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CALIBRATION OF AC INDUCTION MAGNETOMETER

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Abstract. *The aim of this paper is to describe a procedure and experimental setup for calibration of AC induction magnetometer. The paper presents an overview of the previous research and results of measurement of magnetic flux density inside large-diameter multilayer solenoid. This solenoid is magnetising coil of the magnetometer. The paper also describes a system of five smaller coils of the magnetometer which are placed inside the large solenoid. Three small coils are pickup coils, accompanied with two compensation coils, of which one is an empty coil for magnetic field measurement. The experimental results of calibration of this coil system have been presented. A proper discussion of all the results presented has been also given in the paper*.

Key words: *Induction magnetometer, calibration, measurement uncertainty, Hall sensor, LabVIEW.*

1. Introduction

Iron loss in induction motors can reach up to 20% of the total losses [2]. Large efforts were made to improve production of the electrical steel and to reduce losses. Amorphous materials have been also used because of lower losses. Measurement of their magnetic characteristics has become of great importance in order to obtain reliable data on power loss of these materials. AC induction magnetometer have proved to be a powerful tool for characterisation of the ferromagnetic materials [3, 4].

Induction magnetometer uses a long solenoid for magnetisation of the sample [3, 4]. A pickup coil is placed inside the long solenoid and used for measurement of the magnetic flux density in the sample of ferromagnetic material. A lateral dimension of the sample is not large, usually in order of several millimetres (diameter of wire or bar and width of strips), while its length usually amounts several centimetres and may be up to 10-15 cm. Another pickup coil may be also placed inside the long solenoid, without the sample, and used for measurement of the magnetic field.

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In general, it is easy to control a time waveform of the magnetic field created by the long solenoid. Therefore, the magnetic field has desired shape, while the magnetic flux density shape depends on the material response. When it is used along with the personal computer, as a digital measurement setup, it enables performing of very complex experiments, such as those for measurement of first-order reversal curves [3, 4].

This measurement method is based on two basic laws of magnetism - Ampere's law for magnetising coil and Faraday's law for pickup coil. In the case when a long solenoid with small diameter is used as magnetising coil, according to the Ampere's law, the magnetic field is homogeneous and has longitudinal direction and constant amplitude [4]. However, this is not easy to achieve in practice and in many cases the magnetic field is homogenous only in the middle zone of the solenoid. This limits the length of the pickup coil. Because of this inhomogeneity, the magnetic field can not be always accurately calculated according to Ampere's law, using measured current of the solenoid. The Faraday's law applied to the pickup coil may also provide inaccurate result if the pickup coil is placed in the zone where the magnetic field is not homogeneous. Therefore, the whole system needs to be calibrated.

In this paper, a calibration procedure will be described and performed on the coil systems of one old AC induction magnetometer - Ferrotester 2738/S-3. As an initial step in the calibration of the magnetometer, a homogeneity of the magnetic field inside a large-diameter multilayer solenoid (large solenoid) has been investigated in the prior research [1]. It has been found that the homogeneity zone covers only one third of the solenoid (its central part). A variation of the magnetic field in this zone was less than 1 % of its maximum value. An inner coil system of this magnetometer contains five smaller coils, one coil for measurement of the magnetic field (empty coil) and two pairs of coils in mutual opposition for measurement of the magnetic flux density and magnetisation. The calibration of this coil system, along with the calibration of the magnetising solenoid, will be presented in this paper.

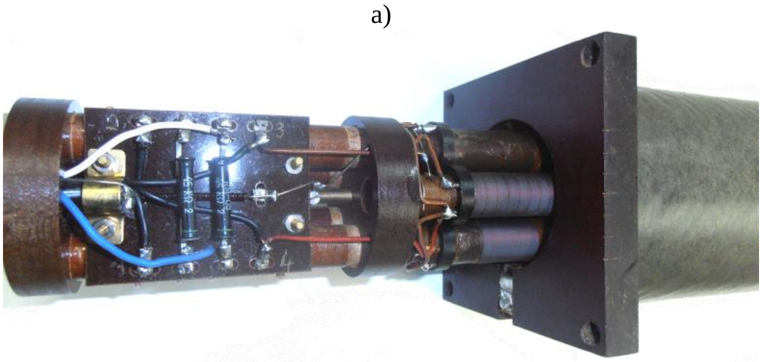
A calibration of the magnetometer has been performed using a PC based measurement setup. The Hall sensor has been used for measurement of the magnetic flux density in a homogeneity zone of the large solenoid. Voltage supplied and electric current of large solenoid have been also measured. Five voltages from the system of pickup coils have been measured: one on the empty coil, two on coils in the opposition and two compensated voltages. Measurements have been performed using NI USB 6009 data acquisition card and application created in LabVIEW software. A ratio of the magnetic flux density maximum and the electric current maximum gives a calibration constant of the large solenoid. A calibration constant of each pickup coil has been calculated from the corresponding voltage maximum.

