Direct field control of AMBs using flux feedback based on integrable Hall sensors

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Abstract
Within the last years magnetic bearing technology has been pushed by a significant upturn in oil & gas industry as well as in machining applications. Nowadays, specific high speed spindles are equipped with industrially standardized active magnetic bearing systems (AMB) allowing for highly precise rotor positioning due to their contact-free and low-maintenance operation. However, compared to conventional ball bearings well-established AMB systems are limited by their relatively low stiffness. In order to improve dynamic performance flux based control algorithms are under investigation for the last decades already. The main challenge is how to integrate commercially available magnetic field sensors into typical AMB air gaps. Within this research ultra-thin and flexible Bismuth Hall sensors with a total thickness of less than 100 μm were developed and integrated into an actively controlled magnetic suspension system. For the first time an AMB control using the direct feedback of bendable Bismuth sensors was implemented and its operational capability for accurate rotor positioning was demonstrated successfully and investigated by frequency response analysis.

Keywords : Direct Field Control, Flux Based AMB Control, Flux Feedback, Ultra-thin-Bismuth Hall Sensor, Integrable Magnetic Field Sensor

1. Introduction

To increase dynamic stiffness and to improve precise rotor positioning of Active Magnetic Bearings (AMB) flux based control algorithms were suggested [Abdelfatah and Emad, 1993]. Moreover flux feedback approaches offer promising possibilities for low cost AMB solutions operating without expensive position gauges [Zlatnik and Traxler, 1990]. Realization of direct field control requires real-time data acquisition on the actual magnetic flux inside the AMBs narrow air gaps. Therefore, either flux observation [Jaatinen et al., 2013] or integrated magnetic field measurements [Bleuler et al., 1995] are the methods of choice. Nowadays the latter option strongly demands the elaborate design of integrable sensors including their manufacturing and assembly processes, which are supposed to be the key challenges. Typical air gaps are too small to fit there conventional magnetic sensors with thicknesses of more than 400 μm. Recently ultra-thin Bismuth (Bi) Hall sensors fabricated on a polymeric material (PCB) were presented [Koseva et al., 2010; Melzer et al., 2015; Mönch et al., 2015]. Integrated into different setups the down to 150 μm thin and flexible sensors provided a technology platform for flux monitoring up to 2.3 T [Mönch et al., 2014]. However, initial tests revealed that for successful realization of the intended flux control, a significant improvement of both the sensor sensitivity and its mechanical stability is essential. Here, the total sensor height is reduced and the performance of the bendable sensors was optimized by tuning the Bi film thickness and their structure. The new 100 μm ultra-thin Hall sensor reveals a sensitivity which is up to 10 times higher compared to previous Bi based solutions [Bahr et al, 2012]. On a proof-of-concept level its performance is demonstrated by implementing a flux based AMB control.

2. Ultra-thin Bismuth Hall sensors

To ensure proper functioning of integrated magnetic field sensors in AMB applications smart material combinations in reliable packages are indispensable. In particular all sensor components have to resist thermal and mechanical aging. At the same time the sensor elements are to be designed in ultra-thin structures to enable integration into typical tiny air gaps. Specific combinable packaging materials need to be selected carefully in order to withstand both the temperature cycling as well as potential variable frequency micro vibrations during operation.

The proposed Bismuth Hall sensors (Fig. 1) are prepared combining conventional thin film deposition and Silicon (Si) micro-fabrication technology onto Polyimide (PI) foils [Ernst et al., 2015]. Fabrication in brief: 100 nm thin Gold (Au) pads are sputtered onto prepared 50 µm thick Silicon (Si) dies. Therefore a 5 nm Chromium (Cr) layer acting as adhesive was deposited to the Si die before. Afterwards the 200 nm thick Hall sensitive Bismuth (Bi) film is sputtered. The prepared Gold pads (200 µm x 200 µm) are fully uncovered and enable the proper contacting of the Bi deposited sensor die to a copper cladded PI foil by stud bumping and an adhesive bonding process. A lithographically defined 36 µm thin (total thickness) double layer PI foil design is used for highly flexible cabling. All four pads for contacting the Hall sensitive Bi element are stud-bumped using a conventional wire bonder and 25 µm thin Gold wires. The prepared sensors are bonded onto the PI foil. Although all chosen materials are bondable by ultrasonic processes [Harman, 2010], adhesive bonding using an anisotropic conductive film beneficially ensures flat and planar interconnection. The thermosetting polymer type film remains its elasticity unaffectedly after the bonding process. This reduces (thermo-) mechanical stress in between the sensor element and the PI foil effectively. A final passivation protects the sensor against environmental influences by an additional 10 µm coat or single layer foil.

