*REVIEWS - LETTERS - REPORTS*

# MEASURING OF THE SCALAR HYSTERESIS CHARACTERISTIC WITH A CONTROLLED FLUX DENSITY USING ANALOG AND DIGITAL INTEGRATORS

**Zoltán Pólik — Tamás Ludvig — Miklós Kuczmann** [*]

We have managed to build up a computer controlled system using National Instruments Data Acquisition card and National Instruments LabVIEW software package. First, the specimen under test has been simulated by the Jiles-Atherton model, but simulated measurements have been performed using LabVIEW functions. Our main goal now is to control the magnetic flux density during measurement by using a toroidal core with a feedback controller. In this paper, we show the developed procedure which is suitable for measurement of the hysteresis characteristics using analogue and digital integrators, and to control the waveform of the magnetic flux density determined from the induced voltage of the secondary coil wound on a toroidal core. Our experience is that the developed controller is robust. This work is an initial step to the future work on a vector hysteresis measurement system.

K e y w o r d s: scalar magnetic hysteresis, computer controlled hysteresis measurement system

## 1 INTRODUCTION

Exact simulation of scalar hysteresis characteristics of ferromagnetic materials, *ie* to know the magnetization $M(t)$ as a function of the magnetic field intensity $H(t)$ is very important in the computer aided design. Simulation of this nonlinear system having memory is very difficult because it is hard to find a good structure for the simulation. There are well known models to simulate the scalar hysteresis characteristics, for example the Jiles-Atherton model, the Stoner-Wolfarth model, and the Preisach-model [1, 2, 4, 6]. To compare the known hysteresis models and the measured characteristics is of some importance if we want to see that the simulation procedures are working properly.

The implemented procedure developed in LabVIEW can be used to measure the scalar hysteresis characteristics. The block diagram is in Fig. 1. The control signal of the amplifier can be defined by a mathematical formula; and the amplifier can follow the control signal. The amplifier excites the primary coil of the toroidal shape core which current is known. The magnetic field intensity generated by the excitation current results in magnetic flux inside the core. The magnetic flux density can be measured by the induced voltage of the secondary coil and the magnetic field intensity can be measured directly from the current of the amplifier. The measured results have been post-processed by the developed LabVIEW program, and the hysteresis characteristics have been plotted by LabVIEW functions as well. Results can be saved into files for further use [3].

We have created two procedures to measure the magnetic flux density based on the induced voltage of the secondary coil of the toroid. The first is a digital procedure which calculates the magnetic flux density with the left integration rule. The other is an analog method with passive RL or RC integrator circuits.

We can measure the BH-loop in two ways: by controlling the magnetic field intensity in the core with a known current signal, or by controlling the magnetic flux density with the iteratively modified current signal. The control of current signal is based on the difference between the waveform of measured magnetic flux density and the defined waveform in advance.

## 2 MEASUREMENT OF FIELD QUANTITIES

It is well known that the measurement of magnetic field intensity $H(t)$ inside a toroidal shape coil is based on Ampere's law, because the current of the primary coil $i_1$ is in direct connection with this electromagnetic quantity (the primary coil has $N_1$ turns), *ie* [5]

$$\oint_l \mathbf{H}(t) \cdot \boldsymbol{dl} = \int_A \mathbf{J}(t) \cdot \boldsymbol{dA}, \text{ and } \int_A \mathbf{J}(t) \cdot \boldsymbol{dA} = N_1 i_1(t). \quad (1)$$

The magnetic field intensity vector and the magnetic flux density vector are supposed to have component only along the polar axis of the core. Equation (1) can be simplified as

$$H(t)2r\pi = N_1 i_1(t), \quad (2)$$

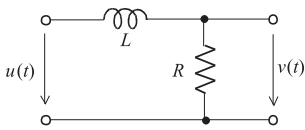**Fig. 1.** The block diagram of the measurement system
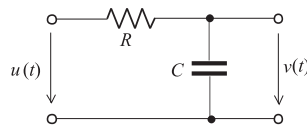


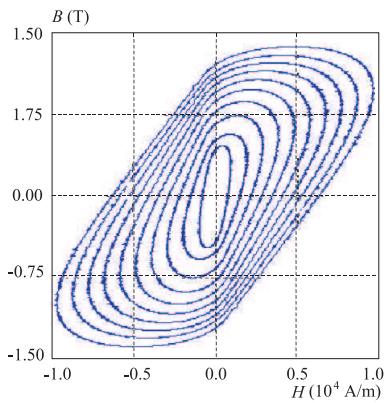**Fig. 3.** RL passive integrator      **Fig. 4.** RC passive integrator



**Fig. 5.** BH-loops at 200 Hz with RC passive integrator

where $r$ is the mean value of radius of the core, and $l = 2r\pi$ is denoted in Fig. 1. From expression (2), the mean value of the magnetic field intensity $H(t)$ can be determined as

$$H(t) = \frac{N_1 i_1(t)}{2r\pi}\,, \qquad (3)$$

and the waveform of current can be measured directly from the amplifier, because it has an output which voltage is proportional to the generated current.

