NEW RADIAL SENSOR FOR ACTIVE MAGNETIC BEARINGS

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ABSTRACT

Inductive and eddy current type sensors are widely used in active magnetic bearing (AMB) systems for measuring the position of the levitated body. State-of-the-art sensors provide a good robustness but, quite often, an unsatisfactory cost-efficiency. Cost-efficiency, however, is a key issue for industrial AMB systems, especially for volume applications. While it is evident that cost reduction programs must consider every component in an AMB system, this paper describes a patented[1] approach which specially focuses on the sensor technology, where a substantial potential for cost reductions is expected. Differing from the known and ongoing approach to totally abandon the integration of sensors and to implement a so-called self-sensing AMB system [2] – most often at the expense of a loss of system robustness and an increase in controller complexity – a new type of radial sensors based on a printed circuit board (PCB) with printed coils as a sensing element is introduced. This design features minimum space requirement, high sensing quality and low production costs at the same time.

INTRODUCTION

State-of-the-art AMB systems are usually equipped with sensing elements providing one or several electric coils, which are powered by an AC current source. The modulation frequency of the sensor circuitry depends on the sensor principle (inductive or eddy current), which also determines the appropriate material for the sensor target (ferromagnetic for inductive sensors, electrically conductive for eddy current sensors). By measuring the coil's inductance and/or the damping factor as the sensor target changes distance from the sensor coil a displacement dependent signal can be generated. In figure 1 examples of state-of-the-art eddy current and inductive sensor units are shown. An overview of state-of-the-art sensor systems for AMB systems is given in [3].

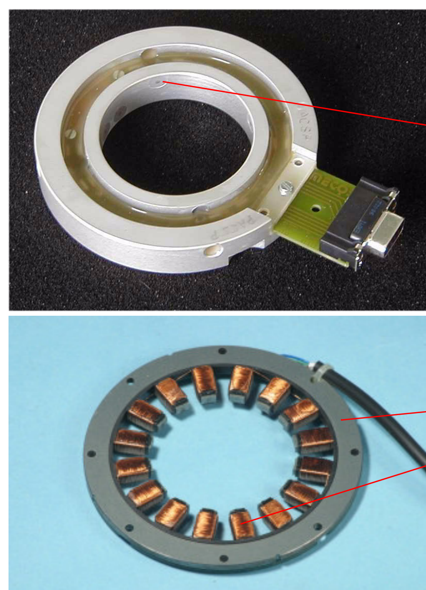

FIGURE 1: Examples of state-of-the-art sensors for AMB systems

Common to all of the shown sensor designs is the way how the magnetic field of the sensor coil is directed towards the rotor: the axis of a radial sensor coil is always perpendicular to the rotor surface (figure 2), requiring a certain amount of installation space along the rotor axis for the sensor itself and its mounting parts. In order to measure the radial position of the rotor within a plane perpendicular to the rotation axis (e.g. x and y directions) several sensors must be placed around the rotor in an accurate and reproducible manner, as shown in figure 1. Production costs for this type of sen-

1. Patent applications concerning the subject-matter presented in this contribution have been filed [1].

sor setup are important (coil windings, coil positioning, mountings, wiring, connectors, etc.), especially if manual assembly work is required.

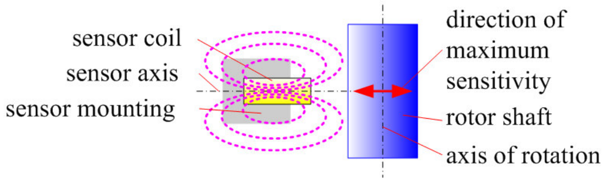

FIGURE 2: Standard sensing principle with sensor coil axis perpendicular to target surface

Moreover, in many applications the available space for the components of a magnetic bearing system is limited. The shorter along the rotor axis the sensors including their mountings can be built the more space is left for the bearing magnets or the more compact a system can be designed. Therefore, for a given volume, bearing forces can only be maximized by minimizing the size of the sensors.

The following section describes a new sensor design yielding at overcoming the described shortcomings of current AMB sensor designs.

