Measurement of the Rotor Position of an Active Magnetic Bearing Using Interpolar Stray Flux

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Abstract

The very most active magnetic bearings need somehow natured shaft measurement systems. To reduce the significant cost which are caused by the measurement systems a HALL-principle based system is proposed where low budget industrial standard sensors are applied. Contrary to other approaches the HALL-sensors are integrated between the bearing poles instead the air gap. Thus the use of low budget sensors is enabled.

Contents

1 Introduction

Magnetic bearings increasingly are finding application in industry and research. So they are used for suspension of neutron beam choppers, gas ultra-centrifuges, high speed cutting machines, Compressors and pumps[4]. Also in medical engineering magnetic bearings are applied in the form of blood pumps [1]. Previously the advantages of the non-contact, low-wear suspension is usually used only for special applications. In addition to the lack of acceptance the relatively high cost for the measurement systems which are required for the operation of active magnetic bearing could be the reason why the field of application is limited to special use. Thus, the cost of a complete measurement system for an entire magnetic suspended shaft is mount up to about a third of total costs [3]. To expand the application fields of magnetic suspended shafts it is necessary to keep on reducing the cost of measuring systems. For this reason, different options are discussed for some time. A widespread possibility is the abdication of any distance sensors. So-called sensorless bearing determine the shaft position from systemic variables such as the coil currents or the voltages across the bearing coils [6], [2], [5]. An alternative approach is to determine the shaft position using the dependency of the magnetic field strength in the air gap from the air gap length. Starting from:

$$H_{\mathrm{Air}} = \frac{B}{\mu_0} \tag{1}$$

the magnetic field strength depends only on the magnetic flux density and the vacuum permeability. Assuming that the magnetic flux is homogeneous and no stray flux will occur the magnetic flux density can be written as:

$$B_{\mathrm{L}} = \frac{I \cdot N}{(R_{\mathrm{mAir}} + R_{\mathrm{mFe}}) \cdot A} \tag{2}$$

Is the cross sectional area defined as constant for the whole magnetic circuit the magnetic flux density in the air gap considering to equation (1) is given by:

$$B_{\mathrm{L}} = \frac{I \cdot N \cdot \mu_{\mathrm{r}} \cdot \mu_0}{s_{\mathrm{Fe}} + s_{\mathrm{L}} \cdot \mu_{\mathrm{r}}} \tag{3}$$

Is the relative permeability μ_{r} assumed as constant initially while the length of the ferromagnetic elements of the magnetic circuit s_{Fe} are unchanged for that the magnetic resistance R_{mFe} stays unvaried and the number of turns N is fixed the dependence of the magnetic flux density in the air gap and the air gap length s_{L} becomes apparent.

For measuring the magnetic field strength magnetoresistive sensors and HALL-sensors are well suited. Due to the active sensor area is positioned in the direction of the magnetic flux the application of magnetoresistive sensors like e.g. GMR-sensor based on the giant magnetoresistive effect or the AMR-sensor based on the anisotrope magnetoresistive effect in the air gap of conventional pole shapes is limited. More suitable for integration in the air gap are HALL-sensors whose active sensor area is aligned crosswise to the magnetic field to measure.

Due to the reduction of the cost of the necessary measuring systems is a main target preferably low-cost standard sensors should be used. In consideration of air gap length from less than a millimetre even the smallest component packages are hard to apply or even not deployable. In order that however low-cost HALL-sensors can be used for detection of the rotor position a method is suggested where the rotor position is determined based on the magnetic stray flux outside of the air gap

2 Stray Flux Measurement and Detection of the Shaft Position

To generate reliable informations about the shaft position using stray flux measurement it is necessary to know more about strength and the orientation of the stray field in a magnetic bearing. It is important to know how these characteristics depend on the air gap. Whether they are non-linear or if they can be linearised.

