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Sensorless Control of a Three Phase Radial Active Magnetic Bearing

Matthias Hofer[1],Wolfgang Staffler[1], Manfred Schrödl[1]
[1]Institute of Electrical Drives and Machines
Vienna University of Technology
A-1040 Vienna, Austria
http://www.tuwien.ac.at

Abstract: This paper presents results of a three phase radial active magnetic bearing architecture combined with a sensorless position control algorithm. Therefore the three coil bearing structure is utilized by a three phase voltage source drive inverter. To reduce bias current consumption permanent magnet bias fluxing is used and iron losses are reduced by gaining homopolar architecture. The sensorless position detection algorithm and the control architecture are presented. Experimental results confirm the sensorless concept by measurements and quality measures for the sensorless method are investigated to show the limits of operation.

Introduction

For frictionless levitation of rotors in high speed applications Active Magnetic Bearings (AMB)are used for years.The advantage in high speed operation compared to classical rolling bearings or friction type bearings combined with the active controllability of the radial rotor position allow utilization for special applications.Due to the complexity of this electromagnetic control system,containing an actuator module,control logic,a power converter and a sensor unit the system costs are much higher compared to standard bearing solutions.Using sensorless techniques in AMB technology for component reduction a cost reduction potential can be figured out.The sensor unit is replaced by an integration of the rotor position measurement system in the actuator itself,combined with the control logic.This work is following this strategy.By cost optimized design of the AMB an additional reduction of system costs can be achieved.A novel bearing design with homopolar rotor magnetization and only three stator coils which are driven by an industrial voltage source inverter,follows the cost reduction strategy as well.Finally a complex mechatronic system is simplified to a low cost concept which will permit increased fields of applications.

Magnetic Bearing Architecture

The radial active magnetic bearing(AMB)consists of three magnet poles in the stator with equidistant distribution of 120 degrees.Each pole has a coil with concentrated winding connected in star connection,like described in[1]-[3].The stator yoke is covered by a permanent magnet(PM)ring and a flux closure ring for the bias flux,see Fig.1.The PM bias flux is closed in axial direction by two additional housing covers(not shown in Fig.1.).The prototype is equipped with single rectangular magnets to allow varying the bias flux value by the usage of more or less magnets.Further details of the experimental setup are presented in[4].

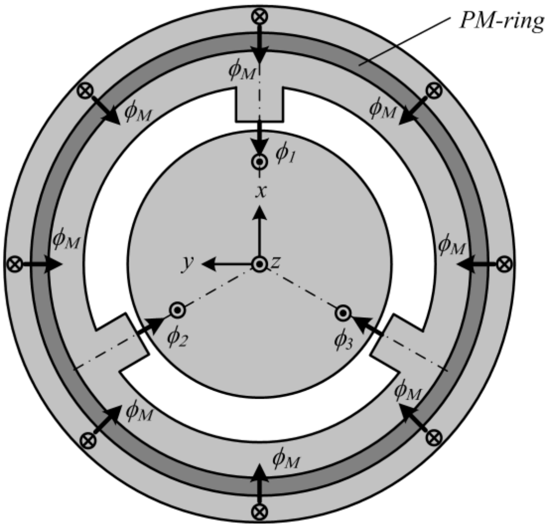

Fig. 1. Cross section of the three phase AMB with permanent magnet biasing

Sensorless Rotor Position Detection

For the implementation of a sensorless control algorithm into the magnetic bearing application, a high frequency voltage injection method known from the sensorless control of permanent magnet drive application is used. The INFORM method (Indirect Flux Detection by Online Reactance Measurement) was optimized to detect the rotor displacement of the bearing by reactance measurement. The inductance characteristic of the bearing was modelled and verified by experimental measurements as shown in Fig.2.

