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Electromagnetic flux measurement in active magnetic bearing with use of flexible Hall sensors

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SUMMARY:

This paper discusses a method of measuring an electromagnetic flux in an active magnetic bearing with use of flexible polyimide Kapton-foil Hall sensors. Specific elements of the system such as an active magnetic bearing, a signal amplifier developed by author as well as Hall sensors are described. A measurement system consisting of an active magnetic bearing was used to examine an electromagnetic flux for a fixed and variable air gap. The configurations used resulted in magnetic induction values corresponding with the parameters of the magnetic bearing. DSpace signal processor and ControlDesk 5.4 software made it possible to monitor and record the measured data. The experimental results validate the correctness of the measurement system proposed. In comparison with other methods (a measurement system comprising a coil and an integrator or estimation based on the displacement and the coil feed current), the accuracy achieved is within a 5% error margin.

1. INTRODUCTION

An active magnetic bearing (AMB) is a mechatronic device combining elements of mechanics, automatics and electronics. It makes use of magnetic levitation, which means contactless floating of a ferromagnetic object in an electromagnetic field. Magnetic bearings have various features differentiating them from more classic solutions and allowing for non-standard applications. The superior features of magnetic bearings are as follows: a possibility of operating within high rotation speeds, a possibility of operation in varied environments (e.g. vacuum), higher coefficient of performance, lack of mechanical wearing, elimination of a loss of energy related to friction, lack of lubrication as well as sealing components, an increase in reduction of contamination, lower failure frequency in comparison with standard solutions, a wide range of working temperature, low maintenance costs, self-alignment of rotation axis, active vibration dumping, self-diagnostics of rotating machinery and a lower noise level [12, 4]. Dynamic working parameters of rotating machinery in magnetic bearing can be influenced by using a variety of controlling laws. The most common solution is control with loopback with use of rotor displacement data [9, 13]. Control algorithms based on measurements of electromagnetic flux in the AMB air gap are becoming more and more common [12, 6, 10]. Such systems allow for direct control of electromagnetic force, which in turn allows for cost reduction and decoupling of control system into a local electromagnetic flux control block and a global rotor displacement control unit. Moreover, the global system can be designed as linear. Also, polyimide Kapton-foil Hall sensors can be placed directly in the AMB air gap. This solution does not require the rotor machinery to be modified and it also allows for a reduction in its size [10, 12]. It should also be noted that the use of Hall sensors allows for a reduction in electric energy consumption in comparison with other sensors (e.g. eddy current ones). The proposed measurement system was developed in the Division of Automatics and Robotics of the Faculty of Mechanics in Białystok University of Technology.

2. DESCRIPTION OF THE ELEMENTS OF THE MEASUREMENT SYSTEM

A prototype of flexible polyimide Kapton-foil Hall sensors of 130 µm thickness was used. The proposed measurement system (Fig. 1) was developed for one horizontal axis of an active magnetic bearing. An electromagnetic flux, treated as a measured signal, was amplified with use of a specially designed and produced amplifying device consisting of operational amplifiers. The data were acquired, monitored and recorded with dSpace signal processor managed by ControlDesk software.

2.1 An active magnetic bearing

An active heteropolar bearing was used in the study (Fig. 2a). It comprised eight electromagnetic coils in 4 series connections. The electromagnetic coils were wound around a stator consisting of a packet of transformer sheets of 0,00035 m thickness. The electromagnetic coils were wrapped with insulated wire DNE180 (able to withstand temperature up to 180°C) with a diameter of 0,00118 m. AMB is equipped with rings used for mounting eddy current sensors that are utilized to measure the radial position of the rotor in the air gap along *x*-*y* axes with precision up to 1 µm.

