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1 Introduction

Recent heightened public demand for reduced audible noise in transformers has led to great expectations for grain-oriented silicon steel sheets, which are used as material in transformer cores, responding to the need for decreased noise.[1]

Transformer noise is believed to originate mainly from magnetostrictive vibration of the core material and electromagnetic vibration at the connections between core segments, but past researches has mainly concerned vibration due to magnetostriction.[2–4] Although it is difficult to separate these two factors, it is considered possible to grasp the main causes of noise using model cores of relatively simple structure and systematically changing the material and construction.[5]

In this study, the authors constructed such three-phase model transformer cores by stacking high flux density grain-oriented silicon steel sheets. To gain a quantitative understanding of the influential factors on transformer noise, the authors investigated the relationship between transformer noise and various factors such as the magnetic properties of the core material, method of stacking and clamping force applied to the yoke portions.

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2 Experimental Method

The core material used was high flux density grain-oriented silicon steel having different B_8 values (flux density at magnetizing force of 800 A/m, 50 Hz) and two thicknesses: 0.23 mm thick NewRGH (grade: 23RGH090N) and RGH (23RGH090); and 0.30 mm thick NewRGH (30RGH105N) and RGH (30RGH110). The sheets were slit and diagonally cut to specified dimensions. The magnetic properties of the material are shown in **Table 1**.

Table 1 Magnetic properties of model core materials

Material	Thickness (mm)	B_8 (T)[1]	$W_{17/50}$[2] (W/kg)	$W_{15/60}$ (W/lb)
23RGH090N	0.23	1.931	0.85	0.358
23RGH090		1.898	0.89	0.383
30RGH105N	0.30	1.930	1.02	0.446
30RGH110		1.896	1.06	0.462

[1]Magnetic flux density at H = 800 A/m, 50 Hz
[2]Iron loss at B = 1.7 T, 50 Hz

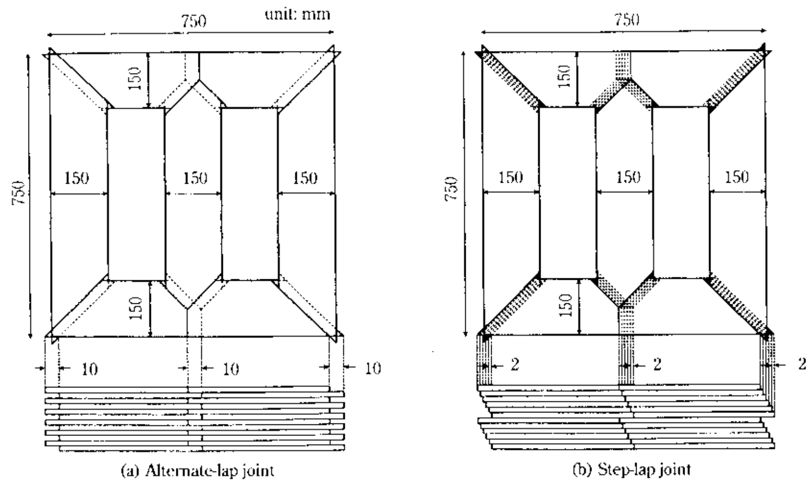

Fig. 1 Structure of three-phase stacked transformer model cores

Table 2 Specifications of model transformer core

Joint geometry	Alternate-lap	Step-lap (6 steps)
Shift length	10 mm	2 mm × 5
Number of lamination /unit lap	2	
Total number of lamination	144 (0.23 mm thick) 108 (0.30 mm thick)	
Core weight	ca. 100 kg	

Model three-phase three-limb transformer cores were constructed. The structure and specifications of the core are respectively shown in **Fig. 1** and **Table 2**. The core weighed approximately 100 kg, was square in shape with outer dimensions of 750 mm to the side, and was stacked on a flat-surface level table. The limbs and yoke had a rectangular cross-section, the yoke having a two-part V-shape notch. Two joining geometries were used in stacking: alternate-lap joining and five-step step-lap joining. Primary and secondary coils of 60 turns wound on the respective limbs were used for excitation and detection of magnetic flux.

To clarify the effect of the clamping pressure applied to the core, a spring mechanism capable of applying uniform pressure to the surface of the yoke portions was constructed. Transformer characteristics were measured under clamping force up to a maximum of 0.2 MPa.

