Self-Sensing Algorithm for Active Magnetic Bearings; Using Direct Current Measurements

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Abstract: In the field of active magnetic bearings (AMBs) the self-sensing theme attracts attention due to the ongoing drive for compact integration and cost reduction. Self-sensing makes use of the AMB's actuator to sense the position and to convert electrical energy to mechanical energy.
The aim of the direct current measurement method (DCM) is to reduce phase shift produced by demodulation methods used in the past. The DCM self-sensing scheme makes use of a specific PWM switching method, which enables the estimation of the rotor position by only measuring the power amplifier ripple current. The DCM technique also has the added benefit of less sensitivity for cross-coupling effects.
In this paper the PWM switching method, the method used to extract the current ripple and scaling are discussed. Simulations are done on a transient AMB model which resembles the physical system and practical results are obtained from the practical implementations.

Keywords: Self-Sensing, Sensorless Sensor, Active Magnetic Bearings, Switch Mode Power Amplifier, Cross-Coupling

Introduction

Active magnetic bearings (AMBs) have become a key technology in industrial applications with a continued drive for cost reduction and an increase in reliability. AMBs require position feedback to suspend the rotor. The major disadvantages of conventional position sensors are their cost and that the sensors are viewed as a weak point in an AMB system.
A self-sensing sensor is a type of sensor which is cost effective, reduces sensor wire-length and increases reliability, thus ideal for the industry. The combination of position extraction and force control with one actuator, known as self-sensing, can follow two approaches, namely state estimation [1] and modulation [2,3,4].
The amplitude modulation technique will be investigated, since the state estimation approach is largely affected by the practical model uncertainties and is rather difficult to match the model with the physical system. Amplitude modulation can be implemented using model inversion or parameter estimation. In this work the model inversion approach, which relies on the demodulated voltage and current ripple of the switch mode power amplifier, will be used as basis [4]. The amplitude modulation method is evaluated on a coupled AMB system, thus cross-coupling effects are included.
A simplified one degree of freedom self-sensing differential mode AMB system is shown in Fig. 1. The current and voltage of the top and the bottom actuators are sensed. These signals are used as inputs for the self-sensing technique. The output of the self-sensing technique is an estimation of the rotor position. The estimated position is used as position feedback to the PID controller. The output of the PID controller is fed to the power amplifiers.
A frequency shifted model of the AMB as used in the model inversion position estimation approach is given by Eq. 1.

$$i_d = -\frac{1}{K\omega_s}\left(2x_g + {}^{l_m}/_{\mu_r}\right)u_d \qquad (1)$$

i_d is the current through the coil, ω_s is the switching frequency, K is an actuator constant, x_g is the air gap, l_m is the magnetic material path length, u_d is the demodulated voltage, which is nonlinearly dependent on the duty cycle, and μ_r is the nonlinear permeability of the material [4,5]. The inverse frequency shifted model is used to compensate for the magnetic material nonlinearities and to obtain the estimated position.

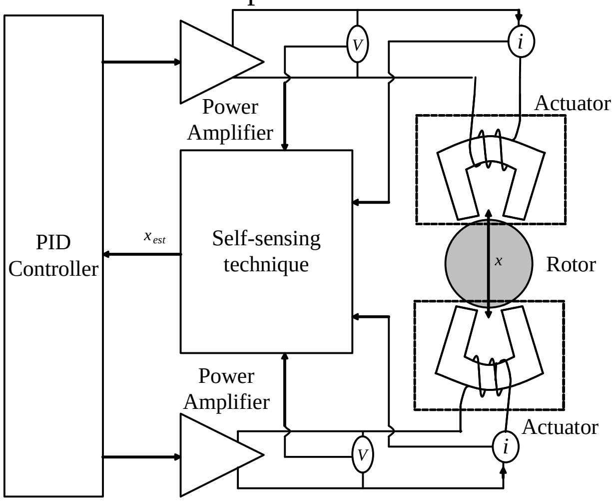

Figure 1: Self-sensing AMB system

Fig. 2 shows the self-sensing block diagram of the inverse frequency shifted model where the fundamental components of the current and voltage signals are obtained through band-pass filtering and demodulation and converted to an estimated position [4,5]. The power amplifier's filtered feedback current (i_L) is used as input to the nonlinear compensation block.