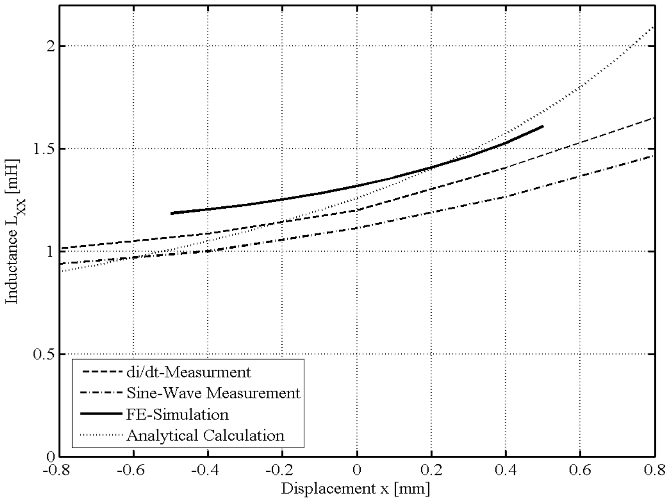

Fig.2. Coil inductance over rotor displacement.
Comparison of model and experimental results.

The coil inductances are dependent on the radial rotor position in the appropriate coil direction x_1, the nominal air gap δ_0 and coil inductances at centred rotor positions l_0.

$$l_{11} = l_0 \frac{1}{1 - \frac{x_1}{2\delta_0}} \tag{1}$$

By the combination of three displacements x_1, x_2 and x_3 to a complex displacement space phasor $\underline{x} = x + jy$ the rotor position is described in orthogonal directions (x,y) can be measured by inductance measurements of l_{11}, l_{22} and l_{33}.

$$\underline{x} = -2\delta_0 \cdot \frac{2}{3}\left(\frac{1}{l_{11}} \cdot e^{j0} + \frac{1}{l_{22}} \cdot e^{j\frac{2\pi}{3}} + \frac{1}{l_{33}} \cdot e^{j\frac{4\pi}{3}}\right) \tag{2}$$

A high frequency voltage injection method based on the INFORM method is used for evaluation of the coil inductances. Therefore the voltage source inverter drives the AMB coils by a voltage pulse sequence and current slopes are measured. A digital signal processor is determining the slope by ADC sampling and during time intervals. The sampled values are marked by blue dots in Fig.3.

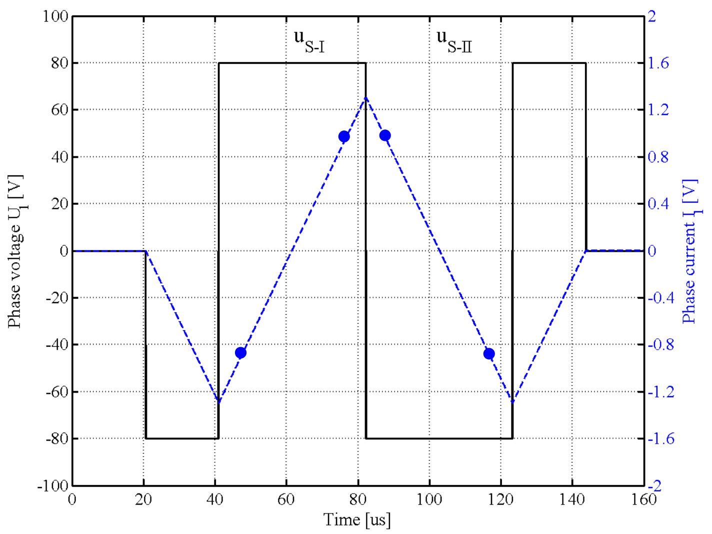

Fig.3. Voltage pulse sequence for current slope measurement

Current Measurement Strategy

Due to high flexibility and the examination and comparison of the influences of different current measurements, the used voltage source inverter prototype possesses two different current strategies. On the one side there is given a phase current measurement with galvanic isolated split core transducer for the electronic measurement of AC waveform currents. On the other side a three-shunt DC-link current measurement is realized. Fig.4 and Fig.5 show the load characteristic of both current measurements during the x-axis position is varied from the lower aiming position to the upper aiming position. In both cases the neutral point is crossed. As it can be seen in following figures the current measurement with galvanic isolated transducer does not offer good linearity for high sensitive current examination. Particularly when the phase current is approximately zero, increased irregularities arises. This special phenomenon results from the zero compensating current transducer which uses the Hall effect. On the opposite the DC- link current examination is realized with simple shunts, and therefore this irregularity does not occur. Finally the shunt measurement is the preferred current measurement strategy especially related to the sensorless rotor positon detection.

