Effect of Eddy Currents on the Stray Flux Based Measurement System for Magnetic Bearing

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***Abstract*—This paper concerns the behaviour and special characteristics of an alternative measurement system for magnetic bearing based on stray flux which depends on the rotor position. The impact of eddy currents on the dynamic properties will be analysed and methods for compensation will be presented. Furthermore the effect of electromagnetic disturbance will be a matter and how it can be reduced by special sensor design.**

I. Basics

A. Introduction

The measurement of the rotor position using flux sensors is a rarely used method. The integration of flux sensors into the air gap is associated with some problems. Most gaps are to small for using standard field sensors. A good possibility is the integration of very thin magnetic sensitive elements [1]. An other option is given by application of additional magnetic circuits which contain flux sensors like Hall elements [2]. A new and alternative opportunity is a measurement system which is based on the often neglected stray flux which also depends on the rotor position [3], [4]. Low cost standard Hall sensors are integrated in the space between adjacent pairs of poles. The magnetic stray flux is also a function of the air gap-length and thus of the rotor position. In previous considerations it has been shown that the direction of the flux is an important fact for positioning flux sensors with only one magnetic sensitive direction. But there is a further correlation between the stray flux and the coil current which has to be considered when the position of the rotor is derived from the stray flux.

B. Problem

While testing the stray flux based measurement system in passive mode a particular behaviour occurred when a step response was recorded. The rotor position is changed stepwise in the way the air gap reduces. Normally the measured flux should increase in the same manner. But like shown in figure 1 there is a short negative peak at the beginning. Caused by the fast rise of the coil current eddy currents appear in the laminated core, which leads to a damped increase of the main flux. Thereby the influence of the coil current is over compensated by the controller for a short time. Just in case of highly dynamic operation modes this effect leads to adverse effects which can compromise a stable operation of the magnetic bearing.

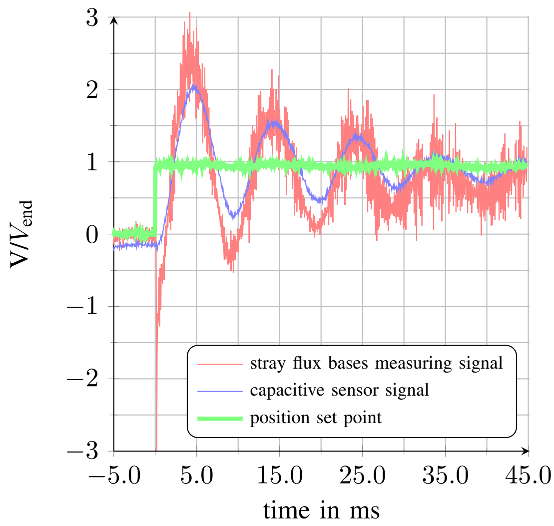

Figure 1. Step response while running the stray flux based measurement system in passive mode. The bearing operates with auxiliary capacitive sensors and PID controller

C. Delay of the magnetic field rise caused by eddy currents and overcompensation of the stray flux based position signal

When a current is applied to an air-core coil the magnetic field around the coil is rising in the same speed as the coil current is rising. Adding a ferromagnetic core to the coil causes a delay in the rise of the magnetic field. The reason for this can be shown with a simplified example. If a monolithic ferromagnetic core is applied the single coil will become a transformer. The secondary coil is formed by the lateral area of the core which represents a single short circuited winding. If the current in the primal coil rises its magnetic field will induce a voltage in the secondary single winding. Because it's short circuited a current begins to flow. Hence the magnetic field counteracts its cause. The rise of the primal magnetic field is damped. If the monolithic core is substituted by a laminated one the effect will be less pronounced. But if the current rises in a steep way there will be still a delay of the magnetic field like shown in figure 2. The control current and the Hall-signal are recorded at the test bearing after a voltage step. It is obvious that the field has a small delay, especially in the beginning when the current is steeply rising. Remembering that the current value is measured and used to calculate a current-compensated Hall-signal it is easy to see that a steeply rising current leads to over compensation.

