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Core loss distribution measurement of electrical steel sheets using a thermographic camera

***Abstract**. The aim of this study is to measure the distribution of core loss in electrical steel sheets by using a thermographic camera. This paper describes the measurement system and method, along with their underlying principles. Measurement problems are investigated, and the measurement accuracy is determined. The iron loss distributions are presented, as measured under various conditions on vector magnetic measurement equipment.*

***Streszczenie.** Zbadano rozkład strat magnetycznych przy wykorzystaniu kamery termograficznej. Przeanalizowano problem pomiarowe i niepewność pomiaru. Straty mierzono dla różnych warunków magnesowania z uwzględnieniem wartości wektorowych. (**Pomiar rozkładu strat magnetycznych przy wykorzystaniu kamery termograficznej**)*

Keywords: Core loss, electrical steel, thermographic camera.
Słowa kluczowe: straty magnetyczne, kamera termograficzna.

Introduction

Core loss measurement, along with magnetization measurement, is one of the typical basic measurements of electrical steel sheets. The core loss of an electrical machine is evaluated by loss separation. While the core loss of the entire machine can be ascertained, it is difficult to find the distribution of localized core loss. In addition, questions regarding accuracy of the measurement arise because the core loss is usually obtained by subtracting various loss factors from the total loss. Core loss can be directly measured using a small probe sensor and an H coil; however, since the measurement covers only localized areas, there are problems of accuracy and convenience in deriving the total loss. On the other hand, the core loss is converted into heat, and the identification of the loss through the rise in temperature is essential and effective. As a means of directly measuring the core loss of an electrical steel sheet, the use of a thermocouple or a thermistor for measuring the local temperature has been suggested [1-4]. According to these reports, the temperature rise is about 0.0035 °C/s at 1.2 T, giving a change rate of 0.14 μV/s of the thermocouple output. Therefore, it is necessary to amplify and record the extremely small thermoelectric force accurately. Further, when using a thermocouple or thermistor, the responsivity of the sensor influences the accuracy of the core loss measurement. Note that the influence of heat transfer to the surroundings has been examined in detail, and it is widely known that measurements are accurately made within the time period of 5-10 s because the magnitude of temperature variation is extremely small.

Generally in electrical machines, the materials may not be uniformly magnetized, and the flux conditions, such as the magnitude and the direction of magnetic flux density, may be distributed. These measurement techniques contribute to achieving efficiency goals, but there are also restrictions that make measurements difficult. In addition, these techniques are not suited to covering multiple sample points. In addition, since grain-oriented steel sheets are highly anisotropic, the magnetic characteristics may be distributed because of the intrinsic properties of the material. It has also been reported that, after rolling of grain-oriented steel sheet, there are both easy and difficult magnetization directions with different magnetic characteristics. While the average core loss of electrical machines and electrical steel sheets is measured using, for example, a wattmeter, various methods for measuring localized core loss have been proposed.

In this study, we describe a method that measures temperature rise with a thermographic camera, a method which has the advantages of (1) non-contact measurement, (2) direct measurement of core loss distribution over a wide range of magnitude, and (3) wide latitude for the configuration of measurement samples.

In this paper, we discuss the measurement principles, equipment and methods, and the problems encountered with measurement and accuracy, and show the evaluated core loss distribution of a model core using sinusoidal excitation.

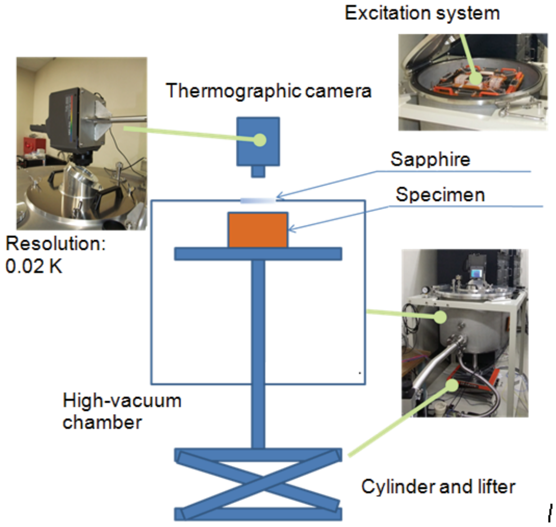


Fig. 1. Thermographic measurement system for assessing magnetic loss distribution

