An Improved Method for Measuring the Magnetic Properties of Silicon Steel With Double Sheets at High Frequency

Ruiying Chen[1,2], Changgeng Zhang[1,2], Yongjian Li[1,2], Qingxin Yang[1,2,3], and Lixiang Wang[4]

[1]State Key Laboratory of EERI, School of Electrical Engineering, Hebei University of Technology, Tianjin 300130, China
[2]Hebei Province Key Laboratory of EFEAR, Hebei University of Technology, Tianjin 300130, China
[3]Tianjin Key Laboratory of AEEET, Tianjin Polytechnic University, Tianjin 300387, China
[4]Tianjin Aviation Electromechanical Company Ltd., Tianjin 300308, China

Single sheet tester (SST) is a traditional method for measuring magnetic properties of silicon steel. In order to make the measurement more accurate, this paper presents an improved SST with double yokes and double sheets. The electromagnetic simulation demonstrates that the magnetic field strength H between the two sheets that are in symmetric magnetic path approximately equal to H of two sheets, proving that the improved SST has higher test accuracy than the traditional double-yoked SST. A novel control method is proposed for the measurement system to make sure the symmetry of magnetic path. In this experiment, the magnetic field strength H and the magnetic flux density B of the tested samples are measured by an induction coil method, and the maximum working frequency of this apparatus can be up to 20 kHz.

***Index Terms*— H-coil sensor, magnetic properties measurement, silicon steel, single sheet tester (SST).**

I. Introduction

A SINGLE-YOKED single sheet tester (SST) with the asymmetrical structure of magnetic path had been developed for measuring the magnetic properties of silicon steel sheet, avoiding the disadvantage of Epstein tester that the length of an effective magnetic path is difficult to determine when Ampere's law is adopted. However, the asymmetry of the magnetic path will increase the leakage magnetic flux and cause the test error [1]. In order to improve measurement precision, the traditional SST formed the magnetic path with double yokes and a single sheet but the leakage magnetic interference still exists, and the contact surface between the yoke and the test sample must be carefully treated [2]–[4]. Then, a magnetic shield was used to reduce the leakage magnetic interference, while the result shows that the use of a shield is not necessary for local measurement and that it can lead to issues regarding the sensor signal treatment [5].

There are two methods of double-yoked SST to test the magnetic field strength H. One is the H-coil method that requires integration of the induced voltage signal to calculate H, compared to the other, magnetizing current method, has better noise suppression ability [6]. However, due to the distance between the H-coil and sample, the test error of H cannot be ignored. A practical way to overcome this shortcoming is the double H-coils method which approximates the magnetic field strength inside the sample with linearly interpolating between the two H-coils. This can effectively reduce the test error caused by the actual position of H-coils. While this method increases the difficulty in assembling two H-coils, the distance between each H-coil and sample is hard to determine because the thickness of H-coil can be long as the distance [7].

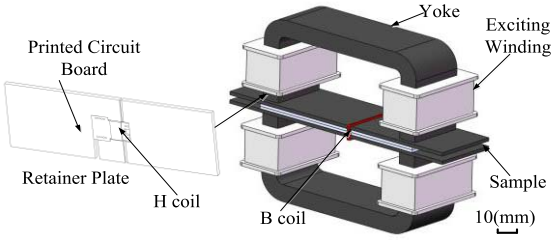


Fig. 1. Model of double-yoked and double sheets tester.

This paper presents an improved SST with double yokes and double sheets. First, the structure of the experimental apparatus is described. Then, the improved double-yoked SST is compared with traditional double-yoked SST through electromagnetic simulations, and the structure and location of the induction coils are also determined by the electromagnetic simulation results. Finally, the feasibility and accuracy of the apparatus are verified by experimental results.

