Current Slope Measurement Strategies for Sensorless Control of a Three Phase Radial Active Magnetic Bearing

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Abstract

This paper discusses the sensorless control of a three phase radial active magnetic bearing (AMB). Self-sensing or sensorless methods mean, that the electromagnetic actuator itself is used as position sensor too and the rotor position information is evaluated by electrical quantities as currents and voltages. Thus, external rotor position sensors can be omitted and allow a simplification of magnetic bearing system architectures. Since many years [7, 11] sensorless AMBs are field of research to reach performance parameters as bearing systems with position sensor do have. The proposed self-sensing method is based on inductance measurement by current slope detection during voltage pulse injection or integrated in the Pulse Width Modulation (PWM) pattern applied to three phase radial AMBs. Different electrical current slope measurement strategies are investigated regarding self-sensing performance and accuracy. Two different three phase AMB prototype setups are explained and used for experiments. The measurement results show improvements by different current slope detection strategies. Finally some examples of the behavior during sensorless levitation in a closed loop position control represent the potential of self-sensing three phase AMBs to industrial applications.

1 Introduction

Classic setups of AMB applications are complex systems consisting modules as the axial and radial AMBs, the rotor position sensors and appropriate measurement amplifiers, the AMB power amplifiers, the control electronics, the electric machine and the motor drive inverter. Especially the sensor systems represent a high cost portion of the AMB system, because they are expensive and for a 5 axis stabilization such units have to be multiple used. Thus, dealing with a sensorless algorithm instead of a sensor unit will reduce product costs significantly by a high utilization of already used components. Another potential for product cost reduction is identified in the AMB power amplifiers. Depending on the bearing architecture usually H-brigde topologies are used for at least each single axis. Supplying two axis of one radial AMB from one three phase inverter allows a reduction of power semiconductors and current sensors. Today, three phase inverters have reached a high grade of modularity from a low up to a high power range, are well industrialized and produced in a huge amount for industrial drive applications. These two topics are the motivation for research on sensorless three phase AMBs. Reaching required system performance with this approach is a possible way to enlarge the field of additional industrial applications of AMB.

Since several years self-sensing approaches are field of research according to [7, 11]. Estimation based methods using the current information alone and methods using the current ripple information by high frequency excitation or voltage injection are known. In the last time the focus is given on current slope based methods, as in [5, 8]. In these works current slope based self-sensing approaches are applied to a single axis setup or to a classical 4 respectively 8 pole

AMB topology. The known limitation factors for self-sensing performance are identified within saturation [7] and eddy currents [2, 7]. Avoidance of saturation can be reached by an appropriate material utilization in the AMB design focused on linearity. The second topic, the eddy current effects related to self-sensing, is also part of this article. By the presented measurement results limitations caused by eddy currents are figured out. One way for a significant reduction is finally found by the introduction of a differential approach. This concept overcomes the general downside of eddy current and brings the self-sensing accuracy close to the performance known from AMB systems with position sensors. This can be seen by the new results related to the sensorless position detection accuracy in an open loop and and the behavior in a closed loop sensorless position control.

1.1 Three Phase Active Magnetic Bearings

The minimum number of stator poles for radial active magnetic bearings was investigated in [6] and results in a number of three stator poles. In this article the focus is given to three phase hybrid magnetic bearings (HMBs). HMBs use permanent magnet biasing for an AMB and is known for three phases as shown in [12]. The advantage is a reduction of the electric current consumption which was already evaluated in [3, 12]. The combination of permanent magnet flux and control flux is realized as shown in Fig. 1. In this way a homopolar flux distribution on the rotor is given which lowers the iron loss at high rotational speeds compared to heteropolar bearings. Three phase AMBs can also be supplied by three H-bridges if the three coils are not

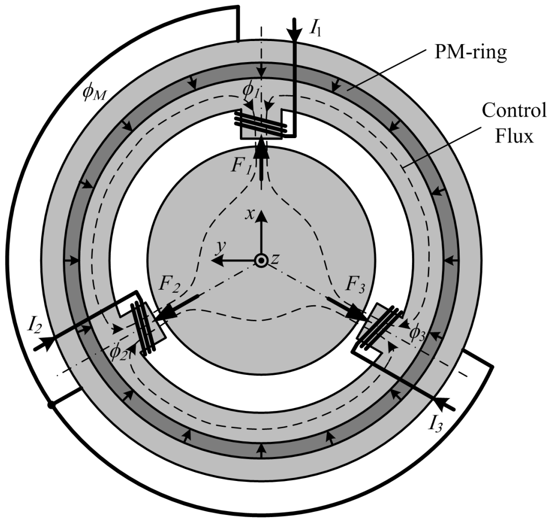

Figure 1: Three phase radial AMB with permanent magnet biasing

connected to each other. In this work the coils are connected to a star point and the three phases are supplied from a three phase voltage source inverter according to Fig. 2.

