Measuring and control the hysteresis loop by using analog and digital integrators

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

1. Introduction

The exact simulation of the scalar hysteresis characteristics of ferromagnetic materials, i.e. to know the magnetization $M(t)$ as a function of the magnetic field intensity $H(t)$ is very important in the computer aided design used in electrical engineering practice. Simulation of this nonlinear system having memory is very difficult, because it is hard to find a good structure for the simulation. However, there are well known models to simulate the scalar hysteresis characteristics, for example the Jiles-Atherton model, the Stoner-Wohlfarth model, and the Preisach model [1,2,3,4,5,6,7]. To compare the known hysteresis models and the measured characteristics is very important, because we want to see that the theoretical models, simulations and procedures are working properly.

The implemented procedure developed in LabVIEW is able to measure the scalar hysteresis characteristics. The block diagram can be seen in *Fig. 1*. The control signal of the amplifier can be defined by mathematical formula; and the amplifier can follow the control signal. The amplifier is a voltage controlled current generator, which 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 amplifier has an output voltage which is proportional to the current. The measured results have been postprocessed 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.

Two procedures have been developed 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 one is an analog method with passive RL or RC integrator circuits.
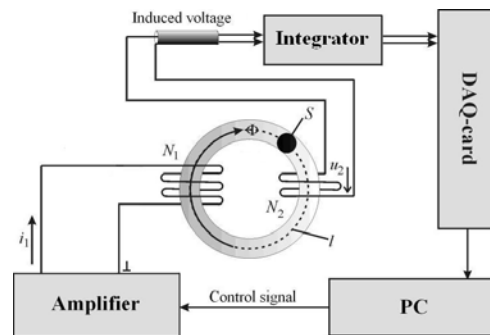

Fig. 1. The block diagram of the measurement system
2. Measurement of Field Quantities

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 $i_1(t)$ is in direct connection with this electromagnetic quantity (the primary coil has N_1 turns), i.e. [8,9,10]

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

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

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

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 $B(t)$ is depending 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, [8,9,10]

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

since

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

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. Unfortunately, it has a noise with high frequency and some mV 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 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. If the frequency of the current signal is lower than 0.5 Hz, the induced voltage is very small and noisy. Some BH-loops measured with digital integrator at 2 Hz can be seen in *Fig. 2*.
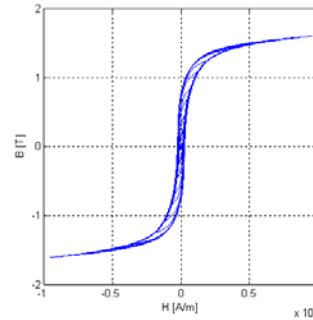

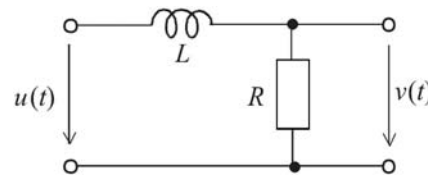Fig. 2. BH-loops at 2 Hz with digital integrator

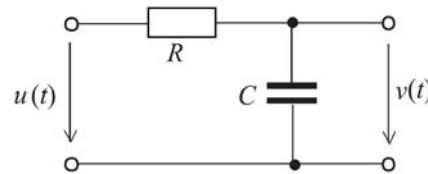
Fig. 3. RL passive integrator

Fig. 4. RC passive integrator

The analog integrators have many advantages. For example, the integration which is a time consuming method with PC must not be done, 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 [8],

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

the output of the RC integrator can be determined as

$$v(t) = -\frac{1}{\tau}\int\limits_0^t u(\xi)d\xi = -\frac{1}{RC}\int\limits_0^t u(\xi)d\xi \ .(8)$$
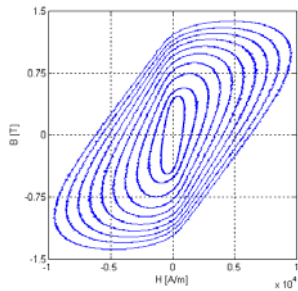

Fig. 5. BH-loops at 200 Hz with RC passive integrator

At last, some BH-loops can be seen in *Fig. 6* at 200 Hz, measured via RL passive analog, digital, and RC passive analog integrators. It can be seen that the loops are exactly the same in the stationary state. They are different only in their transient.
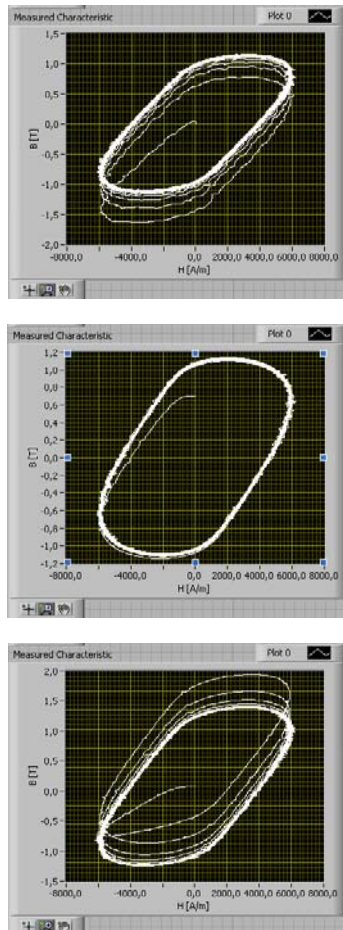

