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PCB Integrated Differential Current Slope Measurement for Position-Sensorless Controlled Radial Active Magnetic Bearings

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Abstract

This paper discusses a current slope measurement principle for self-sensing active magnetic bearings (AMBs). So called sensorless or self-sensing principles avoid external position sensors in the AMB and use the inductance dependency on the rotor position of the AMB itself to determine the rotor position for feedback control. By the help of a transformer core a combined evaluation of both opposite AMB coil inductances is possible. This differential approach determines the sensorless rotor position with high accuracy which allows a robust self-sensing AMB operation. The disadvantage of applying a wound transformer core can be overcome by a novel planar coil arrangement integrated in the printed circuit board of the AMB inverter. Different yoke materials for an optimal flux closure of the novel current slope sensing unit are investigated regarding to dynamic response and a high position sensitivity. Finally, experimental results of high permeable materials with well high frequency properties as ferrites or SMC confirm the sensing principle and allow a position-sensorless control of a three phase AMB.

Key words : Self-Sensing, Sensorless Control, Active Magnetic Bearing, Position Sensor, Current Slope, Position Dependent Inductance

1. Introduction

Active Magnetic Bearings (AMBs) are usually applied to high speed drives, e.g. for turbo pumps or flywheels. They provide a frictionless and wearless mechanical support of rotor shafts and allow operation at special environmental conditions (under vacuum or in fluids) and at high rotational speeds because of low losses (Schweitzer, 2009). AMBs require a stabilization feedback, which is commonly implemented by the help of external position sensors. Hence, AMB systems with a 5 degree of freedom (DOF) control are complex and consequently get expensive. For this reason investigations on a system simplification and cost reduction by sensorless or self-sensing methods represent a research topic since many years. This means, external position sensors within the AMB are replaced by other principles to determine the rotor position according to (Maslen, 2006), (Wang and Binder, 2013), (Schammass et al., 2004), (Gruber et al., 2013). In this work, the inductance change of the AMB itself depending on the rotor eccentricity is evaluated by the derivative of the coil current. The differential three phase radial AMB with permanent magnet bias flux generation does not use a serial connection of opposite coils, because then the information of coil inductance change is lost. Thus, an anti-parallel connection of opposite coils is applied and the rotor position is obtained by a differential transformer principle (Nenning et al., 2014-1). By this principle setup combined with an oversampling strategy (Nenning et al., 2014-2) a sufficient self-sensing operation at same position accuracy compared to position sensors is reached and results in a high robustness shown by a low sensitivity transfer function (Hofer et al., 2014). Although a position-sensorless operation without sensor in the AMBs is given, the differential transformer represents a small current slope sensing unit within the AMB power electronics. For further improvements regarding to manufacturing, assembling and production costs a simple alternative current slope detection unit by a PCB integrated approach is the focus in this paper.

2. Differential current slope measurement

In a previous work a permanent magnet biased three phase AMB with differential arrangement was investigated regarding to self-sensing (Nenning et al., 2014-1). A comparison of different methods to evaluate the current slope for self-sensing AMBs is investigated in (Hofer et al., 2014). Herein, the highest position accuracy, which is competitive with common inductive or eddy current position sensors, is achieved by a differential approach with an open loop transformer. Thus, the transformer combines the differentiation action for slope detection and a differential evaluation of two current slopes. Because the currents of two opposite AMB coils are used within the transformer the load current of both coils compensates and only the small part caused by different coil inductances remains. This allows the utilization of small closed ferrite cores, which do not get saturated from the load current, because the currents i_+ and i_- of opposite coils are fed only one times in counter direction through the core (primary winding turn = 1). The basic arrangement of this current slope detection principle is depicted in Fig. 1. The induced voltage from the secondary transformer coil u_{INF} is provided to the analog to digital (ADC) converter of the digital control. Definitely, this transformer represents an small additional sensing unit within the AMB power electronics, but still no external position sensor in the AMB and no sensor cables and connections are required. A three phase prototype inverter for sensorless controlled three phase AMBs utilizing the differential transformer approach is shown in Fig. 2.

