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Evaluation and Analysis Techniques of Transformer Performance in JFE Steel†

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Abstract:

Iron losses and acoustic noise in transformers are analyzed using model transformers in JFE Steel. In this paper, techniques to measure local iron losses and vibrations in model transformer cores are described. Distributions of magnetic fluxes and iron losses in a three-phase stacked core are analyzed using stylus probes and a hall probe. In addition, development of iron loss measuring technique using infrared thermograph enabled to visualize iron loss increase near the joints of sheets. Three dimensional measurement using laser vibrometer helped clarify the vibration behaviors of the cores under three phase excitation. As one of the investigations of effects of excitation conditions, iron loss and acoustic noise are measured under direct current (DC) biased excitation.

1. Introduction

Grain-oriented electrical steel manufactured by JFE Steel is mainly used for iron cores of transformers for electric power applications. It is important material which is directly related to the properties of transformers. Since global environmental problems is highly recognized in recent years, and environmental regulations have been strengthened, there are increasingly high needs for energy saving in transformers[1)]. Reduction of iron loss is constantly demanded in grain-oriented electrical steel, which has a large influence on the energy efficiency of transformers. Therefore various researches and developments have been carried out to satisfy these requirements. Iron loss in a transformer is normally larger than that of grain-oriented electrical steel used for its iron core. Accordingly, in addition to reducing the iron loss of material, reduction of the increase of iron loss when the material is applied to transformers is an important development topic[2)]. Therefore, JFE Steel has conducted various kinds of investigations and analyses using model transformers[3)].

There are various reasons why iron loss increases in transformer cores in comparison with that of the material. In iron cores, which are fabricated by stacking sheared grain-oriented electrical steel sheets, complex magnetic fluxes have a large influence[2–5)]. Examples include flux circulation and rotating flux, partial concentration of flux, crossing of flux between the stacked sheets and so on. Measurement of the local magnetic flux in iron cores is useful for evaluating the effects of these phenomena. Although much progress has been achieved in numerical simulation techniques for analysis of electromagnetic fields in recent years, many problems still remain, for example, the strong anisotropy of magnetic properties in grain-oriented electrical steel, modeling of iron cores which are consisted of lamination of many thin sheets etc.[6)]. Experimental analysis of magnetic flux distribution helps to solve these problems.

In order to measure the local magnetic flux in an iron core of model transformer, JFE Steel developed and applied a stylus probe method which enables nondestructive measurement of grain-oriented electrical steel with an insulating coating[3,7)]. JFE Steel also developed a infrared thermography method to visualize the distribution of iron loss by measuring the heat generated as the result of iron loss[8)]. The technologies and their measurement results are described in Chapter 2.

Reducing acoustic noise of transformers is another

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important environmental demand[9]. The main causes of transformer noise are thought to be magnetostriction —microscopic expansion and contraction of the steel sheets accompanying magnetization— and electromagnetic fource generated between the sheets[2]. In order to understand how these phenomena cause acoustic noise, a detailed knowledge of the forms of vibration in iron cores is important. Therefore, iron core vibration was measured in model transformers, and their vibration behavior was analyzed[9,22]. The measurement method and results are described in Chapter 3.

Furthermore, even in transformers which are designed and manufactured with due consideration of iron loss and acoustic noise, their operating conditions can also have a large influence on iron loss and acoustic noise. Recentry, with the development of the power electronics, the number of cases in which high frequency or direct current components are superimposed on the magnetic flux of iron cores for electric power applications is increasing. They have sometimes caused problems of increased iron loss and acoustic noise[11]. JFE Steel has also carried out investigations using model transformers in evaluating the effects of these phenomena and studying differences depending on the core material. As an example, Chapter 4 describes the results of measurements of iron loss and acoustic noise using a model transformer which enables measurement under DC biased excitation[12].

2. Analytical Techniques for Local Magnetic Properties in Model Transformers Cores

2.1 Measurement of Local Magnetic Properties by Stylus Probe Method

2.1.1 Purpose

The search coil method has been used to measure local magnetic flux in the iron cores of transformers. However it is necessary to drill holes in the steel sheet, and the space between the sheets for the lead wires effects on the flux distribution. To avoid these problems, a stylus probe method, which enables nondestructive measurement, was developed and applied[7]. JFE Steel developed this stylus probe method to measure the local flux distribution in the iron cores of model transformers to analyze the magnetic flux behavior[3]. The following presents an outline of this technology applied to measurement of a stacked iron core of a three-phase model transformer and an example of the measurement results.