System for visually measuring magnetic loss distribution

Figure 1 schematically shows the system for visually measuring the magnetic loss distribution by thermography. The measurement object is placed in a vacuum chamber, and its temperature is measured by thermography through the upper observation window. Sapphire glass (transparent for infrared light) is used for the observation window. With the capability of housing a measurement machine up to 800 mm in size, the vacuum chamber can realize a vacuum of about 0.001 Pa. In addition, for the focusing of the camera, a lifter is attached (via a cylinder), to the lower part of the chamber. The focal length is set manually. The temperature resolution of thermography is generally 10-100 times inferior to that of temperature measurement using a thermocouple, and a longer time is needed for the measurement. Assuming a vacuum as the atmosphere for the sample, we can ignore heat transfer, while the thermal conduction within the electrical steel sheet and the radiant heat are to be considered.

Table 1. Thermography specifications

Detector	InSb FPA
Number of detecting elements	256 (H)×256 (V)
Detector cooling method	Stirling cooler system
Number of effective pixels	256 (H)×236 (V)
Detection wavelength	3.5~4.1 μm 4.5～5.1 μm
Frame rate	30 fps

Table1 shows the specifications of thermography, where an InSb quantum sensor was used as the detector. The thermography system was connected to an external computer via IEEE1394, and was controlled by the computer. The measured data obtained from thermography are ADC count values, from which the temperature is obtained. In the case of an extremely small temperature change as measured here, we expect a linear relation between the slope of the infrared signal and that of the temperature, and so the calorific value was extracted from the slope of the temperature change.

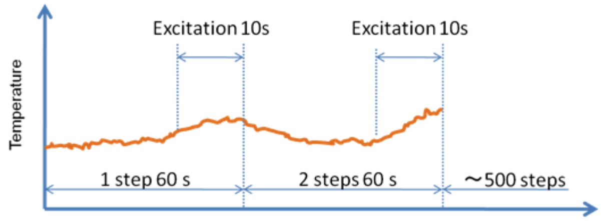


Fig. 2. Temperature gradient measurement method

Figure 2 shows the excitation method. We use 60 s/steps, in which the interval is 50 s and the excitation time is 10 s, and 500 measurement steps. The slope was extracted in each step of excitation and then averaged. The interval was decided by calculating the time needed for the sample's temperature to be sufficiently levelled off, using the two-dimensional heat conduction analysis assuming the excitation time of 10 s as described in the next section.

Two-dimensional heat equation

The distribution of temperature can be calculated from the analysis results by using the following two-dimensional heat equation.

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\mathbb{Q}=\rho c\frac{\partial T}{\partial t} \tag{1}$$

Table 2 lists the parameters, and Table 3 lists the material properties.

Table 2. Parameters for heat conduction

Symbo	Quantity	
T	Temperature	[°C]
λ	Thermal conductivity	[W/(m K)]
Q	Heat source	[W/m^3]
ρ	Density	[kg/m^3]
c	Specific heat	[J/(kg K)]
t	Time	[s]

Table 3. Material Properties

Parameter	Value
Density	7700 [kg/m^3]
Specific heat	486.04 [J/(kg K)]
Heat conduction coefficient	25.14 [W/(m K)]
Coefficient of heat transfer	0
Outside temperature	0 [°C]

The specific heat and thermal conductivity are dependent on temperature. However, the heat generated by core loss is extremely small; therefore, the effects of temperature are also small. In this analysis, the temperature dependence is ignored. The boundary condition is taken as perfect heat insulation and an outside temperature as 0 °C. We consider factors such as the increase in temperature. The amount of heat per unit time generated as a result of core loss is constant.