The above mentioned rings were made of 40HM steel, for which eddy current sensors are of static linear characteristics, which is the relation between the radial rotor displacement and the sensor output voltage. AMB consists of the outer part (stator electromagnetic coils) and the inner part (a packet of steel sheets mounted on the rotor). The stator of the electromagnetic bearing is

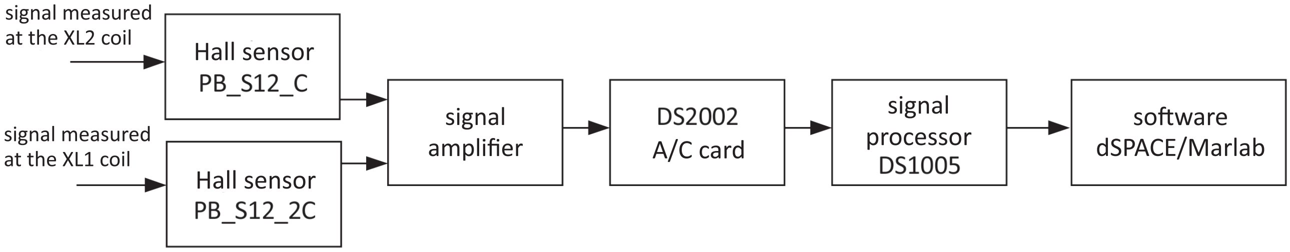

Figure 1 The proposed system diagram

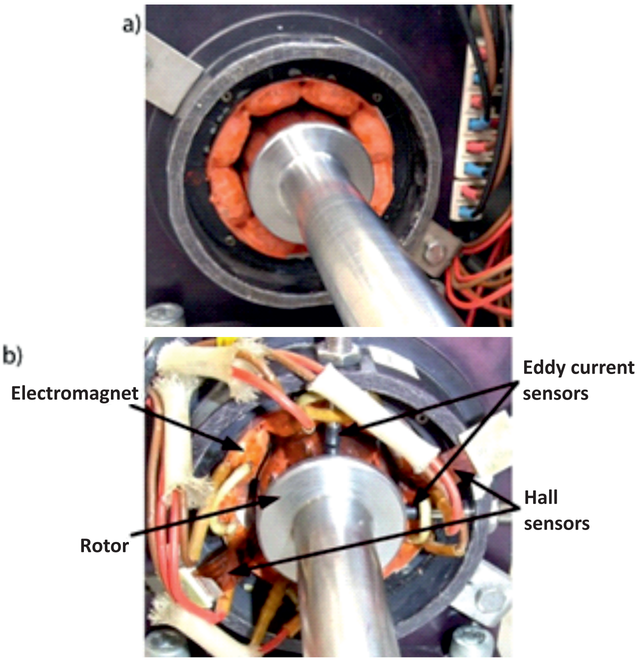

Figure 2 a) Analyzed heteropolar bearing, b) Sensor positions in AMB[7]

made of transformer sheets of the same thickness as bearing raceways mounted on the rotor. The bearing raceways' surfaces were polished up with high precision [9].

Two coil pairs were used for each AMB axis x-y. The coils are controlled through two channels of the amplifier managed from the level of ControlDesk software. The flexible Kapton-foil sensors were places in the air gap of the magnetic bearing along XL2 axis (Fig. 2b and Fig. 3).
The technical parameters of AMB are presented in Table 1.