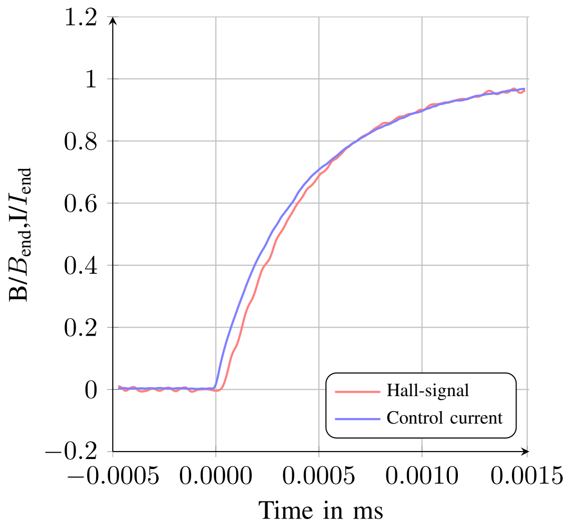

Figure 2. Delay of the magnetic stray flux relative to the control current

In case of suddenly occurring disturbance forces the controller reacts normally with corresponding current to counteract.Especially in this case of steeply rising currents there is a high risk that overcompensation (particular if it is acting contrary) compromise a stable and save operation of the magnetic bearing.

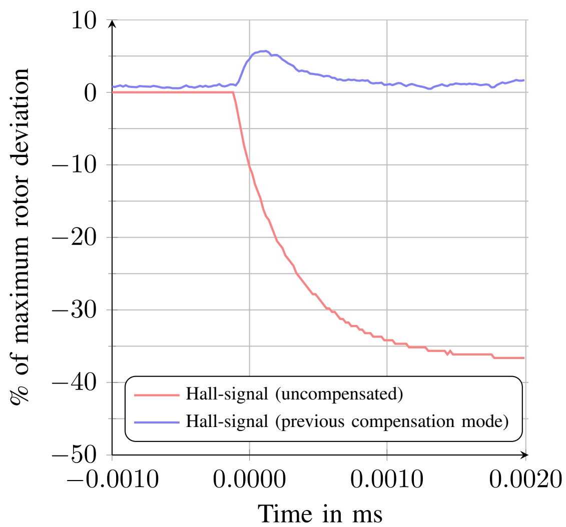

Figure 3. Uncompensated Hall-signal during current step and Hall-signal with previous compensation mode.

The previous current compensation is shown in figure 3 related to the uncompensated Hall-signal after a current step. It is clearly to see that an contrary overcompensation occurs in the beginning when the current rise is steep. The figure shows the difference of the two opposing Hall-signals at bottom and

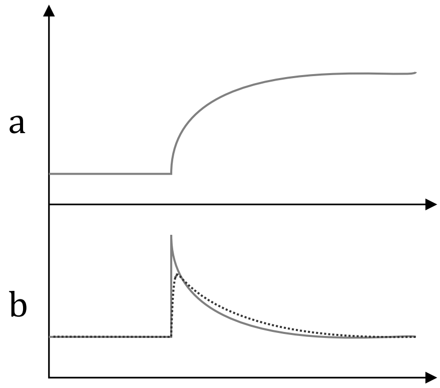

Figure 4. Idealised current raising after a voltage step (a) and its derivation (b-continuous) as well as the filtered derivation (b-dotted).

top position ([4] and [3]) in percent of the maximum rotor deviation. Neither the current compensated stray flux based measuring signal is inaccurate and pretends an rotor deviation of more than 5%. In this experiment the voltage was limited to 15V. In normal operation mode of the test bearing the voltage is set to 325V. Thus the current can rise more steeply and the overcompensation can lead to a bigger position error.

D. *Advanced current compensation*

To minimize the error of the stray flux based measurement system according to fast and wide variations in the control current it is necessary to ascertain not only the momentary value of the control current. There is also a need to know its increase. This can be done by numerical derivation of the measured current signal. But it is well known that the derivation of real and noisy signals is not as simple as the derivation of mathematical function. Every small peek is gained multiple. The result is a signal with a grade of disturbance which is magnitudes higher than the measured current signal. A popular way to reduce this effect is the application of a simple filter.