2.1.2 Measurement device

The schematic diagram of stylus probe method to measure the local magnetic properties of iron cores is shown in **Fig. 1**. The local flux density was obtained based on the principle that the voltage generated between two stylus probes, which are placed in contact with the steel sheet at the surface of the core, is equal to the voltage of a half-turn search coil between the stylus probe contact points[13]. The distance between the stylus probes was 5 mm, and an air flux compensation coil was placed between the probes. The magnetic field intensity of the steel sheet surface was measured by a Hall probe whose width is approximately 1 mm. The distance between the Hall probe and the surface of the steel sheet was approximately 0.5 mm. The stylus probes and Hall probe can be rotated 90°, enabling to measure magnetic flux density and magnetic field intensity in two directions (defined as the x and y directions) of the sheet surface. A mechanism which continuously scans the measurement points on the whole sheet surface was provided by incorporating these probes in a robot arm.

The signals for flux density and magnetic field intensity were measured and recorded by a digital oscilloscope. The iron loss at each measurement point was calculated by dividing the area of the hysteresis loop drawn by the waveforms of the measured flux density B and field intensity H into the x direction component W_x and y direction component W_y by the following equations, the sum was defined as 2-dimensional local iron loss W_{2d}.

$$W_{2d} = (f/\rho)\int H \cdot dB = W_x + W_y \quad (1)$$

$$W_i = (f/\rho)\int H_i dB_i \ (i: x, y) \quad (2)$$

Where, f: Excitation frequency, ρ: Density of the electrical steel sheet. Contour integration was performed for an excitation period of 1 cycle.

The model transformer was a three-phase three-limb stacked iron core and the width of yokes and limbs was 100 mm. The outer shape was square with side lengths of 500 mm, the thickness of the core was approximately 16 mm, and the core weight was approximately 22 kg.

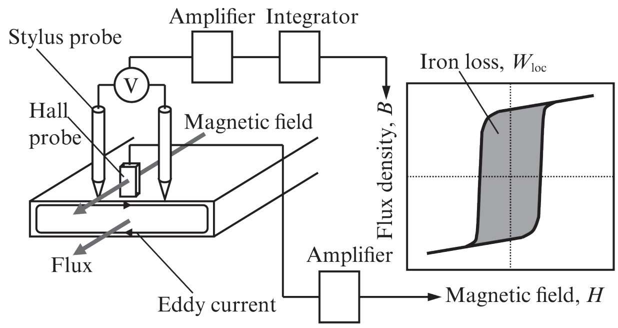

Fig. 1 Method of local magnetic measurement using stylus probes and a Hall probe

The joint geometry between the yokes and the center limb was a V shape-notch. The joint design was 5-step laps of two steel sheets. The iron core was excited by the primary winding of 40 turns on each limb, and the magnetic flux was detected by the secondary winding of 60 turns. The total iron loss of the iron core was measured from the primary current and secondary voltage of each phase by using a wattmeter.

The core material used here was high permeability grain-oriented electrical steel sheet 30JGS™ with a thickness of 0.30 mm. The iron loss $W_{17/50}$ measured at 1.7 T and 50 Hz measured by a single sheet tester was 1.01 W/kg.

2.1.3 Results

Figure 2 shows the changes in the magnetic flux density distribution at the half surface of the iron core. Non-uniformity of flux dinsity was observed in the limbs and yoke. This non-uniform flux distribution is caused mainly by circulation of the flux due to the anisotropy of magnetic permeability in the rolling direction and transverse direction of grain-oriented electrical steel, and induces distortion in the local flux density waveform. The distortion of the local flux density waveform causes an increase in iron loss and the higher harmonic components in magnetostrictive vibration[2]. This is valuable information for analyzing iron loss and acoustic noise in transformers.

Figure 3 shows the distribution of iron loss near the yoke. Areas of extremely large iron loss existed near the T-joint, and on the joints between the yoke and the outer limbs, and are considered to be due to the effects of rotating magnetic flux and flux concentration, respectively.