II. Structure of Sample and Apparatus

A. Structure of Sample and Measuring Coil

In each experiment of this apparatus, two identical samples (silicon steel sheets) from one production batch are used at the same time to ensure that the magnetic path is symmetric, as well as the yokes and the exciting windings. The tested samples are much thinner than the yokes, so the improved double-yoked SST has a good magnetism-collected structure and the samples are easy to reach saturation. As shown in Fig. 1, H and B of the samples are measured by the induction coil method. H-coil is placed in a small retainer plate installed between the double silicon steel sheets, and it is parallel to the surface of the double sheets. Two B-coils are wound on the surface of each sample, respectively, and

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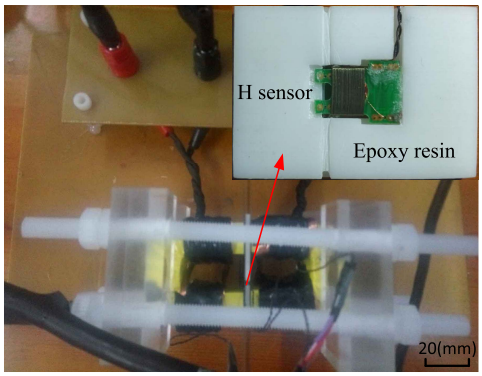


Fig. 2. Physical structure of double-yoked and double sheets tester.

the location of B-coils is also fixed by the retainer plate. Both H-coil and B-coils are located at the middle region of samples.

B. Structure of Measurement Apparatus

The measurement apparatus consists of two identical C-type nanocrystalline cores as yokes, two silicon steel sheets with the same size, material, and cutting direction as tested samples, and pairs of exciting windings which have the same turns wound on each yoke. They are assembled symmetrically, and the structure of the whole apparatus is completely symmetrical in the ideal case. What's more, if the apparatus is not absolutely symmetrical, a solution is proposed in Section III to guarantee the measurement accuracy.

As shown in Fig. 2, the support of the yokes is made of acrylic glass, and its four bolts can fasten the yokes to ensure the yoke is in good contact with the silicon steel sheet. The material of the patch board and the plane, where the apparatus placed is epoxy resin, has excellent insulating property. The retainer plate between two sheets is manufactured by the 3-D printer, the upper and lower surfaces of that are parallel to each other, ensuring that the H-coil between double sheets will not make double sheets deformed. Two B-coils are wound on the surface of each sheet, respectively, and the location of B-coils is fixed by the retainer plate's vertical grooves, which also prevents the deformation of the sheet caused by the winding of the B-coil. This apparatus does not include other ferromagnetic components except the main excitation magnetic circuit avoiding magnetic field interference.

III. Electromagnetic Simulation and Analysis

In order to prove the superiority of the improved double-yoked SST, the traditional double-yoked SST and the improved double-yoked SST are compared quantitatively by electromagnetic simulation using ANSYS electromagnetic. In their electromagnetic simulation models, yokes of them are identical, so as samples. Their exciting windings have the same turns and magnetizing current. Moreover, the model that two sides' exciting windings are asymmetrical is also simulated as a supplement to what may occur in practice. To observe the distribution of H and B obviously, every model has a test line defined non-model perpendicularly passes through the surface of the sample, as shown in Fig. 3.

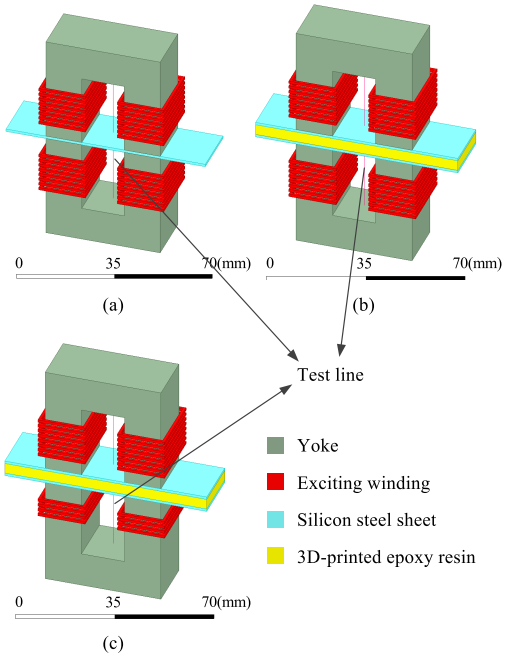


Fig. 3. Electromagnetic simulation model. (a) Traditional double-yoked SST. (b) Improved double-yoked SST with symmetrical windings. (c) Improved double-yoked SST with asymmetrical windings.

