Influence of Shielding on the Magnetic Field Measurement by Direct H-Coil Method in a Double-Yoked SST

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This paper aims at describing the influence of shielding on the magnetizing magnetic field measured with a Hcoil system, used in a double-yoked Single Sheet Tester (SST). By the mean of a positioning system especially conceived for the purpose of the present study, the magnetic field is measured at different distances from the laminated sheet. The evolution of this field along the perpendicular line thus defined shows a distinctive behaviour, whether the measure is realized in the presence of a magnetic shield or not. A description of the obtained experimental results is made, and a comparison with numerical models realized. Finally, an explanation over the observed phenomena based on physical principles of electromagnetism is proposed.

***Index Terms*—Magnetic field measurement, H-coil sensor, Single Sheet Tester, Magnetic field shielding.**

I. Introduction

THE direct measurement of magnetic field, which is realized through the use of a flat air-cored induction coil commonly known as H-coil, is here investigated while applied to a dedicated Single Sheet Tester (SST). It has been a theme of numerous studies [1]-[2], and this methodology already proved to lead toward a better approximation of the actual magnetic field passing within the tested material, in comparison with the indirect method (calculation from magnetization current). However, there are some precautions to take regarding such method.

In particular, it is shown in [2] that the distance between the H-coil and the tested sample influences the output results in the case of a single-yoked SST: the intensity of the field decreases linearly up to 10% at a distance of 10 mm. However, the results are not very conclusive in the case of a double-yoked SST. Thus, a new experiment is here proposed in order to evaluate the influence of distance on the measurement of the magnetic field in a double-yoked SST configuration, with and without the presence of a magnetic shield.

The test bench developed for the experiment respects the international standards for magnetic characterization of thin laminated sheets [3]. In addition, a lifting system, conceived and build for the purpose of the study, allows the positioning of the H-coil along a straight line above the specimen. The experiment is performed on a non-oriented silicon-iron material, at two induction levels and two frequencies, and the experimental results compared to numerical models.

II. Experimental device

A. H-coil and dedicated instrumentation

The physic principle on which the direct measurement method lays on is the conservation of the tangential component of the magnetic field. Thus, the H-coil presents a response to a varying external magnetic field $H(t)$ given by (1), where $v(t)$ is the induced voltage between the terminals of the sensor, S_H its mean section and N_H its number of turns.

$$v(t) = -N_H \mu_0 S_H \frac{\mathrm{d}H(t)}{\mathrm{d}t} \tag{1}$$

The signal of the sensor go through a low-pass analogical filter in order to limit the noise ratio, and is then amplified. This part is complex and highly important since the signal amplitude does not exceed the order of tens of millivolts. The amplification stage is realized using an instrumentation amplifier, thus allowing high-gains as well as a high common-mode noise-rejection. The obtained analogical signal is collected with an oscilloscope, and is then processed (integrated) altogether with the signal from secondary coil in an Virtual Instrument (VI) developed in a LabView environment.

B. Double-yoked SST

The SST used in this work consists in a magnetic circuit, an excitation workbench and a lifting apparatus for H-coil positioning. As mentioned earlier, the SST-type magnetic circuit developed follows all international recommendations. The excitation is realized through a dedicated workbench developed in [4] allowing a close control of the induced voltage of the secondary coil. It is composed of a single-phase voltage inverter coupled with a slide-mode non-linear control loop, which guarantees that the induced voltage waveform follows the reference signal chosen by the user. This is fixed as sinusoidal, since it is commonly accepted that in order to properly characterize and separate the losses, induction temporal derivate in the material must be sinusoidal.

Finally, a dedicated lifting system is implemented in order to easily modify the distance between the H-coil and the sample, without having to stop the experiment and unmount the bench, as shown in Fig. 1. This is a key point as it allowed lowering the variability on excitation conditions and positioning of the whole system.

C. Materials

The specimens tested are composed of three laminated sheet commonly used in the so-called *Epstein frame* of E230-BR non-oriented silicon-iron. The shielding is realized by placing a thin sheet (≈0,02mm) of amorphous-ferrous steel upon the lifting system. This material is interesting for such purpose since it presents extremely high permeability (μ_r ≈100000),

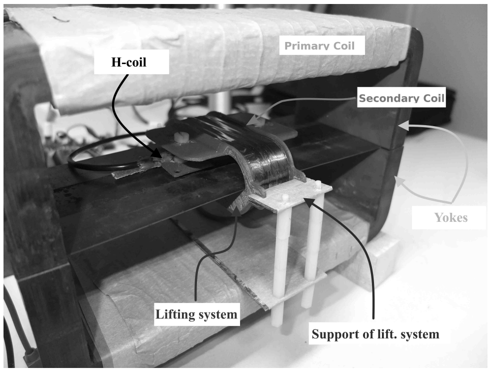

Fig. 1. Magnetic circuit, coils and lifting system

low conductivity and losses. Furthermore, the materials shows a saturation level of $J_S \approx$1,6T. It can be roughly calculated that its saturation should only appear for levels of leakage flux higher than 15A.m^{-1}, which should not be reached within the scope of this study.