NEW SENSOR DESIGN

To obtain a very high reproducibility in the manufacturing process of an AMB sensor unit flat coils can be integrated on a printed circuit board (PCB). This also strongly helps to meet the cost target of a modern AMB system. However, this approach is only feasible if the following main difficulties associated with PCB sensor coils can be overcome:

- For a good signal accuracy the PCBs carrying the individual sensor coils must be precisely positioned and attached in a fitting around the rotor.
- Conventional PCB coils show high position sensitivity only perpendicular to the sensor coil (i.e. the PCB) plane. A measurement of lateral positions within the sensor coil plane, as required for radial sensors, turns out to be very difficult. A sufficiently large sensitivity to lateral displacements can only be achieved if the coil windings are concentrated very close to the edges of the circuit board, where the target body is located, and if the air gap is very small. However, PCB coils must always be spread on the PCB surface in order to get a sufficiently high number of turns and, hence, an acceptable inductance, which means that the sensor coil cannot be entirely located close to the target. It is basically these conflicting requirements – inductance versus sensitivity – that have made the integration of sensors on a PCB board unsatisfactory in the past.

In the following the fundamental ideas to overcome these problems are outlined.

The Basic Problem

A cost-efficient design for a PCB sensor unit for radial sensing can only be made if the necessary coils are arranged on one single annular ring around the rotor. This means that the coils' surface normal vectors will always be parallel to the axis of rotation. Unfortunately, this is exactly the setup for almost vanishing lateral sensitivity, as pointed out above. Consequently, such an arrangement could be used for axial sensing but is completely unsuitable for radial sensing (figure 3).

This behavior is intuitively clear: The target body, being an electrically conductive material (not necessarily ferromagnetic), will change the magnetic field generated by each sensor coil in such a way that no field exists within the target itself (eddy current effect). It can easily be seen that a target approaching in a direction perpendicular to the coil surface, i.e. in axial direction, must have a strong impact on the shape and strength of the coil's magnetic field (figure 3a), whereas any lateral approach will only have a marginal field distortion effect leaving the field strength in the coil's center, where the measurement actually takes place, virtually unchanged (figure 3b).

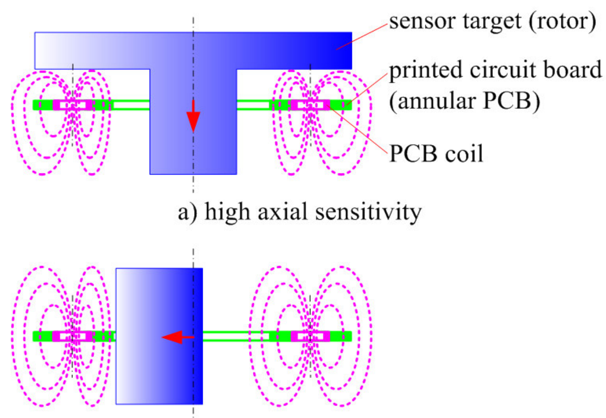

FIGURE 3: Different sensitivities in axial and radial direction

It is important to mention that the proportions in figure 3 are strongly exaggerated. Most often the radial target displacement is only a small fraction of the PCB coil dimension itself. Therefore, field distortion by lateral movement is even much smaller in reality than shown in figure 3.

The New Idea

The fundamentally new idea for achieving a PCB coil arrangement featuring a high lateral sensitivity for measuring the radial position of a rotor while still keeping all the necessary coils arranged in a very thin annular PCB board around the rotor is to combine all the necessary coils into one common and interdependent electromagnetic field circuitry. In other words, the individual coils become electromagnetically coupled which directly yields a much higher sensitivity. However, coupling must be done in such a way that the x and y displacements of the rotor can still be detected as uncoupled signals. A further differentness of the new concept is that separate coils are used for field generation (excitation coil) and field measurement (detector coils), whereas in most conventional setups each single coil serves for both tasks at the same time.

