

A Compensated Mini-Permeameter for Localized Magnetic Loss Measurements on Magnetic Laminations

Original

A Compensated Mini-Permeameter for Localized Magnetic Loss Measurements on Magnetic Laminations / Barrière, O.D.L., Khan, G., Ragusa, C.S., Mazaleyrat, F., Solimene, L., Prete, A.. - In: IEEE TRANSACTIONS ON MAGNETICS. - ISSN 0018-9464. - ELETTRONICO. - (2026), pp. 1-1. [10.1109/tmag.2026.3690917]

Availability:

This version is available at: 11583/3011648 since: 2026-06-03T19:03:30Z

Publisher:

Institute of Electrical and Electronics Engineers Inc.

Published

DOI:10.1109/tmag.2026.3690917

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

A Compensated Mini-Permeameter for Localized Magnetic Loss Measurements on Magnetic Laminations

Olivier de la Barrière¹, Gulaly Khan², Carlo Stefano Ragusa², Frédéric Mazaleyrat¹, Luigi Solimene²,
Alessandro Prete³

¹Laboratoire SATIE, CNRS/ENS Paris-Saclay, 91190 Gif-sur-Yvette, France

²Politecnico di Torino, DENERG, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

³Lagor S.r.l., Cerro Tanaro (AT), Italy

Accurate characterization of magnetic losses in permeameter-based systems is essential for reliable evaluation of magnetic materials. However, the magnetomotive force (MMF) drop in the flux-closing yokes can significantly affect the measurements, particularly in compact geometries where only a limited portion of the specimen is magnetized, leading to systematic overestimation of the losses. This paper presents a compensated mini-permeameter in which the MMF drop in the yokes is counteracted by an auxiliary winding driven by a feedback control scheme. The proposed approach enables the accurate determination of the magnetic field in the magnetized region directly from the magnetizing current. Experimental validation is performed through comparison with local tangential H-coil measurements on 0.35-mm-thick non-grain-oriented and 0.29-mm-thick grain-oriented laminations. Magnetic loss and hysteresis loop measurements at 50 Hz demonstrate that the compensation effectively mitigates systematic loss overestimation and enables close agreement with the reference method for both NGO and GO laminations. The proposed technique provides a compact and robust solution for localized magnetic loss characterization and can be extended to both standard and non-standard single-sheet testers.

***Index Terms*—Magnetic loss measurement, mini-permeameter, MMF compensation, electrical steels, H-coil.**

I. INTRODUCTION

ACCURATE MEASUREMENT of magnetic losses in soft magnetic steels is crucial for the design and optimization of electrical machines and electromagnetic devices. In permeameter-based measurement setups and Single Sheet Testers (SSTs), the magnetic field strength is commonly inferred from the magnetizing current by assuming a well-defined effective magnetic path length [1-3]. However, the magnetomotive force (MMF) drop in the flux-closing yokes introduces systematic errors, leading to overestimation of both magnetic field strength and losses, particularly in high-permeability materials and thicker magnetic samples. Several studies have compared magnetizing current-based (MC) and H-coil-based (HC) field determination methods, highlighting that the MC approach is inherently indirect and strongly dependent on tester geometry. In contrast, the HC method provides a more direct measurement of the internal magnetic field but requires increased experimental complexity and must cope with low signal levels and susceptibility to noise [4 - 7]. Moreover, MC-based methods require high-quality yokes to ensure low, stable yoke losses relative to specimen losses [2]. To overcome these limitations, MMF compensation techniques have been proposed, relying either on physical compensation or robust correction schemes to achieve reference-grade accuracy. A notable contribution was previously reported in [8], in which a compensation scheme uses the yoke as a zero-MMF indicator, combined with a feedback-controlled auxiliary winding. In recent years, increasing attention has been devoted to miniaturized and localized magnetic testers designed to characterize limited regions of a sample or reduced material volumes [9-11]. In such compact geometries, MMF-related errors are further amplified, reinforcing the need for effective compensation strategies.