The magnetic flux density $B(t)$ depends on the hysteresis characteristic of the specimen which can be measured through the magnetic flux $\Phi(t)$ inside the core. The time variation of flux results in induced voltage in the secondary coil having $N_2$ turns according to Faraday's law, [5]

$$u_2(t) = -\frac{\mathrm{d}}{\mathrm{d}t}\Phi(t)N_2 = -\frac{\mathrm{d}}{\mathrm{d}t}B(t)SN_2\,, \qquad (4)$$

since

$$\Phi(t) = \int_S \mathbf{B}(t) \cdot d\mathbf{S} = B(t)S\,, \qquad (5)$$



**Fig. 2.** BH-loops at 2 Hz with digital integrator

where $S$ is the cross section area of the core. The magnetic flux density can be determined from equations (4) and (5),

$$B(t) = B_0 + \frac{1}{SN_2} \int_0^t u_2(\tau)\mathrm{d}\tau\,, \qquad (6)$$

where $B_0$ is a constant.

The magnetic flux density $B$ has been determined by digital and analog methods. In the digital way the left integration rule has been used to calculate the magnetic flux. In this case there is a problem on the input channel of the used DAQ measurement card. It has a noise with high frequency and some millivolts in amplitude. If we calculate $B$, this noise is added to the induced voltage and the outcome was wrong. That is why we used the FFT (Fast Fourier-transform) to see how to create a filter to cut the added noise from the measured induced voltage. After that we could construct the filter which is a Butterworth one. Finally, the program subtracts the offset $B_0$ from the signal. It is our experience, that we can use this method between 0.5 Hz and 200 Hz. In higher frequencies there may appear impulses with wide spectrum in the induced voltage. Exact measuring of this signal could be possible with very high sampling frequency, but it is beyond possibility with the used DAQ measurement card. Some BH-loops measured with digital integrator at 2 Hz can be seen in Fig. 2.

The analog integrators have many advantages. For example they integrate faster than the computer, they can work higher frequencies (here between 50 Hz and 1 kHz) and when using RC or RL passive integrators, it is not necessary to use filters and other signal processing algorithms. The schematic draw of the RL and RC passive integrators can be seen in Fig. 3 and Fig. 4. Some BH-loops measured with RC passive integrator at 200 Hz can be seen in Fig. 5. The output of the RL integrator can be determined as [5]

$$v(t) \cong -\frac{1}{\tau} \int_0^t u(\xi)\mathrm{d}\xi = -\frac{R}{L} \int_0^t u(\xi)\mathrm{d}\xi\,, \qquad (7)$$

the output of the RC integrator can be determined as

$$v(t) = -\frac{1}{\tau} \int_0^t u(\xi)\mathrm{d}\xi = -\frac{1}{RC} \int_0^t u(\xi)\mathrm{d}\xi\,. \qquad (8)$$
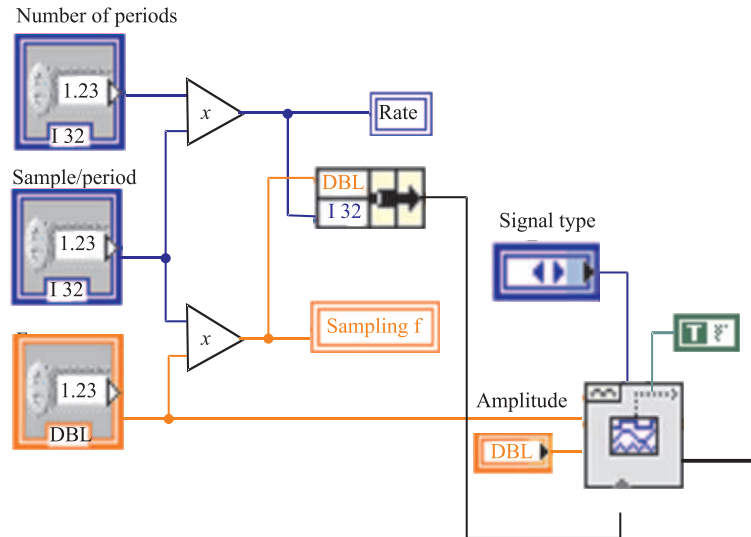
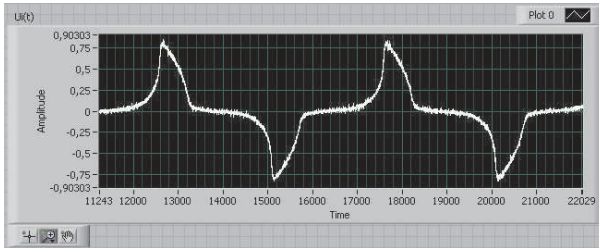**Fig. 6.** Generating the excitation signal



**Fig. 7.** The induced voltage before the filtering procedure
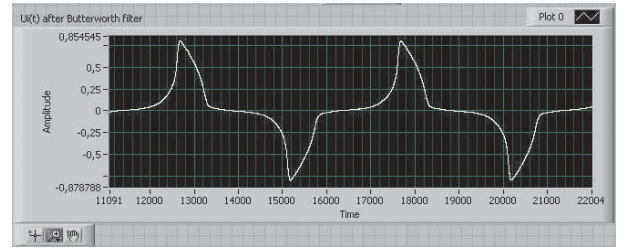


**Fig. 8.** The filtered induced voltage

## 3 ABOUT THE LABVIEW PROGRAM

Applying the developed GUI, one can set the parameters of the excitation signal (signal type, amplitude, frequency, sample per period, number of periods), the parameters of channels and the four parameters of the specimen.

