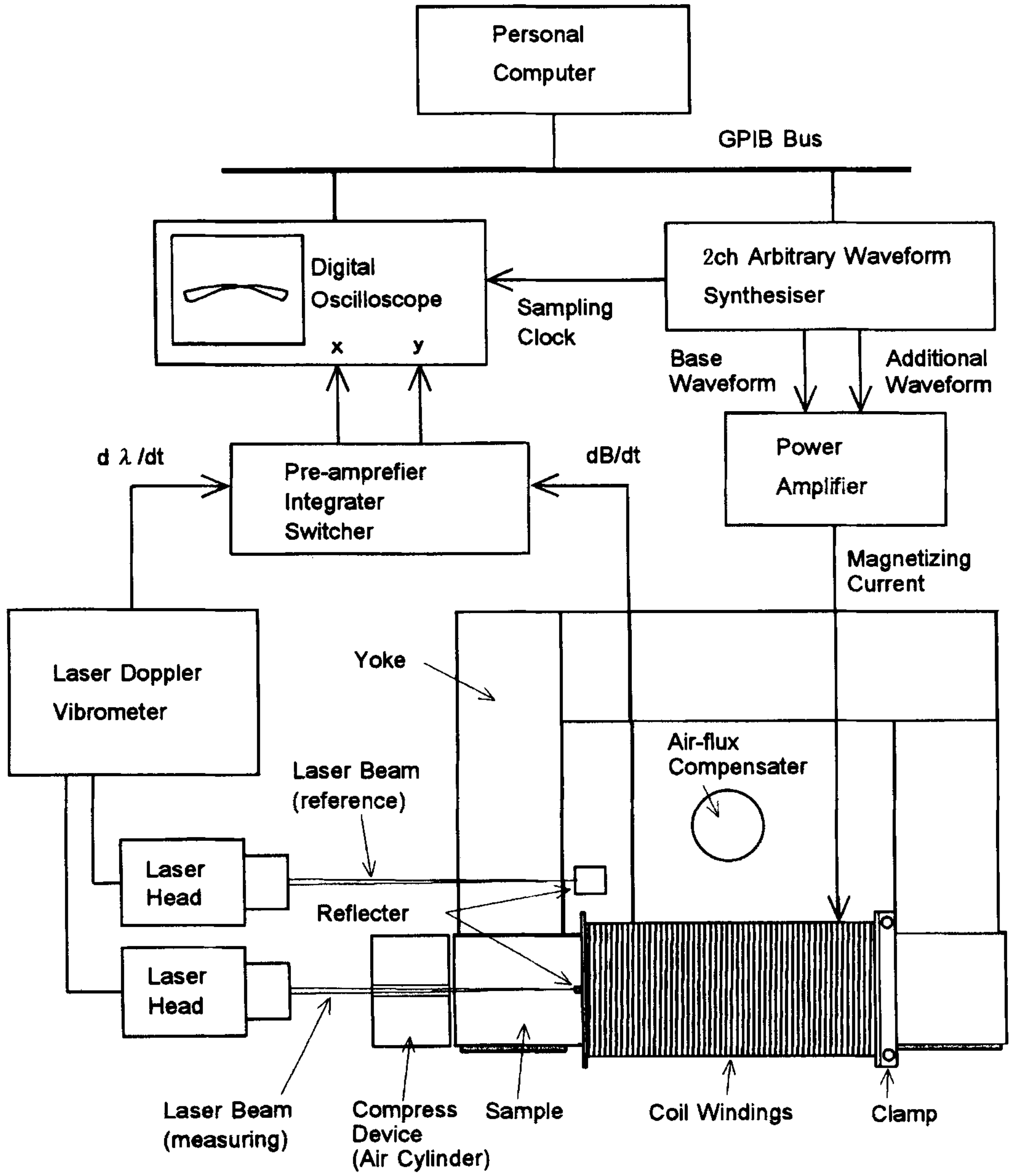


Fig. 4 Block diagram of the new magnetostriction measuring system

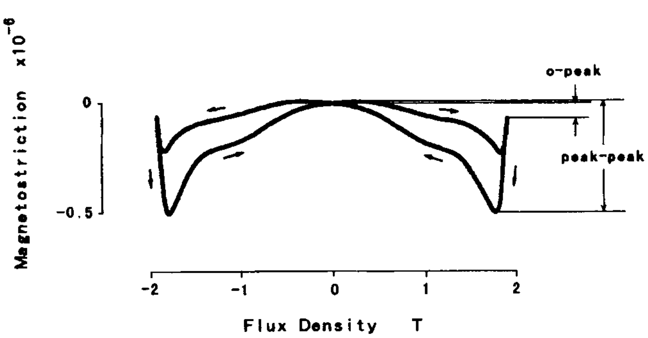


Fig. 5 Magnetostriction butterfly curve and definition of values

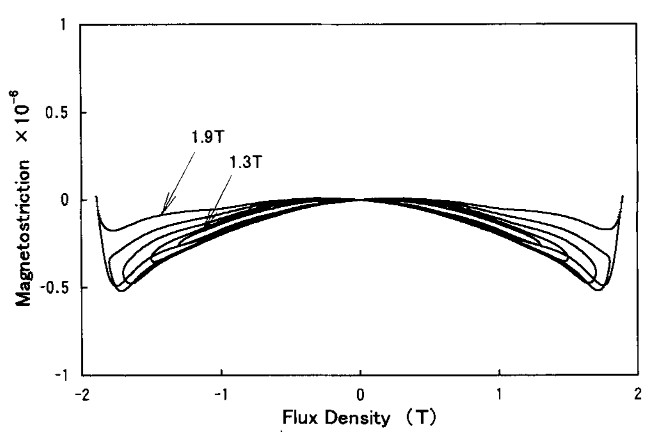


Fig. 6 Butterfly curves (0.30 mm thick HI-B)

2.3 *Measured Data and Analysis*

Figures 6 and 7 show the measured data of a 0.3 mm thick HI-B material under 50 Hz sinusoidal magnetization. Figure 6 shows butterfly curves and Fig. 7 shows time versus magnetostriction curves. Five curves from 1.3 to 1.9 T maximum flux density are overlaid on each figure. These curves have S/N ratios superior to those of conventional methods.

From the butterfly curves, magnetostrictive deformation is seen to change from contraction under 1.8 T to elongation over 1.8 T. The 90° domain volumes increase in accordance with 180° domain widening by flux density increase under 1.8 T and decrease by magnetizing force for further magnetization (Ref 12). From the magnetostriction curves, harmonics components higher than 100 Hz are known to increase obviously over 1.8 T.

Figure 8 shows the results of frequency analysis from the magnetostriction curves in Fig.7. The dominant frequency components are 100 Hz, twice the magnetization frequency. In transformers used on commercial frequencies of 50 and 60 Hz, the fundamental