An idealised course of the current after a voltage step and its derivation is shown in figure 4. The figure also shows the filtered derived current signal. It is clear to see that filtering leads to a less pronounced peak and slower decreasing of the signal which does not reflect the current rising accurately. Based on this filtered derivation only an incomplete current compensation can be realised. A better result can be achieved when the peak is increased and the decreasing is gained in a way that the results look like the course of the unfiltered signal. A feasible way to achieve this is to scale the derived signal with a coefficient which depends also on the derivation. With this method the signal is gained when the raising is steep because the coefficient is big. When the signal decreases the coefficient decreases too which leads to narrower peak. To improve the previous current compensation the current scaling factor is now multiplied by the filtered and modified derivation of the current signal like shown in figure 5. The output is

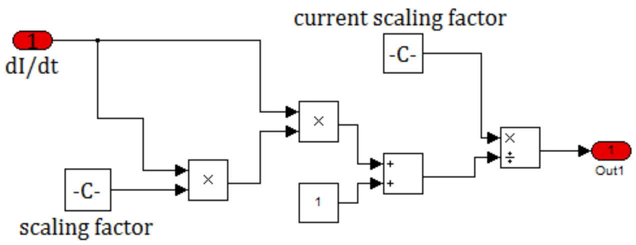

Figure 5. Model of the improved current compensation.

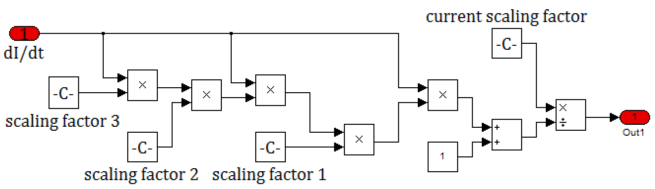

Figure 6. Model of the multi stage current compensation.

added or subtracted from the Hall-signal depending if x- or y-axis control current is treated.

Due to the fact that the scaling factor also depends on the filtered derivation the result of the improved current compensation is better than the previous method but still imperfect. For a further improvement it has been found that a multi staged scaling can be useful. For better understanding the block diagram is shown in figure 6. It is obvious that the first scaling factor is varied by a second factor. This factor also depends on the derived current signal and is varied by a third factor in turn. The scaling can be cascaded more than three times like the following equation shows.

$$c = \frac{c_{\text{static}}}{\left(\frac{dI}{dt}\right)^{n} \cdot c_1 \cdot c_2..c_{\text{n}} + 1} \qquad (1)$$

If the current rises in an steep way the left part of the numerator increases and the compensation factor c becomes smaller to suppress overcompensation. If the current changes slowly or has a constant value the left part of the numerator becomes near zero so that the compensation factor c is dominated by the static current scaling factor $c_{\textbf{static}}$. At the test rig a real time system manages the current compensation. To achieve short cycle times the number of stages is set to three. More stages would improve the result of the current compensation but more time for the calculation is needed. It's a compromise between speed and accuracy.

The application of this improved current compensation method leads to a more suppressed influence of the control current on the stray flux based measurement system. The way the current scaling factor is changing during a step response is shown in figure 7. If the current is not or only slowly changing the scaling factor c is set to 90. It is reduced to almost 40 when a steep current rise appears. These values where experimentally found at the test bearing. By this the stray flux based measuring signal changes rarely like shown in figure 8 when the rotor is fixed in the test bearing and the current raises fast. The improved current compensated stray flux based position signal is shown in figure 8 related to the old compensation method. The level of the peak could be reduced from almost 6% of the maximal rotor deviation to about 2.5% and the time range of overcompensation is shortened clearly.

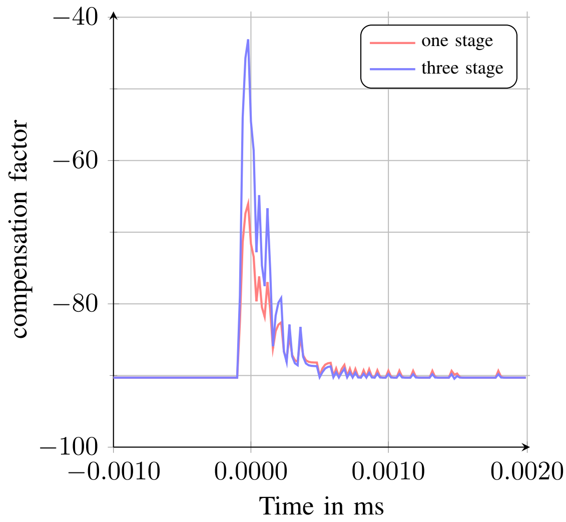

Figure 7. Variation of the current scaling factor with one stage and three stage compensation mode