Noise level was measured by a precision sound level meter with an A-weighted compensation circuit as described in JIS[6] using a condenser microphone located 300 mm directly above each of the three limbs of the model core, and an energy average was taken. The maximum of blank noise levels measured was 31 dB.

The strength of vibration at various parts of the yoke surface was measured using an acceleration vibrometer. The leakage magnetic field was detected with a gaussmeter.

The magnetic flux density and iron loss of the core material were measured by the Epstein test method specified in JIS.[7] Magnetostriction was measured at an excitation frequency of 50 Hz using test pieces cut to a width of 100 mm and length of 400 mm from several sheets taken from the limbs. The magnetostriction harmonic components were obtained by frequency analysis on the magnetostriction signal output without any compensation using a spectrum analyzer.

3 Experimental Results

3.1 Noise Level of Model Transformer Cores

Model cores using NewRGH and RGH sheets with thicknesses of 0.23 mm and 0.30 mm were constructed, and noise level was measured without applying clamping force.

The results are shown in **Figs. 2** and **3** for the 0.23 mm and 0.30 mm materials, respectively. Here, the alternate-lap joining and step-lap joining methods are compared.

As shown in the two figures, the higher-B_8 material NewRGH shows lower noise levels than the lower-B_8 material RGH, regardless of thickness. The difference in noise level between materials is of the order of 2–3 dB at 1.7 T and 50 Hz. This difference tends to increase at higher excitation flux densities.

Comparing the stacking methods, the step-lap joint shows noise levels 2–3 dB lower than the alternate-lap joint at 1.7 T and 50 Hz, and this difference also tends to increase at higher excitation flux densities.

It can therefore be considered as an approximation that the noise level depends on both the core material and the joining geometry in a substantially independent manner.

3.2 Influence of Material Properties on Noise Level

Figure 4 shows the influence of material flux density

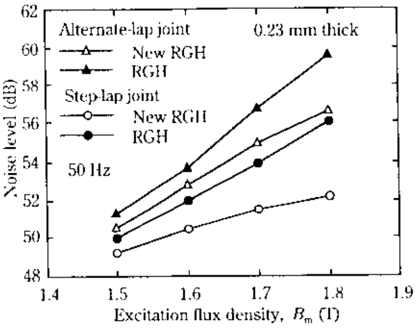

Fig. 2 Noise level of model transformer cores using 0.23 mm thick NewRGH and RGH sheets

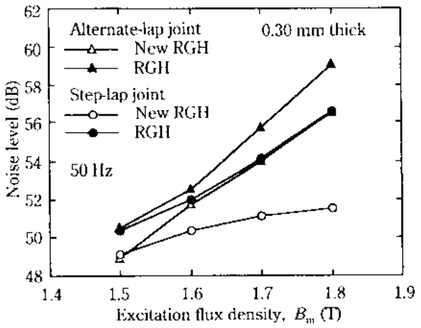

Fig. 3 Noise level of model transformer cores using 0.30 mm thick NewRGH and RGH sheets

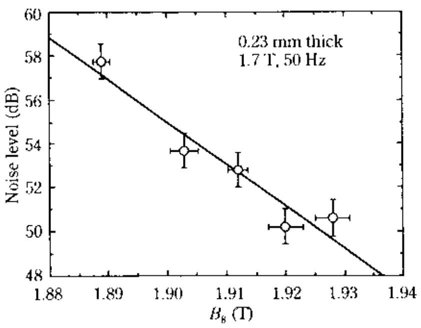

Fig. 4 Relation between noise level of step-lap model transformer core and B_8 value of core material

on the noise level of the model transformer core using 0.23 mm thick materials having various B_8 values. The step-lap joint was used. The noise level shows a clear inverse correlation with the material B_8 value: With sheets of 0.23 mm in thickness, noise decreases by slightly less than 2 dB for each difference of 0.01 T in B_8.

