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Scalar hysteresis measurement using FFT

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The paper deals with a possible realization of eliminating the effect of noise in scalar hysteresis measurements. The measured signals have been transformed into the frequency domain, and after applying digital filter, the spectrums of the filtered signals have been transformed back to the time domain. The proposed technique results in an accurate noise removal algorithm. The paper illustrates a fast controlling algorithm applying the inverse of the actually measured hysteresis loop, and another proportional one to measure distorted flux pattern. Developing the mentioned algorithms aims the controlling of more complicated phenomena, i.e. measuring the vector hysteresis characteristics.

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1. Introduction

From electrical engineering point of view, measuring the scalar hysteresis characteristics aims the numerical implementation and identification of hysteresis models. Finally these models can be inserted into an electromagnetic field simulation procedure based on the Finite Element Method. Unfortunately, the measured curves are sometimes noisy, and some post processing is needed after the measurements which procedure may be time consuming. The aim of this work is to remove any noise in the measurement stage, and generate as fine curves as possible, i.e. to make the identification task easier.

Two methods are proposed in the paper to reach distorted flux patterns by controlling the excitation current. The first one uses the inverse of the actually measured hysteresis loop, which results in a fast technique, however it can not be used (or just in a very complicated way) in the case of distorted flux pattern. The other method is a proportional controller, which controller is universal in this field.

2. The scalar hysteresis measurement system

2. 1. Short background

In this work the scalar hysteresis characteristics have been measured on a toroidal shape core made of C19 steel which is a soft magnetic material. In general, the relationship between the magnetic field intensity vector $\boldsymbol{H}(t)$ and the magnetic flux density vector $\boldsymbol{B}(t)$ is very complicated, e.g. near the corners of a transformer core, or in the stator of an induction motor. The accurate modeling of such arrangements can not be realized without simulating the vector properties of the magnetic material under test. In the case of toroidal shape core, the magnetic field intensity vector and the magnetic flux density vector are parallel to each other, and this behavior is the direct consequence of the simple geometry of the arrangement. It is illustrated in Fig. 1. This advantageous property results in a standard and one of the simplest measurement set up to measure the scalar hysteresis characteristics of ferromagnetic materials. In this special case the axial component of the magnetic field intensity vector and of the magnetic flux density vector are supposed to represent the relationship between these two quantities. This is the scalar hysteresis characteristic, and it is denoted by the hysteresis operator $B(t) = \mathrm{B}\{H(t)\}$. Here the scalar quantities $H(t)$ and $B(t)$ are the axial components of the magnetic field intensity and the magnetic flux density vector, respectively [1,2,3].

The eddy currents flowing inside the core is depending on the frequency of excitation and on the cross section area of the material under test. If the cross section area is given, then increasing the frequency of excitation results in increasing the area of the measured hysteresis characteristic. There is a practical frequency limit: the measured hysteresis characteristic can be supposed to be static below this frequency, which is independent (let's say almost independent) of the frequency of excitation. Above this limit the characteristic is a frequency dependent one (Fig. 2).

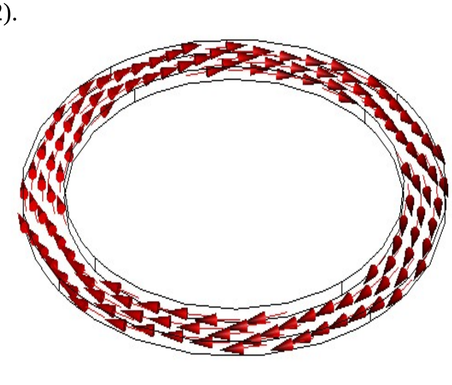

Fig. 1. The magnetic field intensity vectors inside a toroidal shape core

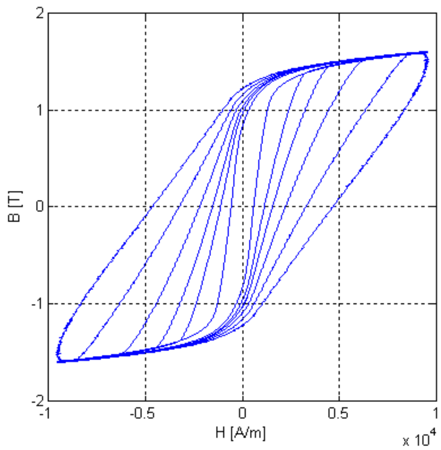

Fig. 2. The area of hysteresis characteristic is increasing by increasing the frequency

2.2. The measurement set up

The block diagram of the measurement set up can be seen in Fig. 3, and the photo of the built system is shown in Fig. 4.