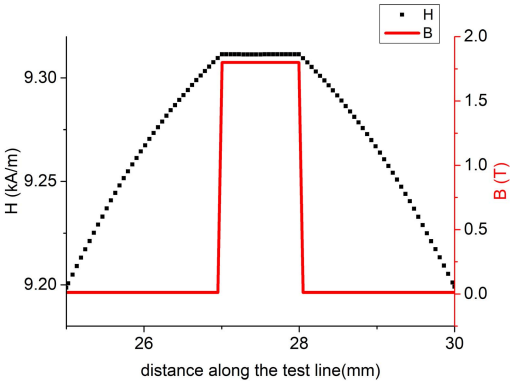


Fig. 4. Electromagnetic simulation of traditional double-yoked SST.

A. Traditional Double-Yoked SST

In Fig. 4, the region between 27 and 28 mm is the sample. It shows that from the surface of the sample to the outside of the sample, the magnitude of H drops fast because of the impact of leakage flux. Even if the distance between the H-coil and the tested sample is only 1 mm, the test error is up to 0.47%. In addition, the thickness of the H-coil is around 1 mm which further increases the test error up to 1%, making SST not accurate enough. In fact, due to the influence of sample size and leakage flux caused by the air gap between sample and yoke, both a growth trend and a reduced trend of the H outward the surface of the sample are possible.

B. Improved Double-Yoked SST With Symmetrical Windings

In Fig. 5(a), 27–28 and 32–33 mm are the regions of two samples, it shows two samples have the same H and B in this situation, and H between the two samples has approximately uniform distribution, if the distance between H-coil which is located in the middle region of two samples and one of

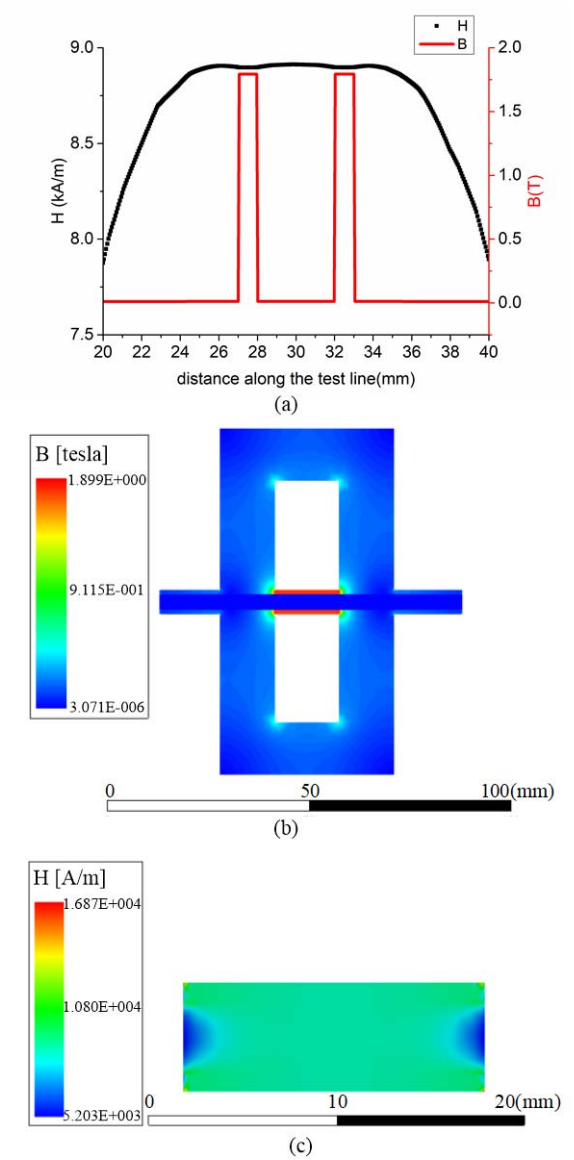


Fig. 5. Electromagnetic simulation of improved double-yoked SST with symmetrical windings. (a) B and H along the test line. (b) Distribution of B on the cross section of improved double-yoked SST. (c) Distribution of H on the cross section of the region between samples and region of samples.

the tested sample is 1 mm, the test error is 0.14%, which demonstrates the test error is greatly decreased when compared with the test error of traditional double-yoked SST, 0.47%.

