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# Determination of Characteristics of Feromagnetic Material using Modern Data Acquisition System*

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**Abstract:** This paper describes the use of modern measuring and data acquisition system for determining characteristics of feromagnetic material. For this purpose data acquisition card NI USB-6009, PC with data acquisition software and fluxmeter Electrical Steel Measuring System MPG 100 D were used. Based on the results obtained by measurements the modeling of hysteresis loop is performed by using appropriate mathematical model.

**Keywords:** Feromagnetics, Hysteresis, Mathematical model, LabVIEW.

## 1 Introduction

In electrical engineering, feromagnetics, including iron, nickel and cobalt, an alloy of these metals and some rare earth are particularly important group of magnetic materials. They are characterized by very high values of relative magnetic permeability, whose maximum value in some special alloys exceeds the value of 100 000. Magnetic permeability of feromagnetics is not constant for a given material, because the connection between the vectors of magnetic induction $\boldsymbol{B}$ and magnetic field $\boldsymbol{H}$ is not linear. Magnetic induction and magnetic moment density of feromagnetics are multiple and ambiguous function of the magnetic field strength and do not depend only on the value of field strength at the time of observation, but also on the strength of the field which the material was previously exposed to. This phenomenon, inherent feromagnetics is called hysteresis [1].

The relation between magnetic induction and magnetic field in feromagnetics can be presented with a hysteresis loop. Several methods of measurement are commonly applied for the recording of hysteresis loop of feromagnetics, such as Roland's and Juing's method [2], for measuring with direct current, and cathodic oscilloscope measuring method, which employs AC current. In this paper, the latter has slightly been modified, and modern

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measuring and data acquisition system (acquisition card and PC with LabVIEW software package) has been used to simplify data acquisition and processing. Thus, the accuracy of the results is higher, as the accuracy of the results obtained by measuring with oscilloscope markedly depended on the method of its calibration. Modern fluxmeter Electrical Steel Measuring System MPG 100 D was used for the comparison of results of the recording of hysteresis loop.

Knowledge of mathematical model of hysteresis is of great importance as it allows knowledge of characteristics of magnetic materials even when the same material is used in different places and under different operating conditions. In addition, mathematical model can be used in the construction of inductive elements, equipment or machinery whose core is made of feromagnetic materials and thus contribute to the better model of the same, which is very important from practical aspect. For modeling of hysteresis loop numerous mathematical models, which include hyperbolic approximation, trigonometric, exponential and other mathematical functions, has been developed. Most commonly used among them is Gil-Atherton model [3-9].

The aim of this paper is to form a mathematical model by using the results obtained by measuring by modern measuring and data acquisition systems, and fluxmeter. The measurement was conducted on the toroidal core made of transformer sheets. Nonlinear model will include the effects of hysteresis and saturation of the magnetic core, as these are the most important in the analysis and solution of electric circuits containing inductive elements with feromagnetic core.

## 2 Measurement Equipment and Measurement Methods

A cathodic oscilloscope is often employed for recording dynamic hysteresis loop in a feromagnetic material. For this measurement, connection scheme is shown in Fig. 1.

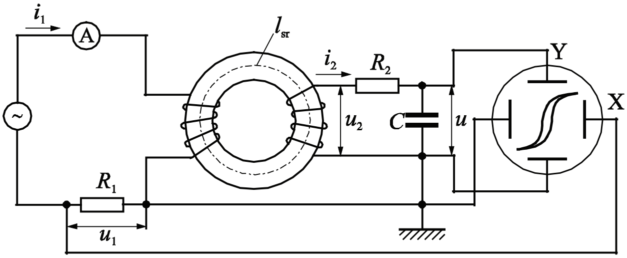


**Fig. 1** – *Connection scheme for recording hysteresis loop.*

When the voltage $u_1$, which is proportional to the strength of the magnetic field $H$, is connected to $X$ input and the voltage $u$, which is proportional to the magnetic induction $B$, is connected to $Y$ input of oscilloscope, the oscilloscope shows the picture of hysteresis loop.