The magnetic field intensity inside the analyzed specimen has been generated by the current $i(t)$ flowing in the primary coil of the core. The primary coil has N_p turns. The arbitrary waveform of current has been built up by applying some LabVIEW functions. The time variation of the magnetic field intensity results in a time varying magnetic flux $\Phi = \Phi(t)$ inside the specimen, finally the effect of this flux can be measured by the secondary coil wound on the core. The secondary coil has N_s turns which output is the induced voltage $u(t)$. Finally, this measurement set up is a simple transformer [2,3].

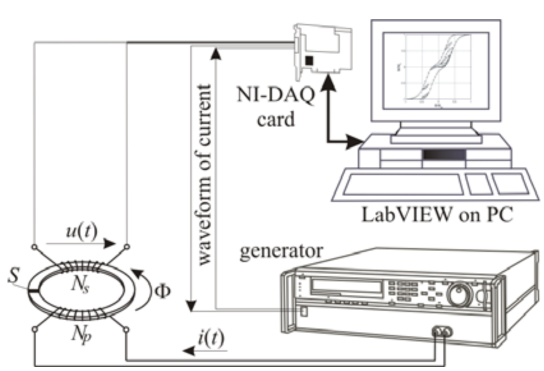

Fig. 3. Block diagram and the photo of the measurement set up

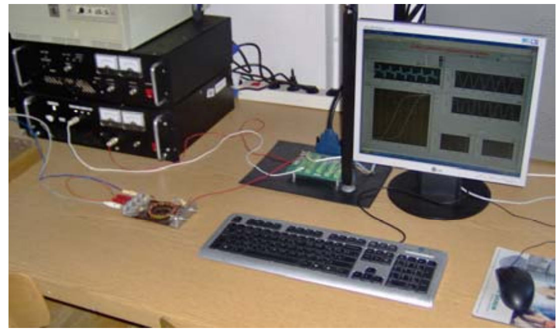

Fig. 4. The measurement system

The waveform generation, the measurements and post processing of measured signals have been worked out by using LabVIEW functions. The waveform of current can be sinusoidal or triangular with given amplitude, frequency and offset, it can be built up as a sum of different harmonics, or it can be arbitrary defined by some samples generated by functions of other mathematical software (e.g. Octave). The number of periods to measure, and the samples per one period also must be given. This waveform controls the current generator through the NI-DAQ card (National Instruments Data Acqusition Card, here NI PCI-6251 has been used) installed on the PC.

The current generator is a voltage controlled current generator which output current is proportional to the controlling voltage ($I_{max} = 30\text{A}, U_{max} = 450\text{V}$). The generator has an output where a voltage proportional to the current can be picked up. The voltage proportional to the excitation current and the induced voltage of the secondary coil have been measured by the installed NI-DAQ card. It is very important to note that the current generation and measurements are happening simultaneously (Fig. 5).

The Analog Input (AI) and the Analog Output (AO) channels must be selected to measure the induced voltage and the waveform of current, moreover to generate the waveform of current, respectively. The channels have a Physical Channel name as well, like AI1, or AO4. The minimum and the maximum limit of the input and of the output range can also be set. This range is divided into 2^{16} segments, because the applied DAQ card is a 16 bit one, i.e. the accuracy of measurements can be controlled. The next step is to reset the device then setting up the sampling parameters. The samples per channel variable, which is equal to the number of samples per period multiplied by the number of periods tells the device how much samples must be measured in one measuring period in one channel, the rate variable is equal to the number of samples per channel multiplied by the frequency. These two parameters are the sampling info of the device. Then the signal generation and the measurement stage are coming. An error message can be got in the case of any problems.

