Techniques and Apparatus for Measuring Rotational Core Losses of Soft Magnetic Materials

Jin-Jiang Zhong, You-Guang Guo, Jian-Guo Zhu, Hai-Yan Lu, and Jian-Xun Jin

***Abstract*—In many situations such as the cores of a rotating electrical machine and the T joints of a multiphase transformer, the local flux density varies with time in terms of both magnitude and direction, i.e. the flux density vector is rotating. Therefore, the magnetic properties of the core materials under the rotating flux density vector excitation should be properly measured, modeled and applied in the design and analysis of these electromagnetic devices. This paper presents an extensive review on the development of techniques and apparatus for measuring the rotational core losses of soft magnetic materials based on the experiences of various researchers in the last hundred years.**

***Index Terms*—Magnetic property measurement, measuring apparatus, measuring technique, rotational core loss, soft magnetic material.**

1. Introduction

Soft magnetic materials are widely employed as the cores of electromagnetic devices thanks to their high permeability. For example, grain-oriented 3% silicon-iron is commonly used in transformer cores, and non-oriented silicon-iron or unalloyed iron is used for motor and generator applications. The magnetic properties, such as hysteresis loop and core loss, of the magnetic materials used are much concerned by device designers and users.

To evaluate and control the quality of magnetic materials, magnetic properties, such as flux density vs field strength (**B**-**H**) curves and core losses, are measured with alternating or two-dimensional (2-D) rotating magnetic fluxes, depending on the application. In a single-phase transformer, for example, the magnitude of the flux varies with time sinusoidally but the direction of the flux does not change. This flux is known as the alternating or one-dimensional (1-D) flux.

In a rotating electrical machine or the T-joints of a multiphase transformer, the direction of the magnetic flux varies with time as well in the plane of the electrical steel lamination. This kind of flux is known as the 2-D rotating flux. Fig. 1 plots the measured alternating and rotational core losses of NiFe at 50 Hz where $\theta = 0°$ and $\theta = 90°$ are the rolling and transverse directions respectively [1]. It is shown that the rotational hysteresis loss behaves very differently from its alternating counterpart. A rotational field causes more core loss than the alternating field with the same peak value at a mid-range flux density. However, at saturation the loss caused by a rotating field falls markedly to the levels well below that caused by an alternating field.

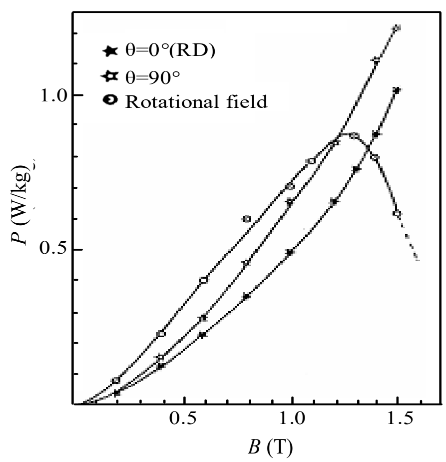

Fig. 1. Alternating and rotational core losses of NiFe at 50 Hz[1].

Therefore, it would be very advantageous if the rotational core loss can be considered properly in electrical machine design. For various reasons, however, the study in this area is still at an early stage, although a considerable amount of work has been done on the subject. So far, the techniques for measuring rotational core loss have not been fully developed, and there is no model bearing a strong physical background for predicting the core losses with practical accuracy, since the mechanism of rotational core losses have not been well understood.

This paper aims to present an extensive review about the research and technical development of the rotational core loss measurement in the last hundred years. Four methods for measuring core losses are introduced in Section 2. Section 3 discusses the measuring techniques for magnetic field strength and flux density. A development of measuring apparatus is presented in Section 4.

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2. Methods for Measuring Rotational Core Loss

As early as in 1896, Baily conducted the first quantitative investigation on rotational hysteresis loss [2]. He measured the torque exerted on a cylindrical armature consisting of a stack of iron laminations between the pole pieces of a rotating electromagnet. After eliminating the error produced by eddy currents he obtained the hysteresis loss as a function of induction for several materials.

