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Application of Soft Magnetic Composites (SMCs) in Position-Sensorless Controlled Radial Active Magnetic Bearings

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Abstract

In this paper a soft magnetic composite (SMC) material is applied to permanent magnet (PM) biased radial active magnetic bearings (AMB) and investigated regarding position-sensorless control. A bias flux generation by permanent magnets with a homopolar bearing structure requires the closure of the bias flux in axial direction. Thus, accordant magnetic properties in all three dimensions are required from the applied materials. The isotropic behavior of SMCs may offer advantages compared to a classical realization with laminated electrical steel. Further, for a self-sensing AMB operation the high frequency (HF) aspects of the iron path have relevance for the sensorless position evaluation regarding dynamics and accuracy. Because of these two reasons applying SMC material to this AMB topology is an interesting alternative to common setups with laminated electrical steel. Two AMB prototypes at same geometry and different materials are investigated by experiments. In this work key parameters of bias flux density, force-current characteristic, operational losses and self-sensing properties are compared. Finally, a conclusion shows, that the apparent material advantages of SMC are not utilized in this AMB application.

Key words : Soft Magnetic Composite, Active Magnetic Bearing, Hybrid Magnetic Bearing, Permanent Magnet Biasing, Self-Sensing, Sensorless Control

1. Introduction

Active Magnetic Bearings (AMBs) offer a contactless support of rotating shafts and therefore they are often used in high speed drive applications like turbo pumps or flywheels. Because of the high rotational speeds, in the AMB rotor the flux density changes with high frequencies. To achieve low rotor losses (especially eddy current losses) and avoid rotor overheating usually the AMB components are built of laminated electrical steel. Another aspect of eddy current effects at AMBs is related to self-sensing technologies. Self-sensing or sensorless technologies do not use external position sensors implemented in the AMB setup, but they use the AMB itself as a sensor additionally. For determination of the rotor position the inductance dependency on the rotor eccentricity is evaluated by current slope measurements (Hofer et al. 2014). According to (Maslen, 2006) a limitation factor for self-sensing AMBs are eddy current effects, which affect the current change in the AMB coils. An alternative soft magnetic material for potential usage instead of laminated electrical steel is a Soft Magnetic Composite (SMC) as shown in (Boehm et al., 2012). SMCs consist of small iron powder particles separated by an electrical insulating coating to avoid eddy currents. Usually, such sintered materials (e.g, ferrites) are used for high frequency (HF) applications, e.g. transformer cores in power converters. By the isotropic behavior, SMC can be well used for three dimensional flux applications and is already investigated for AMBs in (Fleischer et al., 2011), (Mason, 1998), (Seifert et al., 2015).

For permanent magnet (PM) biased homopoloar AMBs the application of SMC show two possible advantages. First, the three dimensional flux distribution in a homopolar bearing topology can be improved. Because the lamination stacking effect with insulated electrical steel sheets, which lead to a low average relative permeability in axial direction is avoided. Second, the HF aspects of the iron path have impact on the coil currents and further affect the dynamic response of sensorless position evaluation. Thus, in the following sections the bearing topology, measurements on the bearing forces as well as bearing losses and finally results regarding to sensorless properties are presented.

2. Magnetic Bearing Prototype

For an experimental investigation a magnetic levitated drive prototype according to Fig. 1 is used. This setup consists of a Reluctance Synchronous Machine (RSM) with two permanent magnet biased three phase radial AMBs built of laminated electrical steel. The stabilization of this drive in axial direction is pure passive, because of axial reluctance forces from the radial AMBs. The AMBs use exchangeable rectangular permanent magnets arranged in axial direction to provide the bias flux (Hutterer et al., 2016). Hence, the bias flux can be adjusted by changing magnet types and number of magnets. The three phase AMB topology is implemented with 6 poles, where two opposite coils are used for a differential current slope detection. This is realized by an open loop transformers, which combines the derivation of the current difference from both opposite coils as described in (Hofer et al., 2014). This setup allows a high accuracy of the self-sensing position at a high robustness.