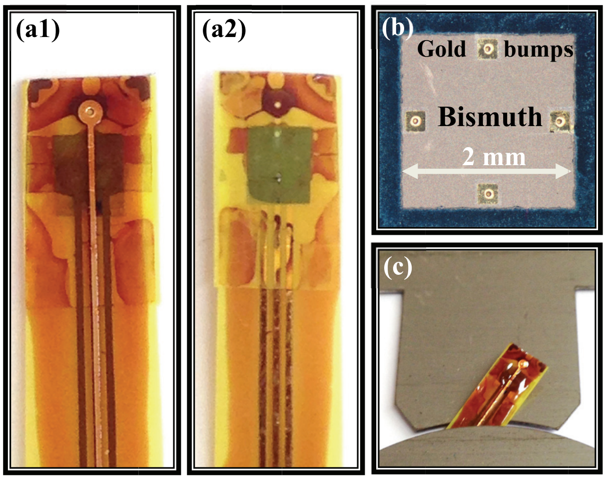

Fig. 1: (a) Bi Hall sensor package: a1 top side, a2 bottom side) including cabling. (b) Stud bumped Bi sensor element (film 200 nm) on Si interposer (50 µm). (c) Sensor in between exemplary stator and rotor sheet.

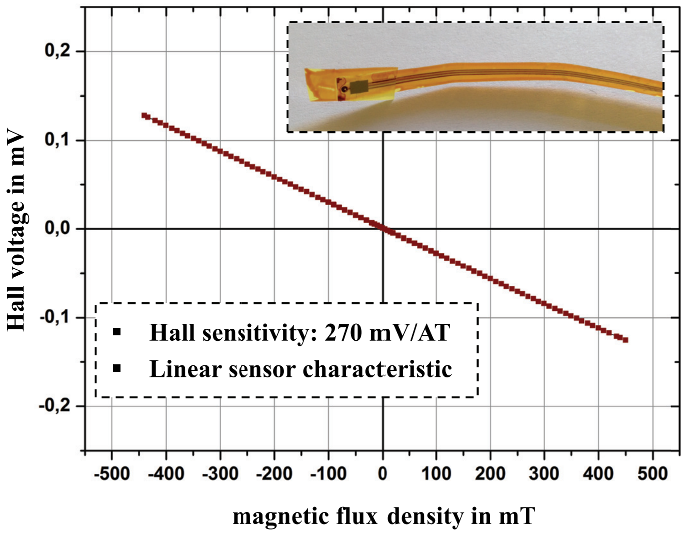

Fig. 2: Characterization of Bismuth Hall sensor: Hall voltage vs. magnetic field, supply current 1 mA.

After characterization the fabricated sensors reveal total heights <100 µm and impressive Hall sensitivities of up to 800 mV/AT. Figure 2 nicely shows the linear sensor performance by Hall signal vs. applied magnetic field of an exemplary sensor supposed for integration into the AMB test setup. Table I summarizes characteristic sensor parameters for operation for i_{Hall}=10 mA supply current. The new Bi Hall gauge features output levels of 4 V/T. Using an in-house developed two stage amplifier electronics for Hall voltage conditioning enables resolutions <5 mT for sensing out-of-plane magnetic fields up to 3 T and allowable service temperatures of 120 °C.

TABLE I: BISMUTH HALL SENSOR PARAMETERS

	Parameter	Value
A_{Hall}	Active Hall area	1.5 mm x 1.5 mm
d_{total}	Total thickness	< 100 µm
d_{Bi}	Bi film thickness	200 nm
S_{Bi}	Bi Hall sensitivity	(200..800) mV/AT
i	Sensor supply current	(1…10) mA
S_{output}	Output sensitivity	≈4 V/T
	Sensor resolution	< 5 mT
b	Sensor width	5 mm
l	Sensor length	80 mm
d_{Cu}	Cabling: PI / copper	50µm

Reliability analysis: Prepared test vehicles were artificially aged by thermal shocks with -40 °C / +85 °C (dwell time: 15 min). Within the initial test nearly one quarter of all samples failed after 25 cycles already. Another 20 % showed deficits in contacting after 50 thermal cycles carried out continuously. Slightly diminished test requirements reduced the failure rate significantly: 4 % of prepared sensors broke after 25 cycles for alternate temperature shocks from -20 °C to +85 °C. In total less than 20 % failed after 150 cycles. Allocating all failure modes in detail indicated the importance of accurate and highly precise parallel positioning of the Bi deposited Si die and the PI foil during the placement process. Intensive X-ray analysis showed a strong influence of bump diameters on the sensors reliability. Both, the alignment during placement process as well as the stud bumps sizes are under optimization.

