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A simple compensation method for the accurate measurement of magnetic losses with a single strip tester

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We present a new method for the accurate characterization of soft magnetic sheets using a permeameter based on the precise compensation of the magnetomotive force (MMF) drop in the flux-closing yoke. It has been developed in order to overcome the systematic uncertainty affecting the value of the magnetic fieldstrength in single sheet testers when obtained, according to the standards, through the measurement of the magnetizing current. This phenomenon is more critical for high permeability materials, because of the reduced MMF drop across the sample. While additional sensors and auxiliary windings have been proposed in the literature, a novel approach is demonstrated here, based on the use of the permeameter upper half yoke as the MMF drop sensor and of an auxiliary winding on the lower half yoke, implementing compensation. This solution, dispensing one from dealing with the usually small signal levels of the conventional MMF drop sensors (e.g. Chattock coils), provides best results with the introduction of wedge-shaped magnetic poles, in order to accurately define the magnetic path length. The method is validated by measurements of power loss, apparent power, and hysteresis cycles on non-oriented and grain-oriented Fe-Si steel sheets, which are compared with local measurements performed on the same samples using *H*-coil and *B*-coil across a uniformly magnetized region.

***Index Terms*—Magnetic loss, hysteresis cycle, compensated permeameter, apparent power.**

I. INTRODUCTION

THE PROPER design of electrical machines and electromagnetic devices requires an accurate prediction of iron loss. Indeed, in modern embedded applications such as hybrid or electric vehicles [1][2], the best compromise must be found between the machine efficiency [3][4] and torque density [5]. But any predictive model starts from a proper material characterization [6][7]. The standard testing technique of soft magnetic steel sheets is based on the use of the Epstein test frame [8]. It shows good reproducibility, as demonstrated by inter-laboratory comparisons of power loss and apparent power measurements [9]. However, this method, besides requiring tedious preparation of the samples, is inevitably affected by appreciable systematic deviations (up to about 10 % at high inductions) from the true values of the measured quantities, as obtained, for example, by accurate measurements using *H*-coils [9][10][11]. But the *H*-coil method requires the integration of low-level signals and is hardly acceptable in the industrial practice. Increasing interest is therefore attached, at present time, to the Single Sheet Testing (SST) method, applied according to the pertaining IEC Standard [12][13], because of the convenient use of wide lamination samples. The STT method does not require stress relief of samples upon cutting, can be directly applied to the domain-refined high-grade grain-oriented materials, and shows good reproducibility of measurements [9] [14]. Consequently, there is demand by industry for including SST reference values in the material specification standards. With the SST arrangement, where the sheet sample is inserted in a double-C laminated yoke, the magnetic fieldstrength is calculated using the measured magnetizing current and a defined magnetic path length ($l_m = 0.45$ m) is adopted. A main problem here is that the magnetomotive force (MMF) drop in the flux-closing yokes may not be negligible with respect to the one across the sample, especially with high-permeability materials. This can lead to overestimated magnetic field values. At the same time, the yoke itself can provide a certain contribution to the measured loss, depending on its manufacture and the possible existence of interlaminar eddy currents at the pole faces [15].

One way to overcome this difficulty is, as discussed in [16], one of compensating the drop of the MMF in the yokes of the permeameter by an auxiliary magnetizing winding. This is driven by a Chattock coil, placed over the measuring sample region of length l_m and a very high-gain amplifier, implementing a feedback control on the auxiliary current, such as to compensate the MMF drop outside the length l_m [16]. Like all the *H*-coil measurements, this method has a weak point in the necessity of handling small signal levels.

