Monitoring of Active Magnetic Bearings

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Abstract

Two simple but efficient methods for integrity monitoring of position transducers within an active magnetic bearing are presented. Position transducers may be considered as a critical component in a control loop of the active magnetic bearing. Continuous monitoring of their integrity during operation may hence increase reliability and robustness of the active magnetic bearing and may improve quality and safety of a related industrial application. The proposed methods rely on a cross validation of sensorial information between different control axes of the active magnetic bearing and may be implemented entirely in software without additional hardware.

1 Introduction

Two simple but efficient methods for integrity monitoring of position transducers within an active magnetic bearing are presented. The methods are intended to increase reliability and robustness of active magnetic bearings used in applications where high quality and safety levels are required. In general, industrial components are typically designed to address demanding reliability and safety requirements and to provide a high maturity level of industrial equipment (see also [1]). However, it is common practice to additionally monitor particularly critical components and, in case of detecting a critical failure, to bring the machinery into a safe state.

Closed loop position control in active magnetic bearings may use signals produced by position transducers as feedback signals. As such, a transducer can be considered as a critical component wherein a transducer failure may cause damage to equipment or even injuries to operating personnel. Failure cases concerning position transducers may comprise, for example, a broken transducer cable which can normally be detected by appropriate electronic circuitry. More difficult to manage are transducer failures when a malfunction is less obvious such as a drift or a sporadic dropout which may lead to wrong position values.

The proposed methods are intended to provide a means to detect the latter kind of malfunctions. They are based on a consistency check between the signals produced by the position transducers of at least two different individually controlled active magnetic bearing control axes, wherein each of the axes has two position transducers in, with respect to a cross-sectional view of the rotor, diametrically opposite positions. Although the application of the proposed methods is particularly advantageous in radial bearings, they may be used for monitoring the correct functioning of position transducers of an axial active magnetic bearing as well. Furthermore, for an implementation, there is no need for extra hardware. Instead, the proposed methods can be implemented with a relatively simple software routine within a magnetic bearing control unit (see also [2, 3]).

2 Methods

2.1 Technical Background

A schematic cross-sectional view of an arrangement of a rotor with four position transducers as typically used in an active magnetic bearing is depicted in Figure 1. The transducers s_1, s_2, s_3 and s_4 are aligned with two orthogonal axes denoted as x axis and y axis. The center of the rotor is typically disposed at the point of intersection (x_0, y_0) of the two axes, wherein the point of intersection is also denoted as a central position. In order to keep the rotor at the central position, closed loop position control may be performed independently with respect to each of the axes (decentral control).

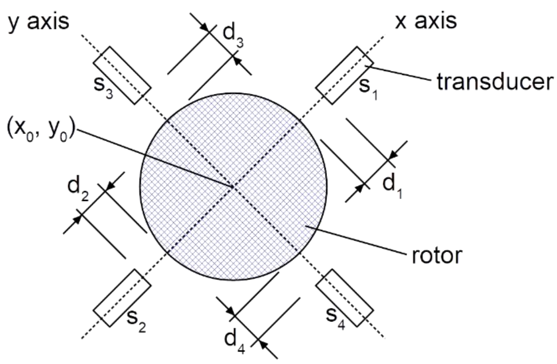

Figure 1: Cross-sectional view of a rotor, orthogonal (control) axes of a radial active magnetic bearing and transducers in diametrically opposite positions

The transducers s_1, s_2, s_3 and s_4 are configured to measure the distances d_1, d_2, d_3 and d_4 between the rotor and the respective transducers. They are usually calibrated such that, when the rotor cross-sectional center is at the central position, the distances are $d_1 = d_2 = d_3 = d_4 = d_0$, with d_0 as the nominal distance between the respective transducer and the rotor.

During normal, that is, error-free operation, the distance between each of the transducers and the rotor may vary according to

$d_1 = d_0 – \Delta_{th} – x$,
$d_2 = d_0 – \Delta_{th} + x$,
$d_3 = d_0 – \Delta_{th} – y$, and
$d_4 = d_0 – \Delta_{th} + y$,

where the term Δ_{th} represents a thermal expansion of the rotor, depending on an operating temperature and time, and where x and y denote a deflection of the rotor in a direction of the x and y axis, respectively. Furthermore, since, at least for a large rotor diameter, the deflections are small in comparison to the rotor diameter, in the above equations the deflection in the y direction is neglected for d_1 and d_2 and the deflection in the x-direction is neglected for d_3 and d_4.