The magnetostriction harmonic components of the core materials were analyzed. **Figures 5** and **6** show the strengths of the magnetostriction harmonic components of the test pieces extracted from the laminations of 0.23

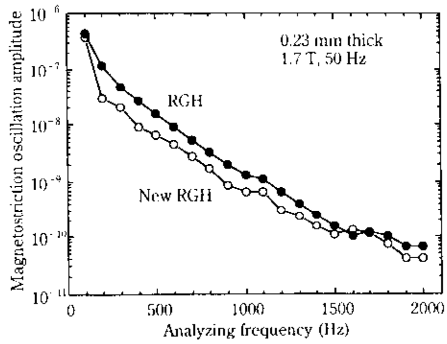

Fig. 5 Spectral intensity of magnetostriction oscillation amplitude in 0.23 mm thick NewRGH and RGH sheets

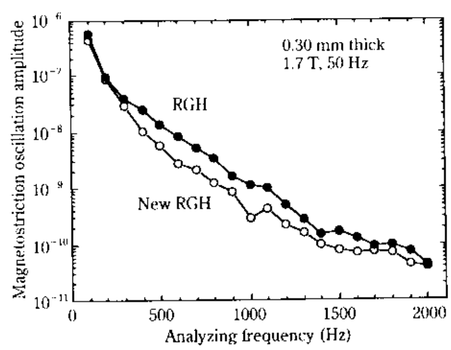

Fig. 6 Spectral intensity of magnetostriction oscillation amplitude in 0.30 mm thick NewRGH and RGH sheets

mm and 0.30 mm thick materials, respectively. In both cases, the strength of the harmonic component is smaller with NewRGH having higher B_8 values.

In order to examine the correlation between the noise level and the magnetostrictive vibration, the harmonic components of magnetostrictive vibration acceleration were calculated using Eq. (1), with the results for an excitation of 1.7 T and 50 Hz shown in **Figs. 7** and **8**.

$$p_n = (2\pi f_n)^2 \lambda_n \gamma_n \cdots\cdots (1)$$

Here f_n is n-th harmonic frequency, λ_n the magnetostriction harmonic component, and γ_n the coefficient for the A-weighting audibility compensation.

Reflecting the strength of the magnetostriction harmonic component, the strengths of the acceleration spectra of NewRGH show lower values than those of RGH.

The A-weighted magnetostrictive vibration acceleration level P is obtained by integration of the harmonic components calculated by Eq. (1) using Eq. (2).

$$P = 20 \log \left(\sqrt{\sum_n p_n^2} \Big/ p_0 \right) \cdots\cdots (2)$$

In Eq. (2), the value $p_0 = (2\pi)^2 \cdot 10^{-5}$ was used for the reference level.

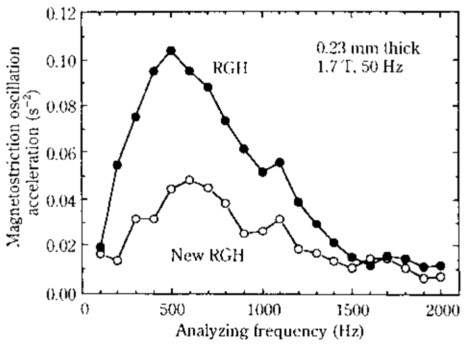

Fig. 7 Spectral intensity of magnetostriction oscillation acceleration in 0.23 mm thick New RGH and RGH sheets

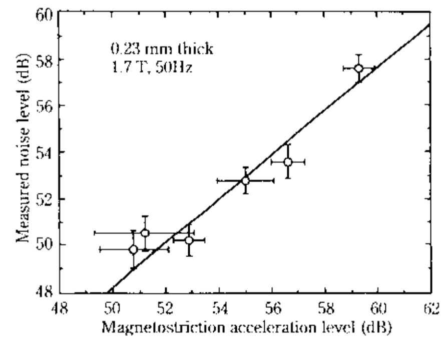

Fig. 10 Comparison of measured noise level with magnetostriction oscillation acceleration level

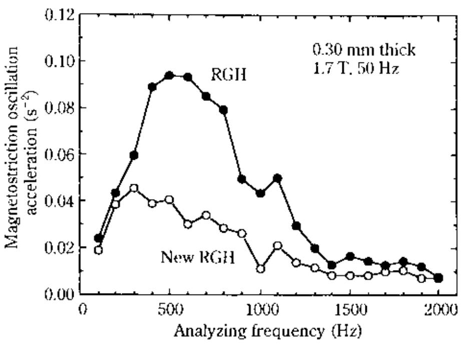

Fig. 8 Spectral intensity of magnetostriction oscillation acceleration in 0.30 mm thick New RGH and RGH sheets