For investigation of SMC material, two AMBs with same geometrical dimensions are built from SMC as shown in Fig. 2. Commercial SMC parts are pressed in a desired shape and sintered afterwards, but for these AMB prototypes the parts are machined from a cylindrical SMC prototyping material (type Somaloy from Höganäs, diameter 120mm, height 20mm) with magnetic properties according to Tab. 1. The comparison with electrical steel NO20 shows a lower saturation level as seen from the B-H parameters. Although the SMC has very low eddy current losses the total losses per kg are roughly four times higher at the SMC material compared to NO20 laminations.

Fig. 1 Prototype drive setup: SynRM with laminated three phase permanent magnet biased radial AMBs

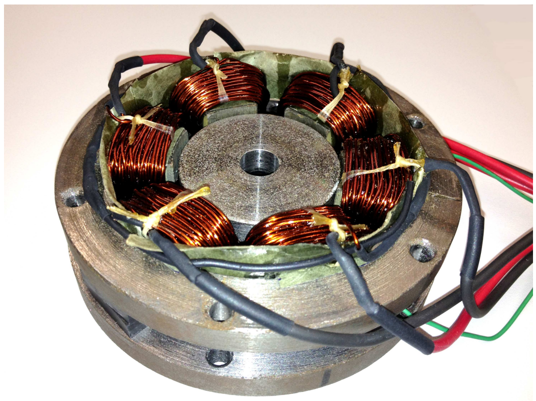

Fig. 2 Radial three phase AMB prototype built with SMC material

Table 1 Material parameter comparison according to data sheets

	lamination NO20	SMC Somaloy
Mass density	7600kg/m^3	7300kg/m^3
B @ 4000A/m	1.58T	1.23T
B @ 10000A/m	1.76T	1.49T
Losses @ 1T,200Hz	5W/kg	22W/kg
Losses @ 1T,1000Hz	42W/kg	147W/kg

3. Bearing Forces

The levitation force of AMBs is generated by the electromagnetic circuits. To achieve a high efficiency of the AMB, high forces shall be provided by low current demands and further low copper losses are intended. An increase of the bearing force is reached by applying a bias flux caused from PMs. Thus, the magnetic operating point is shifted and the so called force-current coefficient k_i of the linearized force behavior increases. For both AMB setups the bias flux density B_0 without any electrical excitation at centered rotor is measured by a Gauss-Meter according to Tab. 2. In the prototype two rectangular magnets are applied in serial connection. Therefore two ferrite magnets (type SrFe Y30BH), one ferrite magnet combined with one rare earth magnets NdFeB (type N30H) or two NdFeB are applied. Definitely, applying only rare earth magnets the highest bias flux density is achieved. Comparing the impact of the soft magnetic stator and rotor material shows, that at SMC the bias flux density is lower that at NO20 lamination. This is by the reason of low relative permeability $\mu_r \approx 400$ of the Somaloy SMC. The evaluation of the generated bearing force is evaluated at centered rotor by applying additional mass to the rotor. The measured force-current characteristic for NO20 and SMC at different PM bias configuration is depicted in Fig. 4 and Fig. 3. In general, a minimum current is required to compensate the part of the rotor mass. As expected at higher bias flux values B_0 the stationary current is lower. At the electrical steel NO20 the forces are higher than at SMC. This is caused by the lower permeability of SMC, which leads to a lower bias flux density on the one hand and second also the additional flux density in the airgap generated by the coils is less. Finally, the NO20 generates nearly double force at same phase currents.