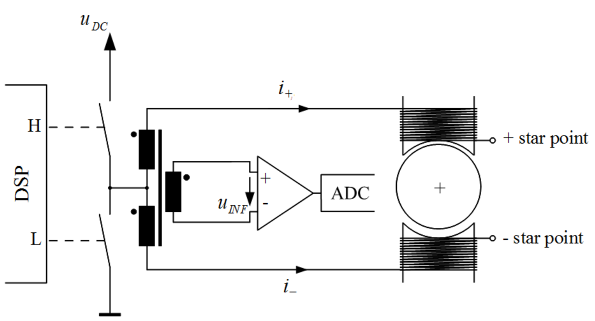

Fig. 1 Basic principle (one phase) of differential current slope measurement by a transformer for sensorless controlled three phase AMB

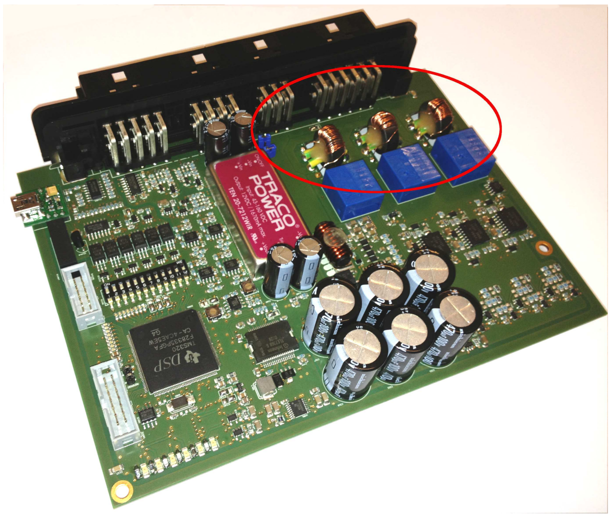

Fig. 2 Three phase inverter with three wound differential transformers (red circle) for differential current slope measurement for sensorless three phase AMBs

3. PCB integrated approach

The utilization of wound ferrite cores to an industrial product can be difficult and/or cost intensive. Therefore a PCB (printed circuit board) integrated approach is presented (Schroedl, 2015) and investigated in this work. The basic principle uses planar copper windings integrated in the PCB beside the two phase currents i_+ and i_- from the AMB coils according to Fig. 4. As nowadays multilayer prints are commonly used, all PCB layers can be used to implement coils for realization of a small package at a high number of winding turns. To avoid leakage flux and increase the flux density through the PCB caused by the current difference a high permeable material (e.g. electrical steel sheets) on top and on the bottom of the PCB is used (Fig. 3). Thus, a nearly homogenous magnetic flux (flux density B_{PCB}) crossing the PCB (thickness d_{PCB}) and the integrated coils is achieved. Applying the Ampere's law to the PCB cross section yields

$$\oint H \cdot ds = i_{total} = i_+ - i_- \tag{1}$$

and assuming an ideal electrical steel ($\mu_r \to \infty$) the induced coil voltage u_{INF} derives by Faraday's induction law as

$$u_{INF} = \frac{d}{dt}\Psi = N\,\overline{A_{winding}}\,\frac{d}{dt}B_{PCB} = \frac{N\,\overline{A_{winding}}\,\mu_0}{2\,d_{PCB}}\,\frac{d}{dt}\,(i_+ - i_-) \tag{2}$$

depending on the current difference $(i_+ - i_-)$ and the average area $\overline{A_{winding}}$ of each winding turn. This induced voltage u_{INF} represents directly the time derivative of the current difference from the positive and negative AMB coil and is further linked to the ADC of the digital controller. To avoid insulation failures the steel closures are glued to the PCB with an insulation foil in between. The coil dimensions and number of PCB layers can be used to adjust the current slope voltage

u_{INF} to the AMB parameters. A physical prototype PCB as a replacement of the wound transformers (Fig. 2) is built up and uses an electrical steel plate dimension of 18mm x 31mm with a 6 layer PCB with N=22 turns for each of the 12 coils. In total 264 turns at a variable area $A_{winding}$ for each winding turn are implemented for the secondary coil. In contrast, with the closed ferrite ring only N=30 turns on the secondary winding are used, because there is no airgap given.