In this paper, a compensated mini-permeameter magnetizing only the central 60 mm region of a single Epstein strip is presented. The system is experimentally validated by comparison with local tangential H-coil measurements on 0.35-mm-thick non-grain-oriented (NGO) laminations, with samples cut along the rolling direction (hereafter denoted as L) and the transverse direction (hereafter denoted as T), and on 0.29-mm-thick grain-oriented (GO) laminations. With MMF drop compensation, the loss values and hysteresis loops obtained using the MC method exhibit improved agreement with the corresponding H-coil measurements. Although the MMF compensation principle is related to the scheme proposed in [8], the present work extends that approach by demonstrating effective compensation in a strongly localized magnetization geometry, namely a mini-permeameter magnetizing only a 60 mm segment, while introducing a feedback implementation with PID tuning optimized for the compact configuration and its characteristic frequency response. Compared to the approach in [8], which was developed for standard single strip tester configurations, the present work considers a configuration in which only a limited portion of the sample is magnetized, leading to increased sensitivity to MMF drop and magnetic field non-uniformity.

II. COMPENSATED MINI-PERMEAMETER DESCRIPTION AND CONTROL

A. Compensated permeameter description

1) Principle

The proposed mini-permeameter, depicted in Fig. 1, was originally developed at Laboratoire SATIE. It accommodates a single Epstein strip that is magnetized only in its $L_a = 60$ mm length central region. As a consequence of this localized magnetization, the MMF drop in the flux-closing yokes may represent a non-negligible fraction of the total MMF that must

be compensated to ensure accurate magnetic field determination. MMF compensation is achieved by introducing an auxiliary compensation winding on the bottom yoke and implementing a feedback control loop that suppresses the MMF drop outside the 60 mm magnetic path length defined by the sample.

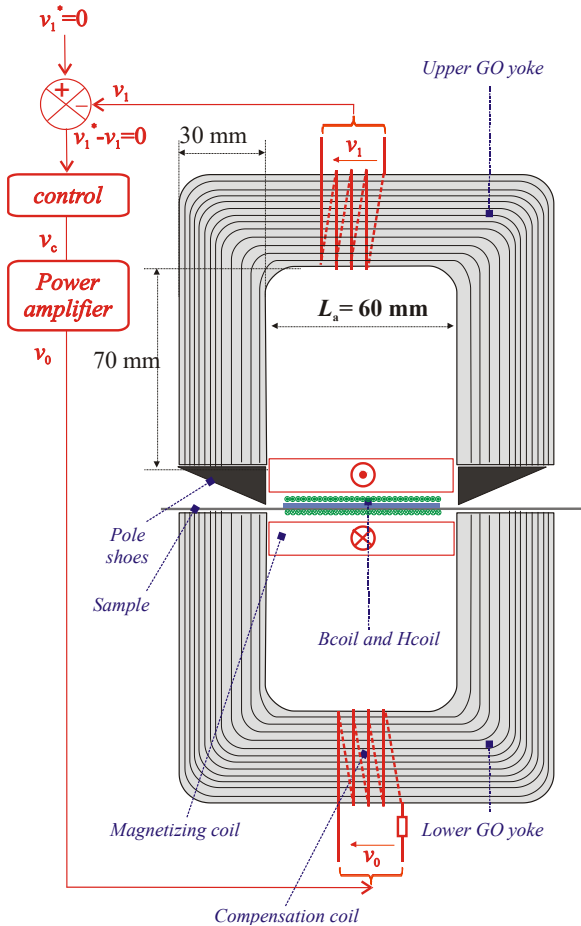


Fig. 1. Compensated Mini-Permeameter. It accommodates a single Epstein strip that is magnetized over its central region, defined by a magnetic path length of 60 mm. MMF compensation is achieved by using a compensation coil on the bottom yoke and a feedback control that suppresses the MMF drop outside the defined magnetic path, as measured by the sensing coil on the upper yoke. Under compensated conditions, the magnetic field within the magnetized region of the strip can be accurately derived from the magnetizing current.

As shown in Fig. 1, pole shoes have been introduced between the upper yoke and the sample to ensure that if zero flux flows in the upper yoke, the magnetic path is nearly equal to the internal length L_a . The magnetic field is then obtained from the equation

$$H(t) = \frac{N_H \cdot i(t)}{L_a} \quad (1)$$

being $i(t)$ the current flowing in the main magnetizing coil around the sample (Fig. 1), with N_H the number of turns. The effect of the pole shoes is of critical importance in this small permeameter configuration, for which the yoke thickness (30 mm) is by no way negligible with regard to $L_a = 60$ mm.