The above method gives good results, but requires extensive preparation of the measurement procedure (e.g. calibration of the oscilloscope, proper selection of $RC$ element in the secondary electric circuit). In addition, measurement results cannot be stored in an easy and simple way in the proper format. Therefore, there is an idea to improve the measuring method by removing the oscilloscope and adding modern measuring and data acquisition system consisting of the data acquisition card and personal computer [10]. The equipment for measurement with the modified method is shown in Fig. 2.

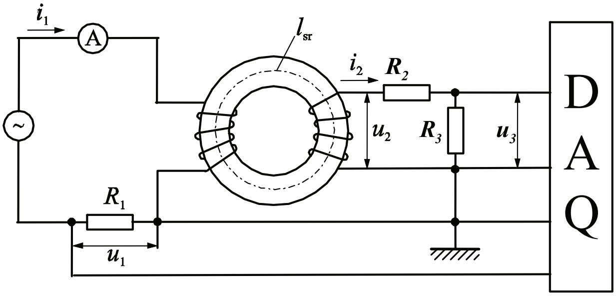


**Fig. 2 –** *Measuring equipment adapted to modern measuring and data acquisition system.*

DAQ on Fig. 2 presents data acquisition card connected to computer. Data acquisition card connects measuring equipment, sensors and instruments to the computer. The role of the card is to adjust signals for processing by computer. Thus, the card converts analog signals to digital ones and sends them to the computer. Signals that were previously brought to the card inputs are adjusted. Data acquisition card should not be connected to high currents and voltages (currents up to few mA and voltages up to few V). Signals that are brought to card inputs must be within the input range of voltage so they do not lead to its damage or destruction.

For this measurement data acquisition card NI USB-6009 [11] was used. Some important technical characteristics of card are as follows:

– number of analog inputs: 8,
– resolution: 14 bits,
– sampling rate: 48 kS/s, and
– input range: ± 10 V, etc.

In this case, the voltage $u_1$, proportional to the strength of the magnetic field $H$, is connected to the input 1 and voltage $u_3$, proportional to the magnetic induction $B$, to the input 2 of the acquisition card (Fig. 2). Resistance $R_1$ is chosen so that the voltage does not exceed the value of 10 V, and voltage divider consisting of resistances $R_2$ and $R_3$ is adjusted so that the voltage $u_3$ is not greater than 10 V. Capacitance $C$ in Fig. 1, which forms integrator of voltage with resistor $R_2$, is not shown in Fig. 2. This is because the integration of the voltage is performed in the program. It can be said that the signal processing is performed in the program and after adapting the value of the signal (in this case voltage higher than 10 V should not be connected to the card inputs) there is no need for any additional processing before bringing it to the inputs of the data acquisition card. Therefore, all further signal processing is performed in the program, so the possibility of interference, which can be produced by certain elements of the measuring circuit, is reduced. The LabVIEW software package contains a comprehensive library of functions for a large number of programming tasks for acquisition, displaying, processing and storing data.

For the comparison of the results the measurements were performed on modern fluxmeter - Electrical Steel Measuring System MPG 100 D [12].

## 3 Mathematical Model of Hysteresis

Nonlinear mathematical model [8] that will be used in this paper is based on linear mathematical model shown in equation (1):

$$H = \frac{B}{\mu} \pm W \mp Y\,\mathrm{e}^{\mp \frac{B-B_0}{T}}, \tag{1}$$

where:

- $\mu$ is gradient of magnetization curve,
- $W$ is width of hysteresis effect,
- $T$ is exponential coefficient of hysteresis effect, or gradient near the starting point are constant parameters.

$Y$ is previously calculated value from the initial conditions: $H = H_0$ for $B = B_0$,

$$Y = \mp\left( H_0 - \frac{B_0}{\mu} \mp W \right).$$

Sign (–) or (+) refers to the change of magnetic induction with the increase or decrease of the magnetic field, respectively.

This linear model is very simple and involves hysteresis effect, but has limited accuracy, mainly due to the inability to involve saturation effect.

A typical change in magnetic induction $B$ with the increase (decrease) of the magnetic field $H$ on the feromagnetic core is shown in Fig. 3.