2.1 Inhomogeneous Magnetic Circuit

One simplification which is supposed to solve magnetic circuits using analytic methods is that the relative permeability of the ferromagnetic elements is set nearly infinite. Thus the whole ferromagnetic length is magnetically short circuited that means $R_{\mathrm{mFe1}} = 0$ shown in figure 1. Therefore no stray field is present. The whole magnetic voltage drops over the resistor R_{mAir1}. If the ferromagnetic region is separated in just three magnetic parts (figure 1 at the right side) with a finite resistance additional magnetic potentials occur between two magnetic resistors in the ferromagnetic circuit. Among these additional magnetic potentials spreads a further magnetic field. The stray field. It is easy to see that real magnetic circuits can be separated in an infinite number of elements with dedicated magnetic resistors and basic analytic solving methods are not longer operable. But it also shows why real magnetic circuits always contain magnetic stray field.

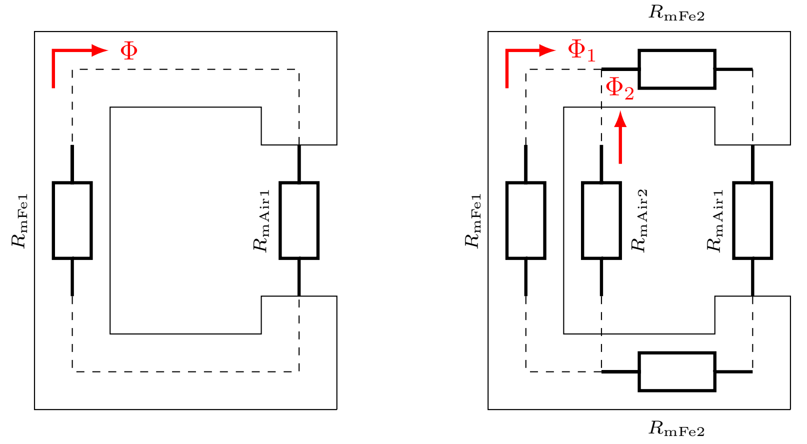

Figure 1: **left:** Scheme of a simplified magnetic circuit. **right:** More detailed scheme of an magnetic circuit with additional magnetic resistors. For a better understanding magnetic sources are not displayed.

Because R_{mFe1} and R_{mAir2} are parallel resistors the following applies:

$$\Phi_1 \cdot R_{\mathrm{mFe1}} = \Phi_2 \cdot R_{\mathrm{mAir2}} \tag{4}$$

So that the ampere turns of the magnetic circuit can be displayed as following:

$$I \cdot N = \Phi_2 \cdot R_{\mathrm{mAir2}} + 2 \cdot \Phi \cdot R_{\mathrm{mFe2}} + \Phi \cdot R_{\mathrm{mAir1}} \tag{5}$$

Thus the magnetic stray flux is given by:

$$\Phi_2 = \frac{I \cdot N - 2 \cdot \Phi \cdot R_{\mathrm{mFe2}} - \Phi \cdot R_{\mathrm{mAir1}}}{R_{\mathrm{mAir2}}} \tag{6}$$

The magnetic stray field intensity can be displayed as:

$$H_{\mathrm{Air2}} = \frac{\Phi_2 \cdot R_{\mathrm{mAir2}}}{l_{\mathrm{Air2}}} = \frac{B_{\mathrm{Air2}}}{\mu_0} \tag{7}$$

Substituting equation 6 into equation 7 is obtained:

$$B_{\mathrm{Air2}} = \frac{I \cdot N - 2 \cdot \Phi \cdot R_{\mathrm{mFe2}} - \Phi \cdot R_{\mathrm{mAir1}}}{l_{\mathrm{Air2}}} \cdot \mu_0 \tag{8}$$

Thereby all values except the magnetic resistor of the air gap R_{mAir1} are constant. Because of the direct dependence of magnetic resistance and air gap length given by

$$R_{\mathrm{mAir1}} = \frac{l_{\mathrm{Air1}}}{\mu_0 \cdot A} \tag{9}$$

the relation of stray flux and air gap length could be shown by means of this simplified magnetic circuit. The magnetic circuits of active magnetic bearing are much more detailed so that precise conclusions about the stray field intensity depending on the air gap are possible using numeric methods only. Therefore the research in the dependence of different shaft positions and the stray flux is based on numerical simulations. To get feasible results a good model has to be created at first. Important are acceptably small meshed air gaps, accurate material properties and a realistic geometry. An exemplary calculation in detail is shown by figure 2.