This paper gives a detailed description of AC induction magnetometer, all information on the measuring equipment and calibration procedure, as well as the results obtained during the calibration. It also gives a detailed calculation of the measurement uncertainty, as well as a discussion of the results obtained, and explains how to calculate the magnetic field, the magnetic flux density and the magnetisation using obtained calibration constants. Moreover, some practical comments on measurements at various frequencies of the magnetising current are given in the paper.

2. AC INDUCTION MAGNETOMETER

A photo of the AC induction magnetometer is given in Fig. 1. It was a part of equipment of Ferrotester 2738/S-3. It has 360 mm long magnetising coil (large solenoid) of inner diameter $2r_0$=65 mm, Fig 1*a*. A number of turns is unknown (it is not given in the user manual). It also has a system of five pickup coils, each 100 mm long with inner diameter 15 mm, Fig 1*b*. A number of turns is also unknown. A cross-section of the magnetometer is presented in Fig. 2*a* and an electrical scheme of connections of pickup coils is given in Fig. 2*b*.

a)

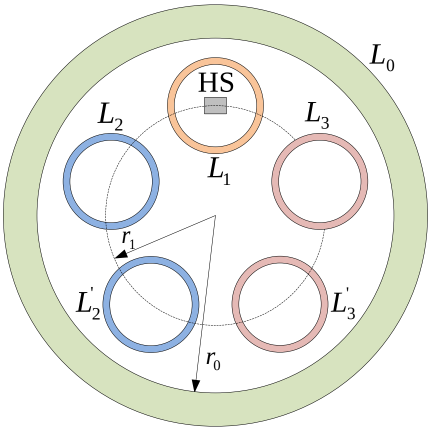


b)

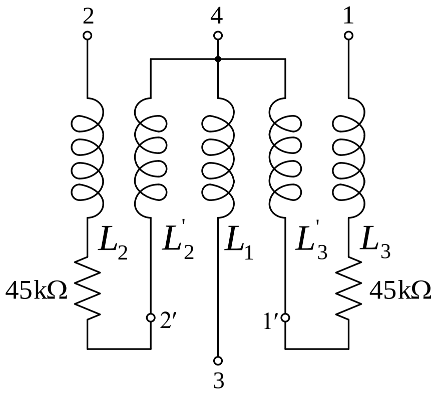
Fig. 1 Photos of the induction magnetometer:
a) large solenoid, b) pickup coils inside large solenoid

Five pickup coils are placed inside a large solenoid L_0 in its central part ($z\in(-5, 5)$ in Fig. 3) at the same distance r_1=20 mm from its axis (x=0 in Fig. 3). As it has been presented in [1], this is a zone with a homogeneous magnetic field in which the variation of the magnetic field intensity is less than 1 % of its maximum.

Since whole system has axial symmetry, pickup coils are exposed to the same magnetic field. Coil L_1 is used for measurement of the magnetic field and its interior should not contain samples of ferromagnetic material. Coils L_2 and L'_2 are two identical coils wound in the opposite direction and connected in mutual opposition, as it is given in Fig. 2*b*. Coils L_3 and L'_3 are identical, wound in the opposite direction, and connected in mutual opposition (Fig. 2*b*). A small difference between coil systems 2 and 3 has been observed. A sample of ferromagnetic material under test can be placed in any of these four pickup coils and the magnetic flux density can be measured. A resistor (45 kΩ) is connected in series with two coils in opposition to reduce the electric current in the coils, Fig. 2*b*.



a)



b)

Fig. 2 Induction magnetometer:
a) cross-section, b) electrical scheme of connections of pickup coils