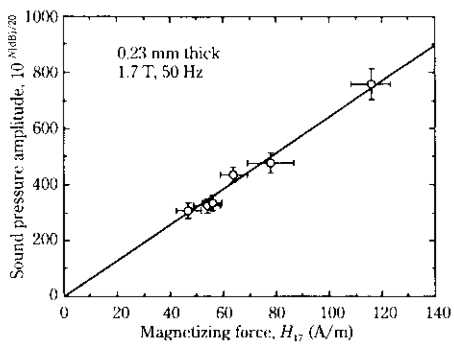

Fig. 11 Dependence of measured sound pressure amplitude on magnetizing force of core material

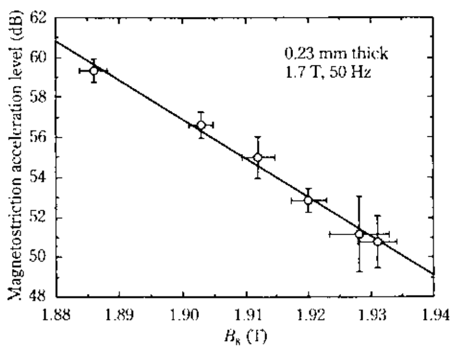

Fig. 9 Dependence of magnetostriction oscillation acceleration level on B_8 value of 0.23 mm thick material

Figure 9 shows the dependence of the A-weighted magnetostrictive vibration acceleration level calculated from the above mentioned magnetostriction harmonic components of the same 0.23 mm materials as shown in Fig. 4 on material B_8 value. **Figure 10** shows the results of a comparison of the A-weighted noise level measured on a model core of the step-lap type and the A-weighted magnetostrictive vibration acceleration level P. The measured noise level and the magnetostriction acceleration level plotted in Figs. 4 and 9 show a good correlation, as shown in Fig. 10.

The relationship between the noise level and the excitation characteristics of the materials is shown in **Fig. 11**. The amplitude of noise and the magnetizing force H_{17} at an excitation flux density $B_m = 1.7$ T show a virtually proportional relationship.

3.3 Distribution of Vibration on a Core Surface and Distribution of Leakage Field

Figure 12 shows the distribution of the surface-perpendicular component of vibration acceleration at the surface of the yoke when model cores which are constructed by the alternate-lap joint and step-lap joint methods using 0.30 mm thick material were excited at 1.7 T, 50 Hz. The vibration distribution is represented by the logarithm of the surface vibration acceleration in $\mu m/s^2$.

As is clear in Fig. 12, vibration is large at the connections between the yoke and limbs. At the center of the yoke, which is the area farthest from the limb-yoke joints, the value is approximately 10 dB lower than at the

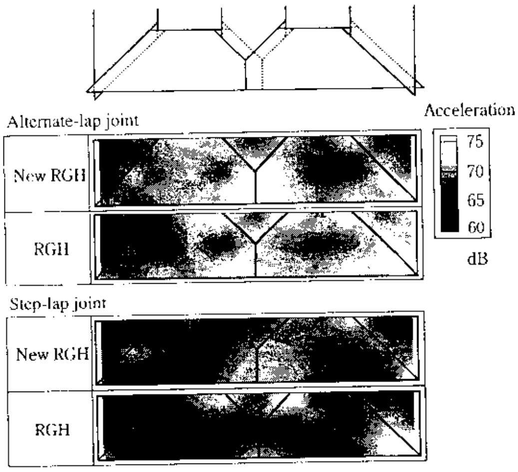

Fig. 12 Distribution of vibration acceleration level on yoke surfaces of model cores using 0.30 mm thick NewRGH and RGH sheets

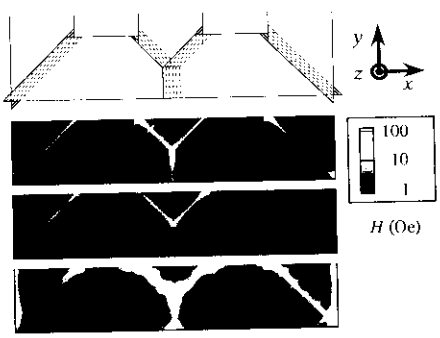

Fig. 13 Distribution of stray fields on yoke surface of step-lap model transformer core using 0.30 mm thick NewRGH sheet

joints. Comparing the joint methods, the overall strength of vibration is larger and the concentration of vibration at the joints is greater with the alternate-lap joint than with the step-lap joint. Comparing the materials, NewRGH shows a lower overall vibration acceleration and a smaller concentration at the joints. These findings agree well with the results of the noise measurements shown in Fig. 3.

