Measuring of rotating magnetic flux in an integrated environment

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Abstract. The paper describes a measuring method and the establishment of a measuring environment for two-dimensional rotating magnetic fluxes and fields. The measuring method relies on measuring currents and voltages in coils attached to the magnetic specimen. For the processing and generating of measuring signals, a PC-based system running LabView is applied extended with a NI ELVIS II board, and two high performance KIKUSUI bipolar power supplies. The measurement results are satisfactory and show that the measuring environment established is capable of non-destructively capture the two-dimensional magnetic characteristics of the specimen investigated.

1. Introduction
Since there are many application areas where rotating magnetic fields and fluxes appear, and the intrinsic vectorial nature of hysteresis can not be neglected, the goal of the paper is to present a possible approach of two-dimensional measurement and investigation of hysteresis characteristics under rotating field conditions. The measuring environment (hardware/software), the two-dimensional set-up, and the theory behind the measurement is discussed along with the brief description of the applicability of hardware and software used. Measurement results are presented in order to prove the applicability of the method.

2. The method of two-dimensional measurement
The schematic of the measurement setup can be seen in figure 1. In the figure it can be seen, that the cross-shaped specimen is equipped by four coils; two primary coils (x and y directions) providing the excitation current [1], and two diagonally attached perpendicular secondary coils for the measuring of induced voltage. The theory behind the measurement can be derived from the quasi-stationary Maxwell equations as follows [2].

The set of equations needed is

\[ \nabla \times \mathbf{H} = \mathbf{J} + \sigma \mathbf{E}, \]  \hspace{1cm} (1)

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \]  \hspace{1cm} (2)
where $H$ is the magnetic field strength, $E$ is the electric field, $B$ is the magnetic flux density and $J_s$ is the external current density. The eddy current term $\sigma E$ in (1) can be omitted due to the thin (0.27 mm) sheet specimen and low (max. 50Hz) frequency applied during this measurement.

2.1. Theory of measurement

As figure 1 shows, the whole measurement procedure is conducted by a PC equipped with National Instruments LabView 8.6 software and a NI ELVIS II board. The NI ELVIS II board is responsible for interfacing the signal flow between the computer and the actual measuring device. The specimen measured consists of two perpendicularly attached Fe-Si 3.1%(wt) transformer sheets, which have thickness of 0.27mm. For the purpose of excitation there are two primary excitation coils ($x$ and $y$ directions) driven by two KIKUSUI PBX 20-20 bipolar power supplies as current sources\(^1\). The secondary coils ($u'$ and $u''$) attached are responsible for measuring the induced voltage by the aid of the NI ELVIS II board.

\[ \nabla \times H = J_s, \]  
\[ \int_{\Omega} \nabla \times H \, d\Omega = \int_{\Omega} J_s \, d\Omega, \]  
and by the application of Stokes' theorem, (4) has the form

\(^1\) The frequency of the excitation signals was 10 Hz.
where the right hand side is basically the sum the excitation currents in the coil-domain, and assuming that the field strength is constant along the path of the integral (due to the symmetrical set-up of Epstein-frame) the left hand side integral can be substituted by $\mathbf{H}l$, thus

\[ Hl = N_p I, \tag{6} \]

where $N_p$ is the number of turns of the primary excitation coil, $l$ is the length of the frame around the specimen, and $I$ is the primary excitation current.

In a similar way the flux density $\mathbf{B}$ can be derived from the integral form of (2)

\[ \int_{\Omega} \nabla \times \mathbf{E} \, d\Omega = -\frac{\partial}{\partial t} \int_{\Omega} \mathbf{B} \, d\Omega, \tag{7} \]

applying Stokes' theorem we have

\[ \int_{l} \mathbf{E} \, dl = -\frac{\partial}{\partial t} \int_{\Omega} \mathbf{B} \, d\Omega, \tag{8} \]

where the left hand side of the equation is the voltage $u_t$ of one turn of the measuring (secondary) coil, and the integral on the right hand side can be substituted by $\mathbf{B}A_s$ under the assumption that the flux density $\mathbf{B}$ is homogenous in the central region of the specimen, and spread flux can be neglected. Now (8) can be written as

\[ u_t = -\frac{\partial}{\partial t} \mathbf{B}A_s. \tag{9} \]

Since the measuring coil has $N_s$ turns, the actual measured voltage $u$ of the secondary coil is $N_s$ times higher than $u_t$, thus finally we have

\[ \frac{1}{N_s} u = -\frac{\partial}{\partial t} \mathbf{B}A_s, \tag{10} \]

where $A_s$ is the cross-sectional area of the the sheet that the specimen is made of, $N_s$ is the number of turns of the secondary coil. Writing (10) in integral form leads to

\[ \mathbf{B} = \frac{1}{N_s A_s} \int u \, dt. \tag{11} \]

At this point (6) and (11) is enough to calculate the field strength and flux density inside the specimen under homogenous assumptions. It is important to note here, that the components of the flux density $\mathbf{B}$ obtained by (11) are not aligned with the $x$ and $y$ directions of the specimen$^2$, due to the diagonally attached measuring coils. As figure 2 shows, the diagonal component $B'_d$ of the flux density has a contribution from both $B_x$ and $B_y$, thus we actually measure the superposition of them.

The orientation of the components of the flux density $\mathbf{B}$ calculated by (11) depends on the angle $\alpha$ between the measuring (secondary) coils and the axes of the coordinate system attached to the specimen investigated. According to the set-up in figure 1, the axes of the coordinate system (aligned with primary excitation coils) are parallel to the horizontal and vertical part of the cross shaped sheet, and the two measuring coils are situated along the diagonals in the center.