The implementation of a three phase structure is also possible using a higher number of stator poles. The second bearing prototype investigated in this work consists of 6 poles connected to three phases as shown in Fig. 3. Here two poles opposite each other are equipped with excitation coils in a way, that on one side the total flux is increased and on the other side the total flux is decreased, see Fig. 4. Thus, the resulting electromagnetic forces on the opposite poles are not compensating each other, but react in same direction. In this topology the superposition

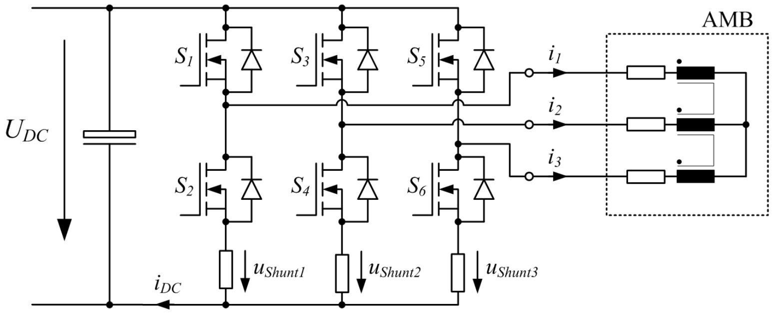

Figure 2: Three phase inverter applied to a three phase radial AMB.

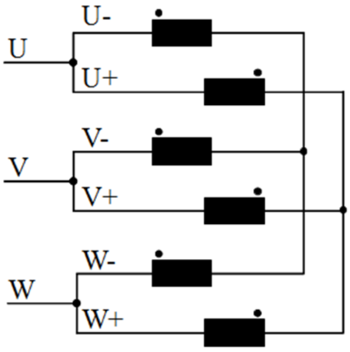

Figure 3: Coil connection of the three phase AMB with 6 poles for the usage of a three phase inverter.

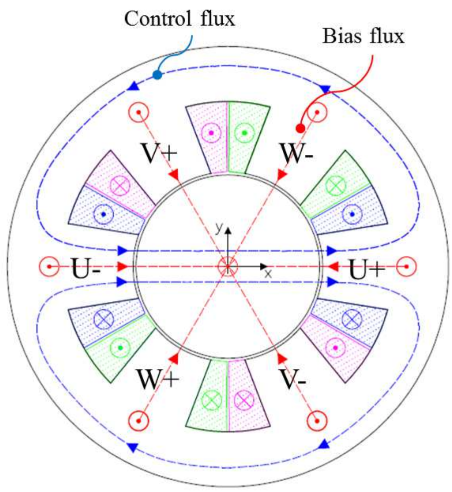

Figure 4: Three phase AMB with 6 poles.

of the control flux and the bias flux also lead to a hompolar bearing and the advantages of a three phase inverter are still used.

1.2 Sensorless Rotor Position Detection

The sensorless control approach used in this work is based on the so called INFORM (Indirect Flux detection by Online Reactance Measuremnt) method which is known from sensorless control of electrical drive applications. The basic idea uses an inductance variation which is evaluated during voltage injection pulses and current slope measurements. At AMBs this method allows the rotor position determination, because the AMB stator inductances are not constant and depend mainly on the radial rotor displacement. Modeling the three stator coil inductances of the AMB according to Fig. 1 in a perpendicular coordinate system (x, y) and considering the behavior in x-direction the inverse of the rated self inductance l_{XX} for ideal permeable iron yields

$$\frac{1}{l_{XX}|_{y=0}} = \frac{L_0}{L_{XX}} = 1 - \frac{x}{2\delta_0} \tag{1}$$

Here L_0 is the nominal inductance and δ_0 nominal airgap at centered rotor. This equation show a linear dependency on the rotor displacement x which is determined by measurement of current slopes during voltage pulses [4].