In this paper, we consider a single strip double-C yoke permeameter, applied to annealed Epstein samples, where a new compensation method, simpler and more effective than previous literature solutions [16], is implemented. Epstein strip samples are used in the present experiments for practical convenience, but the method could be easily adapted to standard SST permeameters. The idea is one of using the upper half of the yoke as a zero MMF indicator and the lower half for accommodating the compensation circuit. It is a simple measuring arrangement, where the signal to be controlled is relatively large and much easier to handle than the weak and noise-prone signal generated by a Chattock coil. As a further advantage, there is no geometrical discontinuity in the magnetizing winding, as required instead, with ensuing inhomogeneity of the applied field, by the insertion of the Chattock coil [16]. The method is validated by comparison with accurate measurements performed upon a relatively restricted median region of the strip sample by the *H*-coil method. Non-oriented (NO) and high-permeability grain-oriented (GO) Fe-Si samples have been tested, with very good agreement between the results obtained with the magnetizing current and those obtained by localized H and B coils.

II. THE COMPENSATED PERMEAMETER

In this section we describe the geometry of the system and the circuit for the compensation of the MMF drop.

A. System geometry and magnetic path length

The sample is a conventional annealed Epstein strip. The induction derivative is measured by means of a 500-turn 30 mm long pickup coil placed at the center of the strip. Inside the B-coil, a many-turn calibrated flat H-coil (1 mm thick, turn-area $2.25 \cdot 10^{-2}$ m^2) of same length is placed upon the sample surface (see Fig. 1). The H-coil provides, after integration of the measured voltage, the tangential field upon the measuring area. Since in the measuring region the applied field and the induction are verified to be highly uniform, tangential field and internal field are bound to coincide. The measured local loss is thus identified with the true loss figure of the material, that is, the reference quantity for the results obtained with the compensated permeameter.

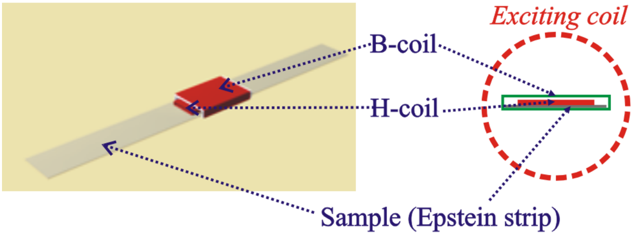


Fig. 1 - Sample (Epstein strip), with enwrapping B-coil and tangential H- coil (3D view and front view).

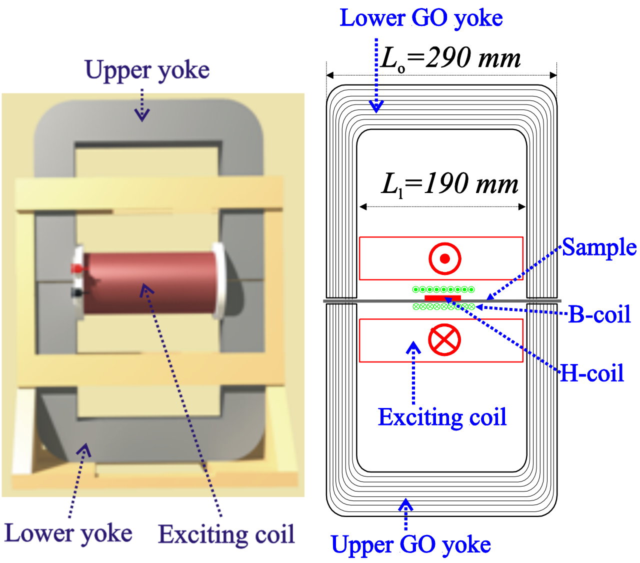


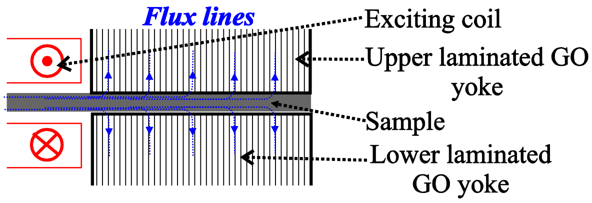
Fig. 2 - a) 3D view of the permeameter. b) 2D view of magnetizer, exciting circuit, and measuring coils.

The developed permeameter, shown in Fig. 2, consists of a double-C laminated yoke of 50 mm × 50 mm cross-sectional area, made of 0.30 mm thick high-permeability GO strips. A uniformly wound magnetizing solenoid covers the distance L_i = 190 mm between the pole faces of the yoke. It is endowed with series connected additional narrow windings at its ends by which maximum uniformity of the applied field across the whole distance L_i is obtained ([11], p. 109).