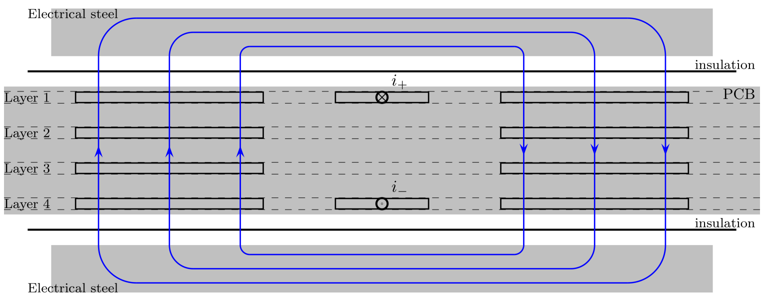

Fig. 3 Principle PCB cross-section of the integrated differential current slope measurement for one phase by the current difference $i_+ - i_-$ (4 layers)

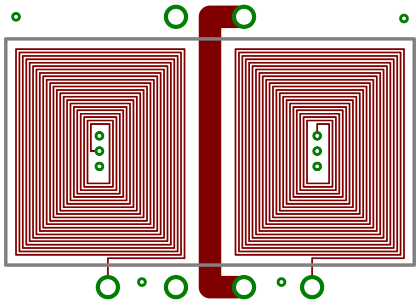

Fig. 4 Top view of PCB integrated differential current slope measurement for one phase and N=22 turns per layer

A theoretical investigation regarding the steel thickness results in a very low thickness requirement. The prototype has a PCB thickness including the insulation layers of d_{PCB}=1.75mm. With a low differential current of $(i_+ - i_-)$ in the range of 0.2A regarding to Fig. 5 combined with the relative big airgap length d_{PCB} a very low flux density $B_{PCB} = 72\mu T$ occurs in the airgap. The total flux from the airgap (PCB) concentrates through the steel yoke above and below the AMB coil currents. With high permeable electrical steel material NO20 (thickness 0.2mm) and its relative permeability of $\mu_r \approx 4000$ the flux density within the electrical steel is $B = 4.7mT$ by using only one sheet. Thus, by implementation of only one electrical sheet on top and bottom of the PCB a low cost current slope sensing unit can be reached.

4. Experimental results

The basic approach of differential current slope measurement with a wound ferrite core is illustrated in Fig. 5. For the three phase AMB a so called three active PWM pattern by alternating the voltage space phasors $\underline{u}_{U+}$, $\underline{u}_{V+}$, $\underline{u}_{W+}$ in each PWM period is applied from the AMB inverter. Depending on the rotor position the current slopes varies. Consequently, the induced voltage from the transformer changes. For measuring the voltage by the controller with the help of an analog circuit the voltage is shifted by +1.5V (half ADC measurement range). After a short settling time at each voltage switching the derivative of the current difference can be sampled or even oversampled from the ADC. The experimental result from the new PCB integrated differential current slope sensor with one electrical steel NO20 is presented in Fig. 6 which shows the dependency on the rotor position.

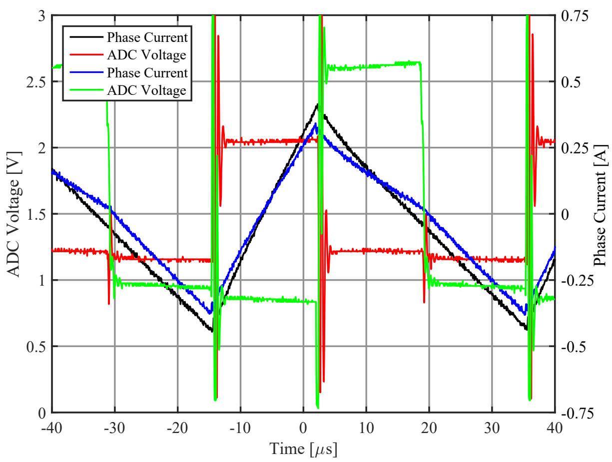

Fig. 5 Transient behavior of the wound ferrite core at two different rotor positions $x \pm 0.5mm$, phase current i_{U+} and ADC voltage