Consindering the inductance behavior of the 6 pole AMB according to Fig. 3 and Fig. 4 it can be easily seen, that by a rotor displacement in x-direction the airgap at the coil U+ decreases as at in the opposite coil U- the airgap increases. Modeling the rated inductances of both systems for ideal permeable iron result in

$$\begin{array}{rcccl} \frac{1}{l_{UU+}|_{y=0}} & = & \frac{L_0}{L_{UU+}} & = & 1-\frac{x}{2\delta_0} \\ \frac{1}{l_{UU-}|_{y=0}} & = & \frac{L_0}{L_{UU-}} & = & 1+\frac{x}{2\delta_0} \end{array} \quad (2)$$

Herein can be seen that a serial connection of the two opposite coils would cancel the inductance dependency on the rotor position. Therefore to achieve a high dependency on the rotor position the two three phase systems (U+V+W+ and U-V-W-) are connected parallel. Using this three phase AMB architecture the simple current slope evaluation of the classical three phase AMB with three poles is not possible any more, because the currents and the current slopes of the coil U+ and U+ containing the rotor position information are part of the phase current i_U. More details how the current slopes are evaluated are shown in the next sections.

1.3 Pulse Width Modulation

Today in most electric drive applications equipped with three phase voltage source inverters a symmetric Pulse Width Modulation (PWM) utilizing six inverter switching states is used. This PWM current control was also used in the first investigations on self-sensing three phase AMBs [4] and current slope detection was implemented as real voltage injection pulses interrupting this PWM pattern. In previous works [3, 9] the three active PWM method was proposed and also implemented for self-sensing AMBs. The three active PWM concept uses only three of six voltage space phasors according to Fig. 5. Considering the achievable maximum space phasor magnitude without over-modulation at the three active PWM a limit is given at $|\underline{u}_S| = 1/3\, u_{DC}$ (inner circle of the triangle) and the symmetric PWM is limited at $|\underline{u}_S| = 1/\sqrt{3}\, u_{DC}$ (inner circle of the hexagon). Although the voltage utilization is different the big advantage of the three active PWM is, that the three active injection pulse sequence [3] is already included and an additional interruption of the PWM pattern is not required any more. This leads to the highest possible bandwidth for sensorless rotor position detection, because at every PWM cycle the rotor position is calculated. Using injection pulses the applied injection rate determines the maximum sensing bandwidth. On the other hand this integrated sensorless rotor position detection method into the three active PWM pattern can require a minimum pulse width depending on the method of current slopes measurement. This would further reduce the applicable voltage space phasor magnitude $|\underline{u}_S|$ and has to be considered in the self-sensing AMB system design.

2 Current Slope Detection

For evaluation of the current slopes several methods are known from literature. In this work the focus is set on principles which are able to fulfill the requirements of high position sensing accuracy combined with low costs and a simple integration considering possible serial production of industrial AMB applications. Therefore current slope sensing principles not fulfilling these demands, e.g. Rogowski coils, current clamps are not considered. In this work three different

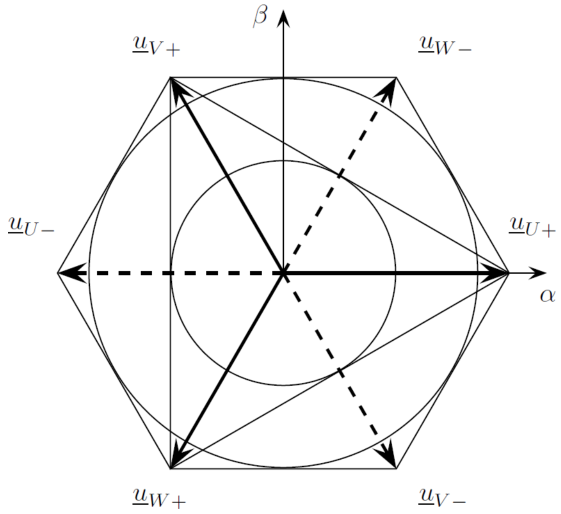

Figure 5: Voltage space phasors and operation limits (circles) in classical PWM and three active using only three positive switching states.

methods are evaluated. First using the current signal itself an calculating the slope out of the current by a $\Delta i/\Delta t$ approximation. Second for differential AMB setups a differential transformer setup is used either for differential current measurement or for direct slope detection by an open loop differential transformer. In the following section these principles are explained and evaluated for self-sensing performance of three phase AMBs.