components of magnetostriction are 100 and 120 Hz. However, sounds of these frequencies are hardly detectable by human ears. Therefore, this figure is not comparable to frequency distributions of transformer noise.

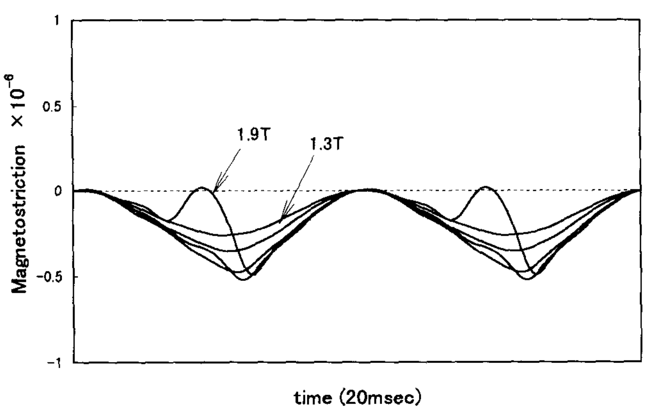


Fig. 7 Magnetostriction curves (0.30 mm thick HI-B)

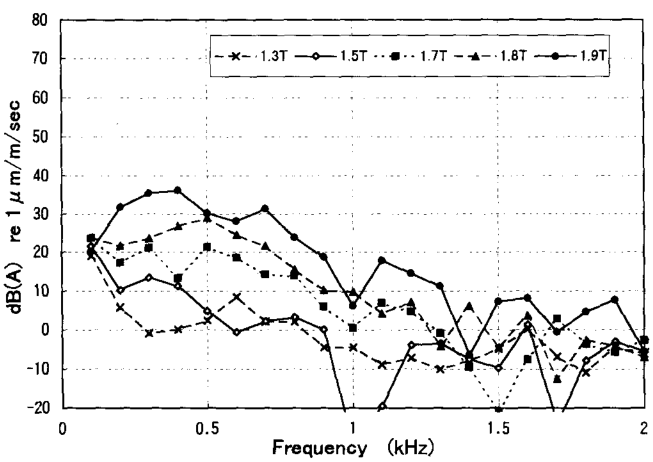


Fig. 9 Frequency components of A-weighted magnetostrictive vibration velocity (0.30 mm thick HI-B)

In order to analyze the relations between transformer noise and magnetostriction, the frequency components of magnetostriction are usually A-weighted. Considering the vibration transmission from core surfaces to air, vibration velocity components are thought to be appropriate for the evaluation.

Figure 9 shows the frequency analysis of A-weighted magnetostrictive vibration velocities. Higher-frequency components from 200 to 800 Hz are remarkably larger than 100 Hz components over 1.8 T. Even in transformers designed for 1.7 T or lower flux density, local flux can be concentrated; therefore, magnetostriction should be tested at higher flux densities than the designed value.

3. Development of Low Magnetostriction Materials

3.1 *Factors That Reduce Magnetostriction*

Table 1 shows the factors that reduce magnetostriction. All of the factors are unified with the keyword of 90° domain volume reduction.