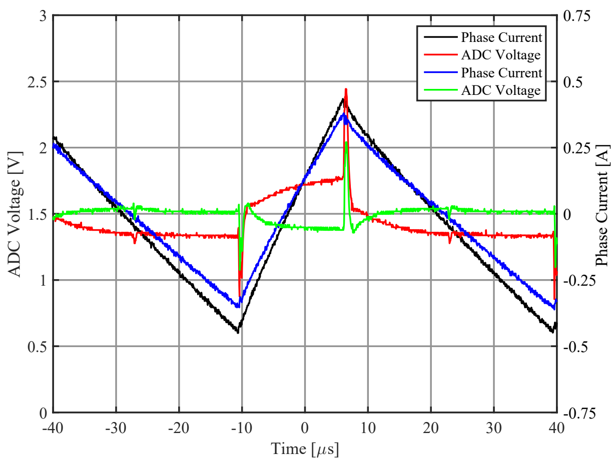

Fig. 6 Transient behavior of the PCB integrated current slope sensor with one electrical steel NO20 at two different rotor positions $x \pm 0.5mm$, phase current i_{U+} and ADC voltage

A comparison with the ferrite core (Fig. 5) identifies two main aspects. First, a relative long settling time of approx. $15\mu s$ is caused by eddy current effects. This low dynamic response do not allow a clear identification of the current slope at a PWM frequency of 20kHz. Especially, if the PWM pattern further changes during operation because of voltage demands from the current control. And second, at same analog amplification the signal ratio at same rotor displacement is much lower. Although the electrical steel sheet is very thin, this measurement show the limitation of solid steel sheets because of eddy currents.

In general, eddy current effects in electrical steel are limiting several technical applications with high frequency components (e.g. HF transformers). Hence, alternative materials are used in such applications. A ferrite material SIFERRIT N87 is typical known and also investigated regarding the PCB integrated current slope sensing prototype. Typical parameters according to the data sheet are a saturation flux density $B_{sat} = 0.49T$ and an initial relative permeability μ_i=2200 which are sufficient for this application. Definitely, this material is very brittle and can not be provided in a low thickness. For first measurements a block shape with thickness 4mm is used and implemented in the inverter (Fig. 9, Fig. 10). The measurement result is depicted in Fig. 7. A clear current derivative signal is obtained although the signal is approximately half of the signal from the wound ferrite ring. The signal settling time is about $3\mu s$ and slightly longer than at the transformer. But still, even at changing the PWM duty cycle the derivative can be sampled by the ADC. Thus, the ferrite plates allow a sensorless position identification out of the current slopes by adjusting analog amplification.

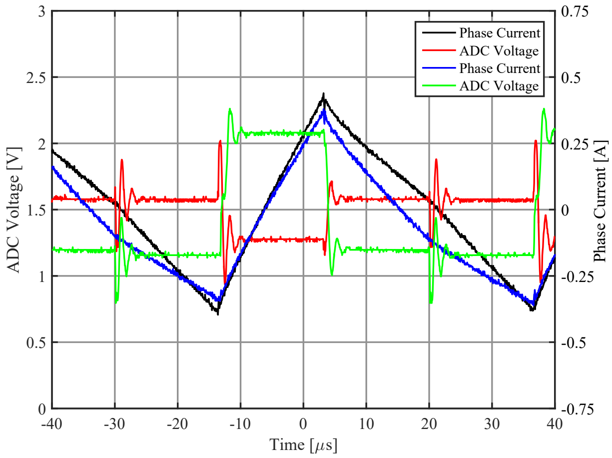

Fig. 7 Transient behavior of the PCB integrated current slope sensor with a ferrite plate N87 at two different rotor positions $x \pm 0.5mm$, phase current i_{U+} and ADC voltage