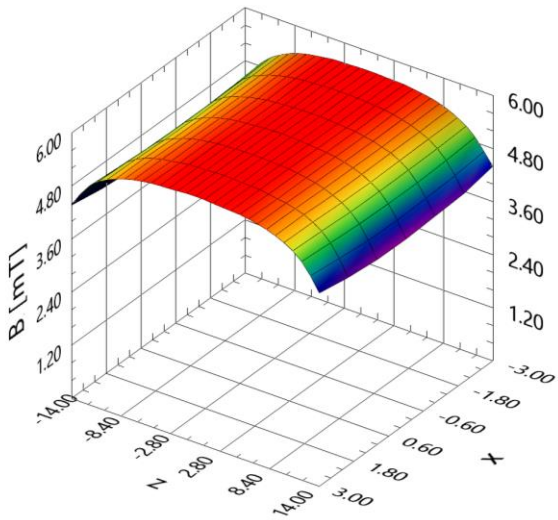


Fig. 3 Total magnetic flux density distribution inside large solenoid

Fig. 2*a* also shows a position of Hall sensor (HS) used for direct measurement of the magnetic flux density inside large solenoid. This sensor (type SS49E) is inserted in the vertical gap of the cylindrical plastic holder (perpendicular to its axis). Along with holder, the sensor is placed inside the coil L_1 in the middle of its length, perpendicular to the longitudinal axis of the coil and perpendicular to the magnetic field. A photo of the sensor and 3D printed plastic holder are presented in Fig. 4.

Fig. 4 Hall sensor and its position inside plastic holder

Usually, the magnetic field H generated by a long solenoid is calculated from the measured electric current i using expression (1) [5], according to Ampere's law:

$$H = \frac{N}{l} i = \frac{N}{l} \frac{u}{R}, \tag{1}$$

where N is the number of the turns of large solenoid L_0, l is its length, R is the resistor connected in the series with the solenoid and u is the voltage measured at the ends of R. However, this can not be used since N is unknown for L_0. In general, the expression (1) can not be used with good accuracy in the case of a large-diameter multilayer solenoid L_0.

If the ferromagnetic sample is placed inside pickup coil, according to Faraday's law, a voltage induced u_L in the pickup coil is equal to [4]:

$$u_L = -N_p \frac{\mathrm{d}\Phi}{\mathrm{d}t} = -\mu_0 N_p \left(S_S \frac{\mathrm{d}M}{\mathrm{d}t} + S_p \frac{\mathrm{d}H}{\mathrm{d}t} \right), \tag{2}$$

where μ_0 is the permeability of vacuum, N_p is the number of the turns of pickup coil, S_p is the cross-section area of the pickup coil, S_S is the cross-section area of the sample, Φ is the magnetic flux and M is the magnetisation. The voltage measured at the non-common ends of the pickup coils in mutual opposition is equal to the first term in the expression (2). If no sample is placed inside the pickup coil in mutual opposition, the voltage induced in that pickup coil is equal to the second term in the expression (2).

If no sample is placed inside pickup coils, induced voltages are equal and the resulting voltage is equal to zero or very close to zero. According to the IEC standard for Epstein frame [6], the resulting voltage should be smaller than 0.1 % of the individual voltages.

Expression (2) can not be applied to the pickup coils of the described magnetometer since these coils are multilayer coils and the number of turns is unknown.

3. Calibration Procedure and Results

The calibration of induction magnetometer is performed in three steps:

1. Calibration of Hall sensor,
2. Calibration of large solenoid and
3. Calibration of pickup coils.

The calibration is necessary because numbers of turns of all coils are unknown for the used induction magnetometer. The large solenoid generates a homogeneous magnetic field only in the central zone. Even if this is not the case, it is always better to perform the calibration and to compare obtained results with calculations.

All measurements are performed with controlled sinusoidal excitation voltage and current, at the frequency of 50 Hz. NI USB 6009 data acquisition card is used in all measurements [7]. Three simple LabVIEW applications are developed for each step of the calibration. In all measurements the averaging is used to reduce the noise [8].

3.1. Calibration of Hall sensor

The Hall sensor SS49E has linear output voltage in the range of magnetic flux density from −100 mT to 100 mT [9]. Therefore, it is suitable for measurement of the magnetic flux density generated by large solenoid L_0. However, it needs to be calibrated in order to determine its sensitivity. A calibration is performed using a long solenoid (l=340 mm) with small diameter (25 mm). A varnished copper wire of 1.8 mm thick is used for winding of N=190 turns of this solenoid. An electric current $i(t)$ of the solenoid is measured using a shunt resistor (20 A, 75 mV). The magnetic flux density is calculated as follows:

$$B(t) = \mu_0 \frac{N i(t)}{l} \,. \tag{3}$$

The sensor characteristic $U_{H\max}=f(B_{\max})$ is obtained according to the maximum of the voltage u_H measured at the output of the sensor and the maximum of the magnetic flux density calculated using expression (3). Measurements are performed in the increasing and the decreasing direction in order to examine the linearity of the characteristic. A sensitivity of the sensor is calculated from the slope of the obtained characteristic. Characteristics of the sensor (blue lines) obtained from two measurements for maximal magnetic flux densities of 10 mT (green squares) and 20 mT (red circles) are presented in Fig. 5.