These local increases of iron loss are influenced by differences in the magnetic properties of the grain-oriented electrical steel used, the joining method and other factors. The technique described here is also being used in analyses of the influences of these factors.

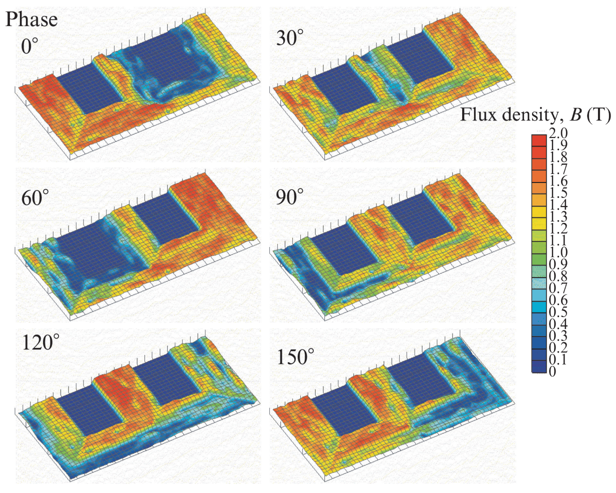

Fig. 2 Magnetic flux density distribution measured by stylus probe method

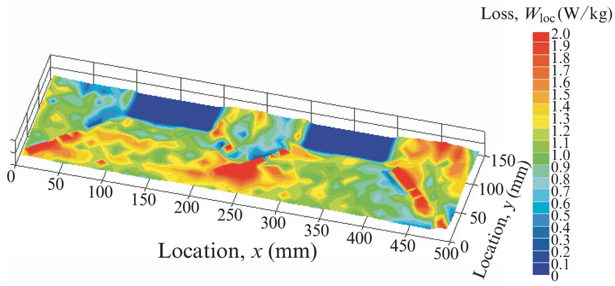

Fig. 3 Distribution of iron loss measured by stylus probe method

2.2 Measurement of Local Iron Loss by Thermography

2.2.1 Purpose

Local magnetic measurement by the stylus probe method is an effective technique to measure iron loss, magnetic field intensity and magnetic flux density simultaneously. However, near joint parts where steel sheets are overlapped, in-plane eddy currents are generated by the magnetic flux crossing between the layers of sheets, and this causes errors in the measured values of magnetic flux density based on measurement of the eddy current in the steel sheet cross section[14]. Therefore another measurement method is required in analysis of the iron loss near the joints. For this purpose the method of calculating iron loss from the temperature increase ratio of the steel sheet is known[15]. In particular, because temperature measurement by infrared thermography enables simultaneous measurement of a wide range of the iron core surface in comparison with methods using thermocouples or thermistor thermometers, it is suitable for measurement of the distribution of iron loss. JFE Steel developed an iron loss distribution measurement method using infrared thermography with high temperature resolution[8].

2.2.2 Measurement method

The infrared thermograph used in this measurement method had temperature resolution of 0.02 K and a maximum pixel count of 76 800 (320×240), and video photography was possible at 380 frames per second. The infrared camera was set 1 m above the iron core so that the entire core could be measured.

To prevent error due to the effects of other heat objects on the iron core surface, the iron core, infrared camera and only the minimum necessary wiring were placed in a soundproof room with no persons present and the lights turned off, and excitation and measurement were controlled from outside. Measurements were performed after confirming that the temperature distribution of the iron core was stable and the temperature difference of the entire core was less than 1 K.

The iron core was excited and temperature measurements were performed by the following procedures:

(i) Measure the background before applying exciting voltage.

(ii) Raise the primary voltage at a constant rate up to the specified flux density.

(iii) Hold the voltage for a certain time at the specified flux density, then measure the temperature distribution.

(iv) Reduce the exciting voltage to zero, then check that the temperature is kept constant.

Using the following equation, iron loss was obtained from the temperature increase rate d*T*/d*t* at each point in (iii) in this excitation pattern.

$$W = C\, dT/dt \quad (3)$$

Where, *W*: Iron loss, *C*: Specific heat of the steel sheet.