The pole shoes are manufactured from solid (non-laminated) magnetic steel, since when the flux in the upper yoke tends to zero, no eddy currents are induced in these components. The important point to stress is that, under compensated conditions, the magnetic field within the magnetized region of the strip can be accurately derived from the magnetizing current, independently of the magnetic properties of the yokes (Eq. 1). Under imperfect compensation, a small residual flux may still be present in the upper yoke, potentially inducing minor eddy currents in the solid pole shoes. However, given the low flux levels ensured by the feedback control and the operating frequency of 50 Hz, their contribution to the overall measurement error is expected to remain negligible.

2) Coils

Magnetizing coil around the sample: Optimal flux homogeneity along the entire length L_a requires the main magnetizing coil ($N_H = 77$ turns) to be designed as flat as possible around the sample. Compared with a cylindrical solenoid with a 30 mm diameter and a length of 60 mm, a flat configuration provides superior flux uniformity and is therefore the most suitable design solution.

B-coil: The magnetic induction is measured using a B-coil wound around the sample over the full 60 mm magnetic path length. The coil consists of 100 turns, and the magnetic induction is determined by numerically integrating the induced voltage according to Faraday's law.

H-coil: An H-coil is positioned on the sample and extends over the same 60 mm magnetic path length as the B-coil, ensuring a consistent comparison between the HC and MC methods, as both measurements refer to the same magnetic path length. This configuration enables a direct comparison between the locally measured losses and those obtained from the magnetic field determined by (1). This local reference measurement is useful for discussing compensation results; however, it is hardly feasible in *in situ* measurement systems such as those presented in [10-11], where hysteresis cycles are acquired under high mechanical stress. Indeed, the machine used to apply the stress may generate electromagnetic disturbances that affect the measurement and numerical integration of the small H-coil signal.

Yoke coils: A detection coil is placed on the upper yoke. The measured voltage v_1 corresponds to the time derivative of the magnetic flux flowing in the upper yoke. This flux is regulated to zero by the controller (Fig. 7). To ensure high sensitivity, a 1500-turn winding is employed. A second coil on the lower yoke provides the magnetomotive force (MMF) required to maintain zero flux in the upper yoke. It consists of 150 turns. In practice, the apparent power required is very low, as it only compensates for the active and reactive power associated with the lower yoke.

3) Numerical simulations

FEM simulations of the magnetic field distribution in the permeameter with an NGO Fe-Si strip were performed to evaluate its behavior with and without MMF drop compensation. Figure 2 shows the magnetic flux lines under MMF compensation. When zero flux flows in the upper yoke, the magnetic path length is nearly equal to the internal length

$L_a = 60$ mm. Figure 3 presents the theoretical comparison between the magnetic field measured using the H-coil method (H_{HC}) and that obtained using the MC method (1) (H_{MC}), both with and without MMF drop compensation. The corresponding relative errors are reported in Tables I and II. Finally, Figure 4 shows the profiles of the simulated normalized H -field along the 60 mm NGO Fe–Si strip for different average induction levels under MMF compensation.

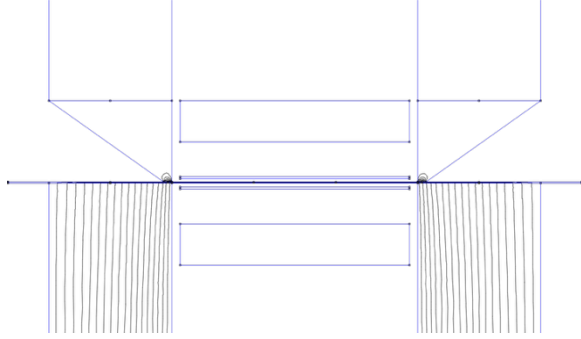


Fig. 2. FEM simulation of the permeameter with an NGO Fe–Si strip under MMF drop compensation. When zero flux flows in the upper yoke, the magnetic path length is nearly equal to the internal length $L_a = 60$ mm.

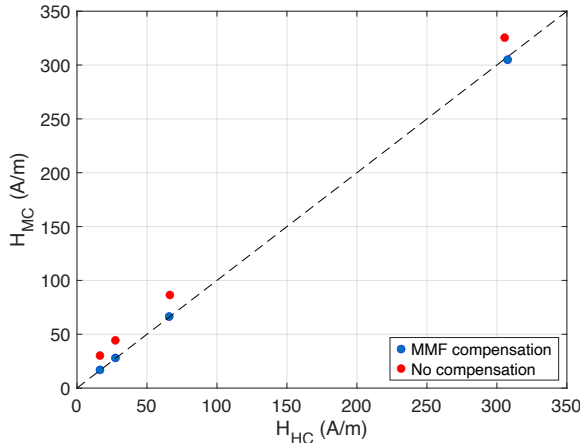


Fig. 3. Theoretical comparison, based on FEM simulations of the permeameter with an NGO Fe–Si strip, between the magnetic field measured using the H-coil method (H_{HC}) and that obtained using the MC method (1) (H_{MC}), for different magnetic polarization levels in the sample, with and without MMF drop compensation. The corresponding relative errors are reported in Tables I and II.