Since then, in the following one hundred years or so, considerable progress has been achieved in terms of measuring techniques and systems.

2.1 Torque-Metric Method

The torque-metric method is usually used in apparatus which use disk or ring sample, as will be described later. The torque due to rotational core loss occurring in the sample is measured by using mechanical torque meters[2-5], or calculated from the variation of sample angular speed [6].

The advantages of this method are the direct reading of the torque corresponding to rotational core loss from the torque meter, and the ability to measure rotational core loss with high flux density. The disadvantage is the difficulty of torque meter construction owing to the complicated mechanics.

2.2 Thermometric Method

In the thermometric method, the temperature of the sample is obtained by thermocouples, thermistors, or thermoviewers. The rotational core loss is proportional to the initial rate of the sample temperature rise if no cooling process is involved, namely

$$P_r = C\frac{d\theta}{dt} \tag{1}$$

where P_r is the specific rotational core loss in W/kg, C the specific heat of the sample material, θ the temperature of the sample, and t the time instant.

This is a very versatile method that has been widely used in apparatus using various types of sample, such as disc [7], ring [8], cross [9], and square [10], with various types of rotating magnetic field. It is also able to measure localized core loss at the T joints of a three-phase transformer core [11].

The major shortcomings of this method are the difficulties of installation and calibration of thermosensors, and isolation against the surrounding. It is therefore being more and more replaced by the field-metric method.

2.3 Field-metric Method

In the field-metric method, rotational core loss is calculated from the measured magnetic field strength **H** at the sample surface and flux density **B** inside the sample. This method features high accuracy and great versatility. Moreover, the set of measured instantaneous **H** and **B** values can yield more desirable information, such as various loss contributions, the loci of **H** and **B** vectors, and harmonics etc. The main disadvantages are the difficulties of manufacture, calibration, and installation of **B** and **H** sensors, and the sensitivity to pre-amplifier phase angle errors.

For the evaluation of rotational core loss, there exist two formulas, which are here referred as the field-metric method type I and type II, respectively. Type I calculates the total specific core loss P_t by using the Poynting theorem [12-17]

$$P_t = \frac{1}{TP_m}\int_0^T \mathbf{H}\frac{d\mathbf{B}}{dt}dt = \frac{1}{TP_m}\int_0^T (H_x\frac{dB_x}{dt} + H_y\frac{dB_y}{dt})dt \tag{2}$$

where T is the time period of magnetization, ρ_m the mass density of sample, H_x, H_y, B_x, B_y are the X and Y components of **H** and **B**, respectively.

In the field-metric method type II [18], the torque per unit volume due to the rotational core loss in the sample is calculated by

$$T_r = \mu_0 \left|\mathbf{H}\times\mathbf{M}\right| = \mu_0 HM\sin\alpha = \mu_0 HM_\perp \tag{3}$$

where μ_0 is the magnetic permeability of vacuum, **M** the magnetization, α the angle between **H** and **M** vectors, and $M_\perp$ the component of **M** perpendicular to **H**.

2.4 Watt-Metric Method

The Watt-metric method differs from the field-metric method in that **H** is determined by the magnetization current[17] and is widely used in the Epstein frames or single sheet testers for alternating core loss measurement[19]. Initially, **H**, **B**, and core loss were measured by ammeters, voltmeters, and wattmeters, respectively. That is why this method is known as the watt-metric method. With the development of digital techniques, **H** and **B** waves can be readily obtained in numerical form, and core losses can then be calculated by using (2). An outstanding advantage of this method is the simplicity in determining **H**.

In apparatuses for rotational core loss measurement, this method can only be applied to the vertical yoke single sheet tester [20], because of the absence of air gaps between the sample and the yokes. Compared with alternating core loss testers, the magnetic flux paths in the sample and the yoke system of the rotational core loss testers are not well defined. This causes excessive systematic error in magnetic field strength measurement by applying Ampere's law. Since the flux density is not uniformly distributed in the sample, the magnetic flux density is measured in the center of the sample by coils wound through small holes, or **B** tips. The accuracy of measurement strongly depends on the structure of the yoke and the shape of the sample, which define the path of the magnetic flux.