Table 2 Measured average bias flux density B_0 per stator pole caused by the permanent magnet at centered rotor position

	NO20	SMC
Ferrite	92 mT	80 mT
Ferrite & NdFeB	175 mT	166 mT
NdFeB	239 mT	227 mT

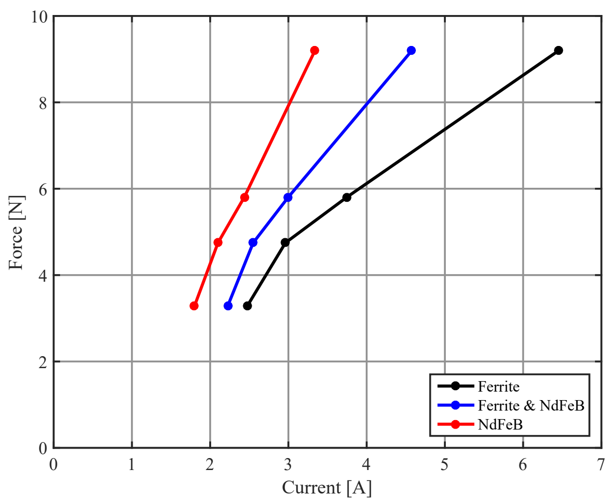

Fig. 3 Force-current characteristic of the three phase AMB with laminated electrical steel at different PM bias configuration

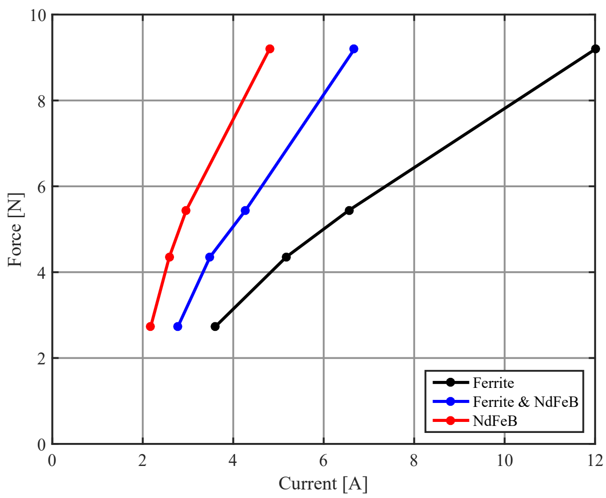

Fig. 4 Force-current characteristic of the three phase AMB manufactured from SMC prototype material at different PM bias configuration

4. AMB Losses

Providing low operational losses at high rotational speeds is a main criteria for application with AMBs. To achieve this target several design methods are known. By PM biasing copper losses in the stator are reduced, because higher forces at lower currents are implemented. Additionally with homopolar bearing architectures the flux direction in each single pole does not change, which leads to lower hysteresis losses. Both aspects are implemented in the AMB prototypes investigated in this paper. For the different bearing arrangements the losses are investigated by simple runout experiments. Here, at a certain rotational speed the electric drive is fully switched off. Because a RSM is applied to this prototype, the electrical machine is free of magnetic flux after turning off and does not generate iron losses as permanent magnet synchronous machines do. Then the only losses, which generate a breaking force to the rotor are caused from the AMBs and air friction. The results from the runout experiments of both AMB types at different PM bias configurations are depicted in Fig. 5 and Fig. 6. The SMC type shows a shorter time to reach standstill, which is caused by higher losses and confirms the values of Tab. 1. Further, at a higher bias flux value higher iron losses occur, which reduces the time to standstill further. Hence, for designing AMBs a compromise between operational losses and required bearing forces has to be taken.

5. Sensorless Parameters

The sensorless rotor position of the three phase AMB is evaluated from the current slopes of opposite coils. During a

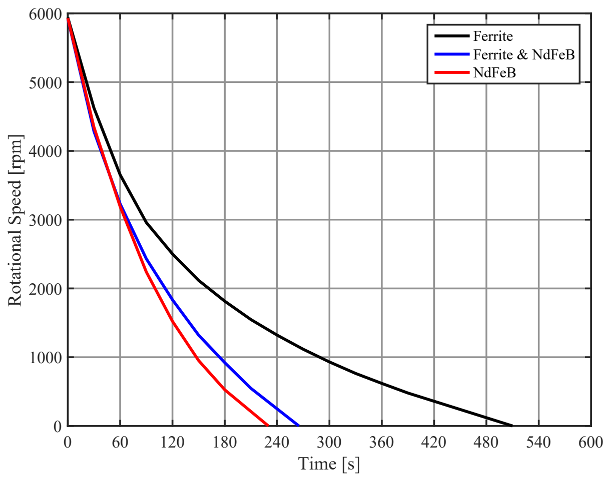

Fig. 5 Runout from 6.000rpm of the laminated three phase AMB at different PM bias configuration