2.1 Current Sampling Method

Nowadays digital signal processors (DSPs) are common in three phase electric drive inverters and consist of an on-board analog to digital converter (ADC) for time discrete sampling of the analog current signals. A three phase inverter topology with a simple shunt resistor current measurement principle is presented in Fig. 2

Additionally to the information of the current level, the same architecture can be used for detection of the current slope at applied voltages. An example for detection of the current slope by at least two sampling points is shown in Fig. 6. Here, two alternating voltage pulses are applied and the current gradient is detected at both, during the rising and falling slope which increase measurement accuracy and eliminate influences of induced voltages and ohmic voltage drops. In this example of a current slope the influence of eddy current effects can be seen very clear. Immediately after each voltage switching the current slope is disturbed and it takes a certain time after the eddy currents are decayed. Thus the possible measurement range for the current slope is reduced significantly (black line). Introducing additional sample values of the current signal as shown in [10], e.g. based on the mean difference method from outside to inside, result in an improvement of the position noise and also used in this work.

The position signal trajectory at orbital movement of a three phase AMB with current slope measurement by shunt resistors is shown in Fig. 7. For a stationary rotor position a statistic evaluation show a standard deviation of σ=15 μm at a nominal airgap of δ_0 =1 mm. According to [3] by utilization of a three active injection pulse sequence with 16x oversampling the position noise was reduced to σ =8 μm. Finally, with the three phase AMB prototype

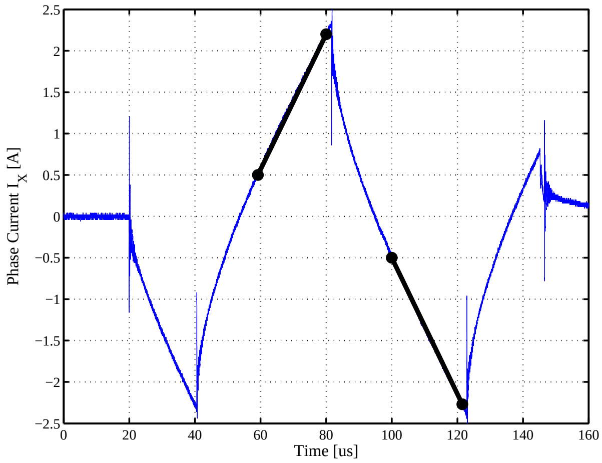

Figure 6: Inductance measurement by symmetric voltage pulse injections. Measured phase current reaction $I_1(t)$ (blue) and linear current slope approximation by two single samples per slope (black)

and the current sampling method this was the best position noise achieved, which is σ =8‰ of the nominal airgap. In the previous work [3] was figured out, that for PM biased bearings with high permanent magnet bias flux for reducing the current consumption this signal to noise ration (SNR) is still too low for sufficient sensorless levitation especially for industrial AMB applications.

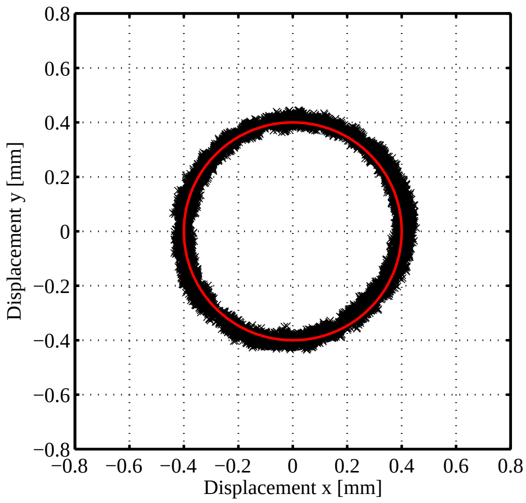

Figure 7: Trajectoriy of the sensorless rotor position at an orbital movement ε=0,4 mm using quad sampling and symmetric voltage pulses (black), real rotor displacement (red).

2.2 Current Slope Measurement by a Differential Transformer

For evaluation of the current slopes at a three phase AMB architecture with 6 poles the three phase inverter topology is slightly extended. Additionally a differential transformer is used to sum up the current slopes e.g. di_{U+}/dt and di_{U-}/dt of the opposite coils. By this concept the current values i_{U+} and i_{U-} are canceled, which allows the usage of a small and simple transformer, because only the different current slopes define the magnetic operation point of the transformer an not the absolute current levels. The current slope detection principle with the differential transformer is depicted in Fig. 8. The primary coils given by only one turn and the number of turns of the secondary part is adjusted to the signal measurement range. Implementing a low resistance at the transformer output causes, that the measured voltage u_{INF} is proportional to the secondary current Δi of the transformer. Hence, this voltage u_{INF} is evaluated by a separate ADC-input of the controller. A measurement example of the AMB prototype with a nominal airgap δ_0=0,8 mm for two rotor positions is presented in Fig. 9. The figure shows on the left side the coil current i_{U+} and the measurement signal at a negative displacement in x-direction. By the differential approach the output signal has negative slope although the current slope di_{U+}/dt is positive. On the right side the results are depicted for positive displacement in x-direction. With this approach the full ADC operation range is used for current slope detection independently from the current signal i_U.