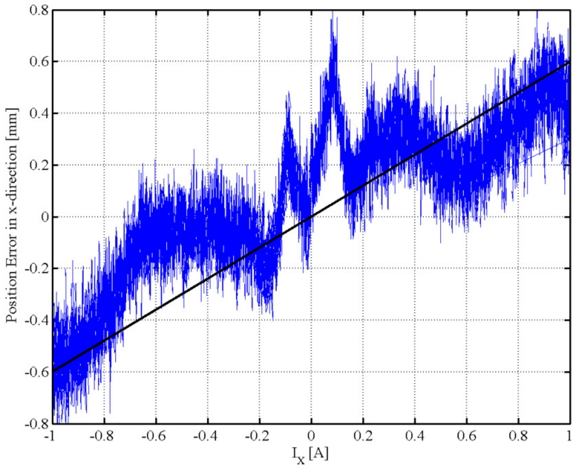

Fig.4. Load characteristic of sensorless detected rotor position with centred rotor. Current measurement by current transducers

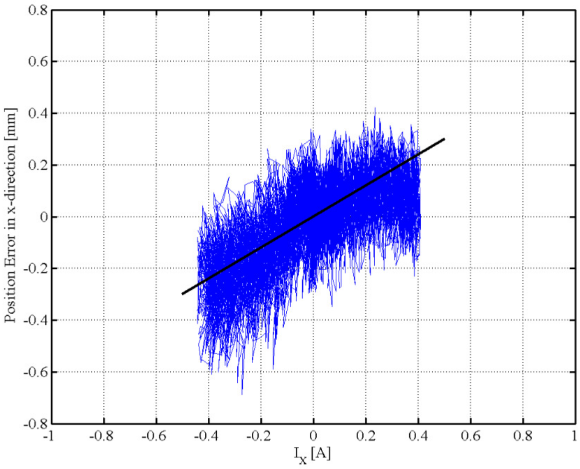

Fig.5. Load characteristic of sensorless detected rotor position at centred rotor. Current measurement by Shunt

Sensorless Control Architecture

For implementation of a stable sensorless control a PD position control strategy is minimum required. Therefore additional to the rotor position information the speed signal or a derivative from the position is required. Considering the fact of a noisy position signal, the speed signal is gained by a mechanical observer using the sensorless position signal as input. The mechanical observer is also described in [5]. A cascaded current control loop for the three phase AMB is implemented in the two-axis reference frame (*x,y*) and uses PID current controllers for both control systems. A general overview of the control architecture is given in Fig.6. The shunt measurement layout is not shown in this figure.