3. Techniques for Measuring H and B

3.1 Magnetization Current Method

When the magnetic circuit of a core loss tester satisfies: 1) the magnetic flux path inside the sample is well defined, 2) there are no dissipative processes outside the sample, and 3) there is no magnetic potential drop outside the sample, the magnetic field strength **H** can be determined from the magnetization current i by applying Ampere's law

$$H = Ni/l_m \tag{4}$$

where N is the number of turns of the excitation winding, and l_m the mean length of magnetic flux path.

This method is widely used in apparatus for alternating core loss measurement, such as annular rings, Epstein frames, and single sheet testers[19]. If used in rotational core loss testers, however, this method is not accurate, since the magnetic flux paths in the specimen are vague [20].

3.2 Sensing Coil Method

A. Conventional **H** *Coil*

The tangential component of magnetic field strength at specimen surface can be measured by a thin search coil placed on the surface, as illustrated in Fig. 2.

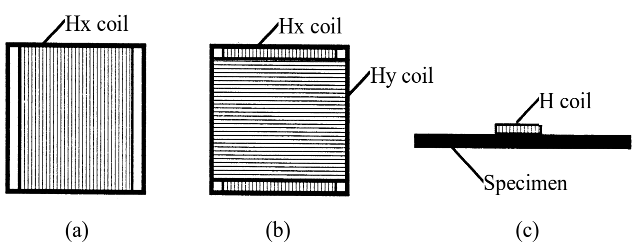

Fig. 2. Sensing coil: (a) 1-D **H** coil, (b) 2-D **H** coil, and (c) position of **H** coil.

When the magnetic field is parallel to the surface, the magnetic field strength can be calculated by

$$H = \frac{1}{\mu_0 K_H}\int V_H dt \tag{5}$$

where K_H is the coil coefficient determined by calibration, and V_H the terminal voltage of the **H** sensing coil.

This method is commonly used in both alternating and rotational core loss testers, and can yield accurate results if the magnetic field on the specimen surface is uniform. In square specimen rotational core loss testers with horizontal yokes, however, the magnetic field varies significantly with the distance between the specimen surface and the **H** coils, as observed by several researchers[12-13, 21-22]. In order to reduce the error, the sensing coils must be made extremely thin and installed as close to the specimen surface as possible, but this is often very difficult.

B. Two **H** *Coil Arrangement*

To reduce the error caused by the variation of magnetic field with the distance above the specimen surface, a two **H** coil arrangement, as shown in Fig. 3, can be used and the field strength at the specimen surface can be extrapolated by

$$H = \frac{d_2 H_1 - d_1 H_2}{d_2 - d_1} \tag{6}$$

where H_1 and H_2 are the magnetic field strength measured by H coil #1 and #2, d_1 and d_2 the distances of two **H** coils away from the specimen surface.

Both numerical analysis [21] and experimental measurement[12, 23] have shown that the linear extrapolation is a reasonable approximation, when two **H** coils are placed not far away from the specimen.

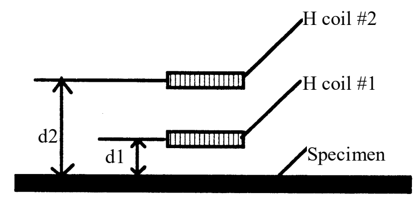

Fig. 3. Two **H** coil arrangement.

C. The Rogowski-Chattock Coil

Another choice of higher accuracy than the conventional **H** coil is the Rogowski-Chattock coil (also known as magnetic potentiometer) [24-26], as shown in Fig. 4.

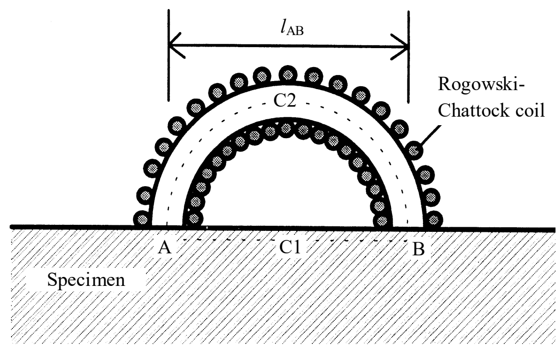

Fig. 4. The Rogowski-Chattock coil.