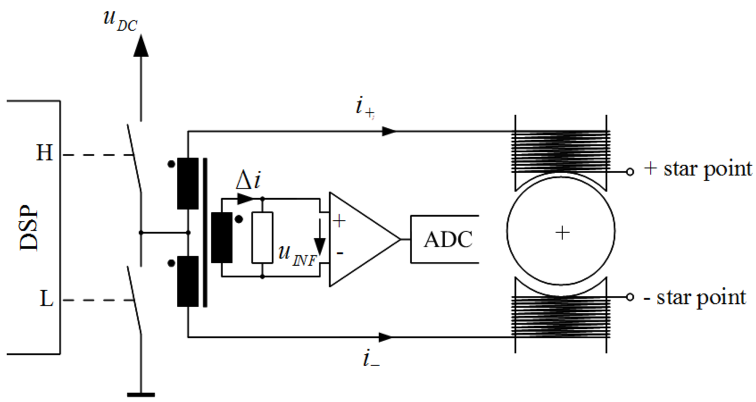

Figure 8: Differential current slope measurement principle.

The rotor position signal at an orbital movement is presented in Fig. 10. At a radial displacement of ε=0,5 mm can be seen that the sensorless rotor position (black) differs slightly from real position (red) in the circular shape. The root cause for this is given by the mechanical tolerances of the prototype, especially as the touchdown bearings define the maximum eccentricity. The rotor position noise is much improved compared to the current sampling method. The statistical evaluation of a mechanical fixed rotor position show a distribution according to Fig. 11. The standard deviation is σ =0,78 μm which is only σ =0,98‰ of the nominal airgap. This is a big noise improvement nearly by a factor of 10 compared to σ =8‰ at the current sampling method.

From the time signals in Fig. 9 can be seen, that the eddy currents influence the coil current i_{U+} immediately after each switching of the inverter, but on the transformer output signal, this influence is much smaller. Therefore the utilization of the current slope signal is higher than at the current sampling principle.

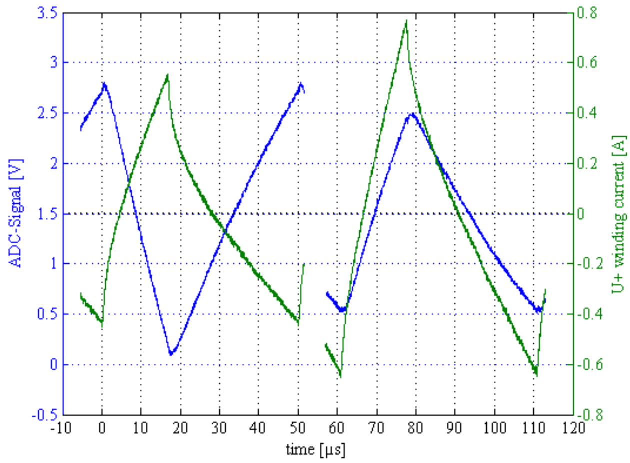

Figure 9: Time signals of the phase current i_{U+} and the differential current Δi in U-direction at two different rotor positions: negative displacement (left) and positive displacement (right).

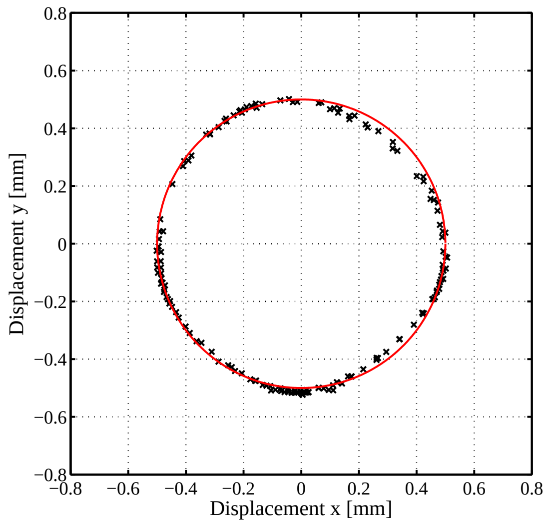

Figure 10: Trajectory of the sensorless rotor position at an orbital movements ε=0,5 mm determined by a differential transformer.