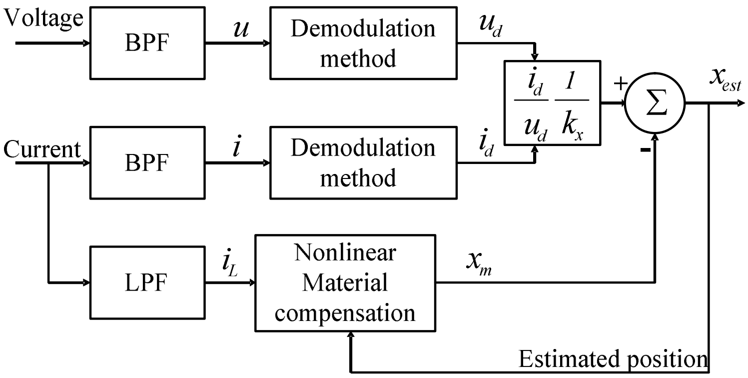

Figure 2: Frequency shifted AMB model

Analog demodulation is most commonly used since it simplifies the programming of the self-sensing algorithm implemented in the controller and also due to digital sampling limitations. The analog demodulation processes usually make use of a band-pass filter (BPF) to extract the fundamental component of the switching ripple and to remove the low frequency control current. The fundamental current component is then demodulated to obtain the envelope which contains the rotor position information. The bandwidth limiting effect of the BPF is of concern, since the filter introduces a phase shift and limits the performance of the demodulation process. Due to the limiting effects of the BPF in the modulation path the direct current measurement method is investigated, which eliminates the BPF.

Direct Current Measurement (DCM) method

In this research the focus is on an analog sensing method which eliminates the analog BPF and a digital self-sensing algorithm. Fig. 3 shows the block diagram of the DCM self-sensing method. Two current measurements are made. The filtered current is used for the power amplifier current feedback and for the position nonlinear compensation function in the DCM method to compensate for material nonlinearities. The ripple current is directly measured and fed to the DCM algorithm to estimate the position. The nonlinear compensated estimated position is fed back to the position controller.

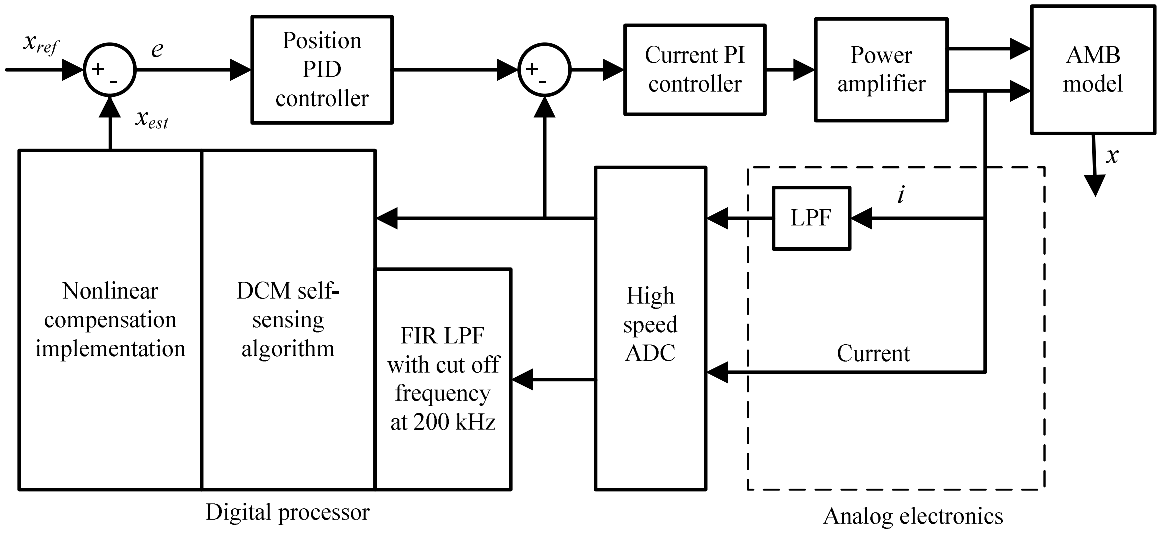

Figure 3: DCM self-sensing method

I. Analog electronics and PWM signal

The DCM method makes use of a PWM sensing cycle and an analog sample and hold to obtain the ripple component without affecting the DCM bandwidth as in the case of using a BPF.
When the duty cycle changes the amplitude of the ripple current is nonlinearly modulated as proved in [4]. The current ripple can then not be directly used to obtain an estimated position. A PWM sensing cycle is used to overcome the nonlinear duty cycle modulation effect, by forcing the duty cycle to 50 % when the self-sensing algorithm is evaluated. Thus by switching one cycle at 50 % for position sensing purposes and using the next cycle for control, the nonlinear duty cycle dependency is overcome and controllability is maintained.
Due to the 50 % PWM switching method the current ripple is only required to obtain the position information, where in other cases the voltage is required to overcome the nonlinear modulation effect. Since this method forces one switching cycle to 50 % the power amplifier slew rate is halved. The hold of the sample and hold is activated at the beginning of the sensing cycle by the digital controller. The sample and hold output is subtracted from the sensed current, of which the remaining result is the ripple current. The ripple is amplified to utilize the full range of the ADC.