For material, higher concentration to (110)[001] orientation, or misorientation reduction, is the most fundamental solution to reduce magnetostriction. As an index to represent the crystal orientation, maximum induction at 800 A/m magnetiz-

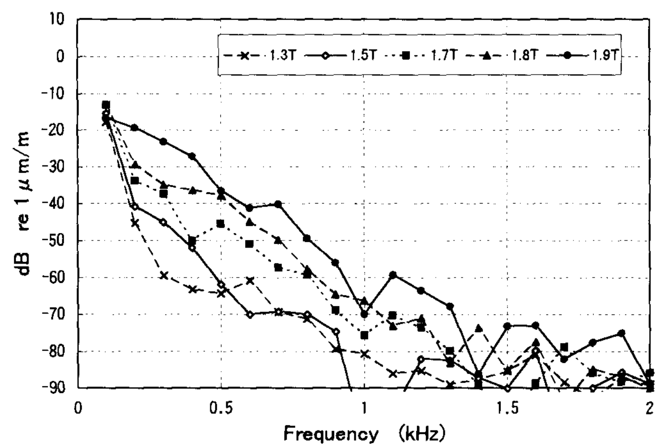


Fig. 8 Frequency components of magnetostriction (0.30 mm thick HI-B)

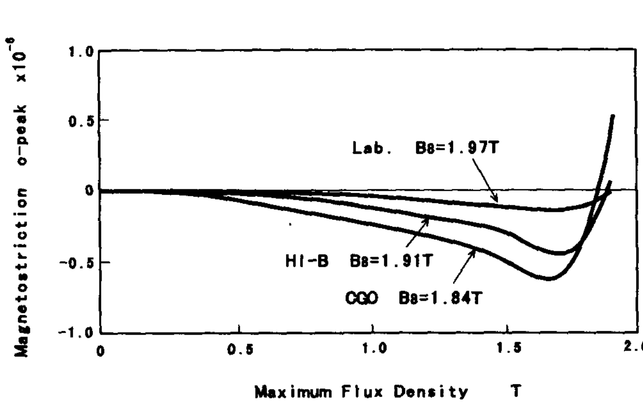


Fig. 10 Magnetostriction of various B8-value materials

ing force, or a B8 value, can be used. Strengthening tensile stress using stress coatings and reduction of the thickness are also effective.

Strains introduced during handling also affect the magnetostriction. Required materials should have unchanged magnetostriction against these strains. Magnetization wave forms are also important factors.

3.2 *B8 Values and Magnetostriction*

Figure 10 shows magnetostriction curves of various B8-value materials. The magnetostriction of a high B8-value material, or HI-B, is largely decreased compared with that of a low B8-value material, or CGO (conventional grain-oriented electrical steel). When the B8 value approaches the saturation flux density, 2.03 T in 3% Si steel, magnetostriction will be reduced. A laboratory sample with a very high B8 value showed still lower magnetostriction.

Reduction of 90 degree domain volume

	Subjects	Methods
Material	Grain-orientation	Improve orientations (B8 up)
	Tensile stress	Enrich surface film tensions
	Thickness	Thin gauge
	Internal strain	Optimize annealing process
	Shape	Improve sheet flatness
Processing	Slitting and cutting	Minimize shear strains
	Handling	Avoid damages to sheets
	Stacking	Keep flatness and avoid local force
Magnetization	Distribution	Avoid local flux concentrations
	Harmonics	Avoid higher flux harmonics

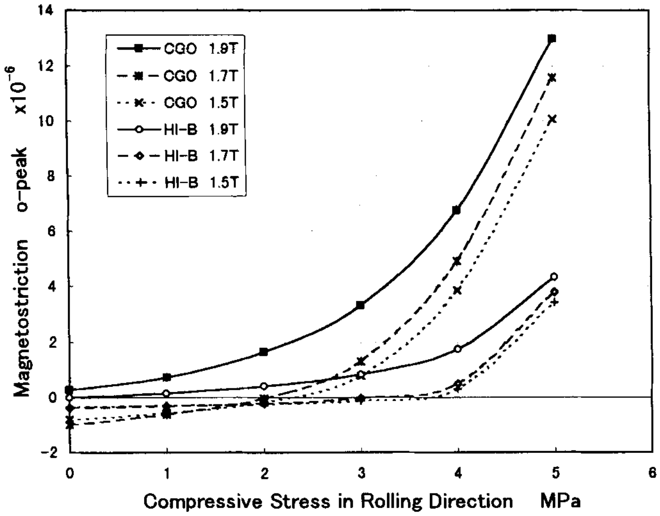


Fig. 11 Increases of magnetostriction by compressive stress (0.30 mm thick CGO and HI-B)