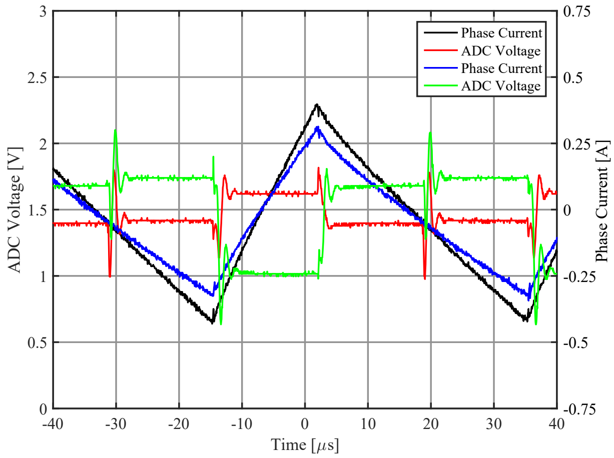

Fig. 8 Transient behavior of the PCB integrated current slope sensor with a Somaloy SMC material at two different rotor positions $x \pm 0.5mm$, phase current i_{U+} and ADC voltage

Another alternative high permeable material with excellent high frequency properties is the soft magnetic composite (SMC) material. Usually SMC materials are used for components which effort three dimensional magnetic properties. The material consists of nano-coated iron particles, which are pressed in the final shape and finalized by a thermal process. For investigation of SMC in the PCB integrated current slope sensing unit a prototype material Somaloy from Höganäs is used and plates with thickness 4mm are machined according to Fig. 9 and Fig. 10. The current slope signal with SMB plates is given in Fig. 8. The ADC voltage shows a shorter settling time of approx. $2\mu s$ compared to ferrite material. The signal magnitude of the induced voltage for a position change of ±0.5mm is a little lower than at the ferrite, because of a lower relative permeability $\mu_r \approx 400$ of the SMC material.

Because of a easier machining of SMC compared to the ferrite N87 three SMC prototype sensor units are applied to the AMB inverter and a rotor position trajectory at constant eccentricity ε=0.5mm is recorded according to Fig. 11. Because a well signal quality is given a position-sensorless control can be realized with this novel PCB integrated current slope sensors equipped with SMC plates. A sensorless start-up from the saftey bearings is depicted in Fig. 12 and confirms the functionality of the new sensor arrangement without wound transformers.

Compared to the wound transformer approach the induced voltage u_{INF} of the PCB integrated sensor shall be further increased for a utilization of the full ADC range. This can be done by changing the coil geometry and increase the number of coils and/or use a higher number of PCB layers. Thus, an increased position signal accuracy is gained. For industrial AMB applications a high robustness, a high reliability and low costs are typical requirements. By the presented current slope sensor prototypes integrated into the three phase AMB inverter the target of a low cost architecture is fulfilled. But definitely, the manufacturing of thin planar geometries out of SMC or ferrite material are not common applications

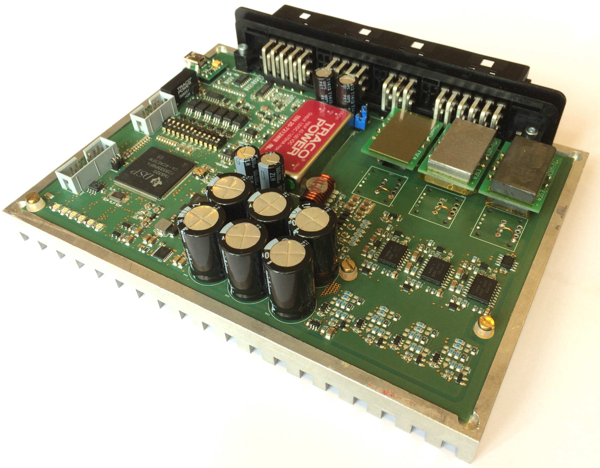

Fig. 9 Three phase inverter with three different types of PCB current slope sensors instead of wound ferrite cores