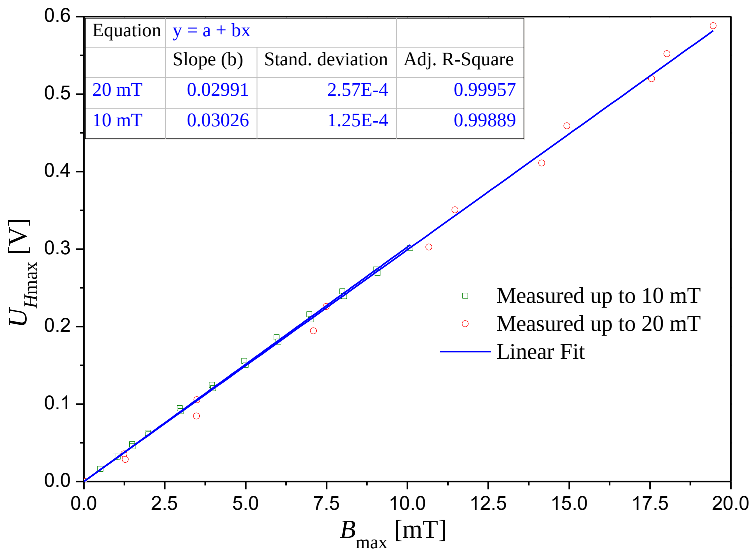


Fig. 5 Calibration of Hall sensor - measurement results and linear fit

The figure presents also a table with calculated slopes, standard errors and adjusted R-squares. For a given dataset (x_i, y_i), i=1, 2, …, n, the standard deviation (error) ε and the adjusted R-square $\bar{R}^2$ of linear model $y=a+bx$ can be calculated as [10]:

$$\varepsilon = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(y_i-(a+bx_i))^2}{n-1}}}{\sqrt{\sum_{i=1}^{n}x_i^2}}, \tag{4}$$

$$\bar{R}^2 = 1-\frac{\dfrac{\sum_{i=1}^{n}(y_i-(a+bx_i))^2}{n-1}}{\dfrac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n}};\ \bar{y}=\sum_{i=1}^{n}y_i\ . \tag{5}$$

According to Fig. 5, the sensitivity of Hall sensor is equal to S=0.03 V/mT.

It is interesting to notice that both measurements in Fig. 5 show a dispersion of results. This effect has been examined more thoroughly. It has been found that this behaviour comes from the heating and cooling of the shunt resistor during the measurement of electric current. For lower values of the supply current (up to 10 A, RMS) this effect is not expressed so much (green squares) and it can be neglected. Therefore, it can be concluded that the sensor output is linear with a constant sensitivity. However, the second measurement (red circles) shows significant dispersion of the results and the calculated slope is lower by 1.16 % than in the first measurement. Such a difference can be in the range or even higher than the overall measurement uncertainty of the experiment (discussed in details in Section 4). Therefore, attention needs to be paid to such effect and its influence on the calculated results.

3.2. Calibration of large solenoid

The calibration of the large solenoid is performed with the calibrated Hall sensor. At this step, dependence of the magnetic flux density generated by the large solenoid on its electric current is examined. A final result of the calibration is $B_{max}=f(I_{max})$ characteristic of the large solenoid. The electric current of the large solenoid is measured using a shunt resistor. The magnetic flux density is calculated using the measured output voltage of Hall sensor and dividing it with the sensitivity S obtained in the previous step. The Hall sensor is placed in the middle of large solenoid, so that the sensor surface is perpendicular to its longitudinal axis and the magnetic field. Measurements are performed with the increasing and the decreasing of the electric current in order to examine the linearity of the characteristic.

The result of the calibration of the large solenoid is presented in Fig. 6. According to the linear fit of measured results, the slope of the $B=f(I)$ characteristic of large solenoid is around 19.77 mT/A. The linearity of this characteristic confirms the conclusion from the calibration of the Hall sensor that dispersion of measurement results comes from the variation of temperature of the shunt resistor. The obtained slope can be used in further measurements in the calculation of the magnetic flux density generated by the large solenoid according to the measured current.