C. Double-Yoked SST With Asymmetrical Windings

In the process of machining and assembling the apparatus, the windings of two sides may be asymmetrical. Moreover, there are two tiny air gaps between the silicon steel sheet and the yoke. The slightly random differences between these air gaps would cause asymmetry of the magnetic path. Fig. 6 shows that H between two samples changes with distance linearly and rapidly. The two silicon steel sheets have a different magnetic flux density B inside them. As a result, the measurement of H between the two sheets makes no sense, which makes the improved double-yoked SST inaccurate. Hence, a novel control method is proposed to solve this problem.

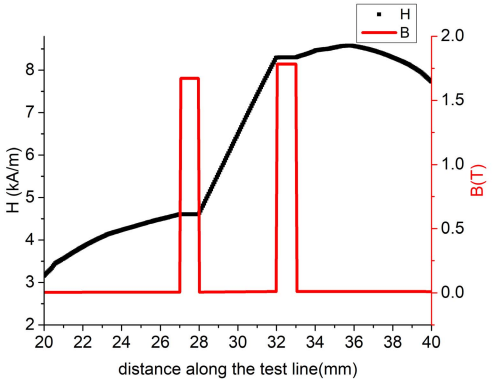


Fig. 6. Electromagnetic simulation of improved double-yoked SST with asymmetrical windings.

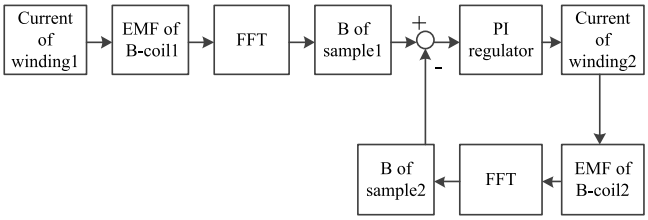


Fig. 7. Block diagram of the control systems.

D. Novel Algorithm to Eliminate the Effect of Asymmetrical Windings

The PI regulator is introduced in the design of the control system to overcome the problem caused by asymmetry in measurement. For the reason that in this situation, two samples have different B, two B-coils are necessary to determine whether the magnetic path is symmetrical or not.

The process of eliminating asymmetry is shown in Fig. 7. On one side of the apparatus, we name B-coil, sample, and winding as B-coil 1, sample 1, and winding 1, on the other side, as B-coil 2, sample 2, and winding 2. First, a current of winding 1 is set as a constant. Second, fast Fourier transform is applied to the electromotive force signals detected by two B-coils, respectively, to acquire B of sample 1, B_1, and B of sample 2, B_2. Finally, the difference between B_1 and B_2 is calculated to regulate the output current of winding 2 by PI regulator. By the regulation of this control system, the same B inside the two samples can be guaranteed at last, so the asymmetry problem of this apparatus is eliminated.

The harmonic content of B may affect the test accuracy of this apparatus, which can be diminished by the feedback method in the frequency domain [8]. Consequently, the improved double-yoked SST is more accurate than the traditional double-yoked SST. The use of double sheets not only makes H of the tested region more uniform but also prevents the impact of a stray magnetic field to a large extent.

IV. Experimental Results

After the testing apparatus is built up, the experimental process is described as following.