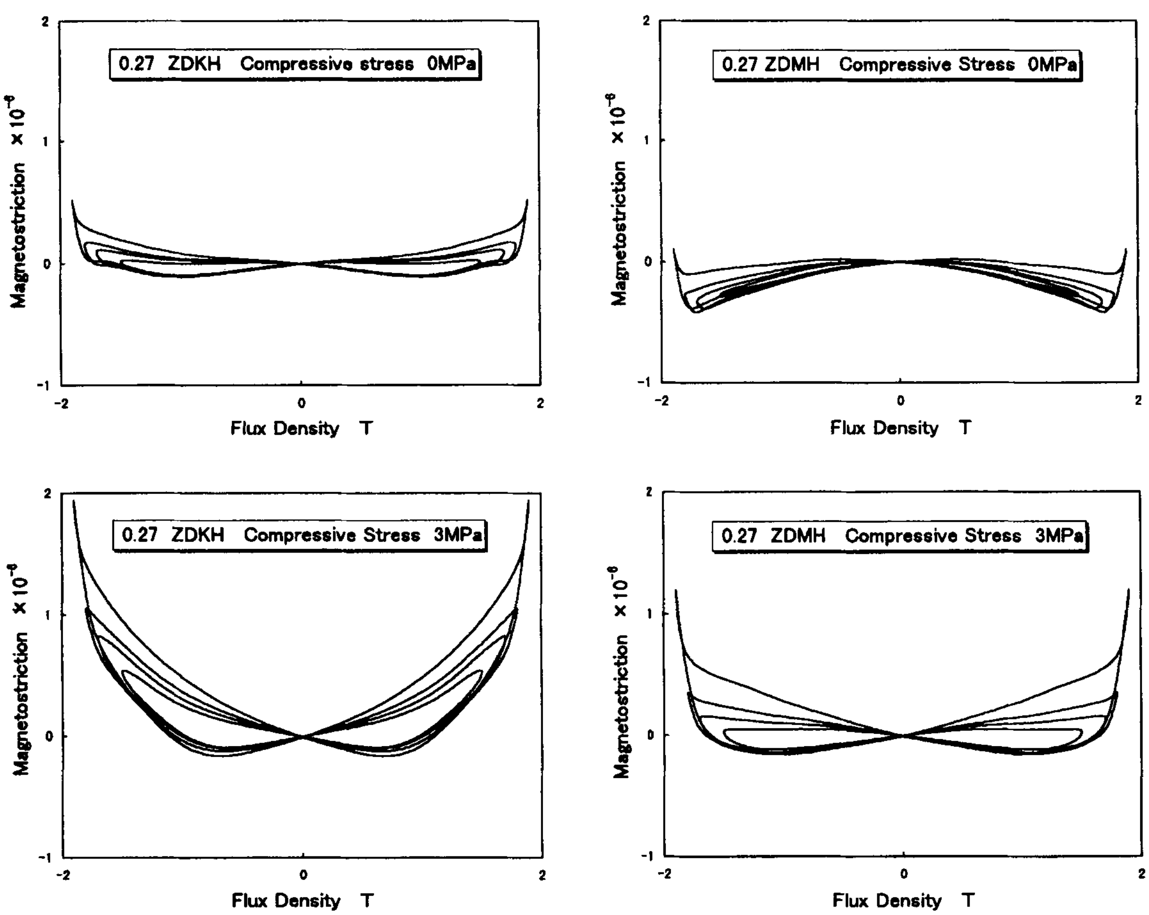


Fig. 12 Magnetostriction butterfly curves (0.23 mm thick ZDKH and ZDMH)

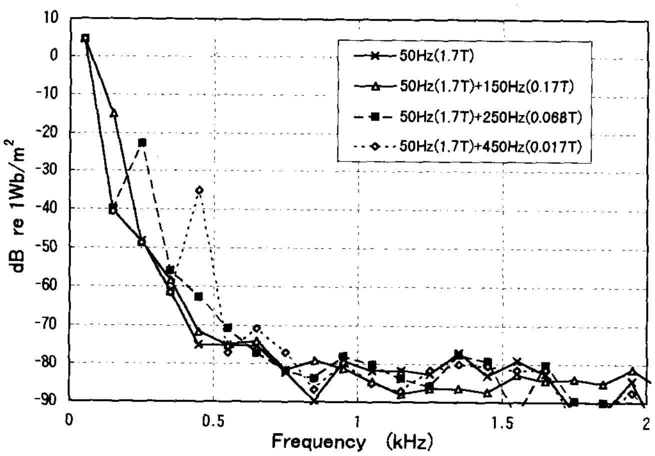


Fig. 13 Frequency components analysis of flux density under non-sinusoidal magnetization (0.30 mm thick HI-B, harmonics superimposed)

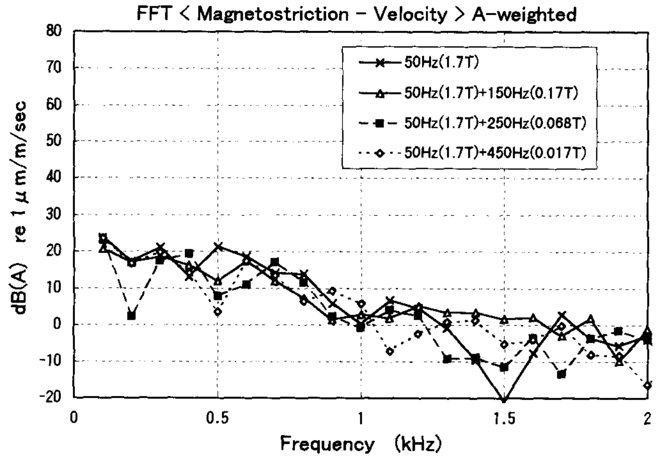


Fig. 14 Frequency components analysis of A-weighted magnetostrictive vibration. Velocity under non-sinusoidal magnetization (0.30 mm thick HI-B harmonics superimposed)