The structure of the model transformer was the same as that described in Section 2.1. However, in order to measure a wider range of the core surface, the primary and secondary windings were reduced to 20 turns. The core material was the grain-oriented electrical steel sheet 23JGS™ with a thickness of 0.23 mm.

2.2.3 Results

Figure 4 shows typical temperature measurement results. The maximum flux density in this measurement was 1.7 T, and the frequency was 50 Hz. The temperature increase rate could be regarded as constant in the state in which the flux density was held at 1.7 T. As the temperature change was slight after excitation was reduced to zero, the effect of heat removal was considered to be small.

Photo 1 shows an image of the temperature distribution of the iron core excited at 1.7 T. A region where the temperature increase was extremely large existed in the T-joint of the yoke, which agreed with the results of measurements by the stylus probe method described in the previous section. In addition, large temperature increases could also be seen in the joints between the outer-limbs and the yoke. Because butt-joints between the steel sheets exist in the lower layer at these regions, it is thought that this result indicates that iron loss increased due to flux concentrations caused by the passage of the flux from the sheets in the lower layer, and the influence of in-plane eddy currents. The temperature increase was larger at one side of the joint side of the W-limb than at the other side, but measurements by the stylus probe method described above confirmed that the distortion of the magnetic flux waveform was large at these points.

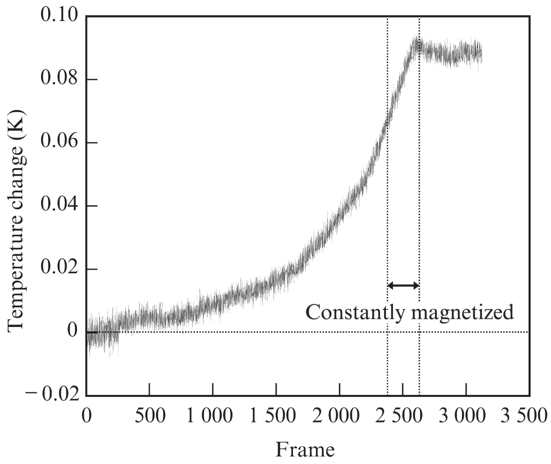

Fig. 4 Example of temperature change measured by infrared thermograph

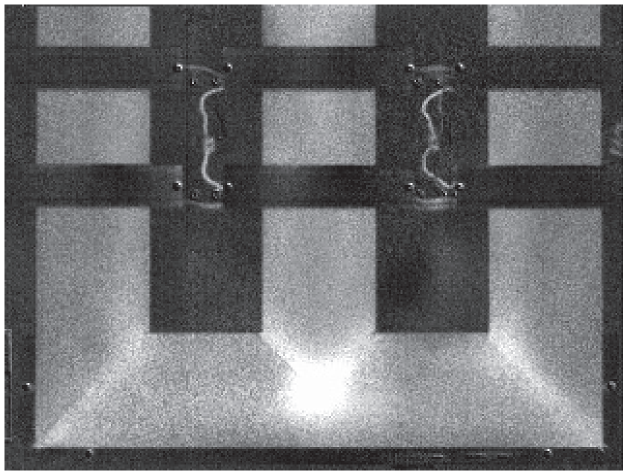

Photo 1 Temperature distribution of model transformer core measured by infrared thermograph

The value of iron loss obtained by totaling the local iron losses in these measurements for the entire iron core was 1.17 W/kg. Since the iron loss measured with the wattmeter was 1.19 W/kg, it was found that measurement by the infrared thermography was effectively accurate.

This local iron loss measurement technique by high resolution thermography has also been applied to analyses of the distribution of iron loss in wound cores.

3. Local Vibration Measurement of a Model Transformer Core

3.1 Purpose

It is known that the iron core of transformer is a source of acoustic noise which is caused by magnetostrictive vibration of the steel sheets and electromagnetic vibration at the joints between the steel sheets[2]. Accordingly, in order to analyze the influence of core materials on transformer noise, it is important to investigate the vibration behavior of the iron core. While there have been previous reports concerning measurements of vibration in transformer cores, many were limited to measurement of the direction perpendicular to the surfaces of the limbs and yoke, and furthermore, those studies discussed their maximum amplitude and the frequency components of vibration[3,16]. JFE Steel developed a method for three dimensional measurement of vibration at various points on the iron core of a model transformer, which has made it possible to analyze the vibration behavior of the core as a structure[9,22].