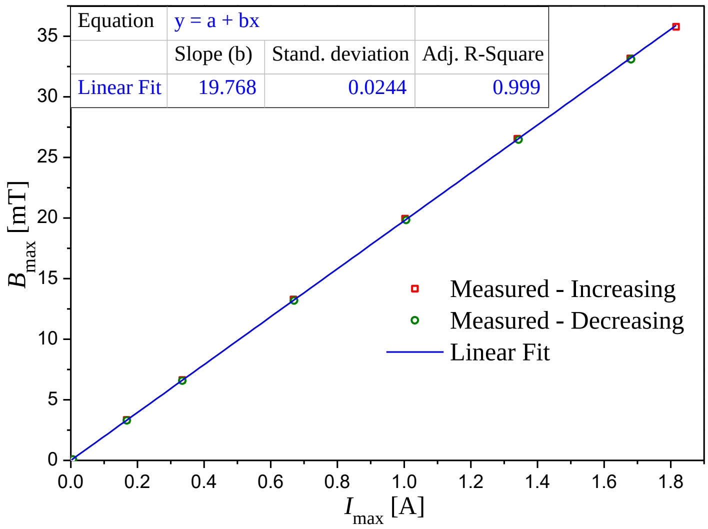


Fig. 6 Calibration of large solenoid - measurement results and linear fit

3.3. Calibration of pickup coils

In the third step of calibration, voltages induced in the pickup coils L_1, L'_2 and L'_3 (Fig. 2*b*) and voltages at the ends of mutual pickup coils L_2-L'_2 and L_3-L'_3 are measured in order to calculate calibration constants for all pickup coils. All voltages have been measured in relation to the ground terminal of a data acquisition card. Additionally, the voltage supplied to the large solenoid u_{L0}, as well as the electric current i and the magnetic flux density B (Hall sensor) are measured. Thus, all quantities of interest for the calibration of magnetometer are measured simultaneously.

Measurements have been performed at six different magnetising currents up to around I_{max}=1.2 A. Each signal (its time waveform) has been measured 1600 times and the averaged signal has been calculated. This reduces the noise in all signals to negligible levels [8]. Because this is the most important calibration step, it has been repeated five times. Finally, the mean value of all measurements has been calculated. Signals measured at I_{max}=0.39 A are presented in Fig. 7.

It can be noticed that signals that represent the magnetising current and the magnetic flux density are in phase, while signal u_{L1} from pickup coil L_1 is lagging for π/2. Signals $u_{L'2}$ and $u_{L'3}$ from pickup coils L'_2 and L'_3 are opposite in phase with signal u_{L1}.

The maximum of the voltage induced in a pickup coil can be derived as:

$$U_{L\max} = K_L \omega B_{\max} = \mu_0 K_L \omega H_{\max}\,, \tag{6}$$

where K_L is a constant proportional to the product of the number of turns and the cross-section area of the pickup coil and ω is the angular frequency. Since the number of turns are unknown for pickup coils of the calibrated magnetometer, this product can be calculated from the measured maximums of the induced voltage and the magnetic flux density. Thus, the calibration constant of the pickup coil can be obtained as: $K_L=U_{L\max}/\omega B_{\max}$.