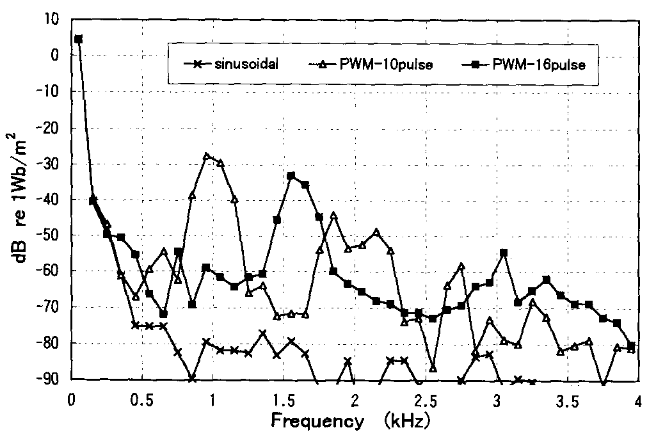


Fig. 15 Frequency components analysis of flux density under PWM magnetization (0.30 mm thick HI-B)

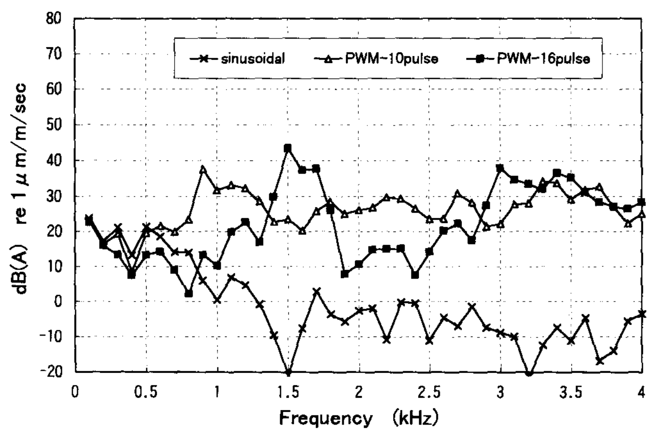


Fig. 16 Frequency components analysis of A-weighted magnetostrictive vibration velocity under PWM magnetization (0.30 mm thick HI-B)