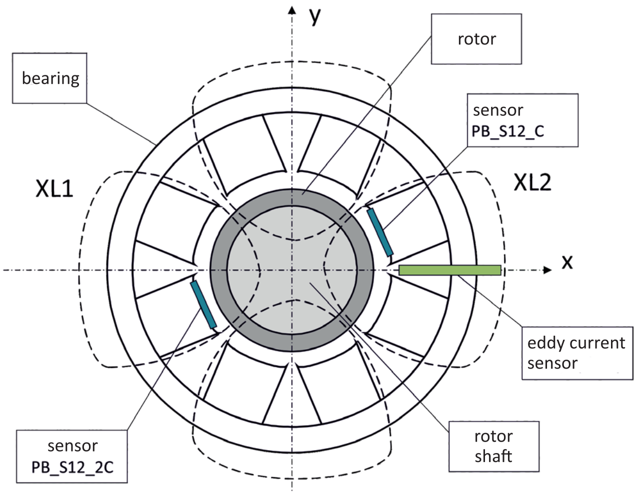

Figure 3 Diagrammatic connection of coil pairs along with Hall sensors position

Table 1 Technical parameters of the analyzed magnetic bearing

Description	**Symbol**
Number of poles	$N_p = 8$
Angle between the poles	$\alpha_p = 22.5°$
Pole shoe cross-section area	$A_p = 0.000360\ m^2$
Number of loops in a one coil pair	N = 60
Air gap width	$X_0 = 0.0004$ m
Inner stator diameter	$d_s = 0.048$ m
Outer stator diameter	$D_s = 0.09$ m
Bearing constant	$K_f = 0.000003912\ Nm^2/A^2$
Maximum current	$i_{max} = 5$ A (10 A for pulse amplifiers)
Operating point current	$i_0 = 2.5$ A (5 A for pulse amplifiers)
Maximum force	$F_{max} = 244$ N (dla $i_{max} = 10$ A)
Electricity rigidity	$k_i = 13.62$ N/A
Displacement rigidity	$k_s = 97656$ N/m
Resistance	$R = 0.26\ \Omega$
Inductance	$L = 0.0021$ H

2.2 Hall sensors

The sensor used to measure the electromagnetic flux utilizes the Hall phenomenon. The thin conductor placed in the electromagnetic field is perpendicular to the magnetic field, which induces a force perpendicular to the conductor's surface. The force interacts with electrons travelling with v speed along the conductor. This results in accumulation of positive and negative charges on both sides of the conductor and creates the potential difference U_b. U_b is called the Hall voltage and proportional to the magnetic induction *B* and current *i* [7]:

$$U_b = k_h B i \qquad (1)$$

The value of component k_h depends on the conductor geometry and material. During the measurement Hall sensors are powered by direct current.

The Hall sensors used marked PB_S12_C and PB_S12_2C are prototypes designed and produced by Leibniz Institute for Solid State and Materials Research in Dresden [14].

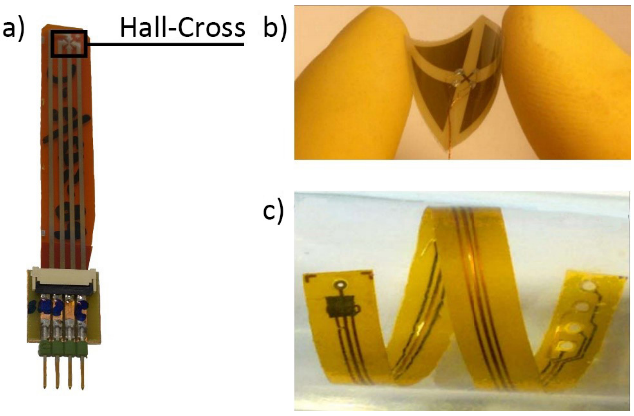

Figure 4 a) PB_S12_C Hall sensor, b) Change in bend radius [8], c) Sample sensor deformation [1]

The sensors used are currently ones of the thinnest sensors of the type. Their size of 130 µm allows for their direct placement in the AMB air gap without affecting its size. It should be noted that an active part of the sensor is not the whole surface but only so-called Hall-Cross area, which is located in the sensor's upper section (Fig. 4a). According to the specification presented in Table 2, Hall-Cross area is of 400 µm × 400 µm size. The observed differences between the sensors used are within measurement resolution. The material used guarantees flexibility of the sensors. Polyimide foil is a flexible material (Fig. 4c), used in electric insulation designed for high temperature conditions. Temperature of continuous work is up to 230°C. This enables foil usage in AMB working conditions, where the assumed working temperature is in the temperature range from -40 to 80°C. Polyimide foil sensors do not show significant measurement differences when the sensor bending radius changes (Fig. 4b) within 0÷22 mm, while the linearity of the characteristics is preserved [8, 1]. The most important technical parameters of the Hall sensors used are shown in Table 2.

2.3 Measuring amplifier of an electromagnetic flux

Due to a lack of amplifiers dedicated for flexible Hall sensors, a dedicated amplifying system was designed and produced (Fig. 5). The specialized amplifying system is essential in view of a low value of the sensor output signal, amounting to 200 to 300 µV. These values render it impossible to record the sensor output signal courses due to the physical resolution of the readings of the DS2002 sampling board of dSpace processor. The amplifying system was based on single-channel operational amplifiers with loopback, whose characteristics is high amplification, differential input (symmetrical) and asymmetrical output. An operational amplifier together with an appropriate loopback enables mathematical operations, which are addition, multiplication or finding logarithm [5]. An ideal operational amplifier is characterized by an infinite amplification combined with an open feedback loop, wide carrier bandwidth, high input impedance, output impedance equal to zero as well as no power loss at the input of the amplifier [2, 15].