3.2 Measurement Method

A laser Doppler vibrometer was used for vibration measurements of the iron core. **Figure 5** shows the vibration measurement method. 5 mm square blocks with reflective tapes on their surfaces were attached to the surfaces of the steel sheets, and vibration was measured in three dimensions. To clamp the steel sheets, the top and bottom sides of the iron core were hold between two Bakelite plates, and a clamping pressure of 0.1 MPa was applied with springs. Holes were made in the Bakelite plates at each measurement point so the blocks could be set to the steel sheet surface. When measuring vibration in the steel sheet in the horizontal direction, grooves were made between adjoining holes, and mirrors were inserted in the adjoining holes. Measurements were then performed by reflecting the laser light irradiated from above to a 90° angle. Measurements were performed at intervals of 20 mm.

The structure of the model transformer was the same as that used in Section 2.1, and the core material was the high permeability grain-oriented electrical steel sheet 30JGS™ with a thickness of 0.30 mm.

3.3 Results and Discussion

Figure 6 shows the displacement of each measurement points on the iron core surface in one cycle of magnetostrictive vibration (a half cycle of excitation). The largest displacement was observed in the direction perpendicular to the steel sheet surface, and its amplitude was much larger than the value obtained by multiplying magnetostriction by the stacked thickness of the

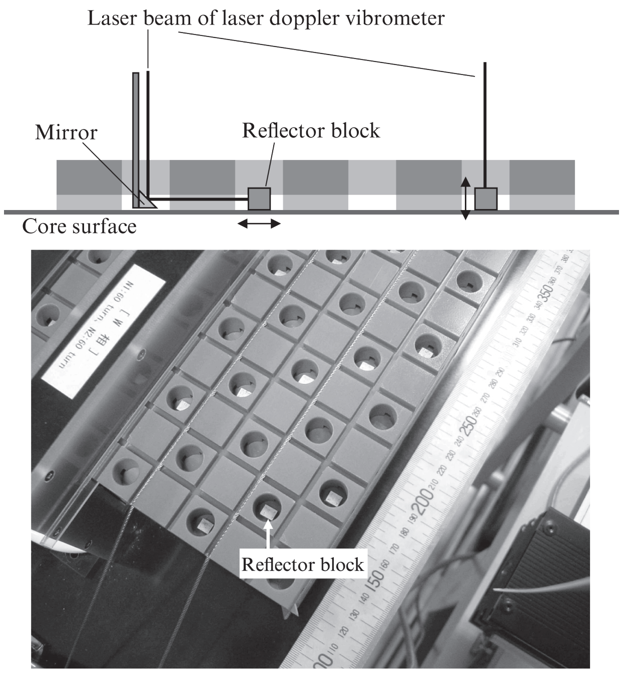

Fig. 5 Method to measure local vibration on model transformer core

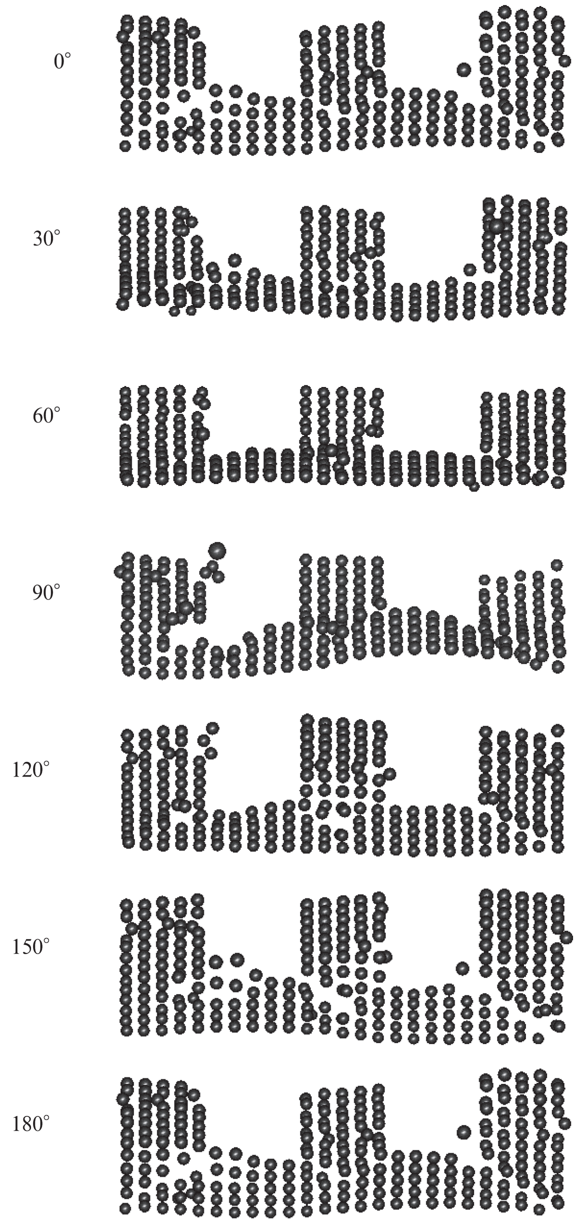

Fig. 6 Vibration behavior of model transformer core surface

steel sheets. Because an iron core is a structure consisting of stacked and clamped steel sheets, and the stacked thickness of this model transformer was small, the stiffness of the sheets against bending in the direction perpendicular to the sheet surface is much smaller than their stiffness in other directions. Therefore, it is thought that magnetostriction acts as a vibromotive force, causing bending deformation in the sheets in the perpendicular direction, and this results in large vibration.

Large vibration occured partially in the joints between the yoke and the respective limbs. This was considered to be an effect of the electromagnetic vibration which is generated in the joint parts. Since the next largest vibration occured in the yoke, it could be understood that bending deformation had occurred. In the U-phase on the left side and the W-phase on the right side in Fig. 6, the phase where the largest vibration amplitude occured was out-of-phase by 1/3 of one cycle, which reflected the phase difference between the phases. Inclination of the surface occurred in all the limbs. As the local flux density of the limbs also differs in the width direction, as shown in Fig. 2, it was thought that the time lag in magnetization caused this kind of surface inclination.