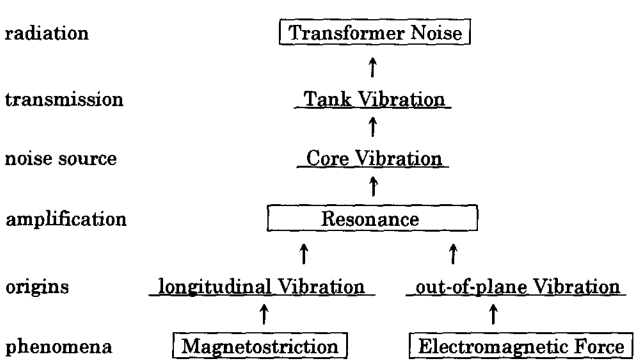


Fig. 17 Flow chart from magnetostriction to transformer noise

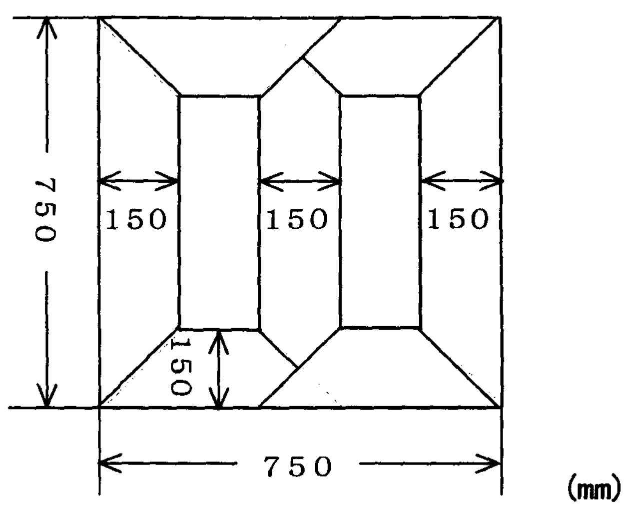


Fig. 18 Dimensions of a model transformer core

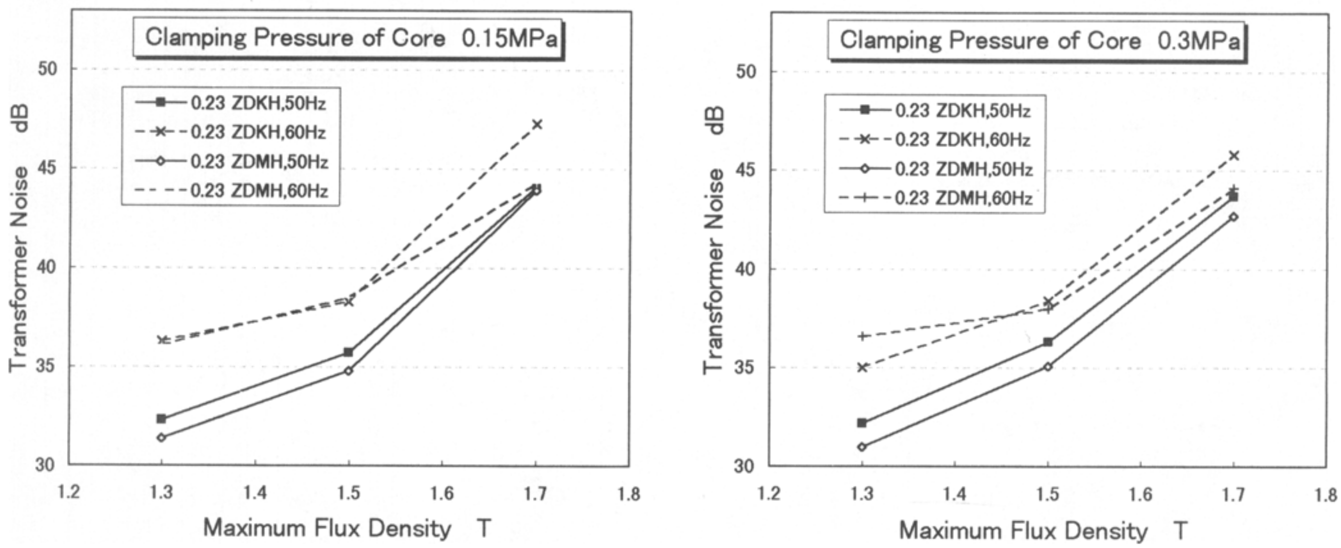


Fig. 19 Noise level of model transformer cores and magnetostriction of materials (0.23 mm thick ZDKH and ZDMH)

Figure 11 shows the magnetostriction of CGO and HI-B materials as a function of compressive stress to the rolling direction. Magnetostriction increases more sharply in CGO than in HI-B. This is because the 9 domain volume is decreased in HI-B by better crystal orientation .

3.3 *Magnetostriction of ZDKH and ZDMH*

The most important property of grain-oriented electrical steel is still low watt loss, and this property is realized by domain refining techniques. Of the several methods for refining domains in grain-oriented electrical steel, two typical products are ZDKH and ZDMH.

ZDKH is a laser-described material, and localized stresses remain on the surface. ZDMH has periodically shallow grooves with micrograins underneath, and localized strains do not remain.

Figure 12 compares the butterfly curves of 0.23 mm thick ZDKH and those of ZDMH with and without 3 MPa compressive stress. In the case of ZDKH, residual strains created 90° domains near laser traces. These 90° domains were initially suppressed in the material by coating tension, but they appeared when the compressive stress was applied and magnetostriction was intensively increased. ZDMH showed less increase of magnetostriction by the compressive stress because of less stress in the material. ZDMH shows low magnetostriction under compressive stress as HI-B without domain refining. ZDMH satisfies low watt loss and low magnetostriction simultaneously.

4. Magnetostriction under Non-Sinusoidal Magnetization

Alternating current magnetostriction is usually measured under sinusoidal magnetization, although magnetizing waves in transformer cores are non-sinusoidal and locally different. We measured magnetostriction curves under two kinds of non-

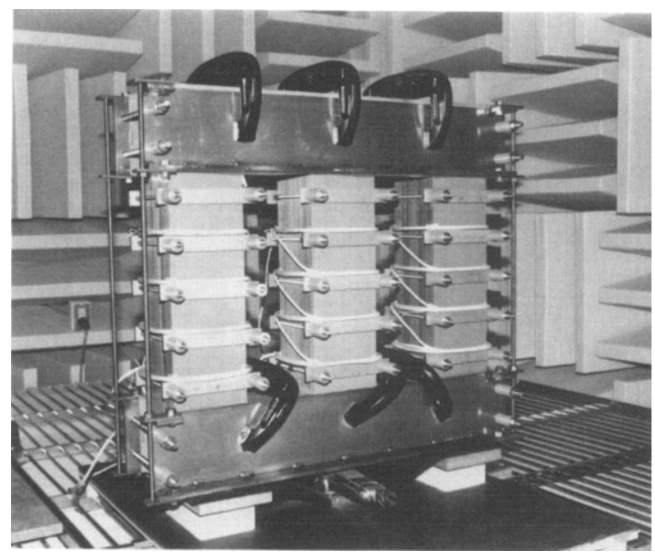


Fig. 20 A model transformer core

sinusoidal magnetization and analyzed those frequency components.