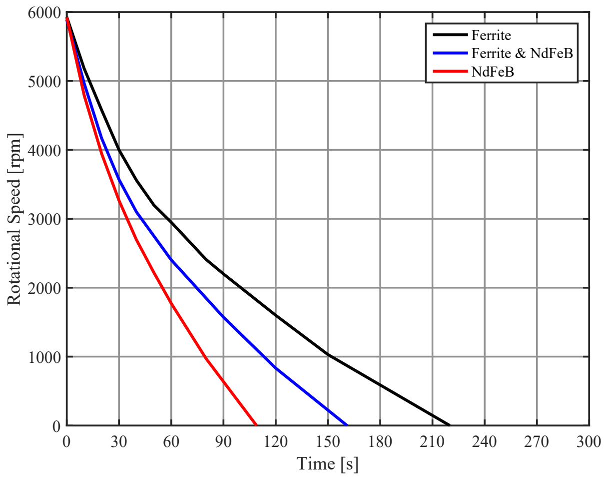

Fig. 6 Runout from 6.000rpm of the three phase AMB manufactured from SMC prototype material at different PM bias configuration

three active PWM pattern (20kHz frequency) no short circuit states are implemented and a space phasor sequence in one of the spatial directions U,V,W is applied. Therefore in every switching state of the PWM one current slope is determined during the accordant voltage phasor is active. Finally, during one PWM period the complete rotor displacement is obtained senorless from the current slopes. The coil current of the laminated AMB is illustrated in Fig. 7 for two opposite rotor positions related to the coil direction. After a voltage switching in the accordant coil eddy current effects are identified. The expected nearly linear slope does not occur before approx. $10\mu s$. Thus, considering only one current slope for sensorless position evaluation seems only possible by sampling within the last third of the voltage pulse duration. In (Hofer et al. 2014) is shown, that by the differential approach the eddy current effect is mainly compensated, because the effect is included in both opposite coils. Therefore the eddy current limitation for self-sensing is less than considering the single coil only. The sensorless determined rotor position is evaluated at constant rotor eccentricity ε=0.5mm in Fig. 8. The nearly circular shape corresponds well with the real rotor position. By this characteristic the position accuracy and noise is identified as difference from the idealized circle. With this AMB setup a sufficient sensorless operation is obtained and reaches high robustness (Hutterer et al.,2016).

Considering the AMB with SMC material the current signal at opposite rotor position is depicted in Fig. 9. Here the eddy current effect within the first microseconds after the voltage switching is not present. This confirms the expected property of low eddy currents of SMCs. Additionally can be seen, that the current ripple is approximately 30% higher compared to the laminated bearing. This is caused to a lower permeability of the SMC, because all other bearing parameters (airgap, coils, PM magnetization,...) remain the same. The sensorless position trajectory of SMC in Fig. 10 also shows a nearly circular shape. Slight deviations from the ideal circle are given, but the position noise by the ”thickness” of the trajectory is comparable and therefore a sensorless controlled levitation is implemented sufficiently. Finally the low eddy current advantage of SMCs related to sensorless position detection is not exploited, because the differential self-sensing approach already compensates eddy current effect related to the position signal.