The principle of the Rogowski-Chattock coil is based on the existence of the scalar magnetic potential V_m in the absence of currents. The magnetic potential difference between two points A and B can be determined by

$$V_{mA} - V_{mB} = \int_{C_1} \mathbf{H}\cdot d\mathbf{l} = \int_{C_2} \mathbf{H}\cdot d\mathbf{l} \tag{7}$$

If the magnetic field is uniform between point A and B, the line integral of **H** along path C_1 can be calculated as

$$\int_{C_1} \mathbf{H}\cdot d\mathbf{l} = H l_{AB} \tag{8}$$

where l_{AB} is the distance between point A and B.

When the magnetic field varies with time, the induced terminal voltage of the coil is

$$V_H = \frac{d\lambda}{dt} = \mu_0 A_H n \frac{d}{dt}\int_{C_2} \mathbf{H}\cdot d\mathbf{l} \tag{9}$$

where λ is the total flux linkage, A_H the cross sectional area, and n the number of turns per unit length of the coil. Substituting (7) and (8) into (9) yields

$$V_H = \mu_0 A_H n \frac{d}{dt}(H l_{AB}) = \mu_0 K_H \frac{d}{dt} H \tag{10}$$

where $K_H = A_H n l_{AB}$ is the coil coefficient, which can be determined by calibration. Therefore, the magnetic field strength **H** on the specimen surface can also be obtained by the time integral of V_H.

Because both ends of the coil can be installed very close to the specimen surface, correct **H** can be detected, and higher sensitivity can be achieved by a larger coil coefficient K_H which is proportional to the number of turns per unit length of the coil.

D. **B** *Coils*

Magnetic flux density **B** vector in core loss testers can also be measured by using a sensing coil[12-13]. When the magnetic flux density is uniformly distributed over the cross section of a sample, the sensing coil can be wound around the whole sample, as illustrated in Fig. 5(a). If the flux density is non-uniform over the cross section of a sample, the sensing coil can then be threaded through small holes at the position of interest, as shown in Fig. 5(b).

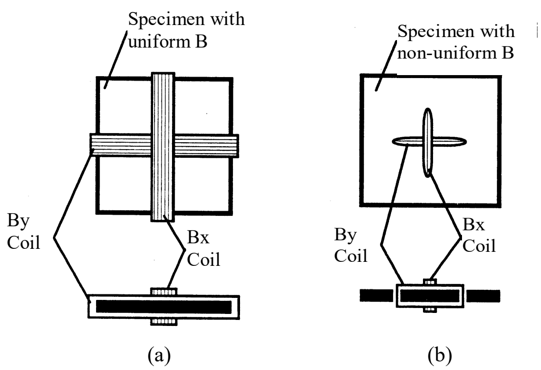

Fig. 5. **B** coil settings for specimens with (a) uniform **B**, and (b) non-uniform **B**.

3.3 Hall Elements

This method makes use of the Hall effect, which occurs in any conductor carrying a current in the presence of a transverse magnetic field. In semiconductors, this effect is much larger than in metals. If there is a current i in a plate-shaped semiconductor, as illustrated in Fig. 6, two opposite points a and b will be the same potential in the absence of a magnetic field. When a magnetic field **H** exists at right angle to the plate, the current path is distorted, and an electromagnetic force e_H (*emf*) is developed between a and b. The magnitude of the magnetic field strength can be determined by

$$H = \frac{e_H t}{R_H i} \tag{11}$$

where t is the thickness of the plate, and R_H the Hall constant, which is a property of the material.

Because of the difficulty of installation, this method is not commonly used in rotational core loss testers, except the one using a rotating disk sample developed by Flanders in 1985 [27].