Figure 4 shows a sketch of the new coil arrangement. An excitation coil is wound around the rotor so that its windings completely enclose the rotor. Due to the large size of the excitation coil combined with the small air gap to the rotor target the inductance of this coil is very high compared to a conventional arrangement. The field generated by the excitation coil is rejected by eddy currents within the electrically conductive rotor material. Therefore, a field concentration takes place within the small air gap between the excitation coil and the rotor surface.

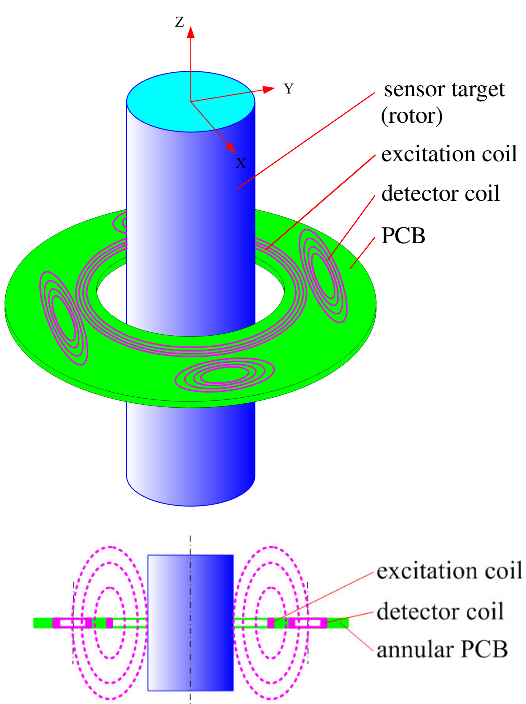

FIGURE 4: New radial sensor coil arrangement

Due to its concentration within the small air gap the magnetic field generated by the excitation coil highly depends on this air gap. Thus, the position of the rotor has a large impact on the overall field distribution. It is important to mention that any lateral rotor displacement, provided to be small compared to the rotor diameter, does not change the electrical properties of the excitation coil as a whole since the total field around the rotor is approximately constant. However, a lateral displacement drastically changes the field on one side of the rotor accompanied by a compensating opposite change on the other side (figure 5). The resulting excitation coil field asymmetries, which are much larger than in the case of separate and independent coils and, hence, yield a high radial position sensitivity of the device, can be measured by the detector coils.

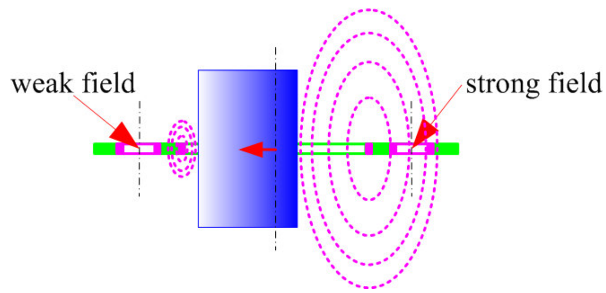

FIGURE 5: Field asymmetries in case of lateral rotor displacement

The PCB Sensor

The arrangement of excitation and detector coils as introduced above results in sufficiently large inductances, which are preferable for the downstream electronic demodulation circuitry. This is true even if the number of windings per coil is low (e.g. five turns) and if the diameter of the detector coil is small. This is mainly a result of the large inductance of the excitation coil itself and of the mutual electromagnetic coupling between all the coils. As a result, this measurement principle is perfectly suited for integration on a printed circuit board. If the coils are set up in a multi-layer arrangement they can be placed very close to the target body, yielding an even improved sensitivity and resolution.

Due to the very accurate and reproducible PCB manufacturing process the sensing device easily meets the requirements for accuracy and reproducibility

Moreover, no other material than the PCB itself with the copper circuit paths is used, hence, there is no need for a ferrite coil core or for ferromagnetic laminations on both stator and rotor as applied in many state-of-the-art AMB systems. This makes the PCB sensor highly interference proof to lower frequency electromagnetic fields as always generated by the magnetic bearings or by the motor. Even shielding is not necessary.