The designed amplifying system is double channel and enables simultaneous use of two sensors. According to the diagram (Fig. 5), channels are powered from USB ports. Each of the USB ports supplies power to AM1S-0512SZ converters, which in turn power Hall sensors as well as other integrated circuits in the amplifier. Hall sensors output signal is fed to the input of the TLC271CP operational amplifier. The amplifier output voltage can amount to 20 V. The amplification depends on the resistance value of the resistors used in the R7 and R8 system (Fig. 5). Gain adjustment is possible with the use of potentiometer, where its value is calculated numerically [15]. One should remember that it is impossible to obtain voltage higher than 12V which is equivalent to the powering voltage of the microchip.

Tabela 2 Hall sensor specification

Model	PB_S12_C/ PB_S12_2C
Material	*kapton-foil*
Material thickness	130 µm
Nominal sensor resolution	500 mV/AT
Measured sensor resolution	661 mV/AT (for PB_S12_C) 900 mV/AT (for PB_S12_2C)
System symbol	Q_2014_1a
Protective layer	none
Heat treatment	none
Hall-Cross area	400 µm x 400 µm
Measured current	1 mA
Maximum current	10 mA
Mounting	mechanical

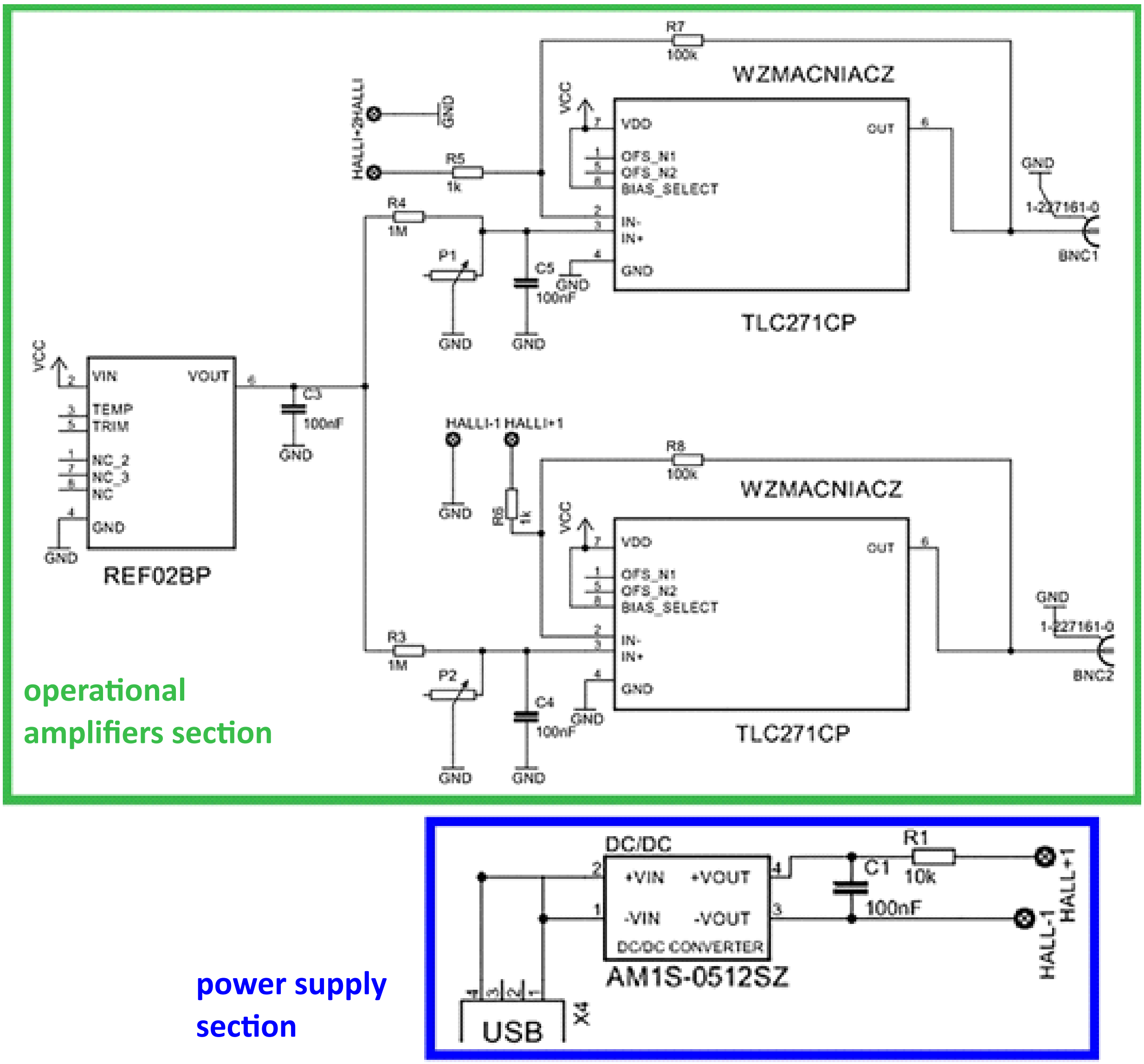