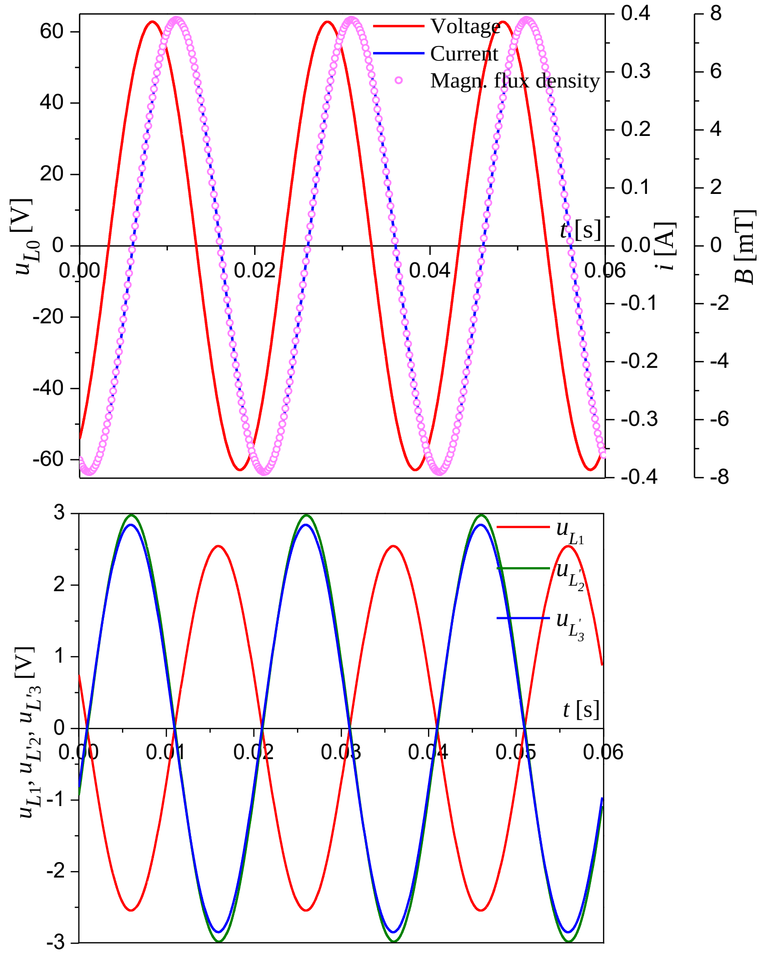


Fig. 7 Calibration of pickup coils - measured signals

Table 1 presents results of calibration of pickup coils obtained for different magnetising currents, containing maximums of the supply voltage and electric current of the large solenoid, maximum of the magnetic flux density measured with Hall sensor, maximum of the voltage induced in the pickup coil L_1 and calculated calibration constants for all pickup coils.

Last row of Table 1 gives averaged values of the ratio of maximums of the magnetic flux density and the magnetising current, which is the calibration constant of the large solenoid L_0 (step two) and averaged values of the calibration constant of all pickup coils.

Obtained calibration constant for the large solenoid is in accordance with the result given in Fig. 6.

Table 1 Results of pickup coils calibration

	$U_{L0\max}$ [V]	$I_{\max}$ [A]	$B_{\max}$ [mT]	$B_{\max}/I_{\max}$ [mT/A]	$U_{L1\max}$ [V]	K_{L1} [m^2]	$K_{L'2}=K_{L2}$ [m^2]	$K_{L'3}=K_{L3}$ [m^2]
1.	31.65	0.195	3.855	19.738	1.267	1.046	1.225	1.170
2.	63.41	0.390	7.718	19.780	2.540	1.048	1.226	1.171
3.	95.22	0.586	11.596	19.801	3.815	1.047	1.225	1.170
4.	127.14	0.782	15.455	19.767	5.088	1.048	1.226	1.171
5.	159.22	0.979	19.321	19.738	6.368	1.049	1.228	1.172
6.	191.37	1.176	23.161	19.685	7.641	1.050	1.229	1.174
Average				**19.751**		**1.048**	**1.227**	**1.171**

4. Discussion of Results

Point of interest and important part of calibration procedure is estimation of the uncertainty of performed measurements [11]. Calibration of Hall sensor is found to be complex and influenced by many variables. Also, the uncertainty of this calibration influences the uncertainty of other two calibrations. Therefore, it is analysed thoroughly in this section.

In order to achieve the lowest possible uncertainty, the calibration of Hall sensor is repeated with another data acquisition card (NI 9205) which has adjustable voltage ranges and better absolute accuracy than NI USB 6009. Voltage range for measurement of Hall sensor voltage is set to 5 V and voltage range for measurements of voltage at the ends of shunt resistor is set to 200 mV in measurements made at magnetic flux density of 10 mT.

Hall sensor sensitivity is calculated as:

$$S = \frac{U_{H\max} - 2.5}{B_{\max}} = \frac{(U_{H\max} - 2.5) l R}{\mu_0 N_1 U_{\max}}, \quad (7)$$

where:

- $U_{H\max}$=2.799 V is the maximum of Hall sensor voltage,
- the quiescent output voltage of Hall sensor is 2.5 V,
- $B_{\max}$ is the maximum of magnetic flux density,
- l=340 mm is the length of solenoid,
- R=0.00375 Ω is the shunt resistance,
- $\mu_0=4\pi\cdot 10^{-7}$ H/m is the magnetic permeability of vacuum (air),
- N_1=190 is the number of turns of solenoid and
- $U_{\max}$=0.05369 V is the maximum of shunt voltage.

The combined uncertainty of sensitivity S is calculated according to the sensitivity coefficients, which are obtained as partial derivatives of sensitivity S expressed by (7), and absolute uncertainties of each independent variable in (7) [11, 12], as:

$$u_c(S)=\sqrt{\sum_{i=1}^{s}\left(\frac{\partial S}{\partial X_i}\right)^2 u_{B,X_i}^2}=\sqrt{\sum_{i=1}^{s}u_{X_i}^2}\ , \tag{8}$$

where $X_i \in \{U_{H\max}, l, R, N_1, U_{\max}\}$, $u_{X_i}=|\partial S/\partial X_i|\, u_{B,Xi}$ and u_{B,X_i} is a Type B standard uncertainty evaluated as $u_{B,X_i}=u_{X_i}/\sqrt{3}$ or $u_{B,X_i}=u_{X_i}/1.960$ for a rectangular distribution or a normal distribution with the confidence level of 95 %, respectively.