All in all the new radial sensing device features the following main advantages over conventional AMB sensor setups:

- high cost-efficiency
- high level of reproducibility and accuracy (no need for sensor calibration)
- high sensitivity
- ultra compact design (thickness of PCB itself)
- no extra components on PCB (only circuit paths)
- highly interference proof to external magnetic fields (no shielding necessary)

Signal Demodulation

The PCB sensing device does not feature different requirements for the electronic circuitry than any state-of-the-art eddy current or inductive sensor type [4], hence, there is no need for the development of new sensor electronics. Due to the suitably large inductance of the setup modulation frequencies in a normal range can be attained. Depending on the sensor target material (ferromagnetic vs. highly conductive material) modulation frequencies are typically in a range between 20 kHz and 3 MHz, thus clearly above switching rates of power amplifiers as used for AMB systems. Further signal treatment comprises standard components for signal demodulation and anti-aliasing filtering. In order to achieve a fairly linear displacement dependency of the sensor output signal two opposite coils can be operated in a differential arrangement, which constitutes a further compatibility to existing sensor electronics.

EXPERIMENTAL RESULTS

To date a number of PCB sensor units based on the new principle presented in this paper have been developed and built as prototypes. Present planning assumes a first integration of such sensors into an industrial AMB system by the end of this year. Figure 6 shows prototype PCB sensing units of different size.

So far all of the different PCB sensing unit prototypes haven proven to nicely fulfill their technical and commercial requirements.

Mathematical modeling has also been carried out. Due to the rather high complexity of the system – three-dimensional electromagnetic field dynamics in air and in electrically conductive solid bodies have to be considered [5] – model predictions do not yet satisfyingly agree with measurement results. Hence, more development work on the modeling side will be necessary.

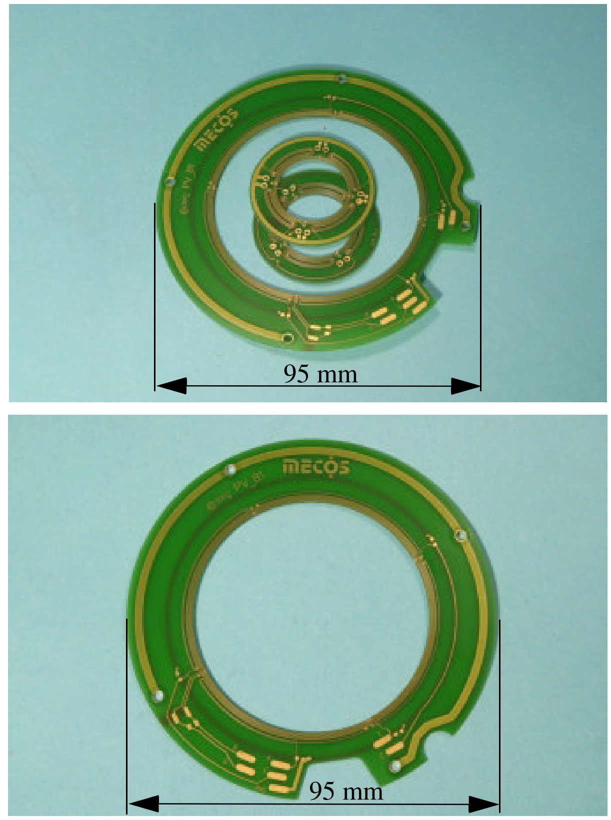

FIGURE 6: PCB sensing unit prototypes

Nevertheless, results in terms of sensitivity, linearity and x-y-coupling from a prototype arrangement can be presented here.