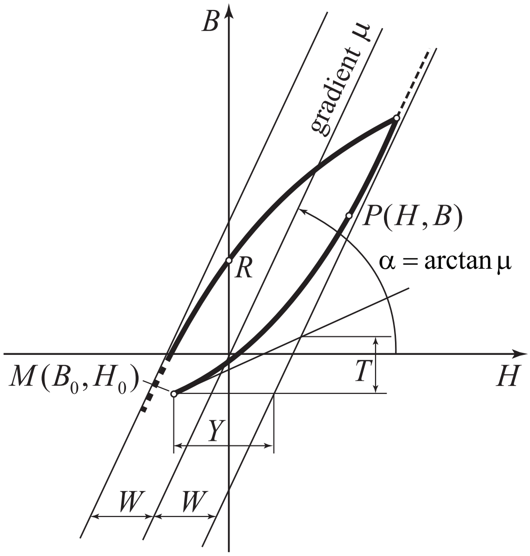


**Fig. 3 –** *Curve* $B = f(H)$ *for the linear model.*

To improve accuracy of this mathematical model, it is necessary to adopt suitable functional dependence of these parameters, while the saturation effect may be modeled by "middle line" anvelope of loop $HK(B)$ and change of the width of the loop by introducing $WK(B)$. The introduction of functional dependence $TK(B_0)$ enables initial gradient of single segment of path to be a variable function of magnetic induction at a starting point.

Thus, nonlinear model is:

$$H = HK(B) \pm WK(B) \mp Y\,\mathrm{e}^{\mp\frac{B-B_0}{T(B_0)}},\qquad Y = \pm\big(HK(B_0) \pm WK(B_0) - H_0\big). \tag{2}$$

It is possible to define various categories of mentioned model and thus achieve different accuracies, depending on which parameter is set to be constant [6]. Therefore, four categories of nonlinear model can be defined:

- $HK$ nonlinear, $WK$ and $T$ constant,
- $HK$ and $T$ nonlinear, $WK$ constant,
- $HK$ and $WK$ nonlinear, $T$ constant, and
- $HK$ , $WK$ and $T$ nonlinear.

Besides the saturation and hysteresis effects, in the analysis of electrical circuits containing inductive elements with feromagnetic material, the effect of eddy currents must be included as this effect often causes greater losses than the hysteresis effect, especially at higher frequencies.

The effect of eddy currents can be included into the nonlinear model by introducing a suitable nonlinear function $E(B)$ where losses are modeled by equivalent ellipses [8],

$$
\begin{gathered}
H = HK(B) \pm WK(B) \mp Y\,\mathrm{e}^{\mp\frac{B-B_0}{T(B_0)}} \pm E(B), \\
E(B) = A\sqrt{1-\left(B/BE\right)^2}\,.
\end{gathered}
\tag{3}
$$

where $A$ is width and $BE$ height of an ellipse.

## 4 Measurement Results

To obtain hysteresis loop for feromagnetic material torus with two windings and with following parameters:

– number of turns on the primary winding $N_1 = 250$,

– number of turns on the secondary winding $N_2 = 30$,

– length of the center line $l_{sr} = 0.264\ \mathrm{m}$, and

– cross-section area $S = 300\ \mathrm{mm}^2$ is used.