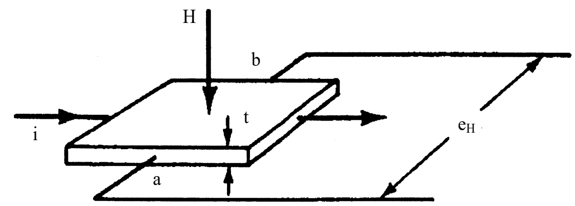

Fig. 6. Relationship between magnetic field, current, and *emf* in the Hall effect.

3.4 *B* Tips

This method was first developed by Werner in 1949 [28], and used for rotational core loss measurement by Kaplan in 1961 [14], Brix in 1982 [16], and Sievert in 1990 [29].

As illustrated in Fig. 7, the induced electromotive force V is measured between two needle tips placed a certain distance apart in contact with the specimen surface. If the specimen is a thin lamination, by Maxwell's equation, the measured voltage can be approximately calculated by

$$V = \frac{bd}{2}\frac{d}{dt}B_y \tag{12}$$

where d is the thickness of the sample, b the distance between two potential tips, and B_y the Y component of magnetic flux density in the specimen. Therefore

$$B_y = \frac{2}{bd}\int V dt \tag{13}$$

Compared with the **B** sensing coils, **B** tips are more suitable for batch measurements, but limited to conducting materials. Essentially, this method is equivalent to a one-turn search coil. In practical measurement, high quality preamplifiers are required, since the voltage signal obtained from the tip is very weak. It is also very difficult to exclude stray fluxes through the air, which may become significant when the specimen size is small. Therefore, the sensitivity of this method is lower than that of the **B** search coil.

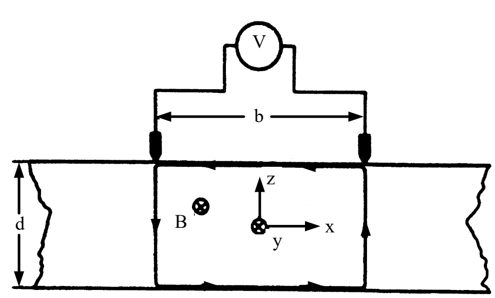

Fig. 7. Principle of measuring one component of **B** using tips.

4. Measuring Apparatus

4.1 Disk and Ring Sample

In earlier measurements, disk samples were commonly used. A typical set up was developed by Brailsford in 1938, as shown in Fig. 8[3]. The rotational hysteresis loss was determined by measuring the torque due to rotational hysteresis, and hence known as torque magnetometer. To eliminate the torque caused by anisotropic effect, a stack of several disks with the easy directions uniformly oriented was adopted, and the sample was rotated both clockwise and anticlockwise. The average torque curve of these two rotating directions would be the torque curve only due to the rotational hysteresis loss. For accurate torque measurement, the friction of the mechanical system should be kept as small as possible.

In 1967, Flanders developed a rotating sample magnetometer [30], which could be used for multiple purposes, such as the measurements of magnetic moment, rotational hysteresis, spin flop, and properties related to anisotropic energy, i.e. anisotropic constants, anisotropic susceptibility, and anisotropic spontaneous magnetization. The measurements were performed on a single-piece rotating sample. Sensing coils were used to detect the magnetization perpendicular to the applied magnetic field. The field metric method type II was used to evaluate the torque due to rotational hysteresis.

To minimize the pickup due to variations in magnetic field or to coil motion relative to magnetic field strength **H**, a set up of two coils connected in series opposition was employed. This method gives better results than the torque magnetometer made by Brailsford, since the effect of mechanical friction has been removed. This magnetometer was further improved by replacing the sensing coils with Hall elements in 1985 [27].

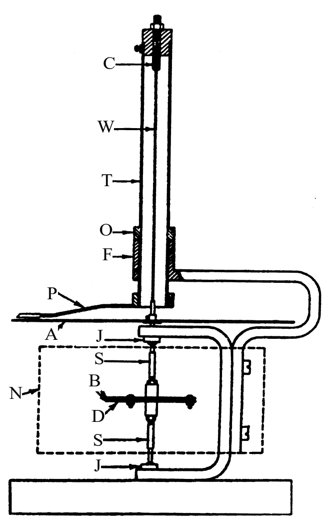

Fig. 8. Torque magnetometer built by Brailsford [3].