II. DCM method and nonlinear compensation

The same least squares method is used as proposed by Schammass [4] and [5] due to the saturation and eddy current effects. The only difference is that $I_u = I_d / U_d$ is replaced by $I_{r_{max}}$, where $I_{r_{max}}$ is the peak value of the ripple current. With the nonlinear effects neglected the position can be estimated by the following equation:

$$x_{ge} = \frac{1}{k_x} I_{r_{max}} \tag{2}$$

With the nonlinearities included the rotor position can be determined by using

$$x_{est} = x_{ge} - x_m = \frac{1}{k_x}\left(I_{r_{max}} - k_{b2} B_e^2 - k_{b1} B_e - k_{b0}\right), \tag{3}$$

where x_m is the nonlinear position component due to material nonlinearities, B_e is the estimated flux determined by using one delayed estimated position and the power amplifier feedback current, k_x, k_{b2}, k_{b1} and k_{b0} are determined by measurements in simulation and from the practical system [4,5]. The theoretical proof of this is found in [5].

III. Duty cycle cross-coupling effects

The poles of an AMB's actuator are magnetically coupled through the back iron, resulting in cross-coupling. Cross-coupling is the effect that each individual pole has on another. In the case of a coupled AMB system, cross-coupling is dependent on geometric changes and the resulting flux distribution due to the back iron.

Geometric cross-coupling is the effect that a change in rotor position has on a specific self-sensing pole due to the air gap change in the remaining poles. This can be explained in terms of the change in the mutual inductance components when the rotor position changes.

By using a reluctance model, the current ripple used for self-sensing can be written in terms of the mutual coupling to other poles. From this coupled model it was derived that a change in the flux at any pole other than the sensing pole will affect the ripple component of the sensing coil. Further investigation reveals that the amount of coupling is dependent on the mutual coupling constant as well as the duty cycle variation from the 50 % sensing cycle. Variation from the 50 % sensing cycle is prevented by ensuring that the switching of all four coils is synchronized, since all the coils are switched at same time. When the rotor moves to the left, the left coil's mutual coupling component increases and the right coil's mutual coupling component decreases and vice versa. From the coupled model, the effect of the horizontal axis on the cross-coupling will always be the same due to the horizontal mutual coupling. For the vertical analysis it was found that the coil opposing the sensing coil results in a mutual coupled component which influences the self-sensing position due to the change in air gap. From simulation results the effect of cross-coupling in the DCM method compared to the analog demodulation method used by Schammass is reduced by a factor of up to 3.3 [6].

Evaluation Platform

The DCM self-sensing scheme is implemented in hardware and evaluated on a 7 A rms, 500 N eight pole heteropolar AMB and evaluated in simulation. Since self-sensing schemes in AMB systems are largely affected by the nonlinear effects due to the material properties, a transient simulation model (TSM), which includes hysteresis, magnetic material saturation, eddy currents and cross-coupling effects, is used to simulate the practical AMB system. Fig. 4 shows the practical implementation platform, which consists of an integrated power amplifier which is capable of suspending one degree of freedom using the DCM self-sensing algorithm.