6. Conclusion

In this work permanent magnet biased homopolar three phase radial AMBs equipped with SMCs are investigated. A modular electrical drive setup is used to compare each two bearings with laminated electrical steel and with SMCs by experiments. In both cases self-sensing operation is realized and key parameters are identified. Because of a lower relative permeability the SMC bearings have smaller force-current coefficients k_i, a lower airgap bias flux B_0 generated from the permanent magnets and a lower inductance. Further the operational losses at SMC are higher, although the eddy currents are lower. This main advantage of very low eddy current effects is not utilized in the AMB by using a differential self-sensing approach. The sensorless obtained rotor position accuracy is comparable in both setups. Thus, a final conclusion considering all mentioned aspects show, that application of SMCs to homopolar self-sensing AMBs do not give performance advantages compared to the classical approach using laminated electrical steel sheets.

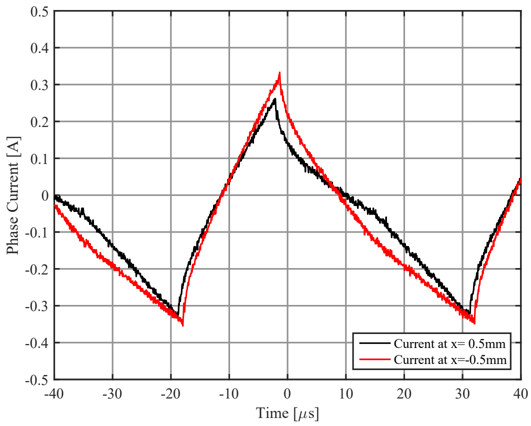

Fig. 7 Phase current of the laminated three phase AMB in three active PWM mode at two different rotor displacements

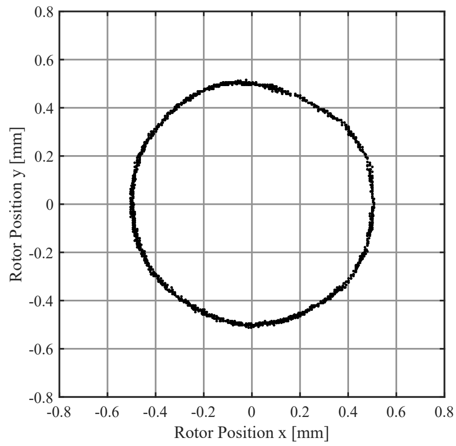

Fig. 8 INFORM trajectory of the laminated three phase AMB at constant eccentricity of ε=0.5mm

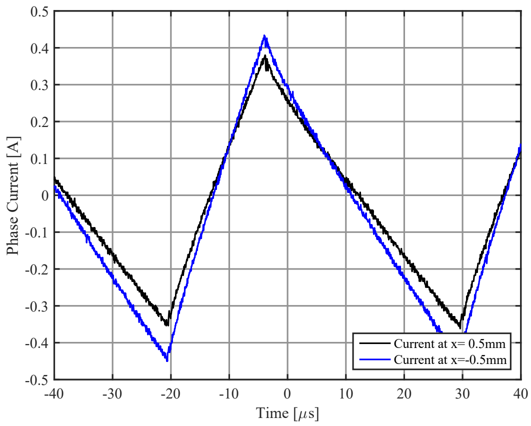

Fig. 9 Phase current of the SMC three phase AMB in three active PWM mode at two different rotor displacements

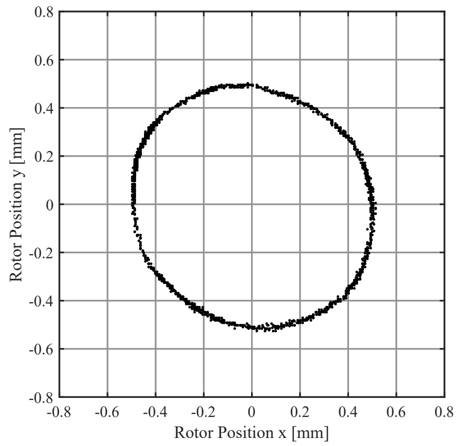

Fig. 10 INFORM trajectory of the SMC three phase AMB at constant eccentricity of ε=0.5mm

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