3. Cascaded control of position and flux density

After fabrication the sensors were successfully integrated into a typical radial AMB (Fig. 3a) representing a two axes magnetic suspension. Here, an industrial like setup (Table II) using permanent bias magnetization and heteropolar control flux pathing is chosen for first performance tests. The bendable Bismuth sensors were bonded onto the curved stator pole (Fig. 3b) by using instant adhesive glue. Figure 3c shows the 100 µm thin sensor head enabling the proposed real-time magnetic field sensing inside tiny air gaps in between the electrical sheet packages of both rotor and stator.

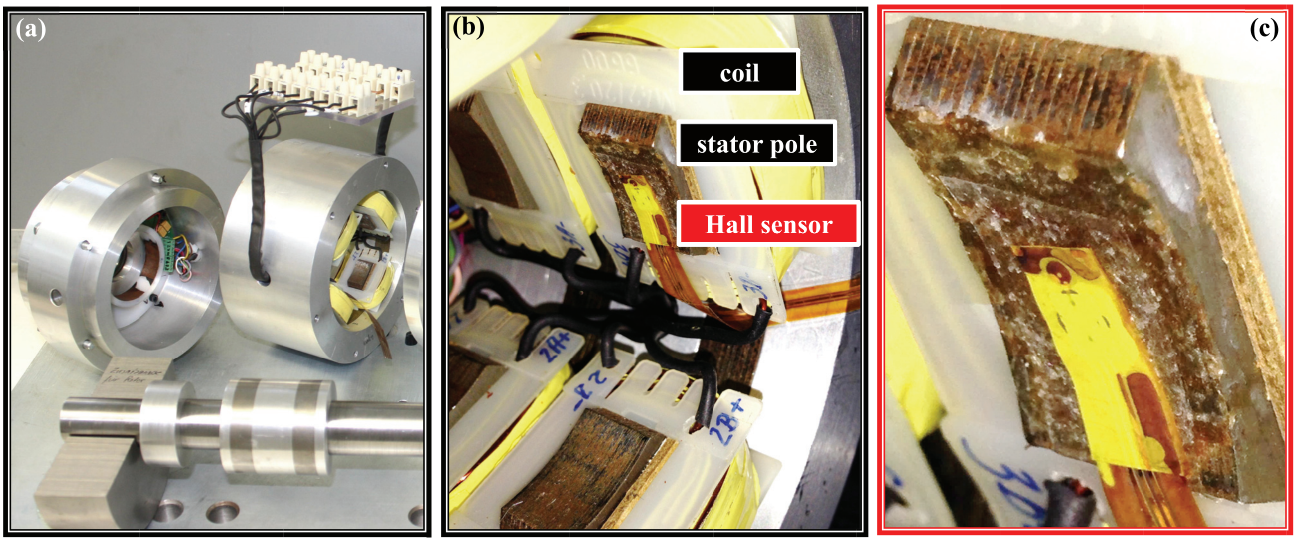

Fig. 3: (a) AMB system: stator, rotor, capacitive position gauge, auxiliary bearings. (b) Flexible Bismuth Hall sensor mounted onto the radial bearing´s stator pole. (c) Adhesively bonded Bi sensor head measuring magnetic field inside air gap.