For closed loop position control, it is possible to use average measured signals x_{meas} and y_{meas} of the transducer signals as feedback signals, wherein x_{meas} and y_{meas} are calculated from

$$x_{meas} = \frac{d_2 - d_1}{2} \quad \text{and} \quad y_{meas} = \frac{d_4 - d_3}{2}.$$

This kind of averaging is advantageous since the thermal expansion term Δ_{th} disappears in x_{meas} and y_{meas}. Furthermore, by way of averaging, it is possible, for example, to reduce measurement noise, thereby reducing noise emissions and/or power consumption of the active magnetic bearing.

In the case where a transducer produces wrong distance values, x_{meas} and/or y_{meas} may become erroneous and the closed loop position control may then bring the rotor into a wrong or at least an undesired position. For example, if the value of d_1 exhibits an offset drift ε, that is $d_1 = d_0 - \Delta_{th} - x + \varepsilon$ then the feedback value x_{meas} becomes

$$x_{meas} = \frac{d_2 - d_1}{2} = \frac{d_0 - \Delta_{th} + x - d_0 + \Delta_{th} + x - \varepsilon}{2} = x - \frac{\varepsilon}{2}.$$

Assuming further that, by convention, the nominal (central) position in x direction is $x_0 = 0$, then the magnetic bearing closed loop control will modify the magnetic field of the magnetic bearing until $x_{meas} = 0$ such that the true position of the controlled rotor is (on average) at $x = \varepsilon/2$. That is, in the exemplary case, the rotor position will exhibit an undesired offset from the desired position.

A further implication of $x_{meas} = 0$ and closed loop position control is that (on average) $d_1 = d_2$. Due to this relation, it is not possible to detect the offset drift ε by comparing d_1 with d_2. Instead, to detect the offset drift ε, it seems to be possible to compare, for example, d_1 or d_2 with the nominal distance d_0. However, since d_1 and d_2 also depend on the radial thermal expansion term Δ_{th} it is not possible to exactly determine what change of d_1 or d_2 is due to the rotor expansion or due to the offset drift. Therefore, the drift ε cannot be reliably detected from comparing d_1 or d_2 with d_0. A possible solution to detect the offset drift would be to install a monitoring system with an additional position transducer that may monitor the rotor position independently. The disadvantage of such a monitoring system is that such an independent measurement chain may be expensive, it may require space, it may also need maintenance and calibration, and it may be defective as well.

The methods proposed in this paper are based on the observation that radial rotor expansion due to a temperature increase applies to both, x and y axis. Therefore, the expansion term applies with the same amount to all four transducer signals d_1, d_2, d_3 and d_4. Consequently, when comparing for example d_1 and d_3, there is only equality $d_1 = d_3$ if the offset drift term $\varepsilon = 0$.

Therefore, if the rotor position in the x axis direction is controlled independently from the rotor position in the y axis direction, it is possible to use position signals of the x axis transducers to verify position signals of the y axis transducers and vice versa, that is, to mutually verify the plausibility of x axis transducer signals and y axis transducer signals and hence the integrity of the transducers. Two methods, method A and method B, based on this idea are proposed in the following.

2.2 Method A

Method A directly compares mean distances (low pass filtered distances) between the rotor and the transducers of the x and the y axis. The mean distances are used for this comparison instead of the instantaneous distance values since the central position of the rotor usually moves on an orbit during operation corresponding to unbalances, rotordynamics, process forces and the forces produced by the active magnetic bearing. An example for such an orbit and $\varepsilon = 0$ is depicted in Figure 2 where, in the left diagram, an example for a trajectory of the rotor center on an orbit is depicted and, in the right diagram, corresponding signals x_{meas} and y_{meas}, calculated as indicated above, are shown.

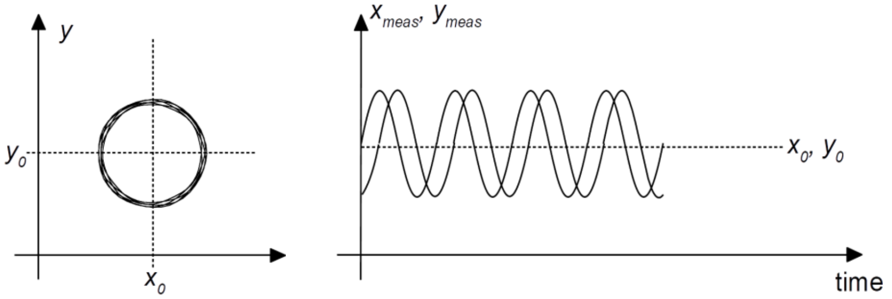

Figure 2: Left - trajectory of movement of the rotor center on an orbit; Right – movement of the rotor center in x and y direction versus time