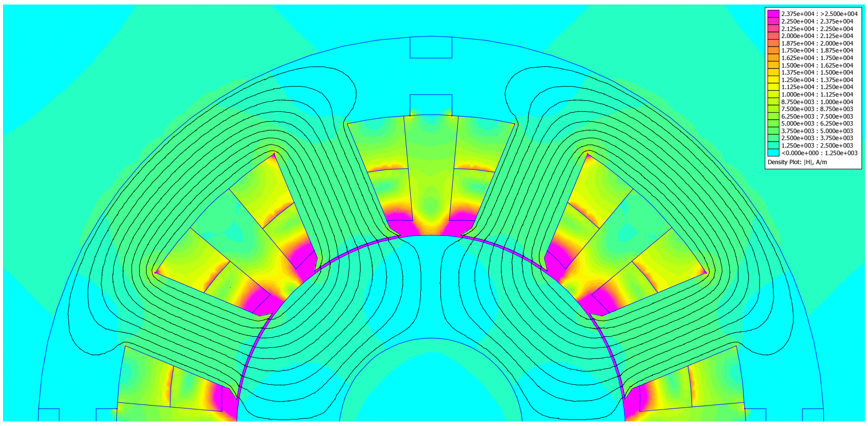

Figure 2: Numeric calculated field distribution. Field intensity larger than 2500 A/m is displayed by purple areas. It is clearly to see that there is significant field intensity in the regions between bearing poles.

2.2 Integration of HALL-Sensors into an Eight-Pole Heteropolar Bearing

Heteropolar magnetic bearing are widely-used so that the flux measurement method should be implemented and tested with such type of bearing. Low-cost standard HALL-sensors do not fit into the air gap of conventional magnetic bearings with dimensions of less than a millimetre. But between poles there is enough space for their placement. Thus, eight positions result, shown in figure 3. Possible is an in-circuit integration between the two poles of one coil unit or an off-circuit position between the poles of adjacent coils

To fix the coil windings against slip in radial direction often special plastic sheets are inserted between the poles. This offers the possibility to replace them by PCB (Printed Circuit Board) which can carry the HALL-sensors. Thus all sensors have equally well defined positions displayed by Figure 4.

The x- and y-axis are the natural bearing axes. The capacitive comparative measurement system detects the shaft position in these axes where also the controller and current amplifier are based on. The best way would be to use the same axes and apply sensors e.g. at the X+ and

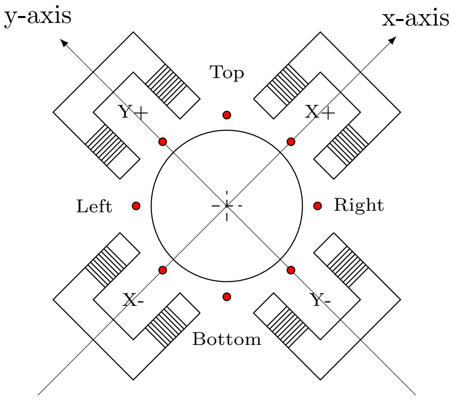

Figure 3: Possible positions for sensor integration (marked by red dots).

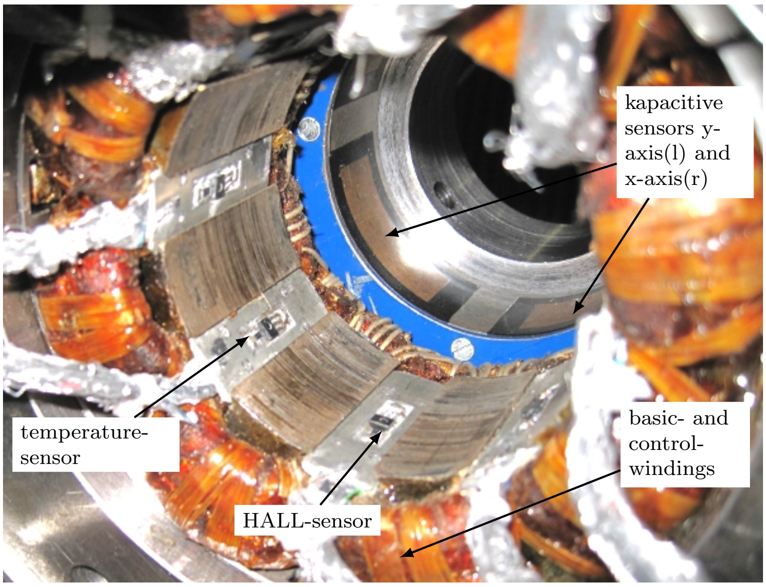

Figure 4: Applied Hall-sensors and parts of the capacitive measurement system.