2.3 Direct Current Slope Measurement by an Open Loop Differential Transformer

In the previous section the introduction of the differential transformer has shown a big improvement, but as the slope has still to be calculated by two sampling values of the differential signal. A further potential is identified in using the differential transformer also for the evaluation of the gradient of the electrical current. For this the differential transformer is used in an open circuit (open loop) behavior as shown in Fig. 12. The transformer voltage output signal

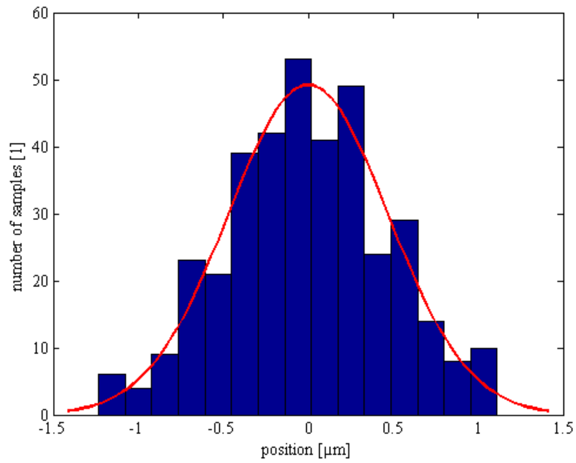

Figure 11: Histogram and related normal distribution with standard deviation σ =0,78 μm at a stationary rotor position determined by a differential transformer.

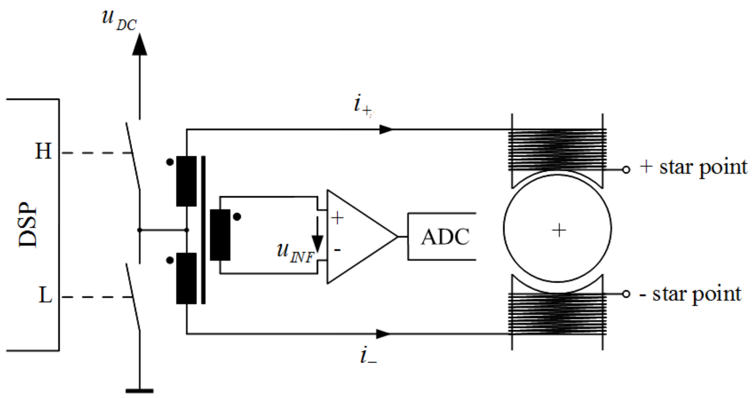

Figure 12: Current slope measurement principle by an open loop differential transformer.

represents directly the current slope $di_{U+}/dt - di_{U-}/dt$ according to Fig. 13. On the left side the signal shows the coil current i_{U+} for negative displacement in x-direction resulting in a negative current slope. On the right side the results for a positive displacement in x-direction is given. The general advantage of implementing the gradient operation into the transformer is, that the signal to the ADC has to be sampled at least once. Therefore only a minimal signal settling time is required for the slope detection and show less limitation regarding voltage phasor utilization. In Fig. 13 the nearly full compensation of the eddy current effects on the slope detection can also be seen. The distortions on the current derivative signal is shorter than on the current signal.

The rotor position trajectory at orbital movement at ε=0,5 mm is depicted in Fig. 14. Here as well as in the previous trajectory the shape is not perfectly circular shaped due to the same reason of mechanical assembly tolerances. As identified in [3] the position noise

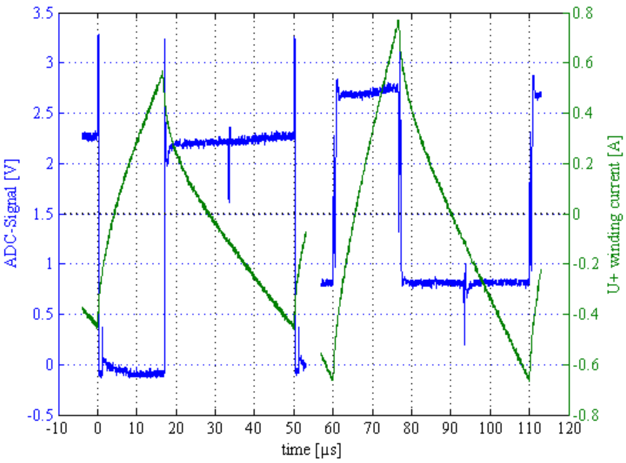

Figure 13: Time signals of phase current $i_{U+}(t)$ and differential current slope u_{INF} in U-direction at two different rotor positions determined by an open loop differential transformer: negative displacement (left) and positive displacement (right).

is much more critical for self-sensing AMBs than the linearity of the position signal. This will be shown also in the measurement results during closed loop sensorless levitation. The statistical distribution at mechanically fixed rotor is given in Fig. 15. The open loop differential transformer method result in a position standard deviation of σ =0,37 μm which is σ =0,46‰ of the nominal airgap. Compared to the slope measurement with differential transformer but without derivative operation the signal noise is reduced further approximately by a factor of two.