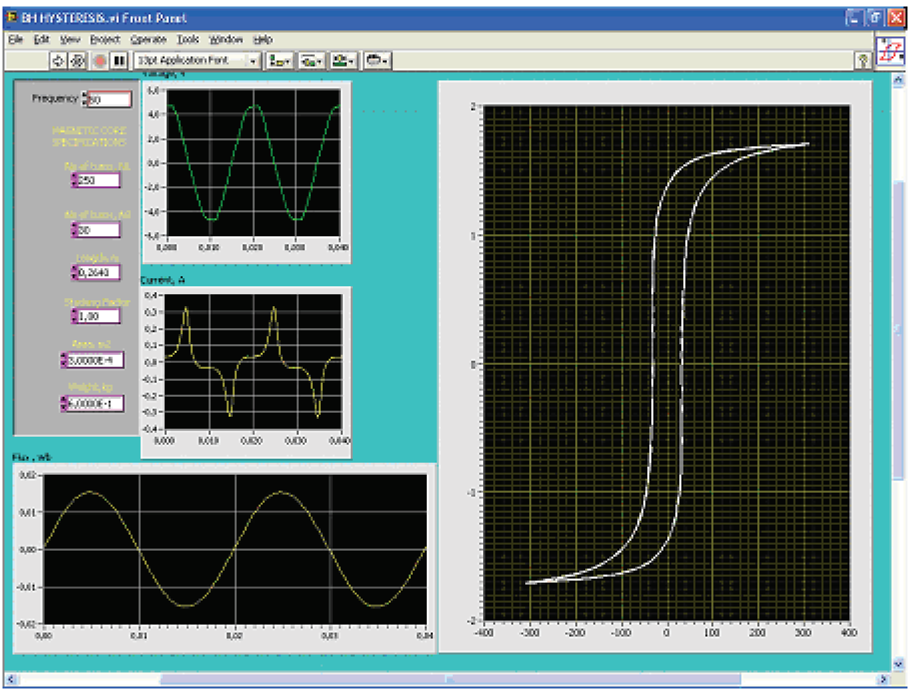


**Fig. 4** – *Show on a Virtual instrument.*

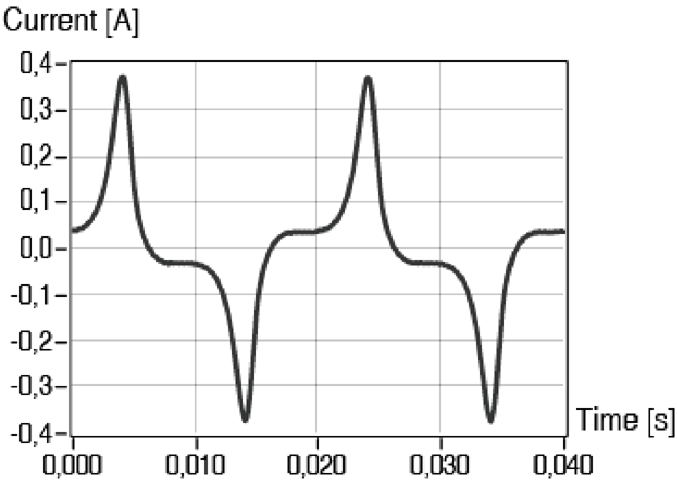


**Fig. 5 –** *Time dependence of magnetization current.*

Fig. 4 shows the Front panel of Virtual instrument which is used for measuring of hysteresis with data acquisition card and PC.

Fig. 6 presents a comparative overview of hysteresis loops measured with fluxmeter and data acquisition card, for magnetic field strength $H_{\mathrm{m}} = 250[\mathrm{A/m}]$ and frequency $f = 50[\mathrm{Hz}]$.

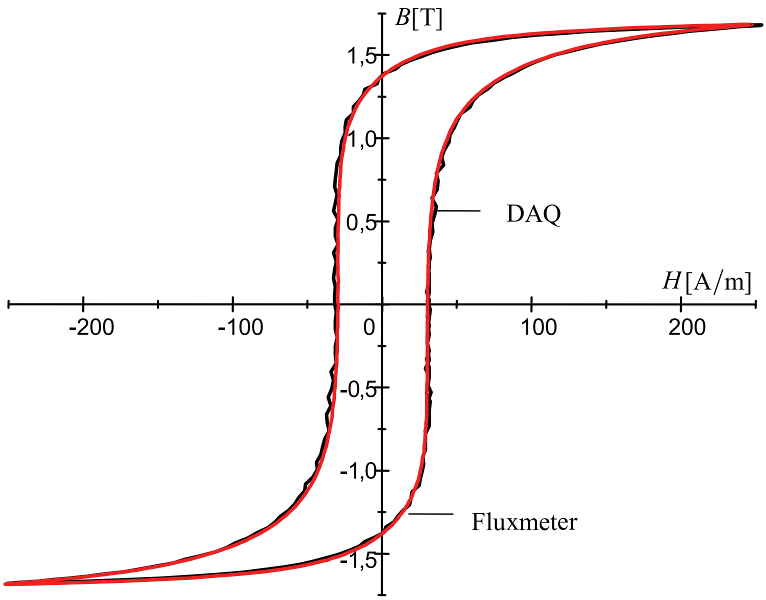


**Fig. 6 –** *Comparison of the results obtained by measuring.*

Fig. 7 gives a comparison of hysteresis loops obtained from the nonlinear model (2) and measured by using the data acquisition card.