III. Results

Experimental results show that in the absence of magnetic shield (W/O), a slight increase of the field measured by the H-coil occurs while incrementing distance between the sensor and the sample, as can be observed on Fig. 2. It is reasonable to estimate that this increase is due to the intensity of leakage flux, higher close to the primary coils, which overcompensate the decreasing of tangential component of the field passing by the tested sheet.

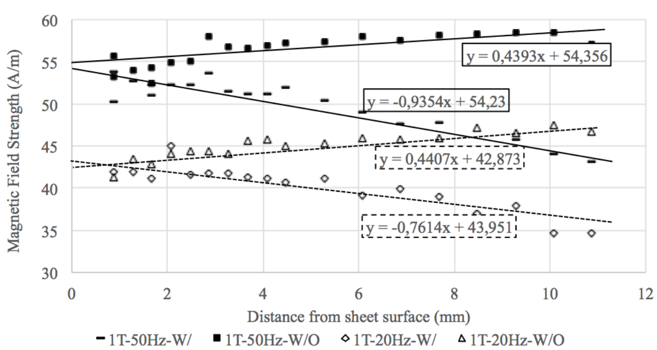

Fig. 2. Magnetic field evolution with H-coil position at 1T & Trend-lines

On the contrary, and as observed by previous authors [2], a decrease which presents a rate twice as high appears when the test is realized in presence of the magnetic shield. In that case, it can be assumed that the shield trapped the leakage flux, thus avoiding the disturbance in the tangential field measurement by the H-coil.

Numerical simulations were realized in order to verify the good run of the experiment and to give additional insights regarding some peculiar phenomena observed in the experimental data. Magnetodynamical version of the EFCAD software [5] was used to perform the calculation, and if the results for an induction of 1T are conclusive and in good agreement with the experimental ones, a great discrepancy is observed for cases at 1,4T. Numerically, a field twice as higher seems to be required to reach this induction level, in comparison with the measured magnetic field.

The concept of *magnetic background* can help giving a potential explanation to the observed differences. Bad demagnetizing procedure can lead to a non-perfect non-oriented material, which means that the specimen can present a certain *magnetic texture*. This texture could then favor the magnetization process, implying that high induction values are reached with a lower magnetic field. As the simulations realized present a low complexity, it is impossible to reproduce such effect numerically, as well as other more complex material characteristics susceptible to produce the bias.

IV. Analysis of initial results

From this initial study, it can be say that the use of a shield should not be automatic. Indeed, depending on the case, it can be interesting to operate without shield in order to maximize the sensitivity of H-coils, since it would not alter the *local* results: various H-coil can be used, and a linear extrapolation realized to obtain the exact magnetic field applied on the sample.

V. Further developments

Analyzing the results, it seems reasonable to think that the shield could be submitted to sufficiently high levels of leakage magnetic flux, and thus present a certain degree of saturation. This aspect should be studied in the near future in order to refine the conclusions drawn within the present article and enhanced the physical meaning of the numerical simulation realized. The *magnetic background* hypothesis will be studied too, and both numerical and experimental results refined. Furthermore, another implementation of the magnetodynamical model will be realized, with an handmade implementation in the open-source FEM tool FreeFem++ [6], in order to produce results with a complex material behavior, and then higher representativity and precision.

References

[1] T. Nakata, Y. Ishihara, M. Nakaji and T. Todaka, “Comparison between the H-coil method and the magnetizing current method for the single sheet tester,” *J. Magn. Magn. Mater.*, vol. 215, 2000, pp. 607-610.

[2] S. Tumanski, “A multi-coil sensor for tangential magnetic field investigations,” *J. Magn. Magn. Mater.*, vol. 242-245, 2002, pp. 1153-1156.

[3] ASTM/International, “A804/A804M-04: Standard test methods for alternation-current magnetic properties of materials at power frequencies using sheet-type test specimen,” 2015.

[4] N. J. Batistela, “Caracterização e modelagem eletromagnética de lâminas de aço silício,” *Ph.D. Thesis*, Universidade Federal de Santa Catarina, 2001, Brazil.

[5] J. P. A. Bastos and N. Sadowski, “Electromagnetic Modeling by Finite Element Methods,” Marcel Dekker, New York, 2003.

[6] F. Hecht, “New development in FreeFem++,” *J. Numer. Math.*, vol. 20, no. 3-4, 2012, pp. 251-265.