For $\varepsilon = 0$, the mean distances between the transducers and the rotor are

$$\bar{d}_1 = \bar{d}_2 = \bar{d}_3 = \bar{d}_4 = d_0 - \Delta_{th},$$

with, as defined above, d_0 as the nominal (calibrated) distance between the respective transducer and the rotor and the radial thermal expansion term Δ_{th}. However, in the case of $\varepsilon \neq 0$ and assuming ε to be present in the transducer signal d_1, one obtains

$$\bar{d}_1 = \bar{d}_2 = d_0 - \Delta_{th} + \varepsilon/2 \neq \bar{d}_3 = \bar{d}_4 = d_0 - \Delta_{th},$$

where the equalities $\bar{d}_1 = \bar{d}_2$ and $\bar{d}_3 = \bar{d}_4$ are due to closed loop position control. So, the mean transducer signals of the different axes differ from each other in case of an offset drift error ε.

To summarize method A: at least one low pass filtered transducer signal of the x axis is compared with at least one low pass filtered transducer signal of the y axis in order to detect an offset drift error of at least one of the transducers. A substantial inequality between the compared signals indicates an offset drift error of at least one of the transducers.

Due to the necessity to filter the position signals with a low pass filter, it may be impractical to use this method for low rotational speeds of the rotor.

2.3 Method B

As method A primarily focuses on the detection of an offset drift of a transducer signal, it is also possible to combine the offset drift detection with detecting a drift of a transducer amplification.

For this, the transducer signals are added to obtain an estimate of the rotor thermal expansion values, that is

$$\Delta d_x = \frac{(d_1 - d_0) + (d_2 - d_0)}{2} = \frac{-\Delta_{th} - x - \Delta_{th} + x}{2} = -\Delta_{th}$$

and

$$\Delta d_y = \frac{(d_3 - d_0) + (d_4 - d_0)}{2} = \frac{-\Delta_{th} - y - \Delta_{th} + y}{2} = -\Delta_{th}$$

Note: the division by 2 is introduced to obtain the same scaling as for method A; it is, however, not essential for the method B.

If there is no drift with respect to an offset or to a transducer amplification then

$$\Delta d_x = \Delta d_y.$$

Both, Δd_x and Δd_y assume values corresponding to the thermal expansion of the rotor relative to the position of the transducers. In this context, one should keep in mind that also machine parts that carry the transducers may be subject to thermal expansion.

In case of an offset drift error ε and a transducer amplification error α, for example in transducer s_1, one obtains for d_1 and d_2 (assuming closed loop position control, that is, ε is visible as ε/2 in d_1 and as ε/2 in d_2)

$$d_1 = d_0 - \Delta_{th} - \alpha x + \varepsilon/2 \text{ and } d_2 = d_0 - \Delta_{th} + x + \varepsilon/2,$$

and hence for Δd_x

$$\Delta d_x = \frac{(d_1 - d_0) + (d_2 - d_0)}{2}$$
$$= \frac{-\Delta_{th} - \alpha x + \varepsilon/2 - \Delta_{th} + x + \varepsilon/2}{2} = -\Delta_{th} + \frac{\varepsilon}{2} + \frac{(1-\alpha)}{2} x$$

At the same time, if the transducers in the y axis as assumed to be error free, then, as calculated above, one obtains for the y axis $\Delta d_y = -\Delta_{th}$.

Therefore, in order to detect a transducer error, it is possible to check Δd_x and Δd_y for inequality. In the above equation, Δd_x has three terms: the first term corresponds to the thermal expansion of the rotor, the second term to an offset drift of a transducer and the third term corresponds to a drift of the transducer amplification. While the first two terms are substantially DC components, the third term comprises a frequency component which corresponds to the rotational speed of the rotor (which is DC only at stand still). For the detection of an offset drift of one of the transducers one may compare the DC components of Δd_x and Δd_y and for the detection of an amplification drift one may monitor the evolution of the AC component of Δd_x and/or Δd_y over time. It is appreciated that this kind of monitoring may be performed in time and/or in frequency domain.

Note: to simplify the analysis, the amplification error α is only applied to the rotor deflection x. In general, the transducer amplification may affect the transducer offset drift ε as well.