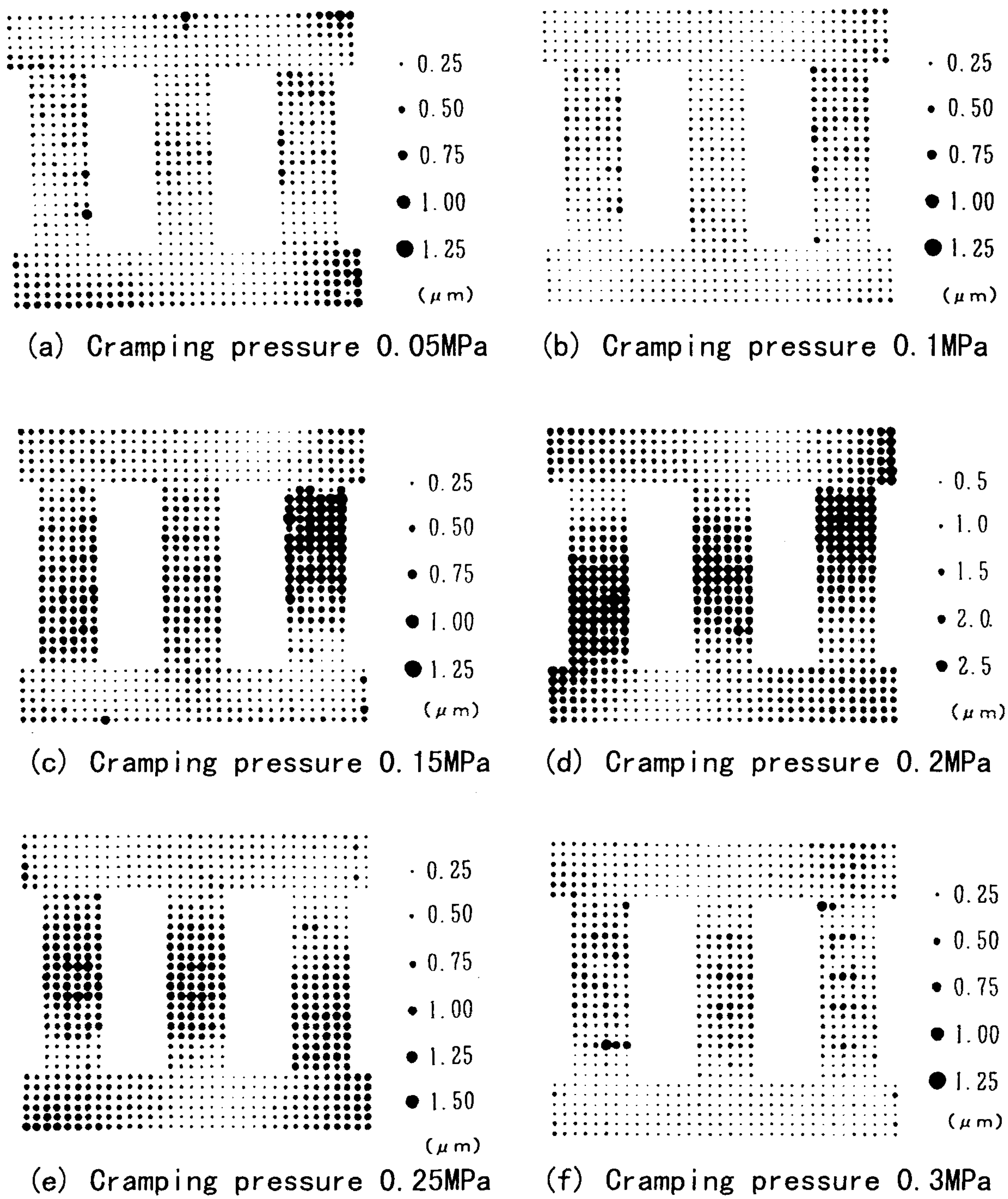
Figures 13 and 14 show the frequency analysis results of flux density and magnetostriction velocity under non-sinusoidal magnetizations that consisted of 50 Hz fundamental components and superimposed components with lower harmonics of 150, 250, and 450 Hz. The results under 50 Hz sinusoidal magnetization are also shown. Frequency components of flux density corresponding to superimposed harmonics increase in Fig. 13, but those components do not increase in Fig. 14. Increases of lower harmonics on flux density did not cause increases of harmonics on magnetostriction in this case.

Figures 15 and 16 show the frequency analysis results of flux density and magnetostriction velocity under non-sinusoidal magnetizations of pulse width modulation (PWM) with 10 and 16 pulses, respectively. The results under 50 Hz sinusoidal magnetization are also shown. Frequency components of flux density corresponding to the pulse intervals increase in Fig. 15, and those components and other higher harmonics increase in Fig. 16. Increases of higher harmonics on flux density caused increases of harmonics on magnetostriction in this case.

This disagreement between the results for lower and higher harmonics suggests that magnetostrictive deformation in real transformer cores should be evaluated and analyzed under magnetization of actual flux wave forms in cores.