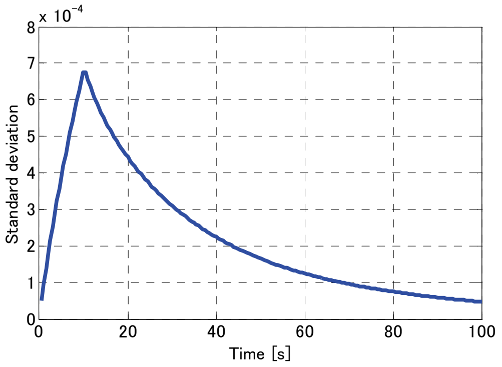


Fig. 3. Standard deviation of temperature distribution

In evaluating the distribution using the temperature gradient, the measurement will be affected by factors other than the loss unless the initial conditions are kept the same. Since the calorific value of core loss is small, a proper interval is necessary to eliminate the influence completely. Figure 3 shows the time-dependent standard deviation of the temperature distribution. The standard deviation is derived as follows:

$$s=\left(\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i-\overline{x}\right)^2\right)^{\frac{1}{2}} \tag{2}$$

$$\overline{x}=\frac{1}{n}\sum_{i=1}^{n}x_i\ . \tag{3}$$

n is number of elements, x is value of elements' temperature.

We can then confirm the time and the smoothing by heat conduction at 10s excitation was assumed for the simulation. From the results, we decided to use the interval of 50 s to reproduce the initial conditions.

C. Core Loss Compensation Method

Each detector element of the core loss equation (4) was used:

$$CoreLoss(i,j)=k\times IR(i,j)\ . \tag{4}$$

Here, *k* is a correction factor. *i* and j are pixels' indexes. *IR* is the average slope. The correction factor is required to accurately determine the material's specific heat and temperature measurements. In this system, accurate temperature measurements are difficult, because emitted infrared photons are attenuated by the sapphire window. Furthermore, accurate specific heat is difficult to obtain. Fig.

6 shows the external appearance of the VH sensor. By this sensor it is possible to measure the core loss accurately because the VH sensor can measure vector magnetic properties [5]. The correction factor was determined from the resulting core loss measured by using the VH sensor in point A1 on fig. 4

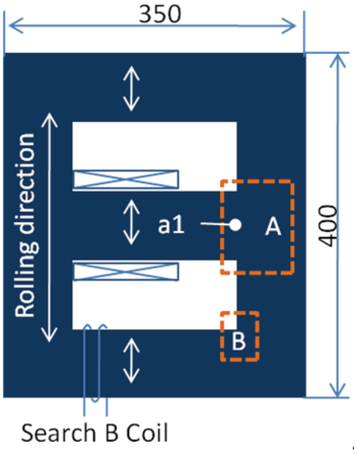
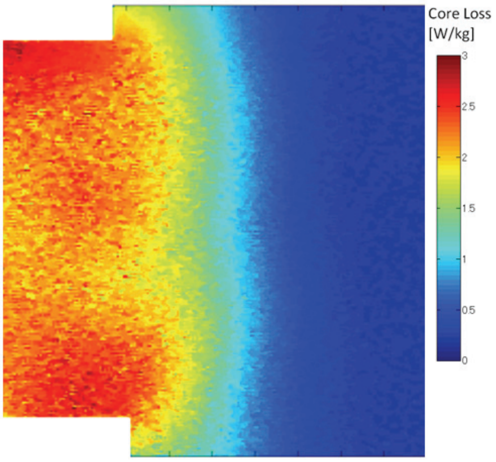