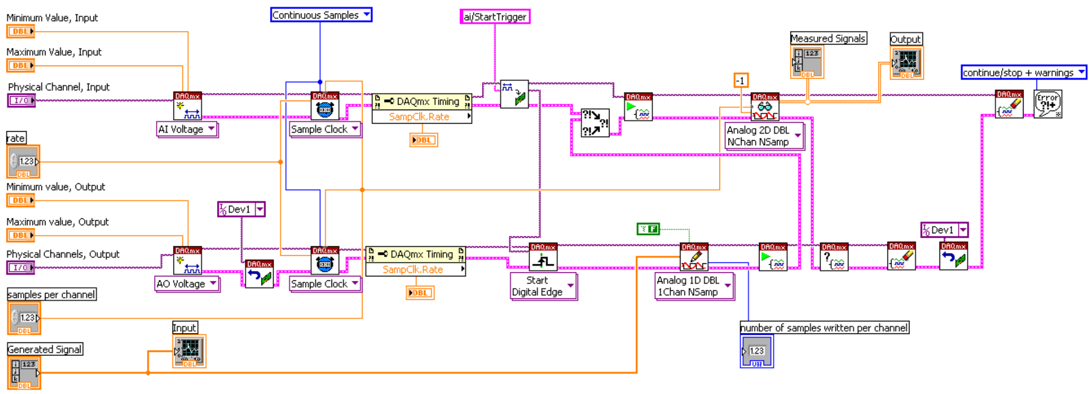

Fig. 5. LabVIEW realization of the simultaneous signal generation and measurement.

The magnetic field intensity can be measured by the well known formulation [2,3]

$$H(t) = \frac{N_p i(t)}{2r\pi}, \tag{1}$$

where r is the mean radius of the toroidal shape core. The magnetic flux density can be calculated by integrating the measured induced voltage, ie [2,3]

$$B(t) = \frac{1}{N_s S}\int_0^t u(\tau)\,\mathrm{d}\tau + B_0. \tag{2}$$

Here B_0 is used to shift the curve to the origin, and S is the cross section area of the specimen.

The parameters are: $2r\pi = 0.176\mathrm{m}$, $S = 2\cdot 10^{-5}\mathrm{m}^2$, $N_p = 170$, and $N_s = 182$.

The measurements can be handled by the user friendly Graphical User Interface (GUI) developed in the LabVIEW environment (Fig. 6).

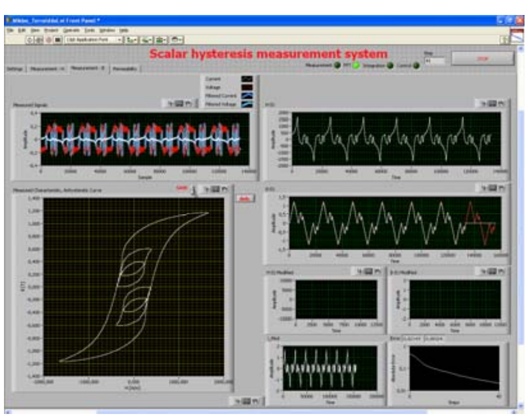

Fig. 6. The GUI of the scalar hysteresis measurement software

2.3. Applying FFT

Unfortunately, the measured signals are a little noisy, and the average value of this noise is positive [2,3]. This noise has a great effect especially in case of small exciting currents, and it can not be eliminated by setting the input range of the DAQ card. This noise results in some offset in the integrated signal (2) which is difficult to eliminate in the time domain. That is why a Fourier analysis of the measured signals has been performed, and its implementation is shown in Fig. 7.

First, the measured signals have been Fourier transformed by the FFT block of LabVIEW, and then the unwanted harmonics have been eliminated by a digital filter. The applied filtering technique is very simple, the unwanted harmonics have been multiplied by zero, and finally the filtered spectrums have been transformed back to the time domain. The DC component of the induced voltage has also been filtered. The number of harmonic components to be used *N* can be set in the GUI. The first period has been thrown out, because it contains the transient component. According to experiments, the stationary state can be reached from the second period and *N*=50 is usually enough.