Figure 5 Signal amplifier diagram

3. RESULTS AND THEIR DISCUSSION

The experiments were carried out in identical conditions, whose reference characteristics were determined both for an eddy current sensor as well as Hall sensors. Use of eddy current sensors enabled determination of the change in the Hall voltage value relative of the change in the rotor displacement in AMB. The experiments were carried out with a sampling rate of 10 kHz, both for a constant and variable width of the air gap in AMB (both for the static and dynamically variable position of the rotor along the x axis of the bearing). The chosen level of amplification is k = 1500. Electric signals controlling electromagnetic AMB actuators were set from in the ControlDesk software provided with a dSpace signal processor. The following results were obtained in the course of the experiments: for XL1 coil current equal to 2 A, and PB_S12_2C sensor without a change in rotor displacement (Fig. 6), for XL1 and XL2 coil currents equal to 2 A, and PB_S12_2C sensor with a change in rotor displacement (Fig. 7).

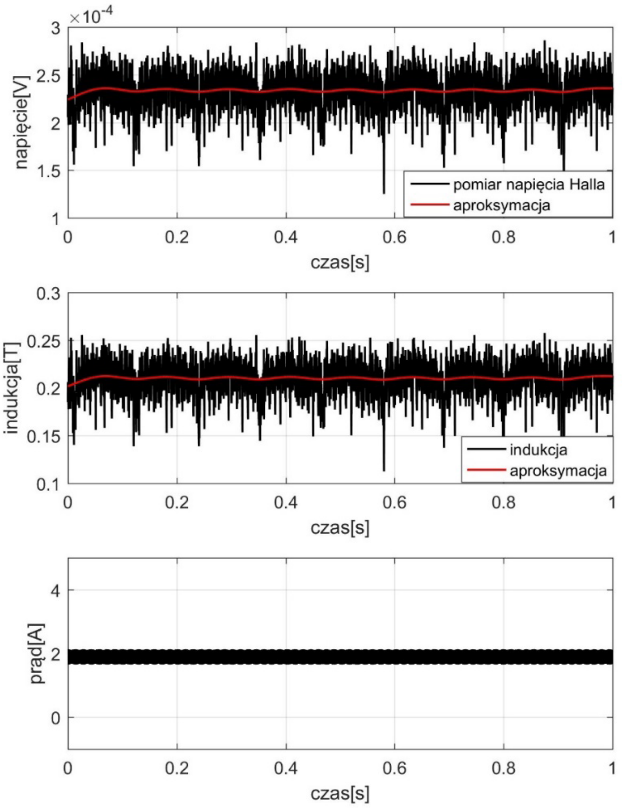

Figure 6 Measurement of Hall voltage as well as induction along XL1 AMB axis for the current feed of 2 A, with no rotor displacement