3 Experiments

3.1 Simulation setup

The principles of method A and method B are analyzed by way of simulation. For this it is assumed that the active magnetic bearing is operated at a sampling rate of 16 kHz. Furthermore, in this simulation, the rotor deflections x and y are considered to be AC signal (sinusoidal) components having a frequency of 10 Hz (600 rpm).

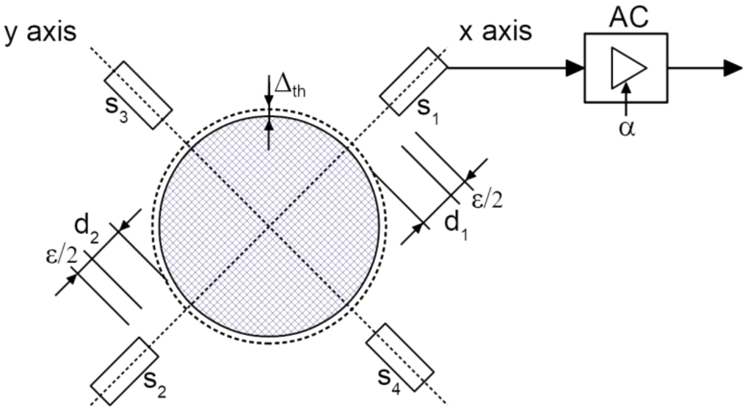

Figure 3: Simulation setup with an offset drift error **ε** and an AC amplification drift $\boldsymbol{\alpha}$ in the x axis and thermal rotor expansion is both x and y axis

The transducer signals d_1, d_2, d_3 and d_4 are simulated according to four setups. Each simulated transducer signal d_1, d_2, d_3 and d_4 includes four adjacent signal segments corresponding to the four setups, respectively. The setups are schematically depicted in Figure 3 and are defined as follows:

Setup I: Floating rotor without rotation. The transducer signals are given as constant values d_1=d_2=d_3=d_4=d_0 wherein d_0 is the calibrated nominal air gap value of the magnetic bearing and exemplarily set to d_0=200µm; the time span of the segment is $t \in [0s; 50s]$.

Setup II: Thermal rotor expansion during rotation. The thermal rotor expansion is simulated as exponential air gap reduction according to $\Delta_{th}= 40\mu m \cdot (1 - exp(-(t - 50s)/10s)$ with time span $t \in [50s; 100s]$. The transducer signals are hence given with

$$d_1 = d_0 - \Delta_{th}(\mathrm{t}) - \mathrm{x}$$
$$d_2 = d_0 - \Delta_{th}(\mathrm{t}) + \mathrm{x}$$
$$d_3 = d_0 - \Delta_{th}(\mathrm{t}) - \mathrm{y}$$
$$d_4 = d_0 - \Delta_{th}(\mathrm{t}) + \mathrm{y}$$

Setup III: Linear offset drift of transducer 1, wherein the offset drift is simulated with $\varepsilon = 50\mu m \cdot (t - 100s)/50s$ with time span $t \in [100s; 150s]$. The transducer signals are thus given with

$$d_1 = d_0 - \Delta_{th}(100\mathrm{s}) - x + \varepsilon(\mathrm{t})/2$$
$$d_2 = d_0 - \Delta_{th}(100\mathrm{s}) + x + \varepsilon(\mathrm{t})/2$$
$$d_3 = d_0 - \Delta_{th}(100\mathrm{s}) - \mathrm{y}$$
$$d_4 = d_0 - \Delta_{th}(100\mathrm{s}) + y$$

Setup IV: Linear drift of the amplification of the rotor deflection, wherein the amplification drift is simulated as $\alpha(t) = (t - 150s)/50s + 1$ with $t \in [150s; 200s]$. Therefore, the transducer signals are given with

$$d_1 = d_0 - \Delta_{th}(100\text{s}) - \alpha(t) \cdot x + \varepsilon(150\text{s})/2$$
$$d_2 = d_0 - \Delta_{th}(100\text{s}) + x + \varepsilon(150\text{s})/2$$
$$d_3 = d_0 - \Delta_{th}(100\text{s}) - \text{y}$$
$$d_4 = d_0 - \Delta_{th}(100\text{s}) + y$$

It should be noted that an amplification error could, in a real setup, also affect the offset value of a transducer. However, in order to demonstrate the effect more clearly, the impact of the amplification drift is, in this simulation, limited to the AC signal component of the rotor deflection.