Sensitivity coefficients are calculated using values of U_{Hmax}, l, R, N_1, μ_0 and $U_{\max}$. Their values are given in Table 2. Absolute uncertainties of voltages are calculated according to the specification for NI 9205 given by the manufacturer [13], taking into account three components of error: error of full scale, error of reading and noise error. The absolute uncertainty of the length of solenoid is taken as one half of measuring unit. The absolute uncertainty of the resistance is given by the manufacturer as 0.5 % of its rated value. The absolute uncertainty of the number of turns is equal to one turn. All values are given in Table 2.

Rectangular distribution is assumed for voltages and resistance with coefficient of division $\sqrt{3}$ and the normal distribution is assumed in the case of length and number of turns with coefficient of division 1.96 (confidence level of 95 % at infinite degrees of freedom).

Its absolute value is 0.174 V/T and its relative value is 0.58 %. Therefore, standard uncertainty is 0.58 %. Moreover, correction factor k=2 can be used for calculation of expanded uncertainty. In such a case, the confidence level is around 95 % and expanded uncertainty is 0.35 V/T or 1.17 %.

Finally, the result of measurement of Hall sensor sensitivity can be reported as:

$$S = 29.77\ \mathrm{V/T} \pm 0.35\ \mathrm{V/T}\,. \tag{9}$$

Table 2 Type B uncertainty for Hall sensor calibration at 10 mT

Variable	Absolute uncertainty	Sensitivity coefficient	Distribution	Absolute standard uncertainty u_B [V/T]	Relative uncertainty [%]
$U_{H\max}$	0.002138 V	99.46 1/T	Rectangular	0.12277	0.412
l	$0.5\cdot10^{-3}$ m	87.555 V/Tm	Normal (95%)	0.02233	0.075
R	$0.01875\cdot10^{-3}$ Ω	7938.32 V/TΩ	Rectangular	0.08593	0.289
N_1	1	−0.1567 V/T	Normal (95%)	0.07994	0.268
$U_{\max}$	$0.08953\cdot10^{-3}$ V	−554.455 1/T	Rectangular	0.02866	0.096

The main contribution to the measurement uncertainty comes from the measurement of output voltage of Hall sensor. The reason is a relatively high value of the measured voltage, as well as high measuring range. The absolute uncertainty $u_{B,UH\max}$ depends on both values. Calculated uncertainty refers only to the measurements performed at 10 mT. Whole calculation described need to be repeated to obtain uncertainty for other values of magnetic flux density.

The results of the calibration can be used in further measurements with a magnetometer to shorten the time needed for measurement and calculation. They can be used in different ways. At first, the calibration constant of the large solenoid can be used for calculation of the time waveform of the magnetic field generated by the large solenoid from the measured electric current $i(t)$, as $H(t)=19.77i(t)/\mu_0$. As a consequence, the Hall sensor may be excluded from the measurement setup. Additionally, the magnetic field can be also calculated from the integral of measured voltage $u_{L1}(t)$ of the pickup coil L_1 as $H(t)=-u_{L1}(t-T/4)/(\mu_0\omega K_{L1})$, $\omega=2\pi/T$ (in the case of sinusoidal excitation current). Thus, the shunt resistor for current measurement can be also excluded from the measurement setup.

Calibration constants of other four pickup coils can be used in calculations of time waveforms of the magnetic flux density B and the magnetisation M of the ferromagnetic sample. Similar to expression (2), in the case when ferromagnetic sample is placed inside the pickup coil L_2, the following expression can be used:

$$u_{L_2} = -\mu_0 K_{L_2} \left(\frac{S_s}{S_{L_2}} \frac{\mathrm{d}M}{\mathrm{d}t} + \frac{\mathrm{d}H}{\mathrm{d}t} \right), \tag{10}$$

where u_{L2} is the measured voltage of the pickup coil L_2, $S_{L2}=\pi r_p^2$ is the cross-section area and r_p=7.5 mm is the inner radius of the pickup coil. The magnetisation of the sample can be obtained by integration of this voltage and by substituting the magnetic field expressed over the voltage u_{L1} as:

$$M = \frac{S_{L_2}}{S_s} \left(-\frac{1}{\mu_0 K_{L_2}} \int_0^t u_{L_2}\,\mathrm{d}t - H \right). \tag{11}$$