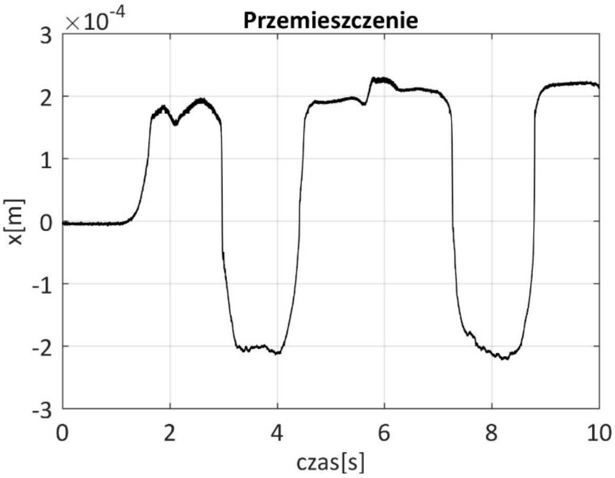

Figure 7 Course of given rotor along *x* axis

In this case, the rotor was dynamically displaced as a recorded course in Fig. 7shows. The displacement is within a range of 0.0002 m to 0.0002 m, which corresponds to a nominal width of the air gap in AMB. The initial position is the geometric center of the rotor in AMB and is the origin of coordinates, as in Fig. 3. For the rotor displacement (shown in Fig. 7) the following results were obtained (Fig. 8).

Taking into account the courses of signal for steady state (Fig. 6) and for a variable width of the air gap (Fig. 8) it should be stated that the courses of change in the recorded output voltage in a Hall sensor as well as induction are distorted by an 18 kH carrier frequency of the current of the AMB amplifier produced with use of PWM technique. In comparison with the results for the XL2 axis, the results achieved with use of the XL1 actuator sensor are influenced by many more external interferences which are repeated but more difficult to identify. Their source can be electromagnetic coupling generated by the remaining electromagnetic AMB actuators. An extra source of noise can be external disturbances affecting the unshielded elements of measurement system, such as connectors. Taking into account the courses of signal recorded for a variable width of the air gap (Fig. 8) it can be stated that the measurement system works correctly, which means there is a decrease in magnetic induction along the increase in the width of the air gap. The obtained results confirm the correlation [7]:

$$B = \frac{\mu_0 N}{2}\frac{i}{x_0}, \tag{2}$$

where: B – magnetic induction, N – the number of loops in the electromagnetic coil, i – current flowing through the coil, μ_0 – magnetic permittivity of free space, x_0 – air gap.