Fig. 6. BH-loops at 200 Hz with RL, digital, and RC integrator

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, i.e. 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 realization of this process in LabVIEW software environment can be seen in *Fig. 7*. The induced voltage before and after the filtering procedure can be seen in *Fig. 8* and *Fig 9*.

Next the Data Acquisiton 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.
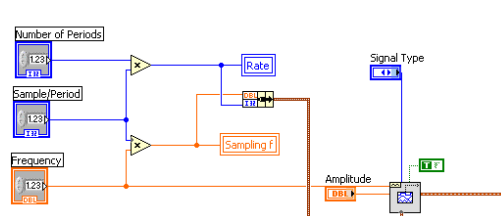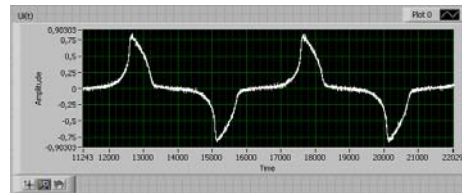

Fig. 7. Generating the excitation signal

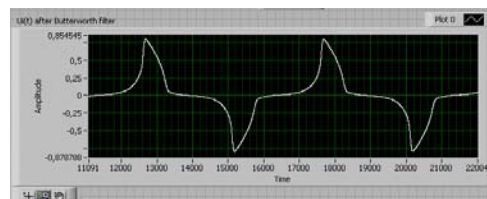
Fig. 8. The induced voltage before the filtering procedure

Fig. 9. The filtered induced voltage

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 $H - B$ 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 a

The reference signal is a given sinusoidal function,

$$B_{ref}(t) = B_{max} \sin\left(\omega t - \arcsin \frac{B(0)}{B_{max}}\right), (9)$$

where B_{max} is the amplitude, ω 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,

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

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

The control algorithm has been applied until

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

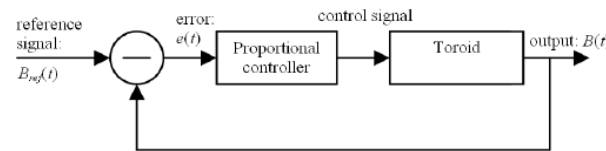i.e. the mean square error is larger then a given limit (here $\varepsilon = 0{,}002$).

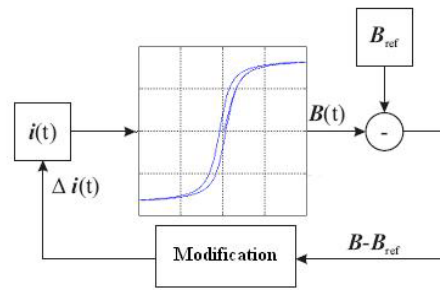Fig. 10. The block diagram of controlling algorithm.

Fig. 11. The realized algorithm

In Fig. 12 and Fig. 13 concentric loops can be seen by using the proposed simple but robust feedback, proportional controlling algorithm. In the first case the amplitude of the magnetic flux density is 1 T, then it is 1.8 T.
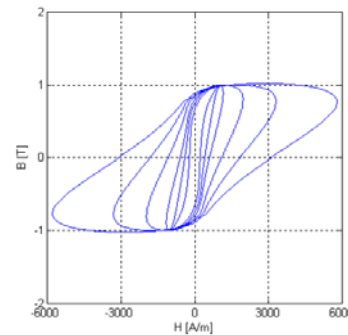

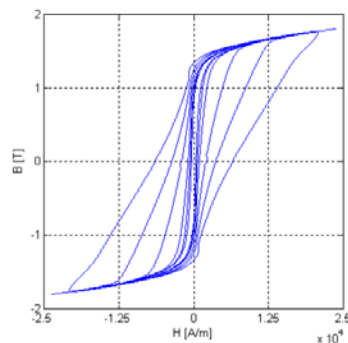Fig. 12. Concentric loops by using the controlling procedure, f=5, 10, 20, 50, 100, 200 Hz

Fig. 13. Concentric loops by using the controlling procedure, f=5, 10, 20, 50, 100, 200 Hz

5. Conclusions

In our Electromagnetic Fields Laboratory we have set up a measurement system to record the scalar hysteresis charateristics 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 belive that this is a roboust 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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