In these results, iron cores showed complex behaviors, reflecting local differences in magnetization of the iron core, as well as mechanical vibration characteristics came from the core structure. Here, the fundamental frequency of magnetostriction which showed the largest vibration amplitude is discribed, but it is also possible to consider the influence on acoustic noise by performing an analysis for higher harmonics. Moreover, a comparison between materials with different magnetostrictive characteristics and the influence of clamping force have also been investigated.

4. Analysis of Characteristics of Model Transformer Under DC Biased Excitation

4.1 Purpose

Because the magnetic properties of electrical steel sheets are nonlinear, it has been reported that iron loss, magnetostriction and the acoustic noise of transformers increases greatly under magnetization conditions in which a direct current (DC) is superimposed on alternating current (AC) magnetization[11,17,18]. However, there have been few reports of investigations in which the biased magnetization conditions were varied from low flux densities to high flux densities with the same measurement device, and there are also few reports of measurements of transformer acoustic noise in comparison with measurements of iron loss.

Therefore, in this research, the AC magnetic flux density and the DC superimposed magnetic field were varied over wide ranges from 0.5 T to 1.8 T for AC flux density and up to 200 A/m for the DC superimposed magnetic field, and the effects of DC biased excitation on transformer iron loss and acoustic noise were investigated[12].

4.2 Experimental Method

4.2.1 Model transformer

Figure 7 shows the measurement system of the model transformer. The model transformer was a single-phase device consisting of a primary winding for AC excitation, a secondary winding for measurement of magnetic flux density and a tertiary winding for application of a direct current magnetic field. The circuit of the tertiary winding comprised a DC power source, an ammeter and a choke coil to prevent AC superimposition.

The iron core was a single-phase, two-limb stacked core, with a square shape having outer dimensions of 500 mm on each side, a stacked thickness of 15 mm and a weight of approximately 18 kg. The joint design was 5-step laps of two steel sheets. The iron core were hold between two Bakelite plates and clamped by applying an average pressure of 0.1 MPa.