Y+ positions. Numerical calculations verified by test series have shown that the correlation of in-circuit stray flux intensity and shaft position is much less distinct as it is for off-circuit sensor positions. When the shaft is moved along x-axis for example Figure 5 shows the changing stray flux at Top and X+. It is apparent that the variation of the stray flux intensity at the X+ position is marginal compared to the variation at Top.

This distinct relationship of stray flux and air gap length is caused by differing stray field directions and the orientation of the active sensor areas. A closer look on the field properties displays that the in-circuit stray field is mainly tangential aligned. That means nearly all field lines of the stray field are crosswise to the bearing axis oriented. The applied HALL-sensors can solely detect magnetic field which are radially aligned. So the in-circuit stray flux is invisible

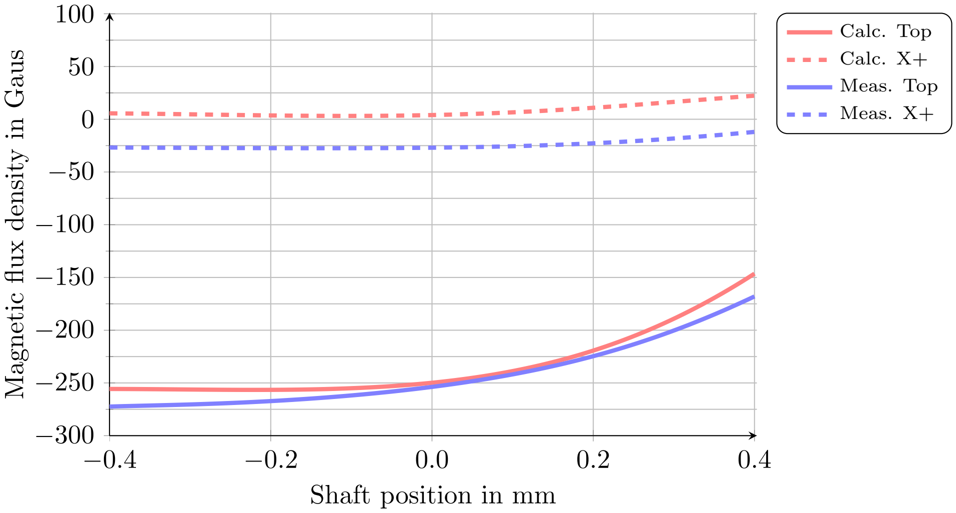

Figure 5: Variation of the stray flux of different measuring positions according to a shaft deviation along the x-axis. Only radial aligned field is included

for most standard low-cost Sensors. If the tangential stray flux contents are also calculated via FEM (Fintite Element Method) a comparison shows that the dependence of stray flux and air gap length for both positions is nearly equal as shown in Figure 6.