Besides permanent condition monitoring (bias magnetization and control flux by electromagnets) [Bahr et al., 2013] the new sensor platform enables the realization of the proposed magnetic field control. Therefore, a cascaded structure of position control with subordinated flux density loop is implemented (Fig. 4). In comparison to a conventional AMB control the shown cascade does not include any current loop. It is reasonable to omit the subordinated current loop as the plant of current flux density are characterized by very similar time constants, here in particular the main field time constant T_h [Bahr et al., 2013]. Therefore the voltage output is calculated directly from the flux density controller. Figure 5 presents the complete flux density control structure. The plant itself shows a PT1 characteristic typifying the electromagnets,

TABLE II: MAGNETIC BEARING / SYSTEM PARAMETERS

	Parameter	Value
f_r	Nominal force	80 N
k_x	Negative stiffness	65000 N/m
k_{Bf}	Force - flux density coefficient	100 N/T
R	Coil resistance	0.67 Ω
L_h	Coil inductivity	3.3 mH
T_h	Main field time constant	4.9 ms
w	Number of windings	4 x 60
m_R; m_{red}	Rotor mass ; reduced mass	(2.4 ; 1.5) kg
δ	Air gap	1 mm
A_δ	Stator pole surface	(10 x 18) mm
$d_{S/R}$	Stator / rotor diameter	(115/49) mm
U_{DC}	DC link voltage	48 V
$f_{P/S}$	Pulse / sampling frequency	21.3 kHz
V_{VSI}; T_{VSI}	VSI gain; time constant	1 V/V; 96 µs
S_{PG}	Resolution of position gauge	50 nm

which generate the control flux density B_C. Within the first investigations a single Hall sensor was installed inside the AMB. As the bearing is biased by permanent magnets the measured air gap flux density B_δ is affected by the position depending bias magnetization B_{bias}. Basically the plant is to be stabilized by a PI type algorithm compensating for the main field time constant T_h. In order to achieve proper reference response the controller needs to be parametrized for amplitude optimum (see Table III). For safe operation of the flux based control, the coil current is to be monitored online and to be limited if necessary since the closed flux density loop does not provide any innate over-current protection. Therefore, an additional safety function has to be implemented to provide a basic protection in case of thermal overload of control coils, permanent magnets as well as for power semiconductors of the power converter. This protection should be based on the internal current measurement in order to avoid any unexpected touchdown. The linear flux based control structure provides the base for the position loop and its controller design. The position plant is shown in Fig. 6. Here, the path includes the subordinated flux loop, linear force generation as well as the mechanical plant. The main advantage of the investigated magnetic bearings type based on differential principle concerns its linear characteristic of flux density and magnetic force when assuming a constant bias magnetization (centered rotor). For proper stabilization of the AMBs plant, a PD type controller is used to achieve the classical spring–damper characteristics with adjustable stiffness k and damping d. In particular a PIDT1 algorithm offers adequate reference accuracy and enables a tunable limitation of the controller´s derivative, which is essentially needed for damping of high-frequency noise induced by the installed capacitive position gauge. Based on the linear force characteristic the controller gain $V_{RB} = k/k_{Bf}$ as well as the lead time $T_D = d/k$ have been chosen for a preset stiffness of 300 % above the AMBs natural stiffness ($k = 3 \cdot k_x$). Within this first study the damping ($d = 2D\sqrt{k \cdot m_{red}}$) was increased stepwise to a total damping factor D=0.9. Thus the suspension system is strongly damped but still oscillatory concerning its positioning characteristic. The controller design was executed by neglecting the comparatively faster operating subordinated flux density loop. Concrete data and controller parameters for all experiments carried out and presented in chapter 4 are given in Table III. For both controllers - flux density as well position - an anti-windup was active. After controller design the complete algorithm was implemented to a dSpace real-time control system (DS1103) operated with sampling and pulse frequencies of 21.3 kHz. One bearing axis was controlled by the presented algorithms; the second axis worked with conventional current based PID control. Within this research both the fully stable initial rotor lift-off as well as the proper operation and accurate positioning were realized successfully by using the integrated Bismuth Hall sensor.

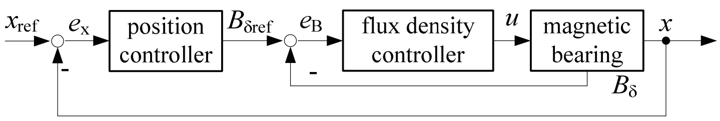

Fig. 4: Basic structure of cascaded position and flux density control.

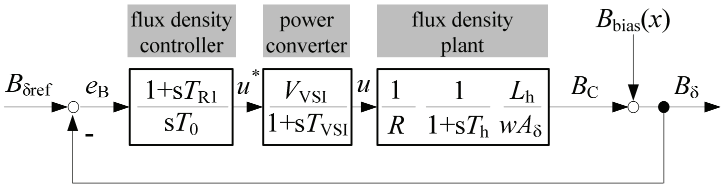

Fig. 5: Closed loop control of air gap flux density.