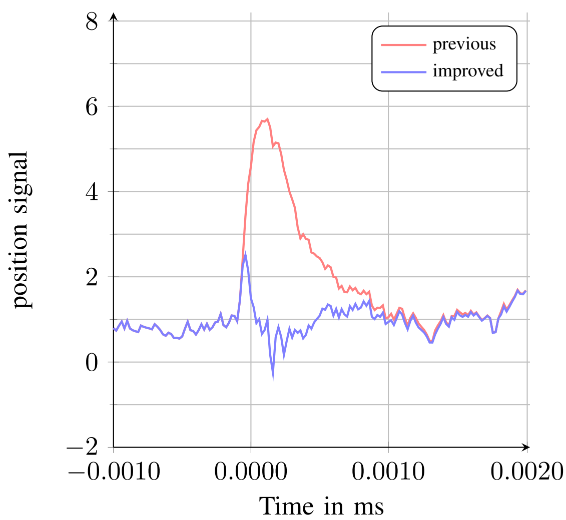

Figure 8. Stray flux based measuring signal previously compensated and improved compensated mode. Rotor is fixed in the test bearing while step response was recorded.

E. Sensor design

In previous experiments with former sensor designs it became clear that electromagnetic disturbance caused by the control coils has a significant influence on the signals from the Hall-sensors. Since the sensors are directly placed near to the coils they are susceptible for such disturbance. In former versions of the sensor there was only one way of signal transmission given and ground areas have been modelled imperfect. The newest Sensor provides direct transmission of

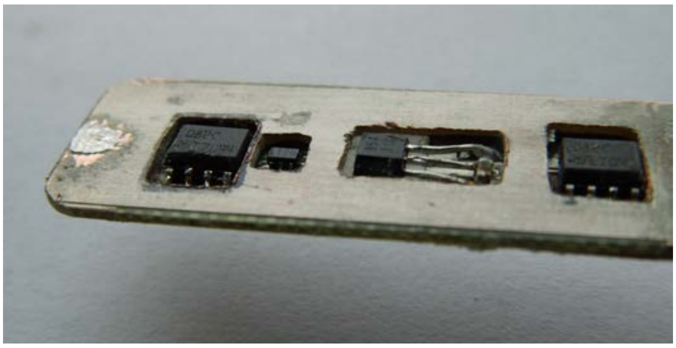

Figure 9. Stray flux sensor V3 (newes version)

Figure 10. Sensors mounted at the test bearing.The lower sensor is the new version.

the Hall-sensor output voltage and two more possibilities like a current based and a differential transmission. The new sensor consists also of four-layer pcb[1] formed by two dual-layer pcb which have been glued together. Now every layer carries a ground area. This is the first step to reduce the influence of electromagnetic disturbance at the place where the Hall-signal is generated. A second step is the implementation of methods for a signal transmission which are more insensitive against electromagnetic distortions like a highly resistive transmission by voltage like it is provided from the Hall-element directly. So the new sensor includes a voltage to current converter and differential signal generator. The signal transmission by current is a well known industrial proved method and the second method originates from audio techniques. As shown in figure 9 the components are placed and soldered at the lower inner layer to minimize the sensor hight. A mounted sensor can be seen at figure 10.

Because only one prototype has been mounted until now extensive measurements and experiments could not accomplished yet but first test has been auspicious.

F. Conclusion

In this paper the delay between current and magnetic field rise caused by eddy currents and their impact on the current compensation of the stray flux based measurement system for the rotor position in magnetic bearing has been discussed. A method has been presented to reduce over compensation significantly by using the derivation of the measured control current. It has been shown how the derived signal should be treated to achieve good results with arguable computing time. Furthermore a new prototype of a stray flux sensor has been presented which permits less noisy measuring signals. Looking ahead all stray flux sensors have to be replaced by the new version and the stray flux based measurement system should switch from passive to active mode and work as input for the loop controller.

[1] pcb - printed circuit board

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