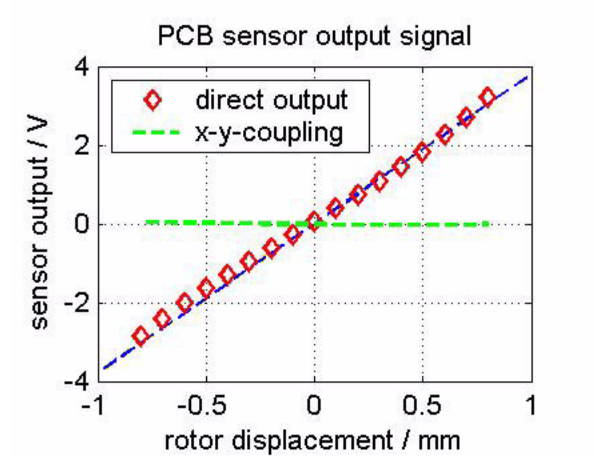

FIGURE 7: Linearity and x-y-coupling of a prototype PCB sensing unit

Figure 7 shows the static output signal as a function of the rotor displacement. The signal has been obtained from a small prototype PCB sensing unit as shown in figure 6 connected to its downstream electronic circuitry. The sensor target material was non-ferromagnetic steel (Inconel) with a diameter of 10 mm.

Sensitivity of the PCB sensing device is very good compared to a standard sensor setup as shown in figure 2 with identical target material and size, whose high frequency sensor signal typically features an amplitude modulation in the range of 10-20% when moving the target over its entire displacement range. In the case of the prototype PCB sensing unit an amplitude modulation of 47% was reached, which clearly demonstrates the superior sensitivity.

The small output signal offset (1.50%) is mainly determined by the geometric alignment of the components and by the tolerances within the electronic circuit. Output linearity (5.60%) is good over the entire air gap range and x-y-coupling (1.24%) is very small.

The dynamic behavior of the unit in terms of its frequency response is not displayed here. Since the modulation frequency is rather high, the dynamics of the unit are almost entirely determined by the filter components of the sensor electronics, which are freely adjustable according to the needs of the application (rejection of modulation frequency component including harmonics, suppression of aliasing effects in case of digital control).

Further tests with different PCB sensing units have been carried out. Most interesting are results from such a unit based on a ceramics substrate with gold and silver circuit paths for the PCB coils. These high temperature PCB sensing units show very similar electrical and sensitivity properties as comparable units based on conventional PCB materials, but are easily applicable at very high temperatures (650 °C). In addition, a long-run measurement at these temperatures (currently 1000 hours) has not shown any drift of system properties so far. Hence, this technology is very promising for application in future high temperature AMB systems [6].

SUMMARY AND OUTLOOK

In this paper a novel and patented design of a radial sensor for an active magnetic bearing (AMB) system has been presented. The sensor is completely integrated onto one single printed circuit board (PCB) and is capable of simultaneously measuring x and y displacements of a rotor. The ultra compact and flat design of the sensor features a new coil geometry and coil arrangement optimized for a high lateral position sensitivity. Moreover, the PCB based design guarantees high mechanical accuracy and reproducibility and offers an unprecedented cost-efficiency at the same time. Hence, integration of this novel sensor technology into a modern AMB system constitutes a technically valuable and very competitive alternative to the ongoing approach of implementing a self-sensing bearing.

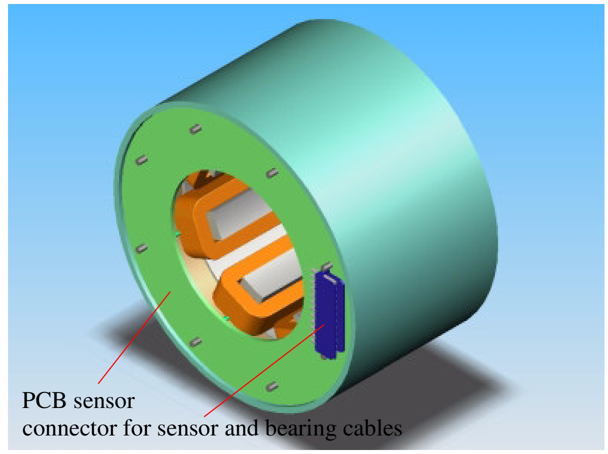

FIGURE 8: Radial bearing unit with PCB sensor

Future development of the new sensing technology will comprise integration of axial and angular position sensors onto the PCB. Moreover, as the sensor is basically an ordinary PCB, it can be used as a wiring device for directly connecting both sensor and bearing coil cables. In figure 8 the design of such a bearing unit with integrated PCB sensing and wiring device is shown.

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