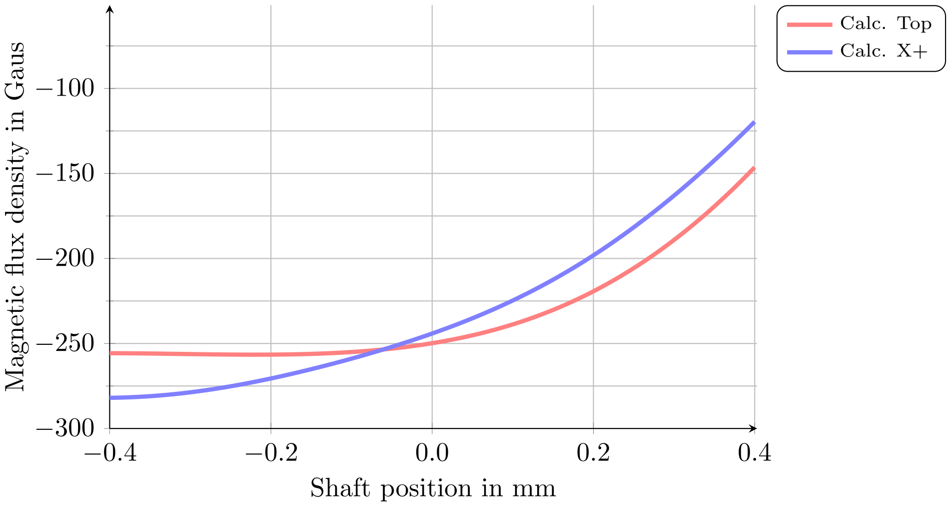

Figure 6: Calculated radial stray flux for sensor positions at Top (off-circuit)and tangential flux at X+ (in-circuit).

2.3 Linearisation I

The previously shown diagrams display clearly the non-linear dependence of stray flux intensity and air gap length. An often used method of linearisation is the differential adjustment of sensors. Thereby the signals of two opposing sensors are subtracted from each other. In this case the signals of the sensors at Top and at Bottom are subtracted. The result is shown in Figure 7. The small divergence from linearity is caused by a small deviation of the shaft from the bearing centre. Thus the variation of shaft positions did not happen exactly along the x-axis. This is also displayed by the intersection of the Top and Bottom curve which is deviated to the right from zero. The procedure has to be deployed also for the opposing sensors at Left and Right. If the tangential flux is measured the corresponding signals of the opposing sensors in the x- and y-axis have to be subtracted from each other.

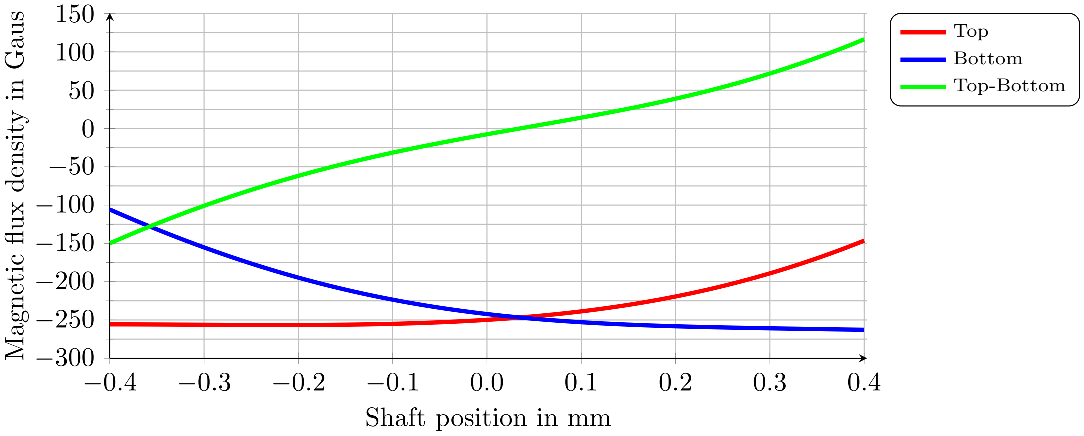

Figure 7: Measured variation of the stray flux of different positions according to a shaft deviation along the x-axis under consideration of tangential and normal flux contents.

2.4 Linearisation II

Based on equations 6 an 7 it is also clear that the stray field intensity not solely depends on the air gap length. An additional dependence exists between stray field and coil current. That means on the one hand if no current in the coils is present there will be no stray field to measure therefore no detection of the shaft position is possible. This case is avoided by using a basic current which is also used for linearisation of the force-way-dependence. But on the other hand the dependence of field and current means that a sudden variation of control current leads to a changed stray field so that there is an apparent deviation of the shaft position. But the new measured position is not real because time was to short for the shaft to move. Caused by the shaft's inertia current can change much faster then the shaft is able to follow. It is easy to see that such a system will not be very robust if it works stable at all. To generate an reliable measurement system it is highly required that the control current is also measured and used for linearisation. The following Figure 8 should clarify how the differential signal based on the signals of the Top and Bottom sensors is changing while control current is increased from -15A to 15A. The current variation correlates with an signal offset approximately.