TABLE I
MAGNETIC FIELD COMPARISON WITHOUT MMF COMPENSATION

B (T)	H_{HC} (A/m)	H_{MC} (A/m)	Relative error (%)
1	16.43	30.21	83.89
1.25	27.43	44.34	61.67
1.5	66.38	86.45	30.23
1.7	305.54	325.46	6.52

TABLE II
MAGNETIC FIELD COMPARISON WITH MMF COMPENSATION

B (T)	H_{HC} (A/m)	H_{MC} (A/m)	Relative error (%)
1	16.43	16.89	2.82
1.25	27.46	28.0	1.97
1.5	65.87	66.42	0.84
1.7	307.67	304.95	0.88

Comparisons of theoretical magnetic fields measured using the H-coil method (H_{HC}) and those obtained using the MC method (1) (H_{MC}).

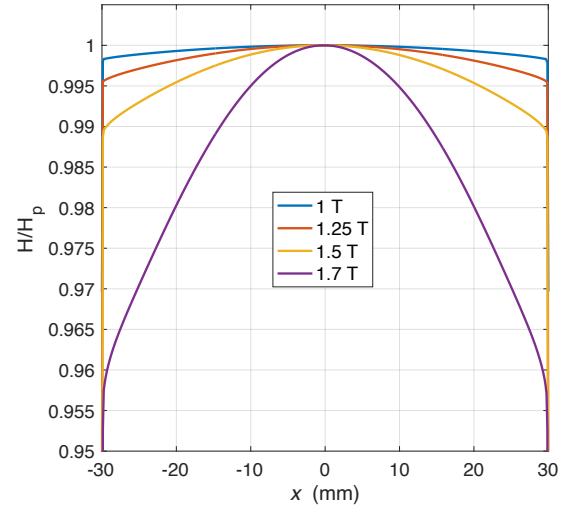


Fig. 4. Profiles of the simulated normalized H -field along the 60 mm NGO Fe–Si strip for different magnetic polarization levels in the sample under MMF drop compensation.

B. Control

1) System identification

The design of the control system requires an accurate identification of the open-loop transfer function. A sinusoidal voltage v_c is therefore applied to the input of the power amplifier (Fig. 1), and the amplitude and phase of the upper yoke winding voltage v_1 are measured. An NGO sample is inserted between the yokes but remains unmagnetized during the test. The corresponding experimental Bode plot is reported in Fig. 5. For control design purposes, it is convenient to approximate the measured Bode plot with an analytical expression of the transfer function. From an electrical standpoint, the system can be represented as shown in Fig. 6(a). The power amplifier is modeled as a first-order transfer function with a cutoff angular frequency ω_p . The parameters r and l_d denote the winding resistance and leakage inductance of the compensation coil. L_m represents the magnetizing inductance. The secondary of the equivalent transformer is assumed to be loaded by a capacitor accounting for interwinding effects. To simplify the analysis, the observed behavior can be interpreted as the superposition of low- and high-frequency contributions. As a first approximation, these two frequency ranges can be considered independently. As shown in Fig. 6(b), the low-frequency range behaves as a first-order high-pass filter, whereas Fig. 6(c) indicates that the system exhibits a second-order low-pass behavior at high frequencies.

