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Development of measurement frame for detailed measurements of hysteresis cycles of ferromagnetic sheets

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A B S T R A C T

This paper describes the electromagnetic design of a new concept of permeameter capable of providing a measurement of the magnetic permeability of sheet strips up to 1.5 mm thick. The measurements are performed in DC. A specific feature of the device is its ability to follow the history of the excitation, representing an ideal tool to experimentally characterize hysteresis cycles as a function of the initial magnetization status of the material. The first preliminary results taken with measurement frame are also presented.

1. Introduction

Different methods and devices can be used to measure the magnetic properties of ferromagnetic strips, typically based on detecting the effect of a change of magnetic field [1–3]. In a typical Epstein frame, the ac magnetic characteristics are determined for sinusoidal induced voltages for specified values of frequency. A measurement system using optical methods has also been developed [4]. All of these measurement systems operate in AC mode. The device described in this report allows a direct absolute measurement of the field induction in the material as a function of the magnetic field in the air gap and hence is used to measure the hysteresis cycle. This device is named as NORMA frame after the normal conducting magnets section at CERN. It was developed at CERN during the authors stay there.

The magnetic circuit (Fig. 1) is similar to that of an Epstein frame, which allows:

1. The field to stay mostly inside the magnetic material thanks to symmetrical geometry.
2. Neglecting the magnetic reluctance of the joints because the overlapping section between the strips is much larger than the cross section of each of the strip.

Differently from an Epstein frame device, only one strip is used in each leg. If more than one strip is used, then reluctance of the joints no longer remains negligible compared to rest of the circuit. Hence the condition of uniform field throughout will not remain valid. Furthermore there is a “measuring” air-gap which, thanks to the favorable ratio between overlapped area and cross section of a strip, constitutes a negligible magnetic reluctance compared to that of the whole magnetic circuit. In practice we will see that we can consider that the magnetic circuit is determined by the ferromagnetic strips.

A specific feature of the device is its ability to follow the history of the excitation, representing an ideal tool to experimentally characterize hysteresis cycles as a function of the initial magnetization status of the material. Hence, it can be used to determine the *BH* curve at any level. Also the first curve of magnetization can be easily determined

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by manually degaussing the steel strips with the help of the device. Hence it has the ability to measure absolute field levels.

This note describes the electro-magnetic design and fine tuning of the device and provides the mathematical relationships to be used for analyzing the measurements.

2. Electromagnetic principle

The magnetic circuit is composed by 5 steel strips, 3 long strips of 280 mm and 2 small strips of 155 mm, all 30 mm wide. The measurement of the field induction is performed in the middle of a 1 mm air-gap between the two small strips.

The magnetic circuit should be symmetric to improve the uniformity of the field in the iron. Hence, five coils are used to cover the magnetic circuit with a uniform magnetomotive force.

Since the magnetic flux Φ remains the same everywhere in the circuit, we have

$$\Phi_{\text{iron}} = \Phi_{\text{air}}$$

$$B_{\text{iron}} S_{\text{iron}} = B_{\text{air}} S_{\text{air}}$$

$$B_{\text{air}} = B_{\text{iron}} \frac{S_{\text{iron}}}{S_{\text{air}}}$$

where S is the cross sectional area with the subscripts representing area of iron and the air gap.

Considering here 1 mm thick strips, in a first approximation the effective circuit sections are $S_{\text{iron}} = 30\ \text{mm}^2$ and $S_{\text{air}} = 900\ \text{mm}^2$:

$$B_{\text{air}} = \frac{1}{30} B_{\text{iron}} \qquad (1)$$

By measuring the field induction in the air-gap we can then compute the field induction in the ferromagnetic material.

This amplification factor is a key for providing an almost linear response of the measuring device with respect to a large range of magnetic field H and field induction B: the air gap is 1000 times shorter than the length of the ferromagnetic circuit, and the field induction is 30 times smaller in the air gap than in the ferromagnetic circuit, making the magnetomotive force used in the air-gap negligible compared to that used in the iron.

Still in a first approximation, the magnetic circuit being about 1 m long, the ampereturns NI [At] correspond numerically to the magnetic field intensity H [A/m] in the iron.

The reality is slightly different because of the non-uniform distribution of the magnetic field in particular around the air-gap, and of the non-linear behavior of the ferromagnetic materials. These aspects are treated in detail in the next chapters.

3. Finite elements modeling

3.1. 2-D

The computations have been made on a model implemented in OPERA 2D [5] using, as a reference, a non-linear low carbon steel B–H characteristic type AISI 1010.

Fig. 2 shows how the magnetic flux remains mostly contained in the magnetic strips: this remains true over a large range of field induction until saturation. Fig. 3 shows the detail of flux lines across the air gap. The field flux in each strip spreads over a surface slightly exceeding the

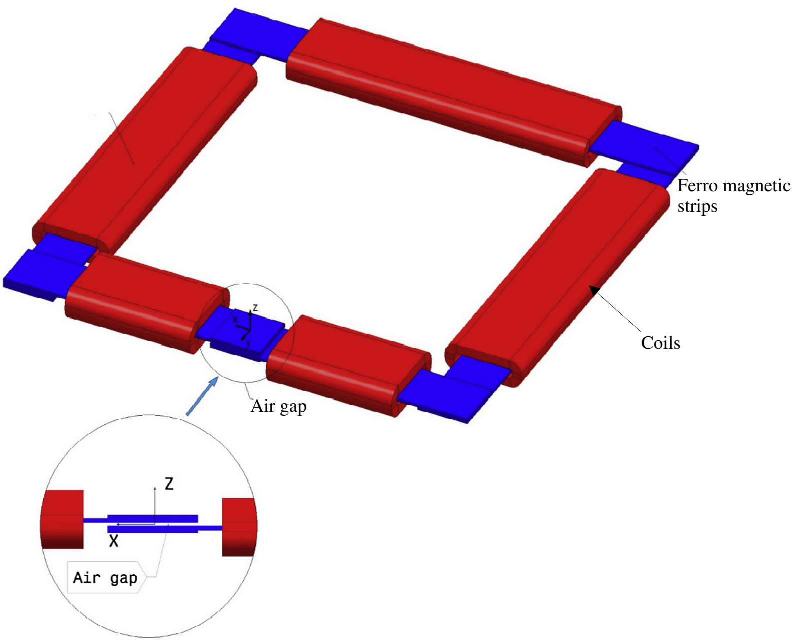

Fig. 1. Schematic of the measurement bench.