On the other hand, the voltage u_2 between points 2 and 4 (Fig. 2*b*) can be obtained using only the magnetisation:

$$u_2 = -\mu_0 K_{L_2} \frac{S_s}{S_{L_2}} \frac{\mathrm{d}M}{\mathrm{d}t}. \tag{12}$$

The magnetisation of the sample is obtained by the integration of (12), as:

$$M = -\frac{1}{\mu_0 K_{L_2}} \frac{S_{L_2}}{S_s} \int_0^t u_2\,\mathrm{d}t. \tag{13}$$

The magnetic flux density of the sample can be calculated using (11) or (13) and previously calculated $H(t)$, according to well-known relation:

$$B = \mu_0 (M + H). \tag{14}$$

Similar expressions can be used for other pickup coils in the case when the ferromagnetic sample is placed inside these coils.

However, the above analysis may lead to measurement errors caused by two effects. The first one is related to the shape of the excitation current. As soon as the ferromagnetic sample is placed inside a pickup coil, for the same excitation voltage, the magnetising current will change by some amount. This change may be large and the shape of the current may be significantly distorted from sinusoidal. The level of influence depends on material characteristics. This effect can be overcome by digital feedback based on computer, as it has been discussed thoroughly in the literature [11]. The second effect also may appear after insertion of the ferromagnetic sample inside pickup coil. The magnetic field inside the pickup coil with ferromagnetic sample will be distorted, as well as surrounding magnetic field. This distortion might reach other pickup coils and disrupt the air flux compensation, which would be no longer effective as it was for the empty coils. This problem can be solved numerically in such a way that the compensating voltage is calculated using measured magnetic field [11]. This voltage needs to be subtracted from the measured voltage induced in the pickup coil, for example u_{L2} in (10). Consequently, the magnetic field needs to be measured accurately to obtain effective air flux compensation. For these reasons, the analysis given by equations (10) to (14) need to be validated through numerous experiments in which different magnetic materials should be used. Also, dimensions of magnetic samples need to be varied, as well as frequency of excitation current and its shape (sinusoidal, triangular and other).

The main purpose of the calibrated magnetometer is to obtain instantly the hysteresis loop of some ferromagnetic sample from calculated time waveforms of the magnetic flux density (or magnetisation) and the magnetic field. It can be used for parallel comparison of the hysteresis loops up to four samples. Samples can be made from different materials with the same dimensions or from one material with different dimensions. If all samples are made from one material and have the same dimensions, one sample can be used as a reference sample while the others can be checked against the reference and classified according to the predefined criteria.

The magnetometer can operate with different frequencies of the magnetising current and with different shapes of its time waveform. It should be taken into account that the voltage induced in pickup coils should not exceed a voltage range of the data acquisition card (usually 10 V). The induced voltage increases with the increasing of the frequency of the magnetising current. Sometimes, it is necessary to use voltage dividers to keep the induced voltage in the desired range. At very low frequencies (below 1 Hz), the amplitude of the induced voltage is relatively small which results in a deterioration of the signal-to-noise ratio. In such cases, averaging of measured signals is useful [8].

5. CONCLUSION

The paper gives a brief description of AC induction magnetometer, its construction and working principle, and emphasises its rising importance in complex measurements with ferromagnetic materials.

The paper describes a calibration procedure of AC induction magnetometer. It has been performed on the coil systems of Ferrotester 2738/S-3. Initially, measurements have been performed on the large-diameter multilayer solenoid in order to investigate a homogeneity of the generated magnetic field. It has been found that the variation of the magnetic field in the homogeneity zone was less than 1 % of its maximum value. This homogeneity zone covers one third of the solenoid volume (its central part). The calibration constant of the large solenoid has been determined using measurements. Further, using numerous measurements the calibration constants for all investigated pickup coils have been determined.

A detailed calculation of measurement uncertainty of Hall sensor sensitivity is also presented in the paper. It has been found that the relative expanded uncertainty amounts 1.08 % at magnetic flux density of 10 mT.

The possible ways to use a calibrated magnetometer for future measurements have been described. The method for determining time waveforms of the magnetic field and the magnetic flux density (or magnetisation) from the measured voltage induced in pickup coils and the calibration constants has been presented. A hysteresis loop of a ferromagnetic sample can be easily obtained from these waveforms. The magnetometer can be used for simultaneous testing of four samples of one material or different materials. Two side effects that can produce errors in such measurements were discussed.

Some practical notes on the measurements with the calibrated magnetometer at different frequencies of the magnetising current have been also given in the paper.

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