TABLE III: CONTROLLER PARAMETERS

	Parameter	Value
	Flux density controller	
V_{RB}	Controller gain	150 V/T
T_{IB}	Integral time constant	4.9 ms
	Anti-windup	active
	Position controller	
V_{Rx}	Controller gain	1950 T/m
T_D	Derivative time constant	5 ms
T_{DT1}	DT1 time constant	0.16 ms
T_I	Integral time constant	10 ms
	Anti-windup	active

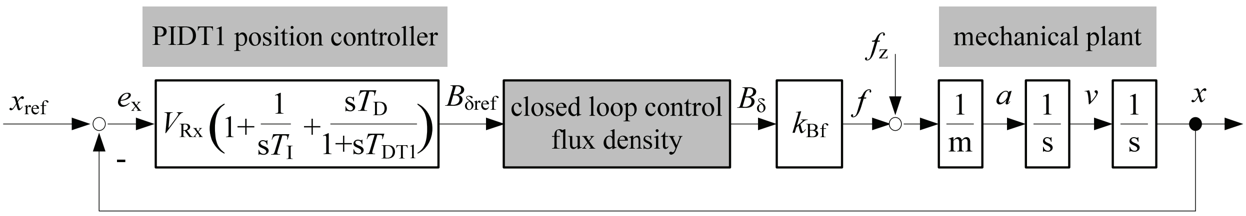

Fig. 6: Closed position loop using PIDT1 controller for stabilization of AMB plant.

4. Experimental results

The stable working flux density control for an exemplary step response is presented in Fig. 7. In order to analyze the systems dynamic performance the closed control loops was investigated by frequency response measurements: Response characteristic of the flux density loop with an optimum amount parameterized controller is shown in Fig. 8. It reveals a quite constant reference response (gain 1) up to 600 Hz and a bandwidth of about 900 Hz (-3 dB) is reached. This behavior is achieved by using the directly integrated air gap flux feedback and is comparable with conventional subordinated current control.

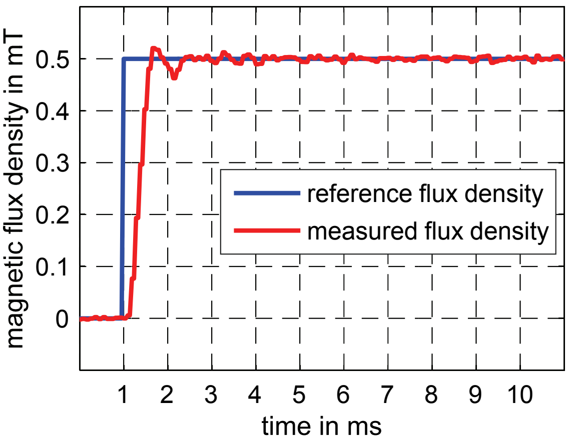

Fig. 7: Step response: closed loop control of air gap flux density by integrated Bismuth Hall sensor feedback.

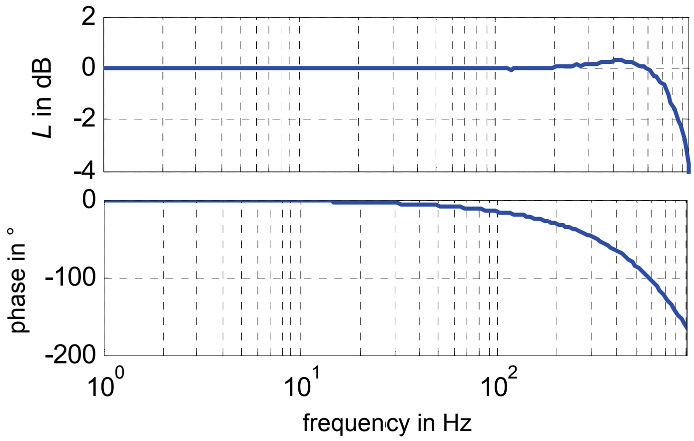

Fig. 8: Frequency response characteristic of the closed loop flux density control using flux density feedback.