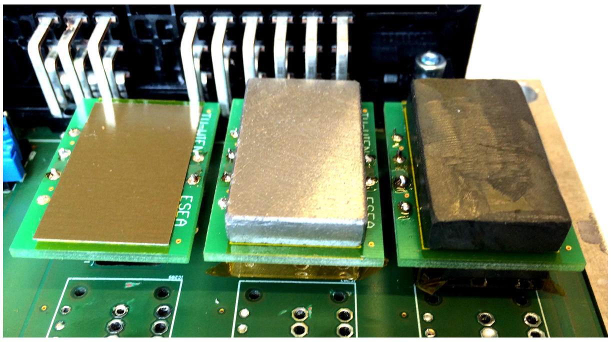

Fig. 10 Detail of three different PCB integrated current slope sensors, left: NO20, middle: SMC, right: ferrite N87

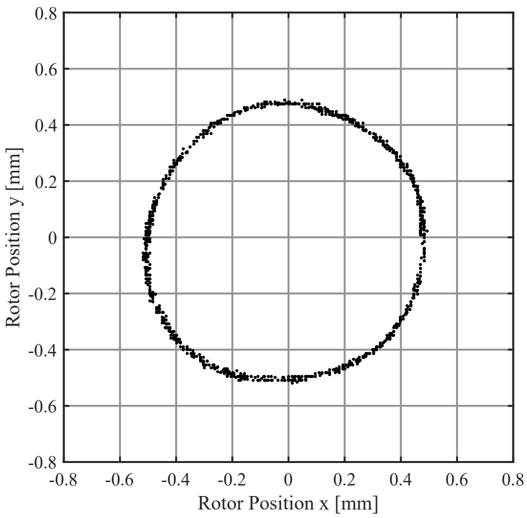

Fig. 11 Rotor position with planar SMC transformers at constant rotor eccentricity $\varepsilon = 0.5$mm

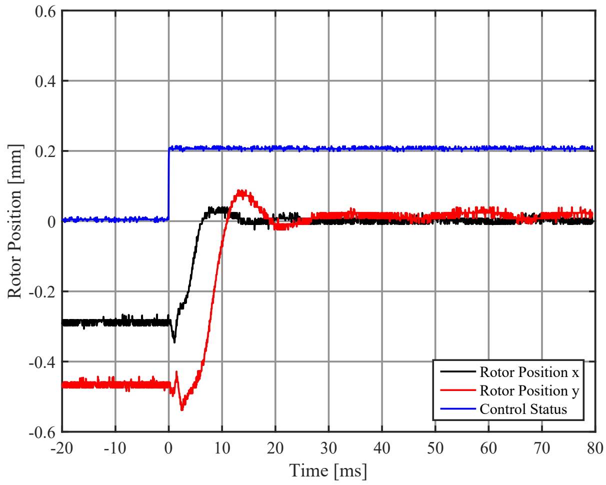

Fig. 12 Startup of the sensorless position control with novel planar SMC transformers

for these materials. Further investigations regarding an efficient production of thin yoke plates or applying alternative materials instead are planned. But finally, in this work the basic principle of the novel PCB integrated current slope sensor is confirmed and the most critical property of a low eddy current requirement is identified.

5. Conclusion

In this work a novel PCB integrated differential current slope measurement for sensorless AMBs is investigated. The basic idea for differential current slope measurement by a planar differential transformer principle is presented and implemented into small print adapters for utilization in the same AMB inverter instead of wound ferrite cores. The application of different high permeable materials show, that even thin electrical steel sheets are not applicable because of too high eddy current effects. With materials optimized for high frequency electromagnetic operation as ferrites and SMC the functionality of the PCB integrated sensor is confirmed by experiments with realized prototypes. A self-sensing control demonstrates the sufficient sensing accuracy. For possible industrial AMB applications based on the novel current slope sensing units the production technology of the high permeable yoke plates by pressing and sintering according to the limits of the process parameters is of interest. Other parameters of the PCB integrated sensor can be adjusted by geometry of the coils and number of the PCB layers. Finally, next steps will cover manufacturing and production topics to confirm the targets of a low cost position-sensorless AMB architecture at a high robustness and reliability.

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