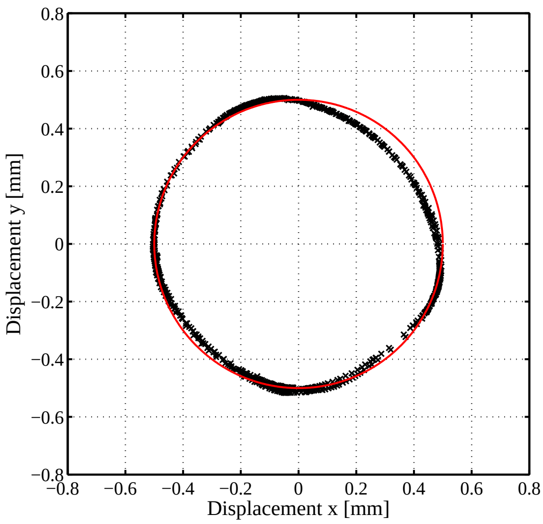

Figure 14: Trajectory of the sensorless rotor position at an orbital movement of ε=0,5 mm determined by an open loop differential transformer.

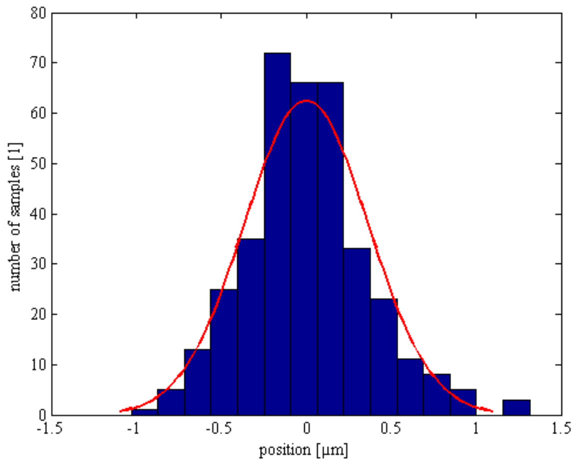

Figure 15: Histogram and related normal distribution with standard deviation σ =0,37 μm at a stationary rotor position determined by an open loop differential transformer.

3 Sensorless Position Control

The self-sensing position accuracy was evaluated and explained in the previous section. Definitely, the main focus is the characteristic in a closed loop sensorless operation mode. Therefore the prototype setup equipped with two three phase AMBs with 6 poles was build up and used for investigations (see Fig. 16). Each bearing is supplied by a three phase inverter and operates with a control rate and PWM frequency of f_{PWM} =20 kHz in the three active PWM mode.

Figure 16: Drive setup equipped with two three phase AMBs in differential arrangement.

For position control a cascaded control structure with a current control loop based on the low side shunt measurement of the three phase inverter and a position control loop with the sensorless detected rotor position from the open loop differential transformer is implemented in a DSP. With the PIDT1 position controller the operation in the bearing center is investigated. The sensorless obtained rotor position during levitation is presented in Fig. 17. Here, the standard deviation compared to the open loop behavior is not much higher and remains approx. σ =0,4 μm. Compared to results of [3], here the position noise is low enough not affecting the closed loop behavior. This experimental results at levitation show that the achieved sensing accuracy is already close to industrial position sensors for AMBs and can be also sufficient for industrial sensorless AMB applications.

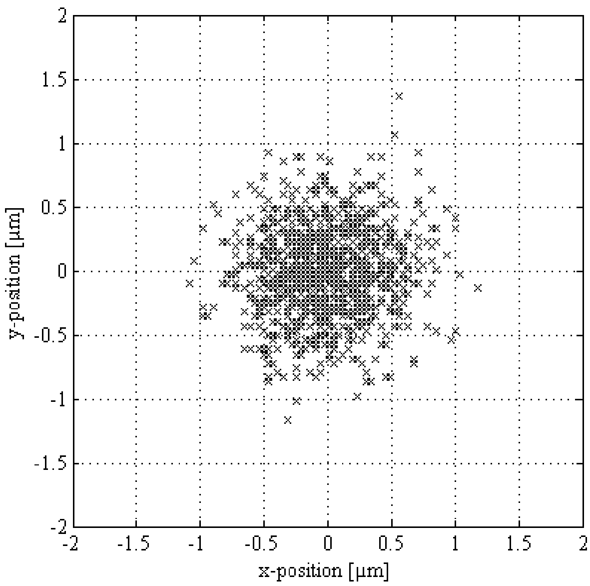

Figure 17: Distribution of sensorless rotor position during self-sensing levitaiton.