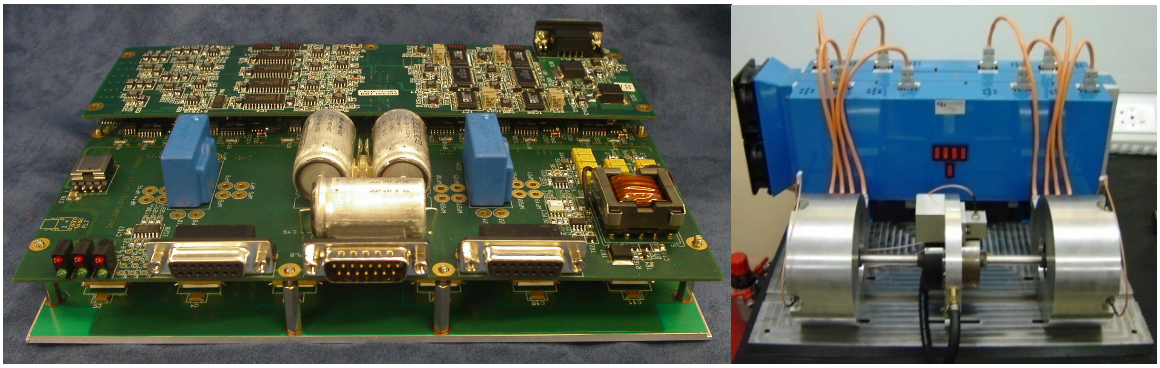

Figure 4: Practical implementation platform (Left: integrated power amplifier. Right: AMB system)

Results

The self-sensing schemes are statically and dynamically evaluated in terms of performance measures. The rotor position is linearly varied from the minimum to the maximum position for the static evaluation. The real and estimated positions are recorded simultaneously. The real position points are plotted versus the estimated position points. The result should ideally be a linear line with a gradient of one. Fig. 5 shows the static evaluation of the practical system. From this evaluation the error made in the ± 100 µm range is below 5 µm and the maximum error is 15 µm over the ± 350 µm range.

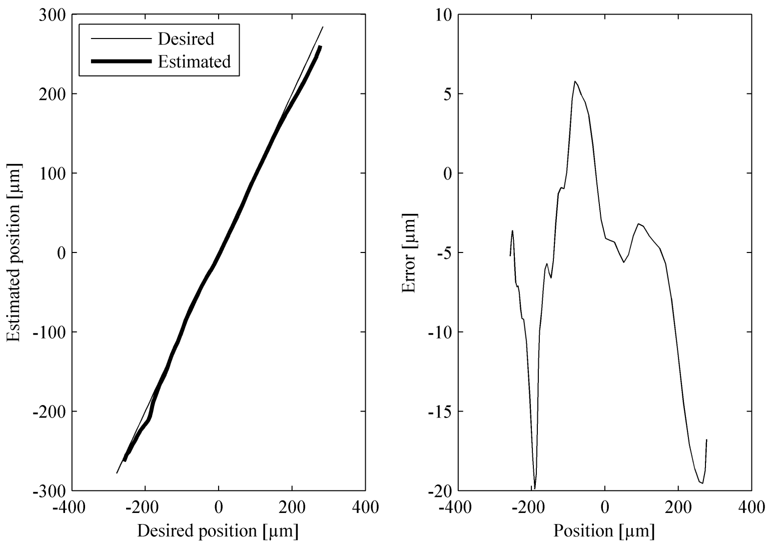

Figure 5: Static position evaluation

The gain and phase analysis makes use of the relationship between the real and the estimated frequency content of the position signals. The gain response is calculated as follows: $G_X(\omega) = 20\log(X_s(\omega)/X(\omega))$, where $X_s(\omega)$ is the estimated position and $X(\omega)$ is the real position. Fig. 6 shows the simulation results on the left and the practical results on the right. The difference between the simulation and the practical implementation was due to the high order PID input filter as well as the dynamic effects due to the sample and hold. The filter was included in the simulation and the gain and phase again showed that filters have a large effect on the overall self-sensing bandwidth. The robustness of an AMB system with conventional sensors is determined through sensitivity measurements as described by the ISO 14839-3 standard [7]. The same method is used to evaluate the robustness of the self-sensing schemes.