The resulting transfer function, denoted by $\underline{H}$, can therefore be expressed as

$$\underline{H}(j\omega) = \frac{A}{1 + \frac{j\omega}{\omega_p}} \cdot \frac{\frac{j\omega}{\omega_0}}{1 + \frac{j\omega}{\omega_0}} \cdot \frac{1}{1 + 2m \frac{j\omega}{\omega_1} - \left(\frac{\omega}{\omega_1}\right)^2} \quad (2)$$

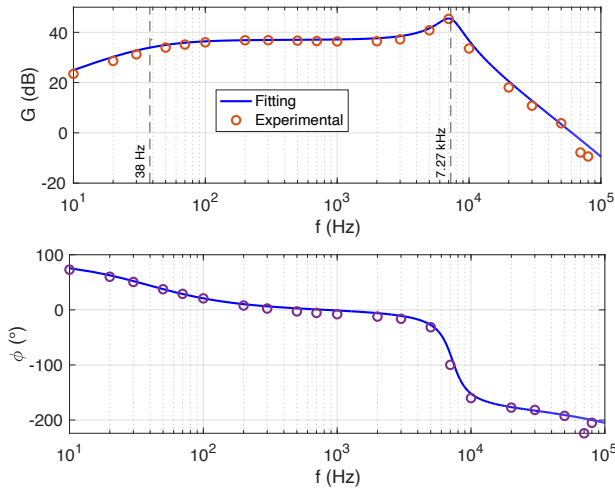


Fig. 5. Bode plot of the open-loop transfer function v_1/v_c (symbols: experimental data; solid line: analytical fit using (2)).

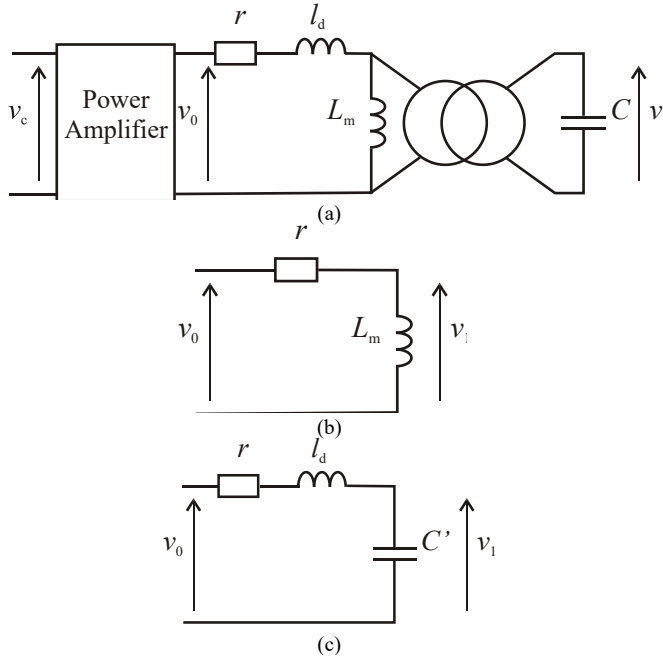


Fig. 6. Electrical schematic of the permeameter system from a control perspective: (a) overall system; (b) low-frequency approximation (capacitive impedance assumed infinite, $L_m \gg l_d$); (c) high-frequency approximation (capacitance referred to the primary side, $Z_{L_m} \gg Z_{C'}$).

The first term in (2) represents the power amplifier, whose overall gain is A . The second term corresponds to a high-pass filter, and the third term to a low-pass contribution. All parameters are listed in Table III and were identified to best fit the experimental data shown in Fig. 5. The agreement between the analytical model and the measurements confirms the quality of the fitting.

Parameter	Value
A	71
ω_p	1.26×10^6 rad/s
ω_0	241.59 rad/s
m	0.1918
ω_1	4.57×10^4 rad/s

2) Compensator design

Due to the large cross-sectional area of the yokes, the magnetic circuit can be reasonably assumed to operate in the linear region. A proportional–integral–derivative (PID) controller was therefore implemented. The control scheme is depicted in Fig. 7, where the PID controller transfer function is denoted by $\underline{C}$.

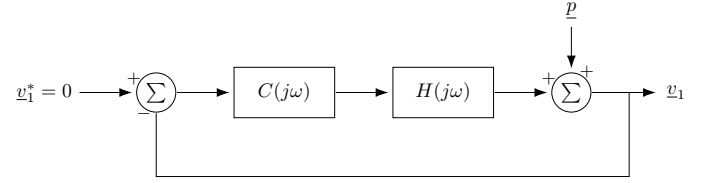


Fig. 7. Block diagram of the closed-loop control system.

The disturbance input $\underline{p}$ accounts for the magnetic flux produced by the sample and entering the upper yoke.