Additionally an important topic for industrial AMB applications is the evaluation of the stability in closed loop operation. As the self-sensing principle is also part of the closed loop position control the stability and robustness criteria are the same as for AMBs equipped with position sensors. Referring to the international standard ISO14839-3 [1] the peak of the input sensitivity function G_S shall be lower than factor 3 (9,5 dB) for newly commissioned machines and lower than factor 4 (12 dB) for acceptable long-term operation. At standstill a first measurement result of the 6 pole setup with self-sensing based on the open loop differential transformer principle was performed and is presented in Fig. 18. Here, the peak of the sensitivity function is approx. 10 dB at a frequency of 330 Hz. This value is within the range of "Zone B" and already close to the border of the best achievable "Zone A" range. It is expected that due to control parameter optimization this result can be improved further and "Zone A" can be reached. Measurements of the sensitivity transfer function at high rotational speeds are currently not performed and will be evaluated in a next step.

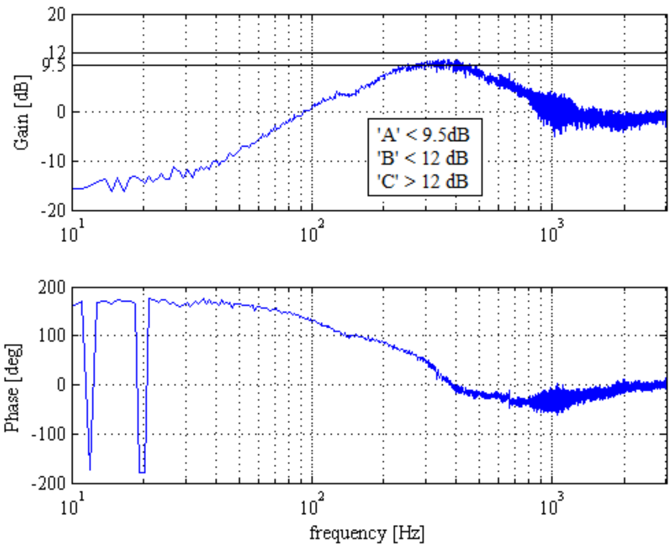

Figure 18: Measured bode plot of the sensitivity transfer function G_S at standstill.

4 Conclusion and Outlook

In this article new results regarding the current slope detection for self-sensing three phase radial AMBs are presented. Two different homopolar permanent magnet biased bearings are investigated by experimental results and show a big improvement by the usage of a 6 pole bearing architecture with differential current slope detection principle. Finally the following key results can be summarized.

- Starting form a classical three phase AMB setup with three poles the self sensing accuracy is improved significantly by the introduction of a 6 pole architecture with a thin lamination thickness of the AMB iron circuit. Here two coils are arranged in opposite direction and therefore any rotor displacement influences both opposite coils, which are combined for position evaluation. Thus, current slope signals with low eddy current influences are achieved and finally the self-sensing position noise was improved nearly by a factor of 10.
- An additional step forward is gained by using a direct current slope measurement with an open loop differential transformer, which allows to consider the current slope independently from the current value respectively the bearing load. Thus, a high utilization of the ADC range can be used for slope measurement which reduces position sensing noise. Compared to the classical three phase AMB setup the noise reduction is much higher than a factor of 10.
- During sensorless levitation it was figured out, that the self-sensing position signal in centered position show still a good position signal accuracy. This means the position noise is quite low and do not further affect the closed loop behavior.
- The evaluation of the sensitivity transfer function, which is a measure for industrial AMB applications, show already good results close to best value, namely "Zone A". Further improvements are expected by control parameter optimization to reach the quality and robustness as required for real industrial AMB applications.

Looking to future research work the focus is on further improvements on the position sensing accuracy and the overall system behavior. Very interesting is the operation at high rotational speeds, which is the main operation condition of AMBs. The question arises, if bearing losses at high speeds are independent from the self-sensing approach or not. Further, the investigation of the sensitivity transfer function have to be done at high rotational speeds.

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