Figure 13 shows the results of mapping the three directional components of the leakage magnetic field on the yoke when a model core constructed by the step-lap method using 0.30 mm thick RGH was excited at 1.7 T and 50 Hz. The leakage field was concentrated at the joints with the limbs. The strongest surface-perpendicular components showed particularly good agreement with the distribution of vibration acceleration in Fig. 12, suggesting that electromagnetic vibration due to the leakage field has a strong influence on noise.

3.4 Influence of Clamping Force on Noise

The foregoing results have concerned only the mea-

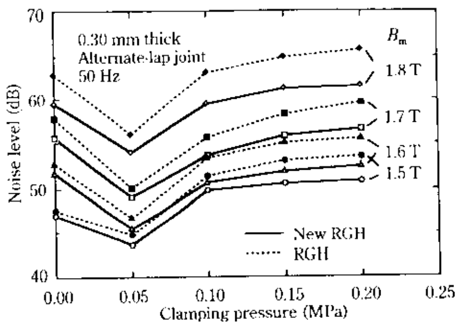

Fig. 14 Influence of clamping pressure on noise level of alternate-lap core

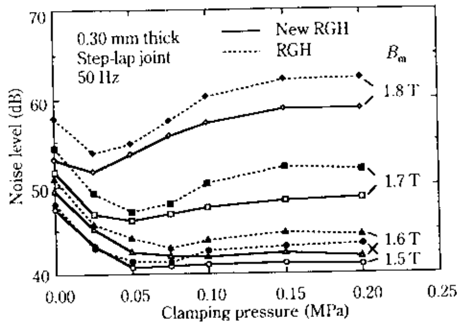

Fig. 15 Influence of clamping pressure on noise level of step-lap core

surements without clamping force applied to the core. However, it is reasonable to assume that clamping force has a strong influence on noise. To understand this influence, noise was measured while a uniform pressure with varying strength was applied to the yoke. NewRGH and RGH with a thickness of 0.30 mm were used in the core. The measured noise levels with model cores constructed by alternate-lap stacking and step-lap stacking are shown in **Figs. 14** and **15**, respectively.

In the case of alternate-lap joint, noise showed its minimum value at a surface pressure of 0.05 MPa regardless of the excitation flux density, and began to increase again when greater pressure was applied. At 0 MPa, NewRGH showed a lower noise level than RGH, but this difference, after decreasing at 0.05 MPa, tended to increase again at higher pressures and became greater than the difference at 0 MPa.

With step-lap joint, the minimum value of noise level was found at 0.075-0.1 MPa at an excitation flux density of B_m = 1.5 T, but as B_m increased, the clamping pressure giving the minimum noise level decreased, reaching 0.025 MPa at 1.8 T. Moreover, the degree of the increase in the noise level at higher pressures was greater when the excitation flux density was high, and the differences between materials tended to increase as the surface pressure increased.

These results are rearranged to show B_m dependence

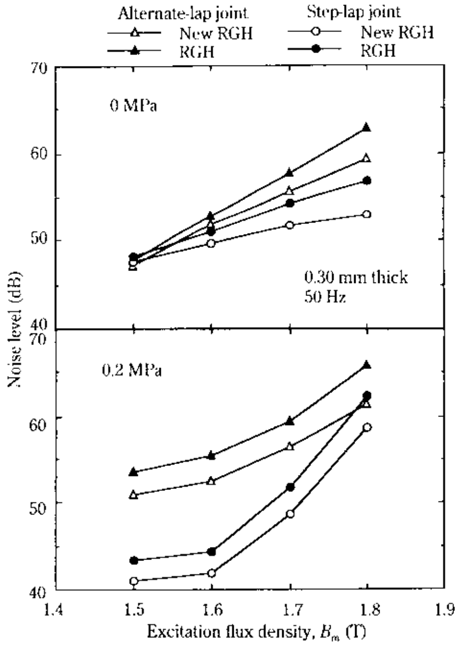

Fig. 16 Dependence of noise level on excitation flux density with and without clamping pressure applied

in **Fig. 16**. When clamping force was not applied to the core, the differences between materials and between core stacking methods tended to increase as B_m increased. In contrast, when a surface pressure of 0.2 MPa was applied, the difference between materials showed little change, while the difference between stacking methods tended to decrease as B_m increased.