Fig. 8 shows a typical amplitude spectrum of the induced voltage. The number of used periods is 6, and the number of samples per period is 22222. The peaks for further use can be selected by a for loop (Fig. 7), the other components associated to noise are much smaller (in the range of about 10^{-5}), and they are eliminated.

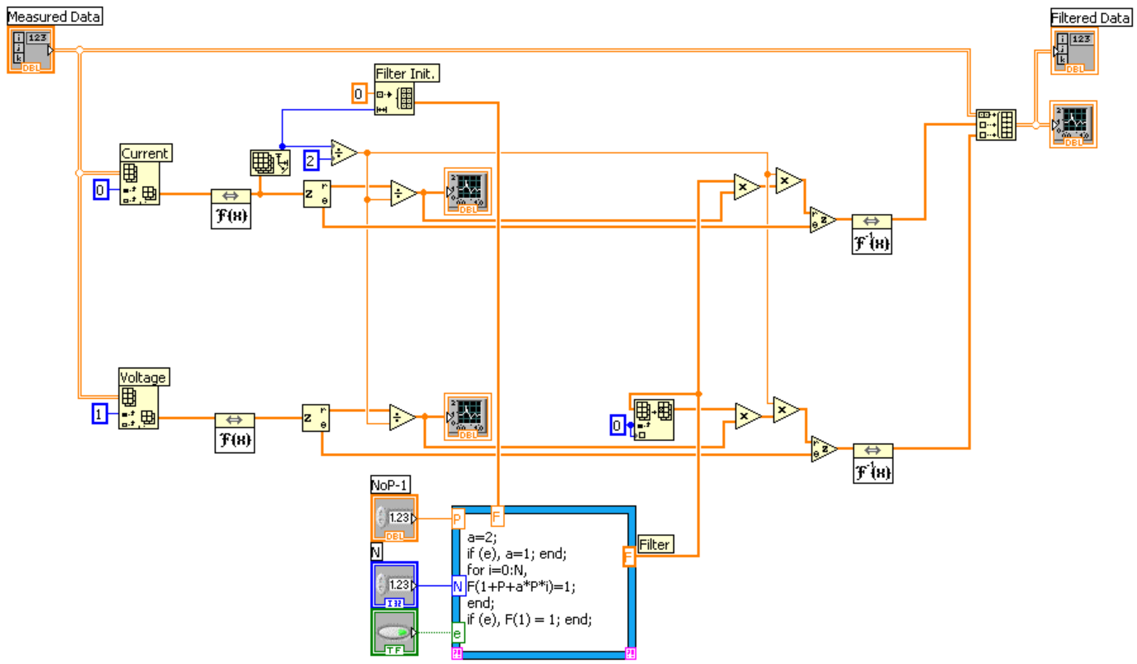

Fig. 7. The FFT algorithm with digital filtering implemented in LabVIEW

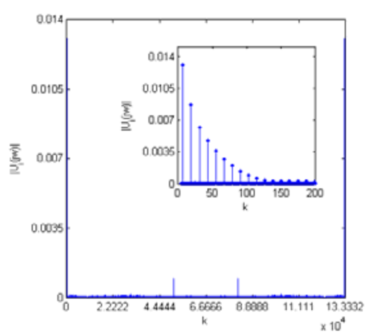

Fig. 8. The amplitude spectrum of the measured induced voltage.

The integration of the induced voltage in (2) can also be performed in the frequency domain by multiplying the k^{th} filtered component by $\mathrm{j}k\omega$.

3. Controlling the waveform of the magnetic flux density

Two controlling algorithms have been developed by LabVIEW functions. The first one uses the actually measured hysteresis curve, the second one uses a simple, but robust proportional controller algorithm. The controller applying the measured hysteresis characteristic is very fast in the case of measuring a concentric loop, or a first order reversal curve, but it is not a general method. Proportional controller can be applied in arbitrary waveform of the magnetic flux density, but it is not as fast as the method using the inverse loop.