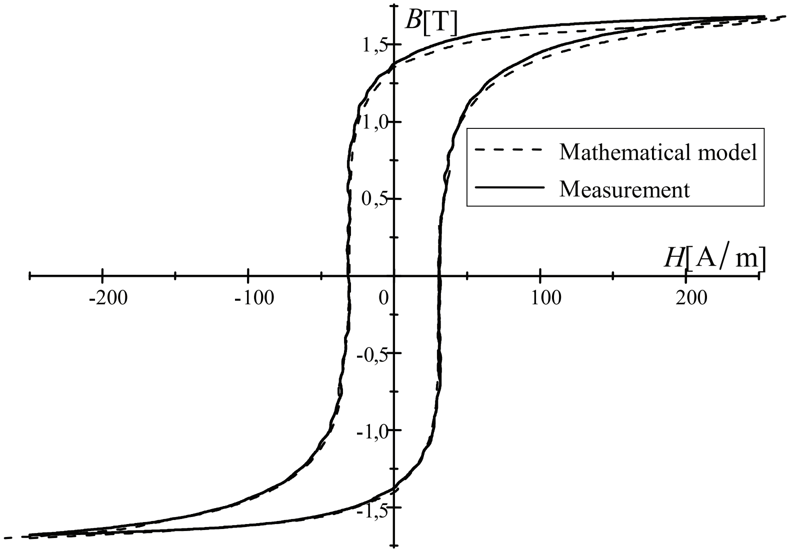


**Fig. 7 –** *Hysteresis loop by nonlinear mathematical model* (2)*, when HK and WK nonlinear, and* $T = \text{const.} = 0.05$*, and measured hysteresis loop.*

Fig. 8 shows hysteresis loops obtained by measuring, for $H_\text{m} = 60[\text{A/m}]$ at frequencies $f = 50[\text{Hz}]$, $f = 100[\text{Hz}]$ and $f = 150[\text{Hz}]$.

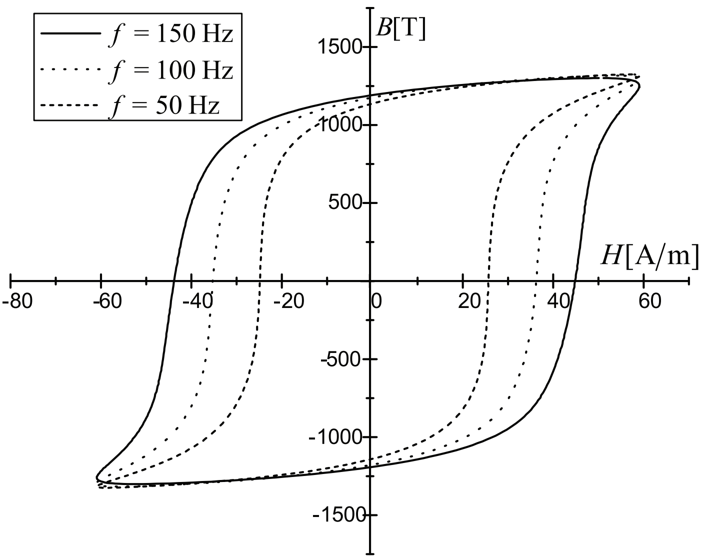


**Fig. 8 –** *Hysteresis loops at different frequencies and* $H_\text{m} = 60[\text{A/m}]$.

## 5 Conclusion

This paper presents the results of measuring dynamic hysteresis loop obtained by using modern measuring and data acquisition system. The presented results were compared with those obtained by using fluxmeter Electrical Steel Measuring System MPG 100 D. Very good agreement of the results has been evidenced. By the results obtained by measuring, mathematical model of hysteresis is defined and used for modeling of hysteresis loop.

The presented measuring method has a numerous advantages over the ones previously used, whereby advantages do not refer only to the storage and processing of the obtained data. Data acquisition card that has been used in the experiment has lower cost compared to the oscilloscope or fluxmeter, and has wider range of application.

Nonlinear model used in this paper can be improved and it will be subject of future research.

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