4 Discussion

The relationship between the mechanism of noise emission from transformer core and material properties as well as core structure will now be discussed on a basis of the experimental results described above.

As for the magnetostrictive vibration, material with higher B_8 value clearly shows smaller magnetostriction harmonic components (Figs. 5, 6), leading to a decrease in magnetostrictive vibration with increasing B_8 value.

The direct proportional relationship between the sound pressure amplitude of noise and H_{17} (Fig. 11) can be understood as follows: The electromagnetic vibration in the core material is proportional to the gradient of the leakage fields at the joint parts. This leakage flux corresponds to the magnetic resistance in the magnetic circuit, and is therefore proportional to the magnetizing force (H_{17} for the present case) according to Ohm's law of magnetic circuits.

Because H_{17} shows a strong inverse correlation with B_8, it is natural to assume that electromagnetic vibration acts in the direction of decrease when B_8 increases.

The noise level decreases in low clamping pressure range, reaches a minimun at a certain clamping pressure, and begins to increase when clamping force is applied to the yoke, as shown in Figs. 14 and 15. This change in noise level can be assumed to correspond to suppression of the vibration in the direction perpendicular to the sheet surface in the unclamped state (mainly electromagnetic vibration), and easier transmission of vibration inside the core (mainly magnetostriction vibration) to the outside of the core as the applied pressure is increased. In other words, this change is considered to be a transition process in which the main cause of noise shifts from electromagnetic vibration to magnetostrictive vibration as the pressure applied to the core surface increases.

The points mentioned above suggest that noise in the model cores is controlled by electromagnetic vibration by way of the excitation characteristic H_{17} in the unclamped state, and is controlled by magnetostrictive vibration by way of the higher harmonic components of magnetostriction when a clamping force of 0.05 MPa or more is applied. The noise level tends to decrease in all cases as the magnetic flux density B_8 of the material increases.

It should also be noted that the noise difference associated with step-lap and alternate-lap joints tends to increase as the excitation flux density increases when no clamping force is applied to the core, while the difference in noise between the two methods tends to decrease when a surface pressure of 0.2 MPa is applied. This change in B_m dependence is attributable to a saturation effect in the concentration of magnetic flux in the joints.[8] Since the degree of flux concentration in the vicinity of joints is more moderate with the step-lap joint than with the alternate-lap joint, the noise increase is assumed to be suppressed both in electromagnetic vibration due to leakage field and in magnetostrictive vibration at the joint parts in the case of the step-lap joint.

5 Conclusion

Using a model three-phase stacked transformer core made from high flux density grain-oriented silicon steel sheets, the influence of material properties, the core structure, and clamping force on noise level was investigated, and the following information was obtained.

(1) The noise level depends, in a substantially independent manner, on both the material and method of stacking. Under excitation at 1.7 T and 50 Hz, the noise level decreased by slightly less than 2 dB for each 0.01 T increase in the B_8 value of the material. The noise level was lower by 2 dB with the step-lap joint method than with alternate-lap joint.

(2) The main factor contributing to noise in the model core when no clamping force was applied to the core was vibration at the connections between the core and yoke. The distribution of this vibration was virtually

the same as that of the leakage magnetic field on the yoke surface.

(3) When clamping force was applied to the yoke, the noise level decreased to its minimum at around 0.05 MPa, but increased at higher clamping pressures. With the step-lap method, the increase in the noise level was gradual at lower excitation flux densities, and as a result, the transformer showed strong dependence on the magnetic flux density under high excitation when clamping force was applied.

(4) Both the higher harmonic components of magnetostriction and the magnetizing force of material show a strong correlation with the noise level. It is suggested that the main factor is electromagnetic vibration, which is controlled by the magnetizing force, when clamping force is not applied to the yoke, and magnetostrictive vibration, which is controlled by the higher harmonic components of magnetostriction, when a clamping force of 0.1 MPa or more is applied. With both mechanisms, the noise level decreases as the B_8 value of the material increases.

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