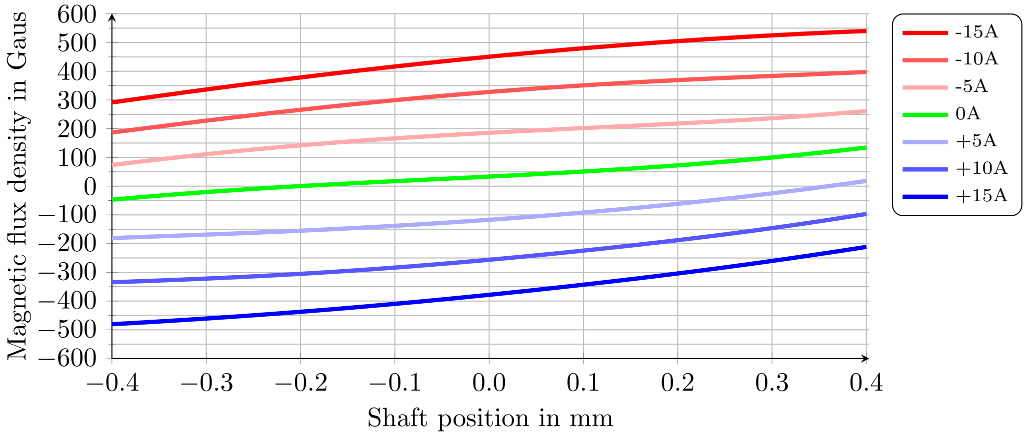

Figure 8: Variation of the position signal of one axis according to different control currents with constant basic current of 6A

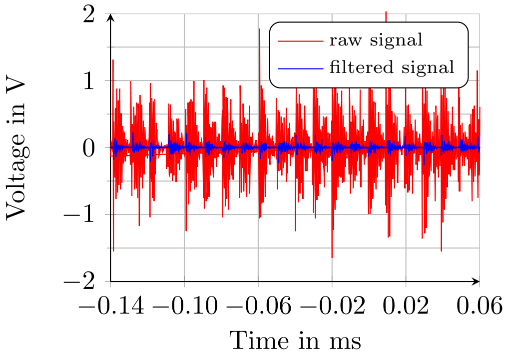

Figure 9: Raw signal without any filtering and signal with first step filter

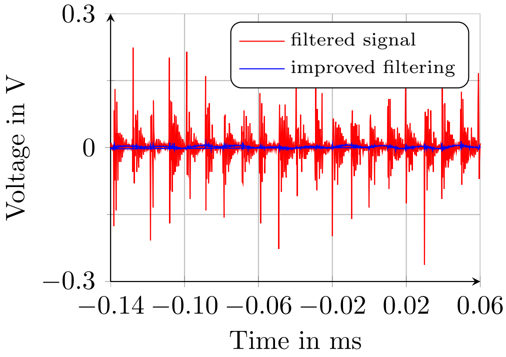

Figure 10: Filtered signal and improved filtering

2.5 Signal Processing

Modern magnetic bearings operate with switched power supplies to drive the basic and control currents. Contrary to analogue amplifiers switched amplifiers e.g. so-called Class-D systems produce significant electromagnetic disturbance. Especially switched current in the bearing coils induces corresponding disturbance of the magnetic field in the air gap and with it the stray field. There is no need to say that this leads to a significant noise in the position signal. To reduce disturbance and improve the signal quality a double stage filter has been applied. The signal improvement after the first step is displayed by Figure 9 after a scaling and amplification stage a second filter further reduces noise (Figure 10). Both measurements where made while the current given value was set to zero. Solely the current controller produces disturbance. While the bearing is operating there is an significant increase of signal noise.

2.6 Comparison of Hall-Based and Conventional Capacitive Measurement System

To say something about the properties of the HALL-based Sensors it is useful to apply them while the bearing is operating with its standard capacitive sensors. Therefore the step function response is analysed as displayed in Figure 11.