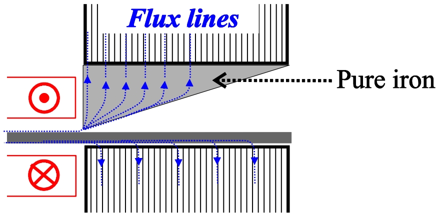
According to Ampère's law, the magnetomotive force NI generated by a current I flowing into the N-turn solenoid is related to the magnetic field H along a closed path L by the equation

$$N \cdot I = \oint_L H \cdot \mathrm{d}l \,. \tag{1}$$

If a method is found by which the drop of the MMF in the flux-closing yoke is made either negligible or fully compensated, (1) simply becomes $N{\cdot}I = H{\cdot}L_s$, where L_s is the length of the mean magnetic flux path in the sample. L_s has value intermediate between L_i, the distance between the pole faces, and L_o, the width of the permeameter (Fig. 2b), as the obvious result of flux channeling from the sample into the yokes (see Fig. 3a). It is actually not well defined and it depends on the magnetization level in the sheet sample. It will appreciably change on approaching the material saturation.



(a) Standard configuration.



(b) Modified configuration.

Fig. 3 - Defining the magnetic flux path length in the sample.

We wish to impose a flux path such that the length L_s coincides with the distance between the pole faces L_i. To this end, the following modification of the upper yoke is proposed. Two identical wedge-shaped pure iron poles are placed beneath the two limbs of the upper yoke, as shown in Fig. 3b and Fig. 5, with the contact lines between the sheet surface and the poles placed exactly at the distance L_i. As discussed in the following Section, this is expected to force, under the action of a feedback system employing auxiliary windings on the yokes, the flux path length in the sample to be equal to L_i. Under these conditions, the magnetic field H in the sample will be obtained according to the relation

$$N \cdot I = H \cdot L_i \,. \tag{2}$$

independent of the way the flux lines enter the lower yoke.

B. The principle of MMF compensation.

The idea here developed follows to some extent the method using a Chattock coil sensor to cancel the MMF on a known length, as described in [16]. *Here we take the yoke itself as a zero MMF indicator.* A few-turn secondary coil wound around the upper yoke provides the derivative of the magnetic flux Φ_1 flowing in it. According to the simplified reluctance description of the system shown in Fig. 4, where the reluctance of the sample is R_S, the reluctance of the upper and lower yokes is R_Y, and that of the wedge-shaped pole is R_P, the MMF drop E pertaining to the magnetic circuit outside the sample is proportional to the flux Φ_1. Since there is no MMF source in the upper yoke, E will be reduced to zero by canceling the flux Φ_1, that is, bringing to zero the voltage correspondingly induced in the secondary coil. This can be accomplished by adding a compensation winding on the lower yoke and controlling it in such a way that the correspondingly generated MMF N_cI_c leads to the condition $E = 0$. The control loop is schematically shown in Fig. 5. An analog control card (PID controller) keeps the voltage $v_1 \propto d\Phi_1/dt$ equal to zero, by properly supplying, via a high-gain linear amplifier, the compensation winding on the lower yoke. Consequently, all the flux Φ_s in the sample is made to entirely flow in the lower yoke.

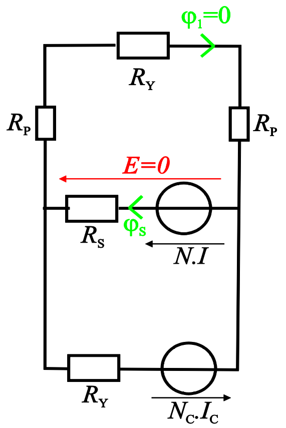


Fig. 4. Reluctance network of the compensated permeameter.