$^2$ It could be useful to introduce a different symbol for this transformed $\mathbf{B}$, but for the sake of easy readability it will be omitted.
Since the measuring (secondary) coils are attached diagonally to the specimen (see figure 1), the calculation of actual flux density $B = [B_x, B_y]^T$ (corresponding to the field strength $H = [H_x, H_y]^T$) requires the solution of the following linear system

$$\begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} B_x \\ B_y \end{bmatrix} = \begin{bmatrix} B' \\ B'' \end{bmatrix}$$

(12)

where $B'$ and $B''$ are the components of the measured flux density calculated by (11).

![Figure 2. Transformation of the geometry.](image)

2.2. The compensated measurement procedure

The goal of the vectorial measurement is to obtain circular (uniform magnitude) flux density, and since the excitation is directly related to the field strength $H$ instead of flux density $B$, an iterative compensation procedure is required in order to achieve the above goal.

During the iterative measuring procedure we get a more and more uniform magnitude flux density by adjusting the input signal in each iteration step according to the error function $\varepsilon(\phi)$ of the preceding iteration. The error function can be defined as

$$\varepsilon^{(i)}(\phi) = \|B_{m}^{(i)}(\phi) - B_{\text{ref}}\|,$$

(13)

where $B_{m}^{(i)}(\phi) = \|B^{(i)}(\phi)\|$ is the magnitude of the rotating flux density at angle $\phi$ at the $i$-th iteration step, and $B_{\text{ref}}$ is the desired magnitude, which is about to be achieved by the iterative measuring procedure. The iteration stops if the total absolute error falls below a given threshold $\varepsilon$, like

$$\int_{0}^{2\pi} \varepsilon(\phi) \, d\phi < \varepsilon.$$

(14)

The schematics of the measuring algorithm can be seen in figure 3.

As it can be seen in the figure, after the $i$-th measurement step is accomplished and the processing of the measured data had been carried out, the error function of the actual iteration step is calculated according to (13). If (14) holds, the iteration terminates, if not, the algorithm adjusts the excitation signal as follows

$$H_{m}^{(i+1)}(\phi) = H_{m}^{(i)}(\phi) - \eta \varepsilon^{(i)}(\phi)$$

(15)
where $H_m^{(i+1)}(\phi) = \|H^{(i+1)}(\phi)\|$ and $H_m^{(i)}(\phi) = \|H^{(i)}(\phi)\|$ are the magnitude of the rotating field strength at angle $\phi$ at the $(i + 1)$-th and $i$-th iteration steps respectively, and $\eta$ is a properly selected feedback coefficient.

3. Results and discussion
In this section various measurement results obtained by the method outlined above is presented.

3.1. Scalar measurements along $x$ and $y$ axes
The specimen investigated is constructed by attaching two Fe-Si sheets with slightly different characteristics. As a consequence of this the set-up shows anisotropic behaviour. In figure 4 the separate hysteresis curves corresponding to the $x$ and $y$ directions can be seen.

![Hysteresis Characteristics](image)

**Figure 4.** Hysteresis characteristics along the $x$ and $y$ axes respectively.

As it is apparent from the figure the sheet aligned to the $x$ axis has a sharper characteristic with smaller coercivity and higher differential permeability. These differences certainly affect the vectorial measurement results as well, as it is shown in the next section.

3.2. Vector measurements
The results correspond to different reference flux density $B_{ref}$ values showing the circular (almost uniform magnitude) flux pattern and the field strength excitation. The allowed deviation of flux patterns from the perfectly uniform circle is controlled by the error threshold $\epsilon$ defined in (14).
Figures 5, 6, and 7 show the circular flux patterns and the corresponding two-dimensional excitation. It is apparent from the figures, that the investigated specimen shows anisotropic behavior, the field strength patterns are not symmetrical. In order to obtain a circular, uniform magnitude flux density, significantly higher magnitude field strength is required to be applied to the $y$ direction.

![Figure 5](image1.png)

**Figure 5.** Rotating field and flux density pattern at reference flux $B_{ref}=1.45$ T.

This magnitude difference between the directions is higher in the case of lower reference flux density values (figure 5), and the difference is lower in the higher magnitude flux density region (figure 7) since as the specimen is getting close to saturation, the differences between the $x$ and $y$ hysteresis characteristics (see figure 4) begin to vanish.

![Figure 6](image2.png)

**Figure 6.** Rotating field and flux density pattern at reference flux $B_{ref}=1.725$ T.

It can also be seen in the figures, that the axis of easy magnetization has a slight declination from the $x$ axis of the coordinate system attached to the specimen. This phenomenon is getting stronger with the increasing of the reference flux density $B_{ref}$, as it is clear from figure 7.

### 4. Conclusion and future works
A possible measuring environment is established, and a non-destructive way of hysteresis measurement method is applied for two-dimensional vector hysteresis measurements in order
to investigate the magnetic field strength and flux density patterns. Both the hardware-software environment - consisting of NI LabView, NI ELVIS II board and the two programmable power supplies - and the theory applied proved to be acceptable for the purpose of successful vectorial measurements, investigations. The PC-based measuring environment provides great flexibility and programmability along with high accuracy.

Figure 7. Rotating field and flux density pattern at reference flux \( B_{\text{ref}} = 1.845 \, \text{T} \).

As a future goal it is planned that the environment is extended by a programmable Finite Element package in order to carry out more complicated modelling/simulation tasks, investigate more complex flux patterns and to validate various vector hysteresis model implementations.

5. References

[1] Enokizono M 1992 Two-dimensional magnetic measurement and its properties: JSAEM studies in applied electromagnetics vol.1 (Oita)

[2] Ivanyi A 1997 Hysteresis models in electromagnetic computation (Budapest, Akadémiai Kiadó)