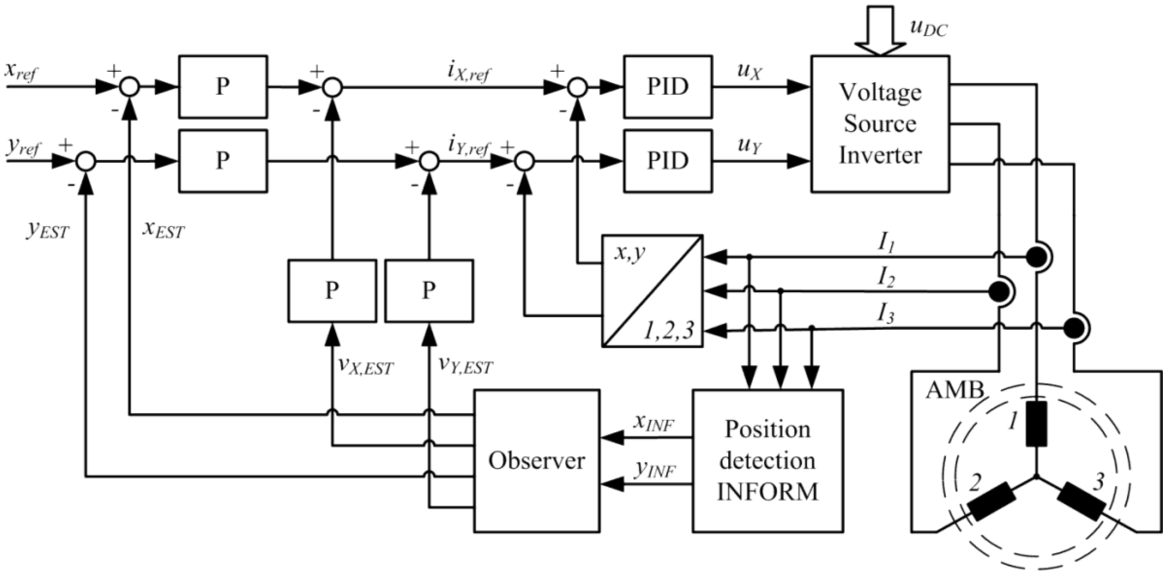

Fig.6. Schematic of the sensorless control architecture

Experimental results

The integration of the sensorless method for the AMB application was done in several steps. After implementation of a sensor based control the INFORM method was tested in parallel operation. In Fig.7. the position signals of the sensor (eddy current displacement sensor) and the sensorless method is shown. A statistical evaluation of was done already in [5] and have shown a standard deviation of σ_X=25µm

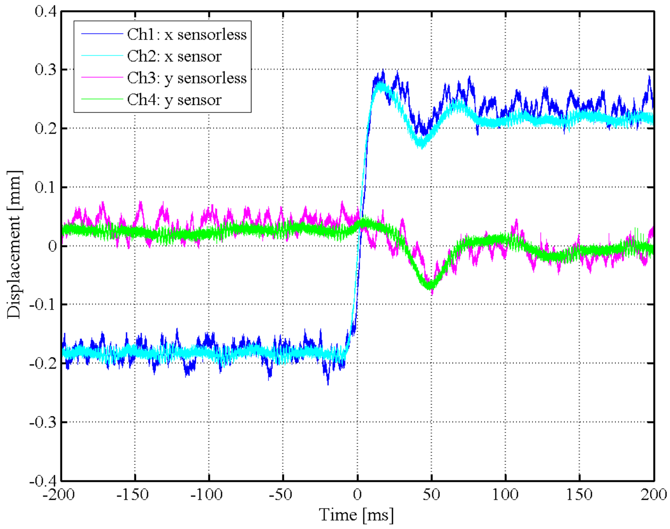

Fig. 7. Experimental results in sensor control mode.
Parallel operation of the INFORM method

In Fig.8. an experimental result of a movement in sensorless controlled operation is shown. A lift up process in x-direction from -0.2mm to +0.2mm was applied. A good matching between the sensor signal and the sensorless rotor position can be seen. Statistical evaluation during this operation results in a standard deviation of σ_X=38µm, which is higher than in parallel operation mode.

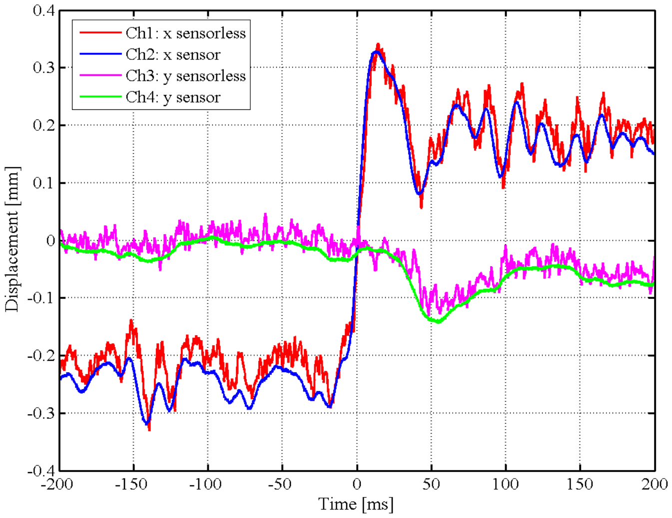

Fig. 8. Experimental result in sensorless operation.
Comparison of sensorless detected position and the sensor signal.

Conclusion

This paper describes the implementation of a sensorless control architecture to a three phase radial active magnetic bearing. The bearing behaviour was modelled by FEM analysis and data was verified by measurement results. The three phase design of the magnetic bearing allows for a utilization of a standard three phase voltage source inverter and furthermore the implementation of a self-sensing method based on the INFORM method. A full sensorless operation was gained by combining a mechanical observer with the sensorless method. A control structure with a PD position control behaviour was implemented. Experimental results of the bearing prototype confirm the capability for the sensorless position detection method for active magnetic bearings. With statistical methods the stationary and dynamical behaviour of the sensorless control is evaluated to show the accuracy of operation. During control operation an accuracy of one tenth of the nominal airgap was achieved with the first prototype.

References

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