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Flux measurement and conditioning system for heteropolar active magnetic bearing using Kapton-foil Hall sensors

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ABSTRACT

This paper addresses the problem of measuring the electromagnetic flux in the air gap of the active magnetic bearing (AMB) without mechanical structure modifications. The designed and fabricated flux measurement and conditioning system based on the ultra-thin flexible Kapton-foil Hall sensors (developed by IFW Dresden Institute for Integrative Nanosciences) and signal amplifiers are presented. The flexible sensors are directly mounted on the curved surfaces of stator poles of the AMB and measure flux density in the AMB air gap. Then, the measurement itself and the conditioning system are verified in different measuring conditions of the heteropolar radial AMB with the air gap width of 0.4 mm. The measurement results were used in identifying crucial rotor flux-AMB system parameters. The proposed direct flux measurement system is successfully verified in the designed test rig in the presence of rotor position disturbances or coil current oscillation. The advantages and drawbacks of the presented measurement setup are discussed.

1. Introduction

Electrical machines, where the electromagnetic flux information is essential, have been used for many different industrial applications. Nowadays, the aim of mechatronics is to develop products with ability to self–diagnosis and self–calibration. Machines with higher performance, less installation and maintenance cost, longer lifetime and easier service are required. These requirements are met with applications of active magnetic bearings (AMBs), which replace the classic bearings in various applications. AMBs have growing potential; and together with proper intelligent control system they can be used in many applications if the overall cost of the systems are reduced. However, major challenges are related to realization of the measurement and control system [7,14]. For small air gaps (usually tenths of a millimetre) and specific construction of AMB actuators, reliable, fast, low-noise and low-cost sensors would significantly broaden the application area of magnetically levitated systems.

From the control point of view, in the flux-controlled AMB system the electromagnetic force is no longer dependent on rotor position. As the position control is not dependent on the electromagnetic field nonlinearities, such a control system enables operation under a *zero-bias* [5]. Another advantage of the flux measurement is that this system can be used instead

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of the position feedback. Thus, the magnetic bearings without position measurement allow cost reduction and miniaturization. However, due to the strong nonlinearity of the AMB system operated with *zero-* or *low- bias flux control*, direct flux measurement enables employment of the nonlinear control techniques developed by the authors [9–11].

Development of an ultra-thin flexible flux sensors during the last three years includes investigation of the Bismuth Hall (Bi-based Hall) sensors made on conventional flexible printed circuit board (PCB). Detailed characterization of the metal-based Bismuth sensor elements can be found in [8]. The 1D linear and 3D Bi-sensors arrays are prepared on 150 μm thick double layer flexible printed circuit (FPCs). The integration of the Bi-sensor in a bent configuration into a flux-density-controlling loop of the one-degree-of-freedom ball magnetic levitation setup is successfully demonstrated in [13]. The flux-based ball magnetic levitation control system using the direct feedback of a flux-density was demonstrated. Experimental results of the reference step and the load drop disturbance responses are given in the time domain, for the nominal air gap of 8 mm. The similar topic with using Bi-sensor for the ball magnetic levitation setup for the air gap of 12 mm is given in [3]. However, the main challenge is how to integrate a flux sensors into typical AMB air gaps. The magnetic field Bi-sensors prepared on PCB with given performance at different temperatures cycles and adhesive mount the sensor to a stator of the AMB is given in work [4]. These sensors with total thickness of 150 μm are demonstrated to be useful in flux-controlled AMB systems. In [2], the Bi-sensors are integrated on curved surface of stator poles of a conventional two-axes permanent magnet bias AMB. Furthermore, the research subject to reduce the total thickness of the flexible Bi-sensors to less than 100 μm is performed d by introducing Bi-film deposited silicon [1]. These sensors are integrated in the direct field control of AMB using flux feedback.

In opposite to the Bi-based Hall sensors, the Hall sensors based on graphene have the total thickness of 50 μm [15]. The potential for reducing the thickness of these sensors by using a thinner foil is more promising for graphene because it has only one atom layer thick. The voltage and current normalized sensitivities of the graphene-based Hall sensors are comparable to the rigid silicon-based Hall sensors. Moreover, the sensitivity of these sensors shows no degradation after being bent to a minimum radius of 4 mm. However, because of the high initial cost, this sensors are reserved and more suitable for selected flexible micro applications.

No papers among the references address the application of the ultra-thin Kapton-foil Hall sensor for the flux density measurements in the air gap of the heteropolar active magnetic bearing together with dedicated signal conditioning system. Therefore, we address this problem in our paper. Particularly, proposed realization of the flux-measurement system for the 1-DOF AMB system using flexible Hall sensors with 130 μm thickness is given. The Hall sensors are incorporated in the AMB air gap directly. The flux measurement signals of the AMB system are collected by sensors and amplified by fabricated amplifiers. Next, the amplified signals are converted to digital data by the designed flux-conditioning system. Information of the electromagnetic flux allows to determine many other parameters of the AMB system. Particularly, the flux measurement and conditioning system comprises designed and fabricated 8-channel signal amplifiers, which are based on the operational amplifiers.

The main contributions of this paper are as follows:

- designs and realizations of 8-channel signal amplifiers for required parameters of the heteropolar AMB flux measurement system using ultra-thin Kapton foil Hall sensors;
- performance two AMB-poles flux measurement system without modification of the magnetic poles structure;
- flux density measurement in the air gap of AMB with prototype of Kapton-foil Hall sensors;
- facilities and calibration procedures;
- Hall-sensors performance validation;
- experimental verification and system validation.

2. AMB flux measurement system description

The main part of the flux controlled AMB is the Hall-effect based measurement system. The Hall sensors used in this work were manufactured by the IFW Dresden Institute for Integrative Nanosciences (see Fig. 1). The sensors are prototypes having comply with the requirements imposed by the authors. All sensors are made of the Kapton-foil with total thickness of 130 μm. What is important, measurement is done using Hall-cross area, which is located at the top of sensor (Fig. 1b).

The whole flux-controlled 5-degree-of-freedom AMBs rotor system needs at least eight Hall sensors. The examined Hall sensors have slightly different properties and require individual calibration before incorporating in the AMB measurement system. The main parameters of the Hall sensors are collected and presented in Table 1. The main difference is the sensitivity actual values which vary from 661 mV/AT up to 900 mV/AT depending on the sensor. Main reason of sensitivity differences is because the sensors were produced at different batches under slightly different preparation conditions (deposition temperature was varied during the Bi sputtering). Particularly, if the conditions are kept constant, the reproducibility of the sensor responses is high.

The characteristics of the investigated two Hall sensors are presented in Fig. 2. The sensitivity of the sensors have been measured two times for each sensors (Prototype A for Fig. 2a, and Prototype B for Fig. 2b) at IFW Dresden Institute for Integrative Nanosciences. In particular, the samples were measured in a standard 4-point cross configuration (Hall geometry) by monitoring the change of the transversal resistance of the samples when they are exposed to an external magnetic field generated between the pole shoes of an electromagnet. The field was applied perpendicular to the sensor plane. The actual out-