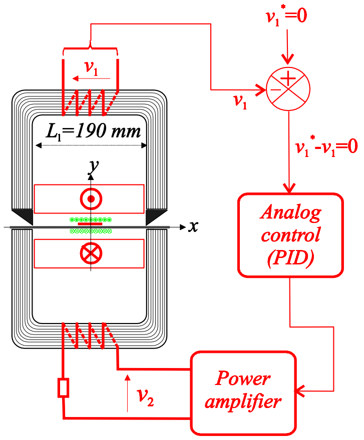


Fig. 5. Compensated permeameter and control circuit.

This compensation method is simple and sensitive, since it does not require any specific MMF sensor and a high signal-to-noise ratio is ensured by the high permeability of the GO laminations employed in the yokes. The voltage v_1 is, for example, always much larger than the one achievable by a Chattock coil, and its control around the zero value is correspondingly easier and more precise. To be remarked that imperfect contact between the wedge shaped poles and the sample, which can be lumped in the pole reluctance R_P, has little detrimental effect on the permeameter performance, because the flux in the upper yoke is made to vanish.

III. Experimental Results

The novel compensated permeameter has been tested on nonoriented Fe-(3 wt%)Si sheets (thickness 0.35 mm) and high-permeability (HiB) grain-oriented sheets (thickness 0.28 mm). Energy loss, apparent power, and hysteresis loops were measured under sinusoidal induction waveform at $f = 100$ Hz and peak polarization values $0.2 \text{ T} \leq J_p \leq 1.5$ T. The value of the magnetic field H was obtained both by measuring the magnetizing current and by integrating the signal induced in the H-coil placed at the center of the Epstein strip.

A. Non-oriented Fe-Si sheets

Fig. 6 shows the measured energy loss vs. peak polarization obtained through the H-coil and current methods.

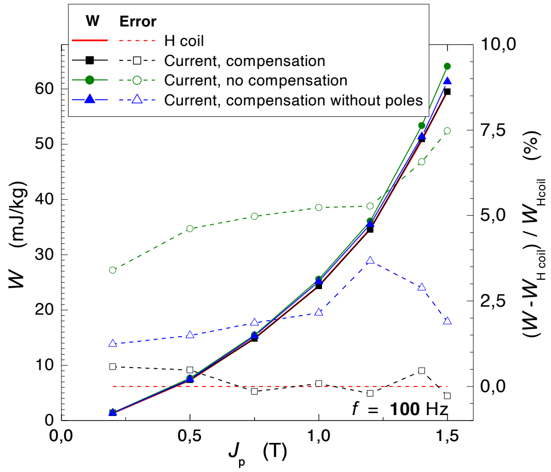


Fig. 6. NO Fe-Si sheets. Comparison of the energy loss measured by the H-coil method and the current measurement method. The permeameter can be compensated as described above, non-compensated (the compensation circuit is not switched on), or compensated without the iron poles. The dashed lines provide the deviations of the loss figures measured with the current method with respect to the H-coil method.

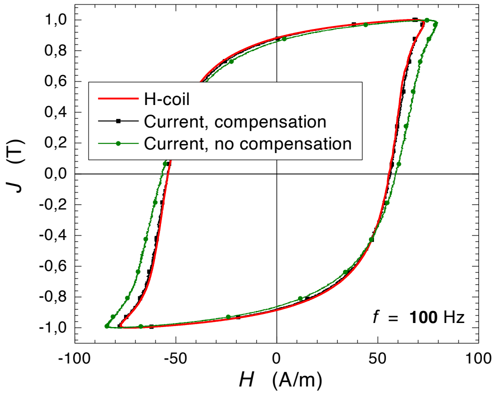


Fig. 7. NO Fe-Si sheets. $J_p = 1$ T. Comparison of the hysteresis loops measured by the H-coil method and by the current measurement method, with and without compensation.