3.1. Applying the inverse characteristic

The below mentioned algorithm is not general, but results in a high speed, convergent algorithm when aiming concentric minor loops or first order reversal curves. The algorithm is as follows (see Fig. 9):

1. Start with sinusoidal or triangular waveform of current with given amplitude, offset and frequency.
2. Measure the time variation of the magnetic field intensity and the magnetic flux density, i.e. the hysteresis characteristic. Of course, filtering must be applied. This is the $(k-1)^{th}$ step.
3. Generate the inverse of the measured hysteresis curve.
4. Generate the new (the k^{th}) waveform of the magnetic field intensity according to the desired magnetic flux density by applying the inverse curve and simple first order interpolation, if necessary. This process is shown by arrows in Fig. 9.

5. Update the waveform of current from the proposed magnetic field intensity according to (1), and then apply the generated current.
6. Repeat the sequence from step 2, while an accurate result is reached.

This algorithm converges in 3-5 steps.

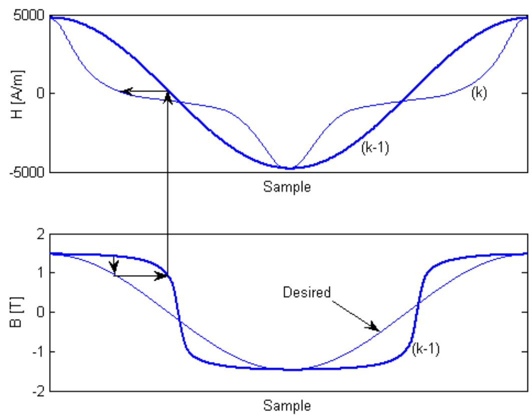

Fig. 9. Illustration for the controller with the inverse characteristic – one step of the algorithm

The first order reversal curves in Fig. 10 and the concentric minor loops in Fig. 11 have been measured by this procedure.

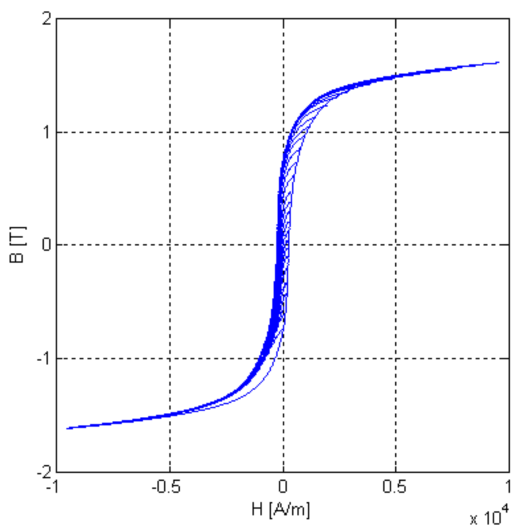

Fig. 10. Measured first order reversal curves

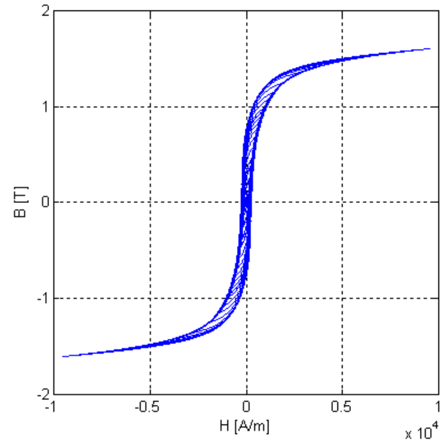

Fig. 11. Measured concentric minor loops

3.2. Applying a proportional controller

The below mentioned algorithm is general, but not as fast as the algorithm mentioned in Section 3.1. The algorithm is as follows:

1. Measure the anhysteretic curve according to the applied frequency, before controlling the flux.
2. Generate an initial waveform of the magnetic field intensity (i.e. the current) by using the inverse of the anhysteretic curve, and the desired waveform of the magnetic flux density.
3. Start with the proposed initial waveform of current.
4. Measure the time variation of the magnetic field intensity and the magnetic flux density, i.e. the hysteresis characteristic. Use the filtering method as well.
5. Compare the measured and the desired waveform of the magnetic flux density, ie build up the time variation of the error which must be minimized.
6. Multiply the error function by a small constant value which results in a controller signal.
7. Modify the actual waveform of current by the controller signal.
8. Repeat the sequence from step 4, while a given value of error is reached.