The transfer function of the PID is

$$\underline{C}(j\omega) = K \cdot \frac{1 + \frac{j\omega}{\omega_i}}{\frac{j\omega}{\omega_i}} \cdot \frac{1 + a \frac{j\omega}{\omega_d}}{1 + \frac{j\omega}{\omega_d}} \quad (3)$$

The second term (with cutoff angular frequency ω_i) corresponds to the integral action. It increases the low-frequency gain (up to 500 Hz), thereby improving accuracy in this frequency range. The third term introduces a phase lead when the parameter a exceeds 1. It acts in the kilohertz range, where the phase shift approaches -180° (see Fig. 5), thus contributing to system stabilization. The parameters listed in Table IV provide a set of values ensuring a phase margin of 50° .

Parameter	Value
K	0.0461
ω_i	18.85×10^3 rad/s
ω_d	6.57×10^3 rad/s
a	14

A key point is to evaluate the ability of the closed-loop system to reject the disturbance $\underline{p}$. From Fig. 7, the transfer function relating $\underline{v}_1$ to $\underline{p}$ is given by:

$$\underline{G}(j\omega) = \frac{\underline{v}_1}{\underline{p}} = \frac{1}{1 + \underline{C}(j\omega) \cdot \underline{H}(j\omega)} \quad (4)$$

As shown in Fig. 8, the closed-loop system exhibits an effective disturbance rejection bandwidth of approximately 1 kHz, ensuring efficient suppression of the MMF drop over the frequency range of interest. The PID parameters were found to be robust with respect to variations in the magnetic properties of the sample, with stable operation observed for both NGO and GO laminations. From a physical standpoint, the control loop enforces a zero-flux condition in the upper yoke, thereby suppressing the MMF drop outside the defined magnetic path

and allowing the magnetic field in the sample to be directly inferred from the magnetizing current.

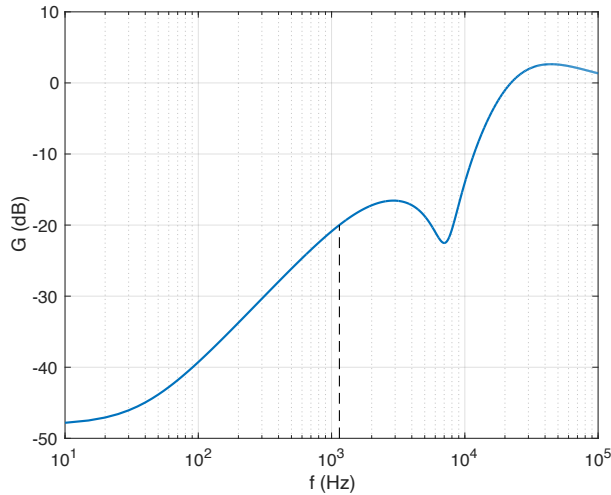


Fig. 8. Magnitude of (4) in dB. The closed-loop system exhibits an effective disturbance rejection bandwidth of approximately 1 kHz, ensuring efficient suppression of the MMF drop over the frequency range of interest.

III. EXPERIMENTAL VALIDATION

Experimental validation was performed on 0.35-mm-thick NGO and 0.29-mm-thick GO Fe–Si laminations. The proposed compensated mini-permeameter was experimentally validated over peak induction values between 1 T and 1.5 T for NGO laminations, and up to 1.7 T for GO laminations, corresponding to the typical operating range of interest for electrical steels. At lower induction levels, the compensation principle is expected to remain valid. However, the accuracy of the reference H-coil measurements becomes limited by the reduced signal-to-noise ratio, making reliable quantitative comparison more challenging. For the NGO material, both longitudinal (L) and transverse (T) directions were investigated. All measurements were carried out under sinusoidal flux excitation at 50 Hz. The magnetic losses obtained using the MC method, with and without MMF drop compensation, were compared with the reference losses measured using the H-coil method. The relative differences for the NGO case are shown in Fig. 9. Without MMF drop compensation, the relative difference is smaller for the T sample, as its lower permeability reduces the relative influence of the yoke. Moreover, in all cases, the error increases as the peak induction decreases, since the ratio of sample to yoke reluctance increases accordingly. With MMF compensation, the residual error is reduced to a few percent, typically ranging from 3–6% in the L direction and 6–7% in the T direction. Despite the agreement achieved with MMF compensation, a residual discrepancy remains due to the non-uniformity of the magnetic field.

