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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 field strength 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.
agreement between the results obtained with the magnetizing force 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

$$N \cdot I = \oint_L H \cdot dl.$$  

If a method is found by which maximum uniformity of the applied field across the whole distance $L$ is obtained, then $L_s$ is the length of the mean magnetic flux path in the sample. $L_s$ has value intermediate between $L$, the distance between the pole faces, and $L_0$, 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.

We wish to impose a flux path such that the length $L_s$ coincides with the distance between the pole faces $L$. 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 $L_s$. 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 $L_s$. Under these conditions, the magnetic field $H$ in the sample will be obtained according to the relation

$$N \cdot I = H \cdot L_s.$$  

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 from 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 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 \( \phi \). Since there is no MMF source in the upper yoke, \( E \) will be reduced to zero, canceling the flux \( \phi \), that is, bringing to zero the voltage across 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 corresponding generated MMF \( M/NL \) leads to the condition \( E = 0 \). The control loop is schematically shown in Fig. 5. An analog control card (PID controller) keeps the voltage \( v_1 \) equal to zero, by properly supplying, via a high-gain linear amplifier, the compensation winding on the lower yoke. Consequently, the flux \( \phi \) in the sample is made to entirely flow in the lower yoke.

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 core laminations employed in the yokes. The voltage \( v_1 \) is, for example, always much larger than the one achievable by the 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 \( f = 100 \text{ Hz} \) and peak polarization values \( 0.2 \text{ T} \leq J_b \leq 1.5 \text{ T} \). 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.](image)

![Fig. 7. NO Fe-Si sheets. \( J_b = 1 \text{ T} \). Comparison of the hysteresis loops measured by the \( H \)-coil method and by the current measurement method, with and without compensation.](image)
constrained to the sample length $L$ and is slightly longer. The good agreement between the $H$-coil and the compensated permeameter method is confirmed by the corresponding 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 negligible with respect to the one in the sample. At the same time, the localized measurements using the $H$-coil method 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 $J_0 = 0.5\, T$, $6\%$ for $J_0 = 1.5\, T$). This is expected, because the loss in the yoke depends only on the sample loss increases with better materials.

Fig. 8. High-permeability GO sheets. Comparison of the energy 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.

V. References