Fig. 4. Measurement model

a) Area A



b) area B

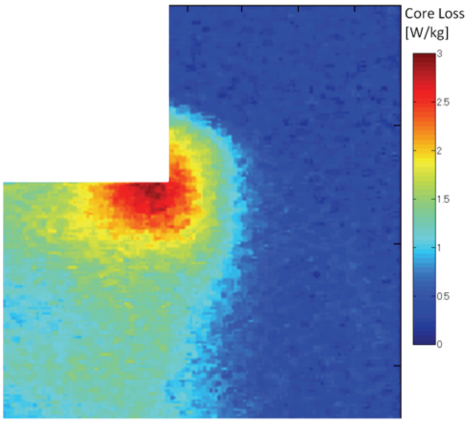


Fig. 5. Measurement result of core loss distribution determined by thermography

Measurement result

Figure 4 shows the measurement model. To simulate the configuration of a 3-phase transformer, the model core is made of a grain-oriented electrical steel sheet with two windows. Unlike a normal 3-phase transformer, the model has a rolling transverse direction in the flux path. The number of laminated sheets is 27, and a B control coil is used so that the target value of the magnetic flux density is achieved. The excitation waveform is sinusoidal, and is not specifically manipulated. The infrared emissivity of the silicon steel metal is usually about 0.6, deteriorating if the surface is smooth. Therefore, the measurement area is painted black to increase this factor. Table 4 shows the measurement conditions. An excitation coil is placed on the central leg, and the excitation conditions include frequency of 50 Hz, maximum flux density of 0.5 T (at the search coil), image acquisition speed 30 fps, and an averaging number of 1,000. A median filter was used as an image filter.

Table 4. Measurement parameters

Parameter	Value
Excitation frequency	50 [Hz]
Magnetic flux density	0.5 [T]
Number of averaging	500
Imaging filter	Median filter
Frame rate	28-30 [fps]

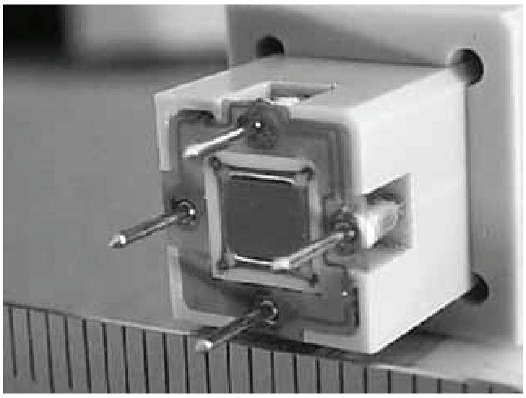


Fig. 6. Photograph of V-H sensor.

Table 5. Specification of V-H sensor.

H-coil	Size [mm]	4×4
	Number of turns[turns]	350
	Area turn (Hx) [cm^2·turn]	5.25
	Area turn (Hy)[cm^2·turn]	7.91
B-needle	Distance [mm]	7

Figure 5 shows the measurement results of thermography. Area A is (a), area B is (b). Figure 6 shows the external appearance of the probe sensor, and Table 5 lists the specifications. The measurement grid pitch is 2 mm.

In area A, a large core loss can be seen in the rolling transverse direction. At the same time, core loss is comparatively small in the longitudinal direction. The grain-oriented electrical steel sheet used in the model is characterized by large magnetic anisotropy, excellent magnetic characteristics in the longitudinal direction, and small loss.

In area B, the loss is large in the rolling transverse direction and small in the longitudinal direction. In addition, it is clear that core loss is concentrated in corners.

Conclusions

The research described in this paper can be summarized as follows:

1. The direct measurement of core loss distribution of an electrical machine was realized using a thermographic camera.
2. The temperature sensitivity of thermography is inferior to the traditional measurement system using a thermistor

or a thermocouple; however, we succeeded in measuring extremely small changes in the amount of generated heat in the form of distribution by means of averaging results from repeatedly measured data.
3. Measurement of a small temperature variation was made using a vacuum chamber to avoid heat conduction into the atmosphere.
4. Reasonable measurement results were obtained when evaluating a model core.
5. Through heat conduction analysis where core loss distribution, which was obtained from vector magnetic characteristics analysis, was used as a heat source, it was confirmed that the initial condition could be reproduced by using the interval of 50 s against an excitation of 10 s.
6. A comparison of the core loss distribution of the model measured by thermography with that measured by the probe method revealed that the distribution was reasonable if we considered the characteristics of the grain-oriented electrical steel sheet.

Acknowledgment

This study was supported by research grants (Oita Prefecture Collaboration of Regional Entities for the Advancement of Technological Excellence) form the Japan Science and Technology Agency.

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