This algorithm converges in 8-10 steps or sometimes more. The proportional constant can be modified by another method during the algorithm but it was taken as a constant in this study. The minor loops in Fig. 12 and in Fig. 13 are measured by this procedure. Fig. 14 and Fig. 15 shows the hysteresis curves according to the following distorted flux patterns f=5Hz and f=50Hz,

$$B(t) = \hat{B}\begin{bmatrix} 0.463\cos(\omega t + 36.33^{\circ}) + 0.234\cos(3\omega t - 89.6^{\circ}) + \\ 0.141\cos(5\omega t + 148.03^{\circ}) \end{bmatrix},$$

and

$$B(t) = \hat{B}\begin{bmatrix} 0.67\cos(\omega t + 16.6^\circ) + \\ 0.072\cos(17\omega t + 163.8^\circ) + 0.034\cos(19\omega t - 177^\circ) \end{bmatrix}.$$

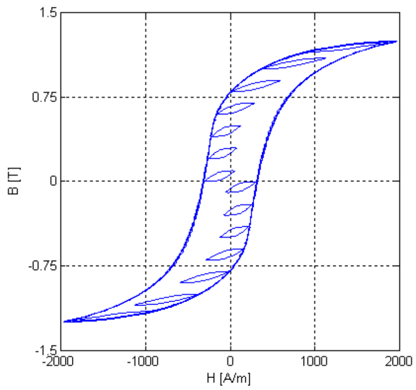

Fig. 12. Measured minor loops along a loop

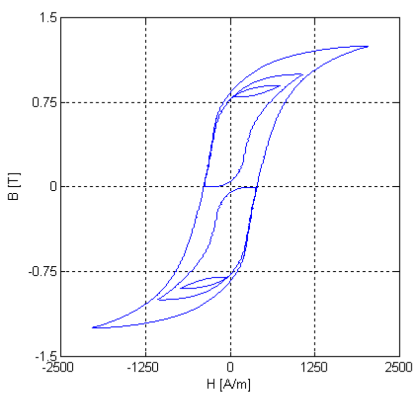

Fig. 13. Measured second order minor loops

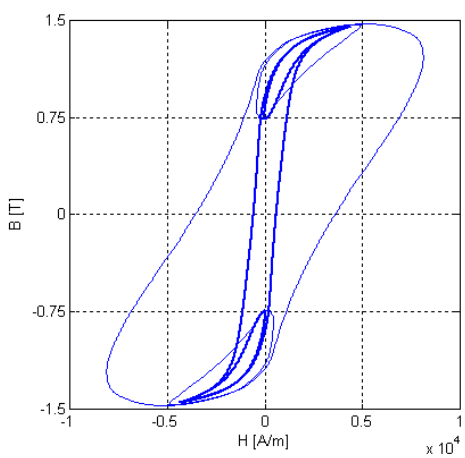

Fig. 14. Distorted flux pattern with low order harmonics

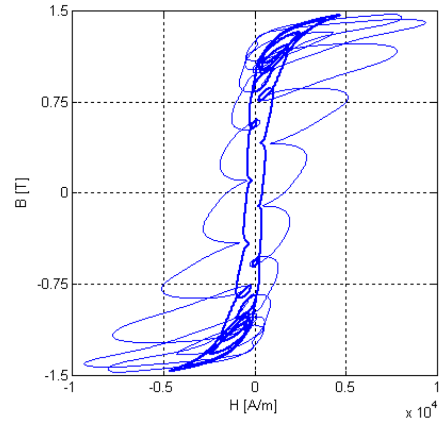

Fig. 15. Distorted flux pattern with higher order harmonics

4. Conclusions

The paper presents a scalar hysteresis measurement system based on a toroidal shape specimen and a procedure developed by LabVIEW functions. The noisy induced voltage has been filtered by digital filtering technique implemented by software in the frequency domain. The drift of the magnetic flux density associated with the noise of the measured induced voltage can be eliminated by the proposed method. Two types of algorithms have been presented to control the waveform of flux with their advantages and disadvantages as well.

Aim of further research in this field is to identify the scalar Preisach model of this material (static and frequency dependent models), and to apply it in finite element procedures.

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