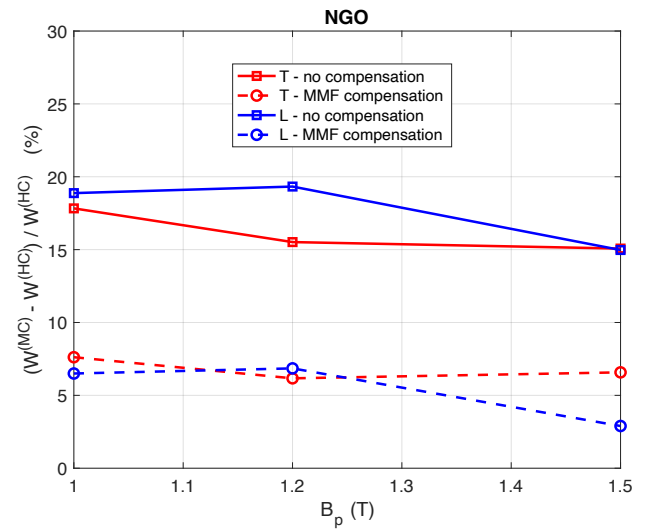


Fig. 9. Relative difference (%) of the measured loss between the MC and HC methods as a function of B_p for the NGO lamination, in the L and T directions, without and with MMF compensation. MMF drop compensation significantly improves the agreement between the MC and H-coil measurements.

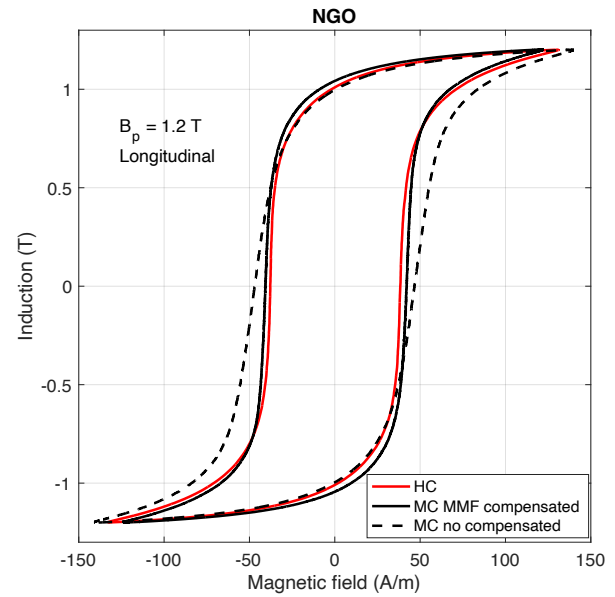


Fig. 10. NGO Fe–Si sheets. $B_p = 1.2$ T and $f = 50$ Hz. Comparison of the hysteresis loops measured by the H-coil method and by the current measurement method, with and without compensation. This result further confirms the effectiveness of the compensation scheme, showing much closer agreement between the compensated current-based measurements and the local H-coil results.

A comparison of the hysteresis loops measured on the L sample at 50 Hz and $B_p = 1.2$ T with and without MMF compensation (Fig. 10) further confirms the effectiveness of the compensation scheme, showing close agreement between the compensated current-based measurements and the local H-coil results. While the FEM analysis clearly demonstrates the effectiveness of MMF compensation, a strictly quantitative relationship between field non-uniformity and residual loss discrepancy cannot be directly established, since magnetic losses depend

nonlinearly on the local field and represent a spatially integrated response.

Measurements on GO laminations are significantly more affected by magnetic field non-uniformity and MMF drop in the yokes due to the high permeability of the material. In addition, the measurements are highly sensitive to mechanical stress, which may be introduced by the presence of the H-coil. Under these conditions, the relative difference between the two methods is reduced to approximately 5%, as shown in Fig. 11, demonstrating that the compensation approach remains effective for GO laminations.

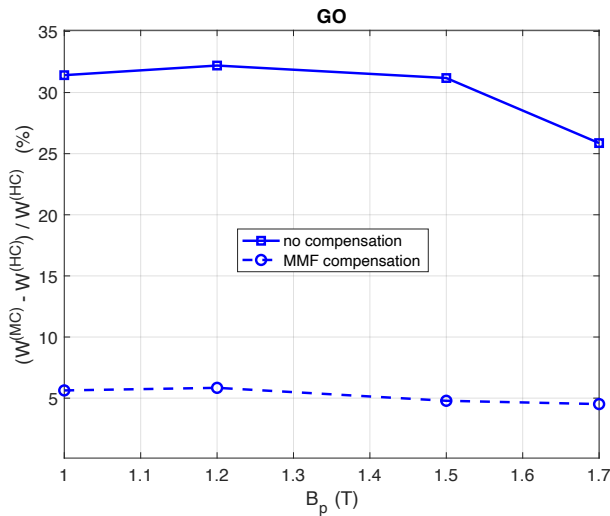


Fig. 11. Relative difference (%) between MC and HC loss measurements as a function of B_p for GO laminations, without and with MMF compensation. With MMF compensation, the relative difference is approximately 5%.