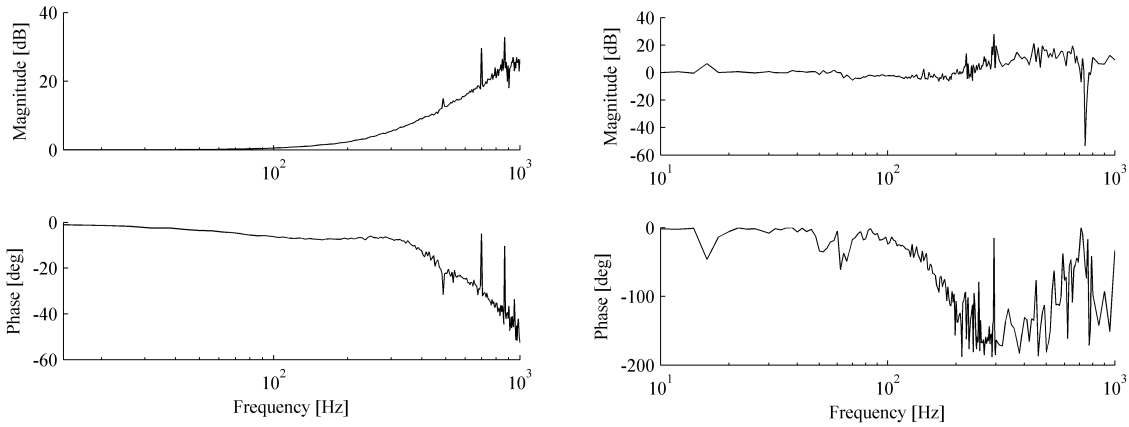

Figure 6: DCM gain and phase response

Fig. 7 shows the sensitivity, as described in the ISO 14839-3 standard, of the AMB system using the DCM self-sensing method. The peak value with the proportional gain set at 10000 (12500 designed value) is 10.3 dB excited with a 7 µm peak to peak sinusoidal position reference. The robustness of the self-sensing system was found to be in the mid range of a class B system, which means that the DCM self-sensing technique is usable in industry.

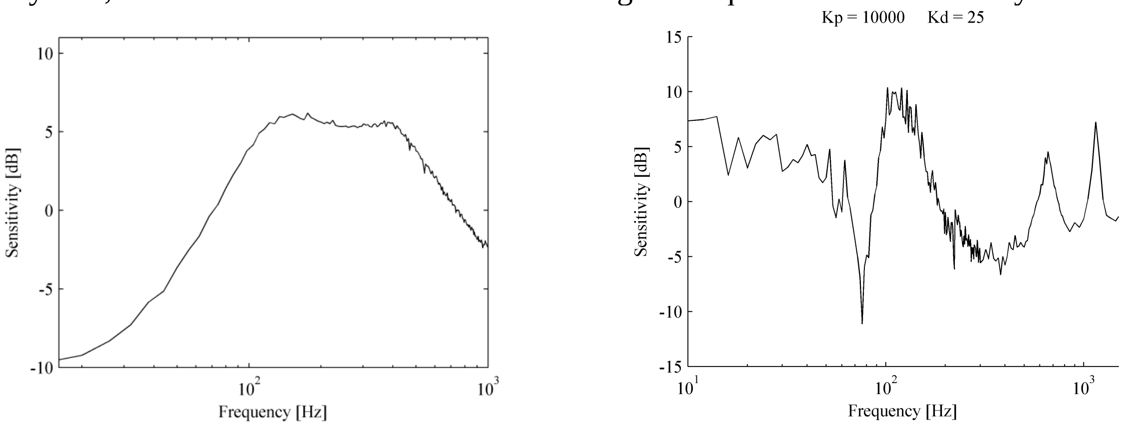

Figure 7: AMB sensitivity with DCM method

The effect of duty cycle cross-coupling could be illustrated and the DCM 50 % sensing technique was shown to be less sensitive. This concluded that the DCM self-sensing method is practically implementable for industrial applications.

Conclusion

The practical implementation proved that the DCM self-sensing scheme and the digital demodulation method are practically implementable on a high current AMB system (0 to 10 A). It was also proved that self-sensing can be implemented on a coupled AMB system which includes cross-coupling. Since a coupled stator is used the manufacturing costs can be reduced. The high current and coupled AMB system is also a step closer to an industrialized self-sensing system. The current sensors used in hardware are off-the-shelf current sensors, which eliminates the development of bulky in-house sensing methods. From the practical implementation it was also learnt that extreme care must be taken to reduce noise. Where possible, the signals must be digitized by using high speed ADCs and the signals must be digitally filtered to eliminate switching noise. The effect of cross-coupling on the DCM technique with the 50 % sensing cycle was evaluated. From the analysis it was found that the coil opposing the sensing coil has the maximum cross-coupling effect. By using the 50 % sensing technique cross-coupling can be reduced by a factor of up to 3.3. Thus the 50 % sensing cycle increases the overall performance in a coupled AMB system.

Future Work

The analog sample and hold method, used to extract the current ripple in the DCM self-sensing scheme, must be replaced by a digital to analog (DAC) extraction method due to undesired dynamic effects. If the analog sample and hold dynamics have such a large effect as suspected, the robustness of the DCM self sensing method may be increased by the DAC method. This may enable the self-sensing AMB system to operate at its designed control constants and stiffness in the practical system.

The effect of cross-coupling due to air gap changes on self-sensing techniques may be investigated. A compensation model may be derived which makes use of all the currents and position signals to estimate the position error due to cross-coupling more accurately.

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