Implementation and initial operation of the whole control consisting of position loop with subordinated flux density loop impressively demonstrate their functional working ability for the first time ever. Within the first investigations a positioning accuracy of less than 1 µm is achieved in standstill for position controller parametrization based on stiffness and preset damping. The proper rotor positioning for a sinusoidal reference trajectory with 5 Hz in frequency and 50 µm in amplitude by using the flux based magnetic bearing control is exemplified in Fig. 9. The entire cascaded control was investigated concerning its dynamic by frequency response analysis. After fine tuning the position controller a very constant gain up to a bandwidth of 80 Hz was achieved for the radial industrial type AMB (Fig. 10).

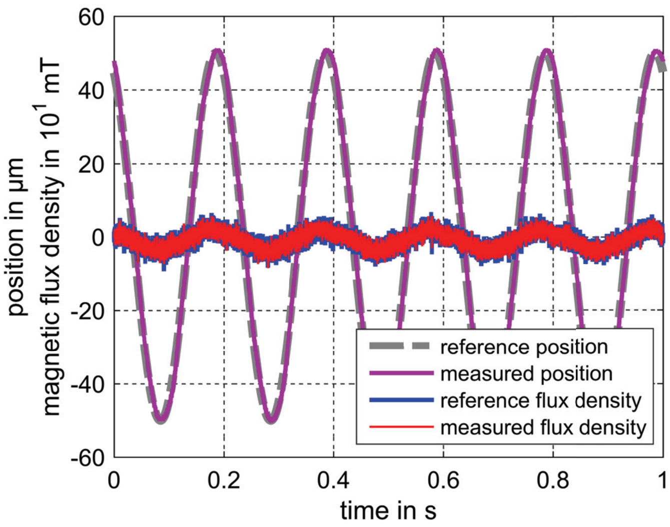

Fig. 9: Sinusoidal positioning: Flux based control of the AMB test system (see Fig. 4). Proper rotor stabilization and positioning using flux feedback (frequency: 5 Hz, ampl: 50 µm).

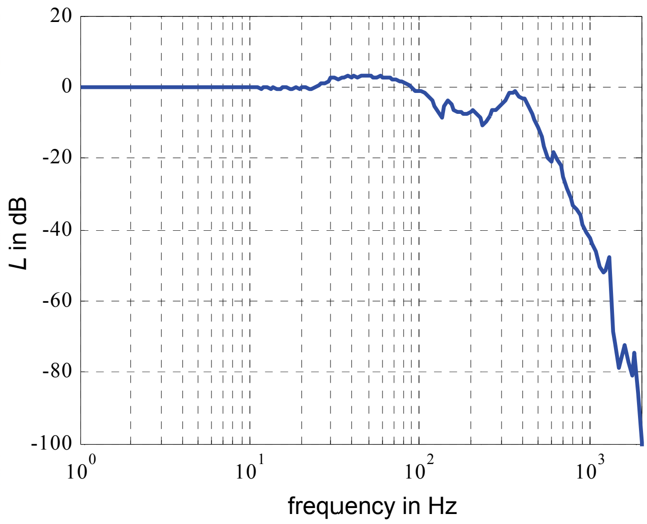

Fig. 10: Frequency response characteristic of the closed loop position control using the subordinated flux density loop. (see Fig. 4).

5. Conclusion

In order to enable flux density measurement in narrow air gaps of magnetic bearings, the total thickness of flexible Bismuth Hall sensors is reduced down to less than 100 µm. The new technology based on Bi film deposited Silicon was developed and investigated intensely for Si dies thinned down to 50 µm. After fabrication and contacting to highly flexible copper cladded PI foils the sensors reveal impressive sensitivities up to 800 mV/AT. As needed for AMB applications the signal level is amplified to several V/T by using a low noise conditioning electronics. Sensors of latest development stage were integrated into a radial AMB. For the first time a flux based magnetic bearing control was implemented successfully. The novel Hall sensor platform enables real-time magnetic field measurement and features both the modification free integration into existing drive systems as well as local flux sensing inside the air gap: Operational capability was demonstrated in stable AMB operation and precise rotor positioning. Applied flux based controls were investigated experimentally by means of step response analysis and frequency response measurements. The industrial like AMB system equipped with an ultra-thin and flexible Hall sensor showed proper operation with positioning accuracies below 1 µm. Future investigations will continue studies of magnetically suspended systems with a full set of air gap integrated Bismuth Hall sensors for all 5 DOF. In parallel the presented sensor technology itself is under permanent development. Successive sensitivity boosting (to several V/AT) and reliability improvements (optimized stud bump size, redundant configurations) are upcoming steps within the interdisciplinary research project.

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