The measured data, *ie* the measured signals according to the magnetic field intensity and to the magnetic flux density (see equation (3) and (6)), the post processed data as the magnetic field intensity, the magnetic flux density and the resulting hysteresis characteristic can be plotted as well. Measured results can be saved to file for further use. This is very important, because measured data can be applied to identify hysteresis models.

The signal generation rate is equal to the value of sample per period multiplied by the number of periods. The sapling frequency of excitation and measurement have been set to be equal, which is the frequency multiplied by the value of sample per period. From these data the signal of exciting current can be set up. The LabVIEW realization of this process can be seen in Fig. 6. The induced voltage before and after the filtering procedure can be seen in Fig. 7 and Fig. 8.

Next the Data Acquisition card have been reset, then output and the input channels, the sample clock of signal generation and measurement must be set, and finally the signal generation and the measurement can be started. These tasks happen simultaneously.

## 4 CONTROLLING THE FLUX

It must be noted that the hysteresis characteristic can be very steep, especially close to the coercive field, when the rate of change of magnetic flux is very high. If the variety of magnetic field intensity is controlled, then very few $HB$ data can be measured from the steep part of the curve. The aim is to get enough information about the variation of magnetic flux from every part of the characteristic. That is why we have started to develop a procedure which aims to control the waveform of magnetic flux.

The aim is to reach sinusoidal variation of the magnetic flux density, and the waveform of current must be modified iteratively by an appropriate control. The block diagram of controlling algorithm can be seen in Fig. 9, and the realized one is plotted in Fig. 10, and it is working as follows.

The reference signal is a given sinusoidal function,

$$B_{ref}(t) = B_{\max} \sin\left(\omega t - \arcsin \frac{B(0)}{B_{\max}}\right), \qquad (9)$$
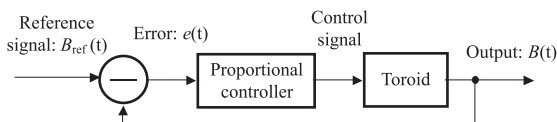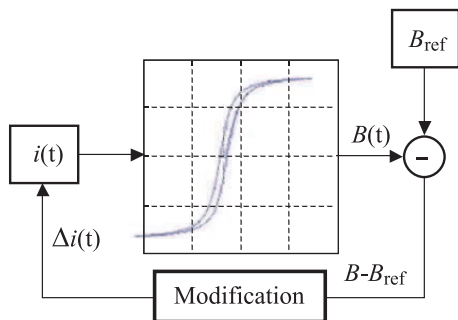
**Fig. 9.** The block diagram of controlling algorithm



**Fig. 10.** The realized algorithm

where $B_{\max}$ is the amplitude, $\omega$ is the angular frequency of the magnetic flux density, and $B(0)$ is the value of magnetic flux density when $t = 0$.

The difference between the reference signal (9) and the measured magnetic flux density is the error which is the input of the controller,

$$e(t) = B_{ref}(t) - B(t) \, . \tag{10}$$

First, the controller is a simple proportional one, ie the exciting current has been modified by $\alpha e(t)$, where $\alpha$ is a small positive number. Here is $\alpha = 0.05$ has been used after some trials.

The control algorithm has been applied until

$$MSE = \sqrt{\frac{1}{N} \sum_{k=0}^{N-1} e_k^2} \, , \tag{11}$$

*ie* the mean square error is larger then a given limit (here $\varepsilon = 0.002$).

## 5 CONCLUSIONS

In our Electromagnetic Fields Laboratory we have set up a measurement system to record the scalar hysteresis characteristics which is based on National Instruments LabVIEW software and National Instruments Data Acquisition card.

We have studied a control algorithm which is able to generate the given signal of magnetic flux density. The aim of further research is to apply the developed algorithms in measuring the hysteresis of the simulated core. The controller is the simplest one, but we believe that this is a robust method which can be used with minor modifications.

Our future plans are to identify and to compare known hysteresis models which can help in computer aided design with numerical simulations of electromagnetic fields.

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**Zoltn Pólik**, born in Győr, Hungary, in 1985. He is now BSc student at the Száchenyi István University. Member of the Laboratory of Electromagnetic Fields.

**Tamás Ludvig**, born in Győr, Hungary, in 1985. He is now BSc student at the Széchenyi István University. Member of the Laboratory of Electromagnetic Fields

**Miklós Kuczmann** (MSc, PhD), born in Kapuvár, Hungary, in 1977. He is graduated at the Budapest University of Technology and Economics in 2000 and received PhD degree in 2005 under the guidance of Prof. Amália Iványi. He is now Assistant Professor of Fundamentals of Electrical Engineering at the Széchenyi István University, Győr.