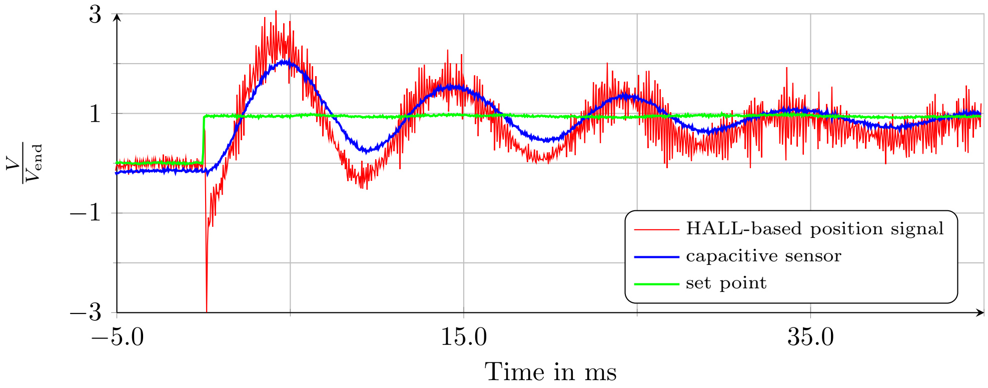

Figure 11: Step response in Top-Bottom direction while the bearing operates with capacitive sensors.

Compared with the HALL-signals while current is set to zero there are much more distortions in this signal. This is caused by the currents which are needed for position control. In a next step the bearing should operate with the HALL-based position signal. So the analogue controller is substituted by a real time computer system where an PID-controller and the current dependence compensation is embedded. Now the capacitive sensor signal stays only for observing the test series. The controller input is changed to the stray flux measurement system. The step response function is show in Figure 12. A stable suspension of the shaft is possible using a conventional PID-Controller but with less robustness as levitation with capacitive sensors. Thus only a small step could be executed. It can also be seen that the capacitive sensor signals contain little more disturbance. This is cause by a more distinct oscillation of the shaft around the zero position. But in contrast to the HALL-signal in Figure 11 noise could be decreased by compensation of the current dependence.

3 Conclusion and Summery

Concluding it can be said that the stray flux based measurement system is a proper system to detect the shaft position in magnetic bearing. Theoretic considerations and numeric simulations where verified by practical tests and measurements. A stable levitation is possible even if a decrease in robustness and accurateness must be accepted. On the other hand the costs of an measurement system could be clearly reduced by application of conventional industrial standard HALL-sensors placed in the space between the bearing poles. In further research there is a need to increase the signal quality by alternative filter designs. Digital algorithms, where the influence of disturbance caused by shaft acceleration or abrupt rise of the control current is not only smoothed but compensated by model based real time calculation, could by applied.

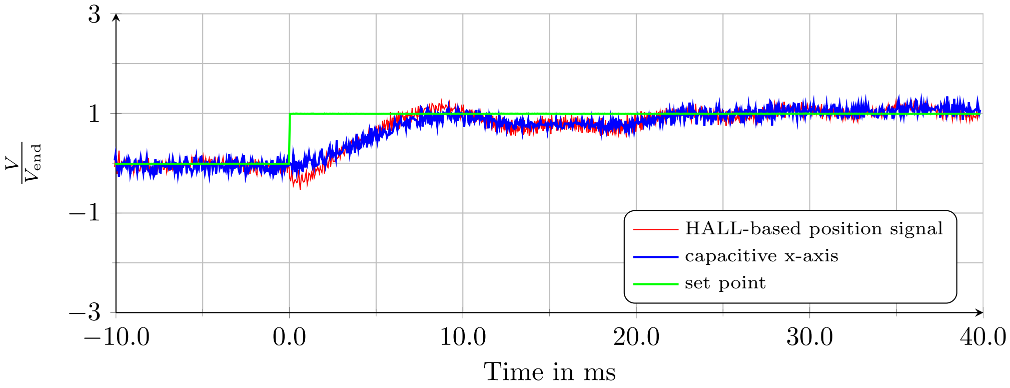

Figure 12: Step response in Top-Bottom direction with stray flux measurement system.)

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