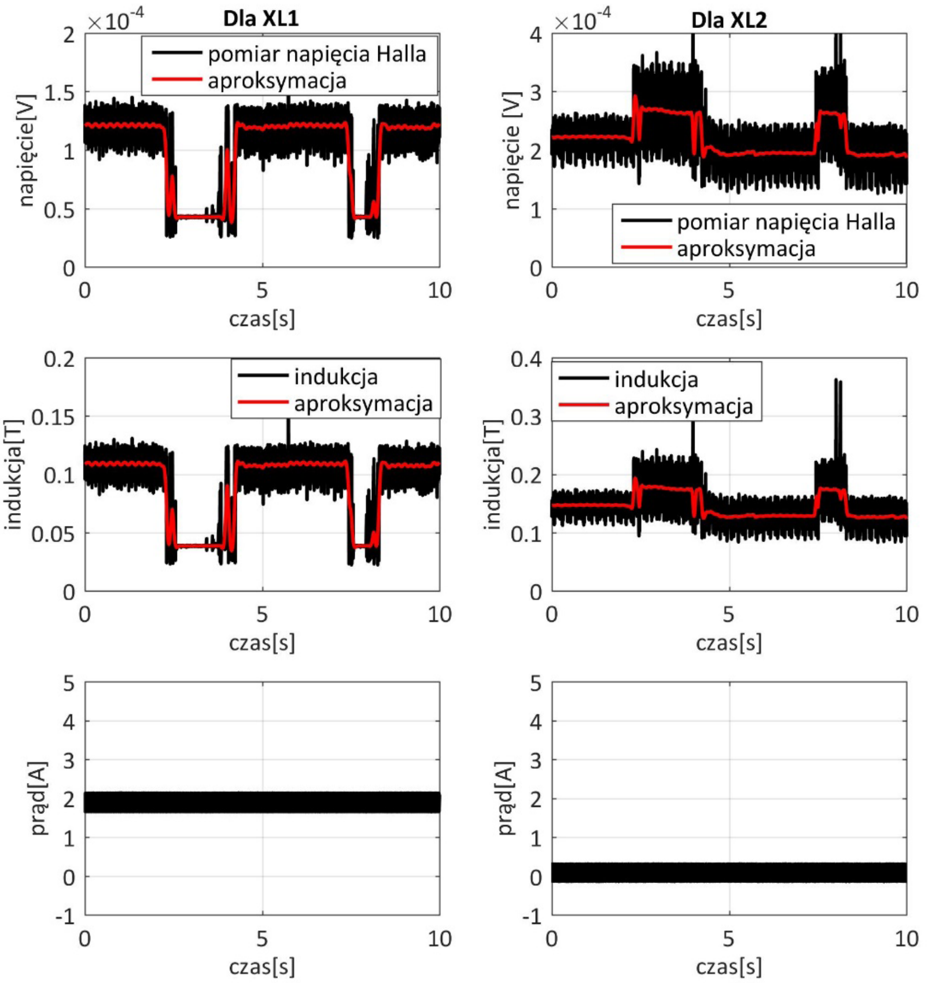

Figure 8 Measurement of Hall voltage as well as induction in AMB for the feed current respectively of 0 A and 2 A, during rotor displacement

In accordance with the equation (2) the value of the denominator of the equation (2) increases along with an increase in the width of the air gap, which leads to a decrease in the value of magnetic induction B, and vice versa. Moreover, the value of magnetic induction changes proportionally to the value of current i. The experimental results (Fig. 8) confirm that the XL2 coil feed current higher than the XL1 coil feed current (the former 2 A and the latter 0 A) results in the Hall voltage and the induction value higher for the sensor along XL2 axis than the XL1 one.

An appropriate low-pass filter needs to be chosen in order to both compensate for the interference and enable a good quality of adjustment before utilising the signal of the measured electromagnetic flux to control the rotor position. It should be noted that the proposed solution is a common practice during measurement of electromagnetic flux in a magnetic bearing without interfering in its mechanical structure [8, 1, 3].

4. SUMMARY

The study describes a way of measuring an electromagnetic flux in an active magnetic bearing. A measurement system was developed in order to study various configurations of feeding electromagnetic AMB actuators, taking into consideration the rotor position. Taking measurements of an electromagnetic flux in an active magnetic bearing is problematic, mainly due to technical aspects, such as the size of the air gap (0.4 mm), interferences originating in the scientific equipment power supply (e.g. oscilloscope). This disqualifies most of the magnetic induction sensors available on the market. The proposed system makes use of flexible Kapton-foil (130 μm thick) Hall sensors, possible to be directly placed in the AMB air gap. Moreover, in view of a lack of dedicated amplifiers and a low value of the analyzed signal amplitude (of the magnitude of 200-300 μV) a signal amplifier making use of operational amplifiers was developed. It should be noted that the proposed amplifier can be used universally as it is not limited to Hall sensors only. The proposed system and the sensors used guarantee repeatability and stability of measurements, which is of utmost importance in control system applications. Experimental results validate the behavious in working conditions of the proposed measurement system. Comparing the proposed method to others (such as a measurement system comprising a coil and an integrator, estimation based on the displacement and the coil feed current), it should be noted that this method is direct, and the one allowing for Hall voltage maintaining a linear relationship with the electromagnetic flux. The difference between the model values (theoretical ones) and the real values does not exceed 5% of the signal amplitude (equaling to approx. 0,005T). It should be emphasized that the uncertainty can result from theoretical simplifications as well as a possible error in the method itself, for instance related to random interferences, minimal difference in the product quality of the elements used or their wear and tear level.

Another way of measuring the electromagnetic flux is using a coil and an integrator. Unfortunately, this method often yields results with convergence of up to 15% in comparison with the theoretical results. The main reason is the indirect method of measurement, where errors accumulate. Similarly, estimating the value of the electromagnetic flux considering the displacement and the coil feed current. Interferences resulting from two measurement channels (displacement and feed current) overlap, which necessitates use of low-pass filters, whose inherent feature is system latency and signal distortion. It should be noted that the proposed system does not contain any filters; yet, it can be extended to include some, as this would allow for a better dynamic quality of the measured signal.

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