The major disadvantages of the disk sample method are: 1) since the magnetic flux density is not controlled by feedback, the flux density fluctuates according to the anisotropic permeability of the sample. This is particularly serious when grain oriented materials are under test; 2) the magnetic field is not uniform within the sample. This will affect the precision of the measurement; 3) disk samples cannot be conveniently used for testing under various flux conditions, such as elliptically rotating magnetic fields. In practice, it is often required to study the core loss under a rotating field of variable magnitude.

4.2 Cross and Strip Samples

On the other hand, the cross samples do not have these problems. In 1973 Moses and Thomas measured the rotating magnetic flux and the rotational core loss in silicon iron laminations with cross samples as shown in Fig. 9 [9]. The 2-D magnetic field was generated by the excitation windings wound on the cross sample. The rotational core loss was measured by the sensing coils wound through very small holes in the center of the cross, while the magnetic field strength was determined from the magnetization current. In this set-up, there was no flux density feedback control. Therefore, in grain oriented samples, the magnitude of flux density was not kept constant.

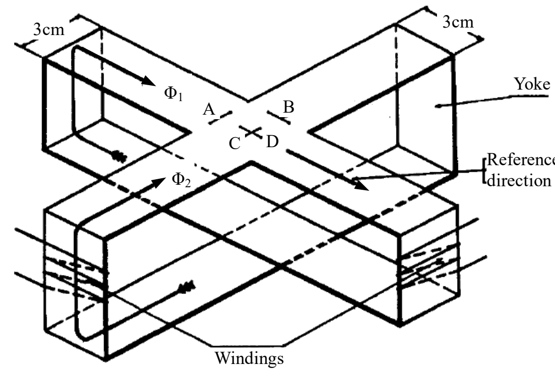

Fig. 9. Cross sample used by Moses and Thomas [9].

In 1978, Basak and Moses [31] studied the sensitivity to mechanical stress of rotational power loss in silicon iron with cross samples and magnetic flux density feedback. In 1982, Brix *et al.*[16] built a fully computerized control and measurement system with cross samples, in which both magnetic field strength **H** and flux density **B** were obtained by the sensing coils, and the power loss was determined by the field-metric method type I.

4.3 Square Sample

In 1984, Brix, Hempel, and Schulte [32] found that the magnetic field was more uniform in a square sample than in a cross sample, and developed a tester using square samples. This kind of tester system is briefly called square sample tester. In this system, **B** tips were exploited for detecting magnetic flux density.

In 1989, Enokizono and Sievert developed a very flexible system consisting of a horizontal magnetic circuit with a square single sheet sample and adjustable air gaps, an analog electronic circuit for flux density feedback control, and a computer which performed function generation and data acquisition in rotational core loss measurement[21],[22],[29],[33]-[35]. The magnetic field strength was picked up by conventional surface **H** sensing coils. For flux density measurement, **B** sensing coils threaded through small holes in the center of square sample were adopted by Enokizono [36], while **B** tips were used by Sievert [37], which is more convenient for batch measurements. This system can be used to examine the behavior of ferromagnetic materials under either rotational or alternating magnetic field. Measurements on rotational core losses of various electrical steels and dynamic magnetostriction under rotational field have been performed with this system.