The core material was the high permeability grain-oriented electrical steel sheet 30JGH™ with a thickness of 0.30 mm.

4.2.2 Measurement method

The amplitude value of magnetic flux density of AC excitation was obtained from the average value of the induced voltage of the secondary winding. Biasing DC magnetic field intensity was obtained from the current value of the tertiary winding. The effective magnetic path length was assumed to be 1.6 m. Excitation was

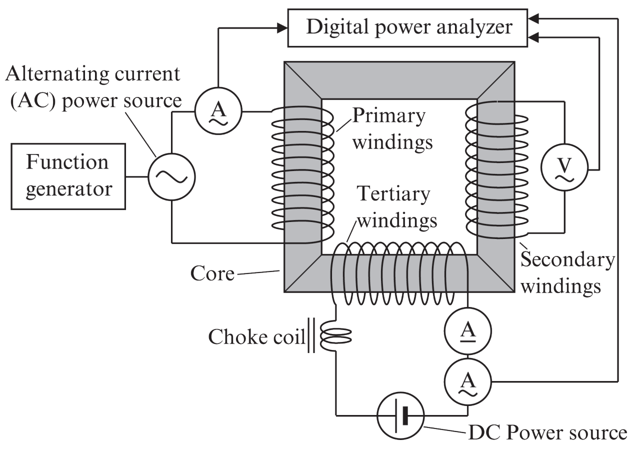

Fig. 7 Schematic of model transformer measurement under direct current (DC) biased magnetization

controlled by the following procedure. First, the iron core was excited with an alternating current at a frequency of 50 Hz by the primary winding, and the maximum flux density was set to the specified value by adjusting the primary voltage. Next, the DC exciting current of the tertiary winding was applied, superimposing a DC magnetic field. After this, the primary voltage was readjusted so as to correct the maximum flux density of AC excitation to the specified value.

In case two exciting windings are used, i.e., one for AC excitation and the other for DC excitation, as in this device, the AC component is superimposed on the tertiary winding, but this causes an increase in iron loss. To prevent this problem, superimposition of the AC component was suppressed by arranging a 3.2 H choke coil in series with the tertiary winding. However, if the tertiary winding was opened, iron loss will also increase in this case. Therefore, correction was made by subtracting the superimposed part of the AC component of the DC excitation system from the exciting current[19].

The acoustic noise levels were measured at two points in the center of the limbs and two points in the center of the yoke, at positions 200 mm from the top surface of the Bakelite plates, and the average value was obtained.

4.3 Measurement Results and Discussion

Figure 8 shows a comparison of the hysteresis curves of the cases without and with DC biased excitation. It could be understood that the magnetizing force deviates greatly due to DC bias, and iron loss increases due to extension of the hysteresis curve.

The relationship between iron loss and DC magnetic field is shown in **Fig. 9**. Iron loss increased with increasing DC biased magnetization, and the increase rate was particularly large at 50 A/m and under.

Figure 10 shows the change in acoustic noise under DC biased magnetization. As with iron loss, acoustic noise increased greatly accompanying direct current magnetization. In addition to the fact that the magnetostriction of the material increased greatly due to magnetization substantially exceeding 1.7 T under biased magnetization, noise increase in acoustic noise under DC biased excitation was also considered to be due to an increase in the odd-order higher harmonics of the excitation frequency, as shown in **Fig. 11**. In the case without DC biased magnetization, essentially the same magnetostriction is generated regardless of whether magnetization is positive or negative. However, the magnetostriction in positive and negative magnetization is different under DC biased magnetization. Thus, this phenomenon is thought to be due to the appearance of large components of 50 Hz and odd-order higher harmonics, even though the fundamental frequency of magnetostrictive