5. Model Transformer Experiments

Figure 17 shows a flow chart from magnetostriction to transformer noise. Material magnetostriction is one of the main causes of transformer noise, but sometimes lower magnetostriction cannot reduce transformer noise sufficiently, because resonance modes of transformers amplify certain frequency oscillations. In order to clarify this effect, we are



(a) Cramping pressure 0.05MPa
(b) Cramping pressure 0.1MPa
(c) Cramping pressure 0.15MPa
(d) Cramping pressure 0.2MPa
(e) Cramping pressure 0.25MPa
(f) Cramping pressure 0.3MPa

Fig. 21 Vibration displacement of each measuring point (magnetization 1.7 T, 50 Hz) measuring noises and vibration distributions on transformer cores, as well as material magnetostriction.

Figure 18 shows the dimensions of the model transformer. In order to simulate real transformer core conditions, clamping pressure was controlled using clamps and plates on the yokes and limbs. The model transformer was placed in an anechoic room of 15 dB background noise and the noise was measured with a noise level meter.

5.1 *Model Transformer Noise of ZDKH and ZDMH*

Figure 19 shows the noise level of ZDKH and ZDMH model transformers. In the case of 50 Hz magnetization, the ZDMH core showed lower noise from 1.3 to 1.7 T. In the case of 60 Hz magnetization, the ZDMH core showed lower noise at 1.7 T and slightly higher noise below 1.5 T than the ZDKH core. These tendencies were observed regardless of clamping pressures of 0.15 and 0.3 MPa. Noise level was slightly decreased with clamping pressure increase, because of the resonance mode change due to the rigidity change.

5.2 *Vibration Measurements in a Model Core*

From noise measurements, information about core vibrations is hardly obtainable. In order to clarify factors that decide transformer noise level, vibration distributions in a model core were measured directly (Ref 13).

Figure 20 is a photograph of the model transformer used for vibration measurements. HI-B sheets 0.23 mm thick were laminated and the limb cross sections were square. The transformer was erected in a anechoic room to shield vibration noise from the circumstance. Vibration patterns were measured with a scanning laser Doppler vibrometer.

Figure 21 shows vibration displacement of each measuring point on the model core under sinusoidal magnetization of 1.7 T, 50 Hz. A circle diameter is proportional to a peak-to-peak value of displacement. Vibration distributions are found to change drastically depending on clamping pressure. As shown in these figures, the vibration amplitudes and the vibration modes changed due to the clamping pressure variation. Core vibration amplitudes are maximal at 0.2 MPa and decrease at higher pressure.

These phenomena could also be understood as the results of resonance mode change caused by core rigidity change.

6. Summary

A new magnetostriction measuring system using a laser vibrometer was developed to develop low-magnetostriction materials and to analyze frequency components. Frequency analysis of magnetostriction under non-sinusoidal magnetization showed contrary results. In a case of magnetization with lower harmonics, corresponding frequency components of magnetostriction did not increase, but in the case of PWM magnetization, high-frequency components of magnetostriction increased. Noise and vibration patterns in model transformers were measured in order to investigate the relations between magnetostriction and transformer core vibration and to realize low-noise transformers using low-magnetostriction materials. An important role of core resonance was demonstrated.

References

1. K. Ueno, N. Takahashi, and T. Nozawa, *J. Mater. Eng.*, Vol 12, 1990, p 11
2. S.L. Foster and E. Reiplinger, Paper F-80-150-3, IEEE, 1980, p 4
3. J.M. Guinter, *Noise Control Eng.*, Vol 13 (No. 3), 1979, p 129
4. Y. Ushigami, H. Masui, Y. Okazaki, Y. Suga, and N. Takahashi, *J. Mater. Eng.*, Vol 5 (No. 3), 1996, p 310
5. T. Iuchi, S. Yamaguchi, T. Ichiyama, M. Nakamura, T. Ishimoto, and K. Kuroki, *J. Appl. Phys.*, Vol 53, 1982, p 2410
6. A. Hubert, V. Heinicke, and J. Kranz, *Z. Angew. Phys.*, Vol 15, 1965, p 521
7. Y.A.S. Shur and Yu.N. Dragoshanskiy, *Fiz. Met. Metalloved.*, Vol 22 1966, p 702
8. N. Bär, A. Hubert, and W. Jillek, *J. Magn. Magn. Mat.*, Vol 6, 1977, p 242
9. M. Yabimoto, Japanese Patent H2-105221, 1990
10. T. Nakata, N. Takahashi, M. Nakano, K. Muramatsu, and M. Miyake, *IEEE Trans.*, Vol 30, 1994, p 4563
11. H. Mogi, M. Yabumoto, M. Mizokami, and Y. Okazaki, *IEEE Trans.*, Vol 32 (No. 5), 1996, p 4911
12. M. Imamura, T. Sasaki, and A. Saito, *IEEE Trans.*, Vol 17, 1981, p 2479
13. M. Mizokami, M. Yabumoto, and Y. Okazaki, *Trans.IEE Jpn.*, Vol 116A, 1996, p 744