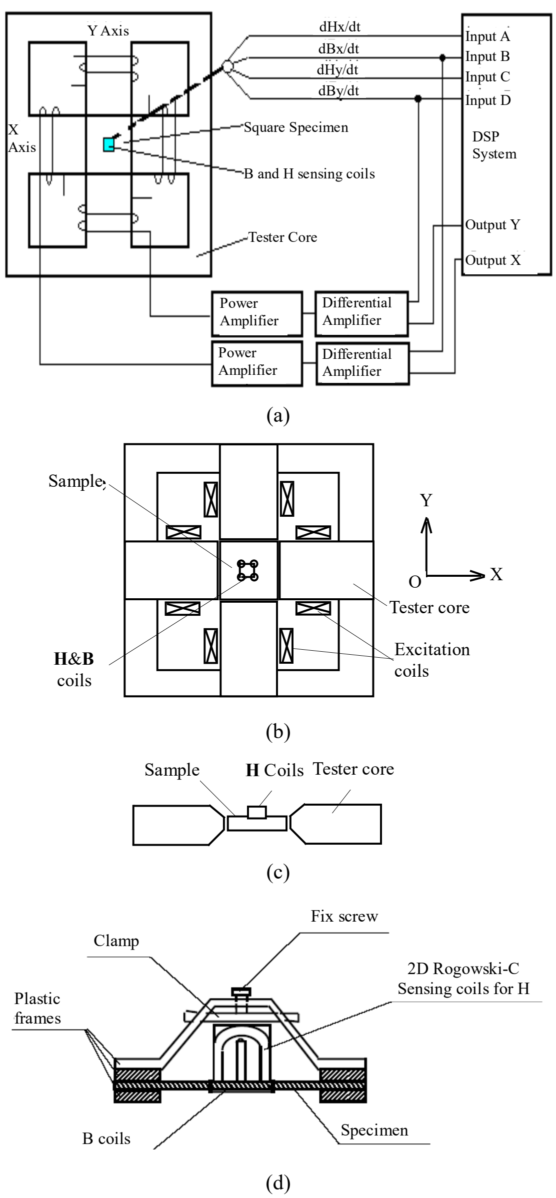

Fig. 10. Schematic illustrations: (a) the block diagram of the rotational core loss testing system at UTS, (b) the square specimen tester, (c) position of the sample between the magnetization poles, and (d) position of sample and Rogowski-Chattock sensing coils[12-13].

In 1992, Zhu developed a system comprising of a horizontal magnetic circuit with a square single sheet sample, feedback control system, and the digital signal processing for the specification of flux density waveforms and the data acquisition at University of Technology, Sydney (UTS)[12]. Fig. 10 illustrates schematically the square sample tester and the whole testing system. By using this tester, the authors of this paper have systematically investigated the alternating and rotational magnetic properties of several magnetic materials, including measurement, modeling and application in analysis of rotating motors[12],[13],[23],[26],[36]-[38].

In conclusion, the computer controlled square sample testing system is more advantageous than other types in the following aspects:

1) Since the magnetic fluxes in the two perpendicular directions are controlled by feedback, the generated magnetic field excitations of various complex magnetic flux patterns can be used to simulate the actual situation happening in electrical machines where the magnetic field is rotating with either constant or varying magnitude.

2) The measurement is carried out in the center of the specimen where the field appears to be most uniform, which leads to more accurate results.

3) More information can be obtained from the measured **B** and **H** waveforms which help in understanding the mechanisms of rotational core losses.

4) Preparation of the specimen is much simpler.

5) This system can be conveniently incorporated into a system for domain structure observation, which is very important for understanding the mechanisms of rotational core losses.

The major drawback of this system is that it is difficult to control the flux density waveforms on the *X* and *Y* axes to be sinusoidal when the sample is close to saturation.

5. Conclusions

In this paper, several methods and development on the measurement of rotational core loss, including various rotational core loss testers, measuring techniques of magnetic field strength and flux density, and evaluation of rotational core loss are reviewed.

It has been shown that the computer controlled square sample testing system seems the most advantageous in all aspects among the rotational core loss measuring systems. In addition, the field-metric method has higher accuracy, contains more information, and gives greater versatility than the other methods for rotational core loss evaluation. However, the problem of controlling the flux density waveforms on the *X* and *Y* axes as sinusoidal, when the specimen is close to saturation has not been solved yet.

In general, although quite a few measurements on rotational core loss have been carried out on various soft magnetic materials, the mechanisms of rotational core loss are still far from being fully understood. In order to obtain more information, the measuring approach needs to be improved, with considerable further experimentation also needing to be done.

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