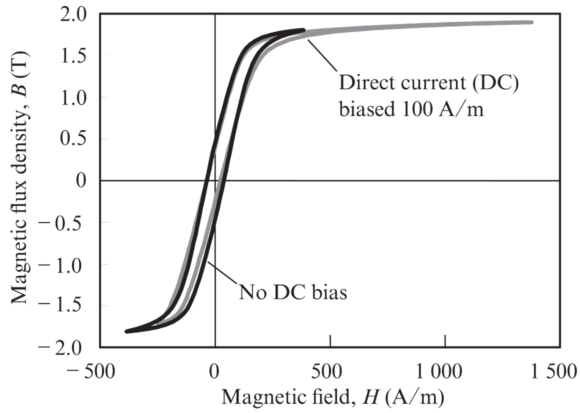

Fig. 8 Comparison of hysteresis curves

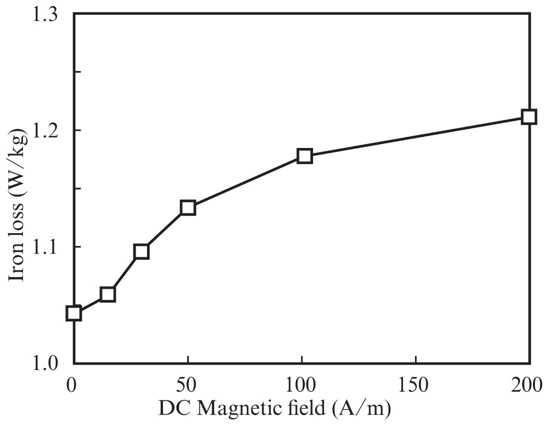

Fig. 9 Iron losses of model transformer under direct current (DC) biased magnetization

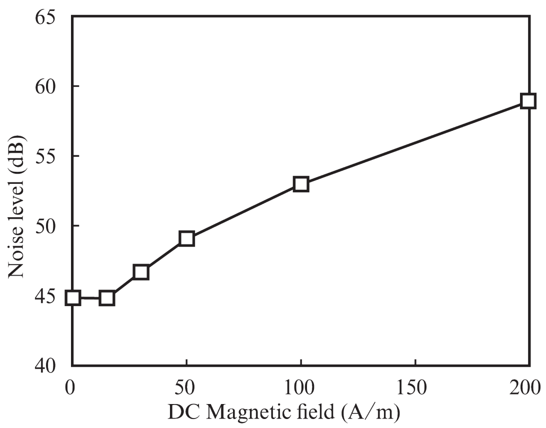

Fig. 10 Acoustic noise of model transformer under direct current (DC) biased magnetization

vibration is 100 Hz[20].

Differences in the increases in iron loss and acoustic noise due to DC biased magnetization have also been investigated using this model transformer, which enables direct current biased magnetization, and the facts that increase of iron loss is larger in materials with higher permeability materials however these materials are superior in terms of acoustic noise[21].

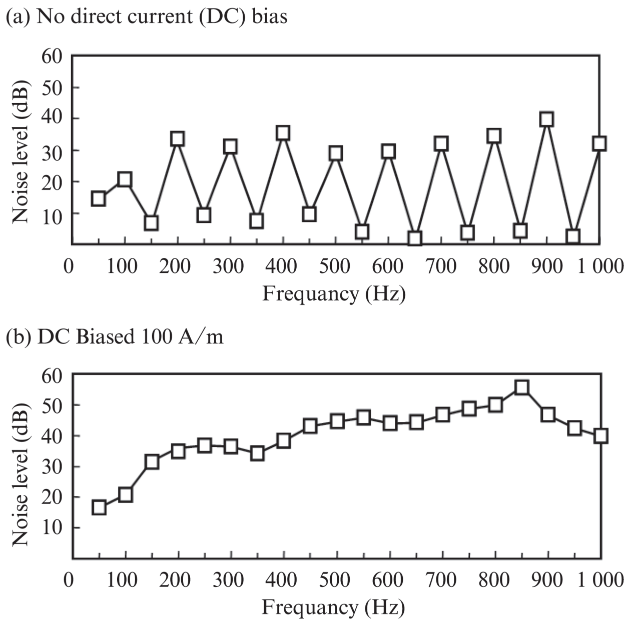

Fig. 11 Comparison of spectrum of acoustic noise harmonics

5. Conclusion

This paper has introduced experimental techniques utilizing stacked core model transformers to analyze iron loss and acoustic noise in transformer cores made from grain-oriented electrical steels. Application of these techniques to wound cores is also possible.

These analysis techniques are actively used in investigations of effective transformer use technologies for grain-oriented electrical steel manufactured by JFE Steel, and in analysis of the transformer properties of newly-developed grain-oriented electrical steels.

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