The excitation signal is generated and regulated by the industrial personal computer (IPC) and amplified by the power amplifier to drive the exciting windings. The impedance matching capacitor box is used to resonate with the excitation

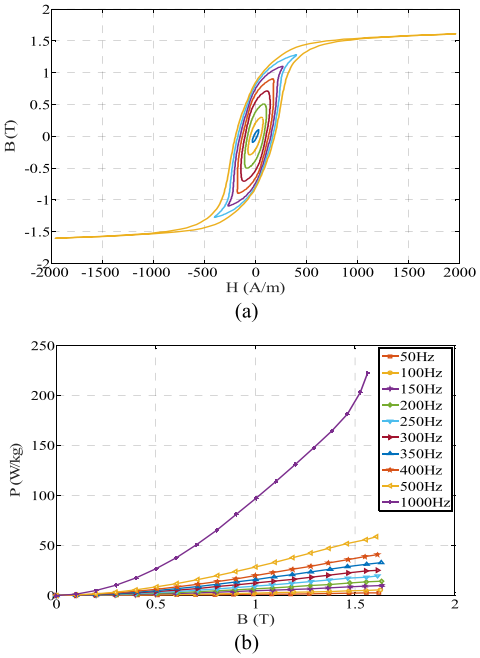


Fig. 8. Magnetic properties of B35A210. (a) B–H hysteresis loops of B35A210 at 500 Hz. (b) Core loss of B35A210 at different frequencies.

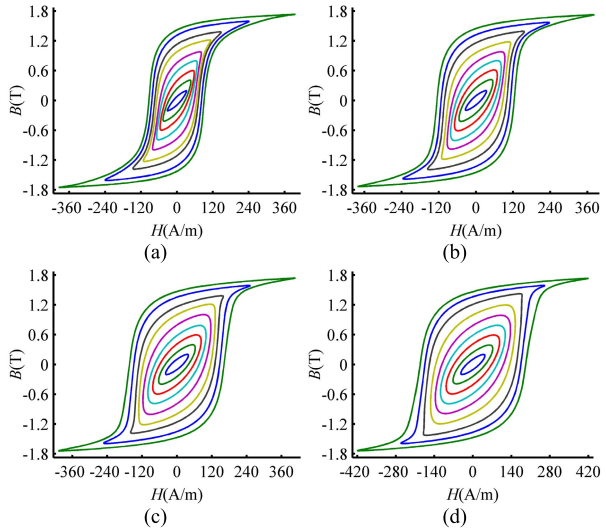


Fig. 9. Magnetic properties of ultra-thin silicon steel at different frequencies. (a) 2, (b) 5, (c) 10, and (d) 15 kHz.

inductance, so the magnetizing current can be increased to an extent that can guarantee the full magnetization of the samples. B-coils and H-coil are used to detect induction signals to acquire B and H, and the coefficient of H-coil is 1.305511×10^{-3} m^2 calibrated by the solenoid method. These signals are amplified by the differential amplifier circuit and then acquired by the National Instrument Pxie-6368 multifunctional card. Finally, the data are processed and stored by the IPC.

The magnetic properties of B35A210 at different frequencies are measured to verify the feasibility and accuracy of the apparatus. Fig. 8 illustrates the magnetic hysteresis loops measured by the improved double-yoked SST. The iron loss of B35A210 at 50 Hz is 2.19 W/kg with B reaching 1.5 T, which is close to the value, 2.10 W/kg, provided by the manufacturer's manuals. The difference between them is less than 4.5%, which demonstrates the feasibility and accuracy of the apparatus.

Fig. 9 shows that ultra-thin silicon steel sheets with the thickness of 0.05 mm are measured by the improved measurement system at high frequency. The maximum working frequency of this measurement system can be up to 20 kHz.

V. Conclusion

An improved double-yoked SST with double sheets and double yokes is presented to measure the magnetic properties of silicon steel sheets more accurately. Based on the electromagnetic simulation, it is demonstrated here that the improved double-yoked SST has higher test accuracy than the traditional double-yoked SST, and it can reduce the impacts of leakage magnetic flux and the stray magnetic field. Moreover, the homogeneous magnetic field between the two silicon steel sheets can be guaranteed by the proposed control method, making the measurement of H easily and accurately. In addition, the high precision of experiment can be reached with the help of the robust control algorithm with the simple structure at high frequency, which is validated by the experiment.

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