IV. CONCLUSION

This study demonstrates that the proposed compensated mini-permeameter enables reliable localized loss characterization of NGO and GO electrical steel laminations. The MMF drop compensation technique effectively mitigates the systematic errors inherent in conventional MC methods. The approach can be readily extended to both standard and non-standard permeameter systems, providing a robust and accurate solution for single-strip magnetic characterization.

REFERENCES

- [1] F. Fiorillo, *Measurement and Characterization of Magnetic Materials*. Amsterdam, The Netherlands: North-Holland, 2004.
- [2] *Magnetic materials – Part 3: Methods of Measurement of the Magnetic Properties of Electrical Steel Strip and Sheet by Means of a Single Sheet Tester*, IEC Standard 60404-3:2022, IEC Central Office, Geneva, Switzerland, 2022.
- [3] O. de la Barrière, C. Appino, C. Ragusa, F. Fiorillo, M. LoBue and F. Mazaleyrat, "1-D and 2-D Loss-Measuring Methods: Optimized Setup Design, Advanced Testing, and Results," in *IEEE Transactions on Magnetics*, vol. 54, no. 9, pp. 1-15, Sept. 2018, Art no. 2001415, doi: 10.1109/TMAG.2018.2846619.
- [4] Du-Xing Chen, Yong-Hong Zhu; Permeameter and solenoid measurements of Epstein strips of electrical steels. *Rev. Sci. Instrum.* 21 September 2023; 94 (9): 093904, doi: 10.1063/5.0127524.
- [5] Q. Xiang, L. Cheng, K. Wu, "Study on the Single Sheet Measurement Method for AC Magnetic Measurement on Grain-Oriented Electrical Steel," *Materials*, vol. 16, 2023, 1648, doi: 10.3390/ma16041648.
- [6] R. Matsubara, Y. Takahashi, K. Fujiwara, Y. Ishihara, D. Azuma, "Distribution of magnetic field strength inside exciting coil of single sheet tester", *AIP Advances*, vol. 8, n. 4, art. 047209, 2018. doi: 10.1063/1.4993997.
- [7] T. Nakata, Y. Ishihara, M. Nakaji, T. Todaka, "Comparison between the H-coil method and the magnetizing current method for the single sheet tester," *Journal of Magnetism and Magnetic Materials*, vol. 215–216, pp. 607-610, 2000, doi: 10.1016/S0304-8853(00)00239-0.
- [8] O. de la Barrière, C. Ragusa, M. Khan, C. Appino, F. Fiorillo, and F. Mazaleyrat, "A simple compensation method for the accurate measurement of magnetic losses with a single strip tester," in *IEEE Transactions on Magnetics*, vol. 52, no. 5, pp. 1-4, May 2016, Art no. 2001204, doi: 10.1109/TMAG.2016.2527829.
- [9] N. Leuning, M. Heller, M. Jaeger, S. Korte-Kerzel, K. Hameyer, "A new approach to measure fundamental microstructural influences on the magnetic properties of electrical steel using a miniaturized single sheet tester," *Journal of Magnetism and Magnetic Materials*, vol. 583, 2023, 171000, doi: 10.1016/j.jmmm.2023.171000.
- [10] Z. Maazaz, O. Hubert, E. Zemmouri, "Inverse identification of pipeline steel mechanical state by means of coupled magnetic measurements and artificial neural networks," *NDT & E International*, vol. 134, 2023, 102782, doi: 10.1016/j.ndteint.2022.102782.
- [11] O. Hubert, Z. Maazaz, J. Taurines, R. Crepinge, F. van den Berg, C. Celada-Casero, "Influence of biaxial stress on magnetostriction—Experiments and modeling," *Journal of Magnetism and Magnetic Materials*, vol. 568, 2023, 170389, doi: 10.1016/j.jmmm.2023.170389.