It appears that the results by the H-coil method and the current method with compensation and wedge-shaped iron poles on the upper yoke show remarkable agreement. On the other hand, because of the additional loss contribution by the yokes, overestimated figures are obtained by use of the uncompensated permeameter, the higher J_p the higher the loss deviation (up to about 7 %). If the compensation procedure is applied to the standard permeameter configuration without wedge-shaped poles, the loss value is still overestimated (from 2% to 4%), because the magnetic path cannot be fully constrained to the sample length L_i and is slightly longer. The good agreement between the *H*-coil and the compensated current methods is confirmed by the correspondingly measured hysteresis loops shown in Fig. 7.

B. HiB grain-oriented sheets

Measurements of high permeability GO materials are demanding, because the MMF drop in the yokes may be far from negligible with respect to the one in the sample. At the same time, the localized measurements using the *H*-coil are difficult, especially at low frequencies, because the signal can be very small. This adds to the interest for the here proposed solution, which includes also the measurement of the apparent power. Fig. 8 compares the energy loss values obtained with the *H*-coil method and the magnetizing current method, with and without compensation, in the GO sheet. It is apparent that the compensated permeameter and the *H*-coil measurements provide close results. Under uncompensated conditions, one finds instead that the current method overestimates the magnetic loss by a substantial extent, especially at low inductions (about 10% for $J_p = 0.5$ T, 6% for $J_p = 1.5$ T). This is expected, because the loss in the yoke depends only on J_p, not on the type of material under test, and its ratio to the sample loss increases with better materials

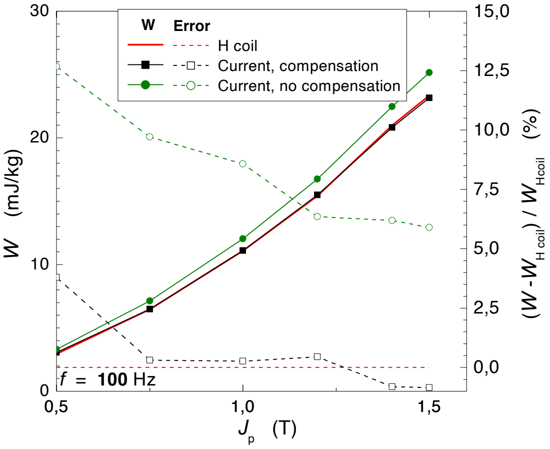


Fig. 8. High-permeability GO sheets. Comparison of the energy loss measured by the *H*-coil method and the current measurement method, with and without compensation.

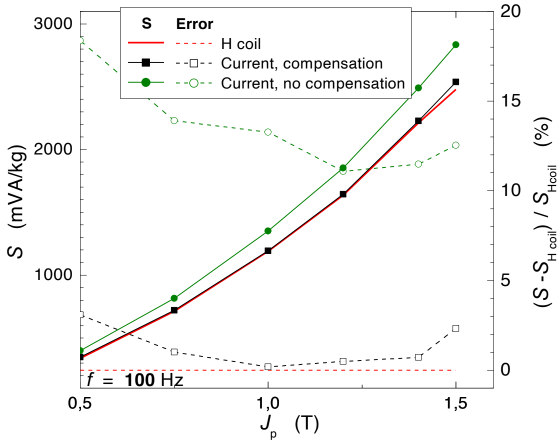


Fig. 9. High-permeability GO sheets. As in Fig. 8 for the apparent power.

Fig. 9 shows the behavior of the measured apparent power. Again, we find good agreement between the results provided by the two methods: *H*-coil and compensated permeameter. It is noted that part of the small discrepancies occurring between the *H*-coil and compensated current measurements could be attributed to the difficulties intrinsic to the *H*-coil method (small signal, integration problems…). This further stresses the merits of the here proposed approach.

IV. CONCLUSIONS

A permeameter has been developed, which applies a simple and effective magnetomotive force compensation method for the accurate characterization of soft magnetic steel sheets. It does not require specific sensors, except wedge shaped pole faces for the precise definition of the magnetic path length. It works on the principle of using the flux-closing yoke itself for both sensing and compensation.

The performances of this permeameter have been validated by measurements on non-oriented and grain-oriented Fe-Si sheets, whose results excellently compare with the results provided by measurements performed using the tangential *H*-coil method.

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