As an example, the signal d_1 of the transducer s_1 is depicted in Figure 4a where all four setups are depicted in a timely adjacent order. Figure 4b shows a low pass filtered signal of the signal of Figure 4a. For low pass filtering an 3rd order elliptic filter was used with a cutoff frequency of 1 Hz and a stop frequency at 5 Hz, pass band ripples of at most 3dB and stop band attenuation of at least 60dB.

Method A uses signals corresponding to Figure 4b (the signals d_1, d_2, d_3 and d_4 are filtered with the same filter) whereas method B uses the unfiltered signals corresponding to Figure 4a (corresponding to the equations above).

The simulation is performed with Octave, version 6.2.0.

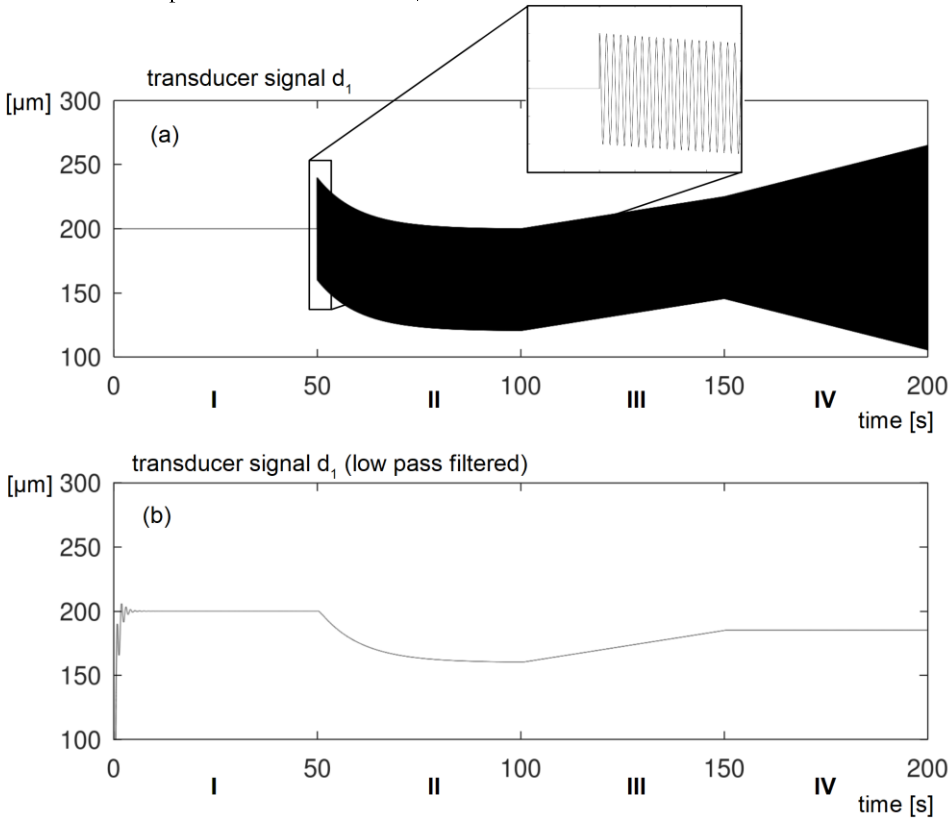

Figure 4: Simulation of transducer signal d1, **(a)** raw signal, **(b)** filtered signal); setup I – levitation of rotor; setup II – thermal expansion of rotor; setup III – transducer offset drift; setup IV – transducer amplification drift

3.2 Results

Simulation results are presented in Figure 5. Figure 5a shows simulation results for method A, that is, a function graph representing the difference $\bar{d}_3 - \bar{d}_1$. More specifically, in setup I (rotor floating without rotation, no drift) the difference $\bar{d}_3 - \bar{d}_1$ equals zero. The same applies to setup II (thermal expansion of the rotor). However, a drift of the transducer offset is indicated in setup III (transducer s_1 exhibits an offset drift). The drift of the AC amplification as simulated in setup IV, however, is not detected by method A, that is, the difference $\bar{d}_3 - \bar{d}_1$ remains at the same level as at the end of setup III.

Figure 5b shows simulation result for method B, that is, a function graph representing the difference $\Delta d_y - \Delta d_x$. For setups I to III the result of method B is similar to the result of method A. However, in contrast to method A, method B indicates an AC offset drift, that is, for setup IV the difference signal $\Delta d_y - \Delta d_x$ exhibits a signal component with an oscillation according the rotational frequency and an increasing amplitude (due to the simulation setup).

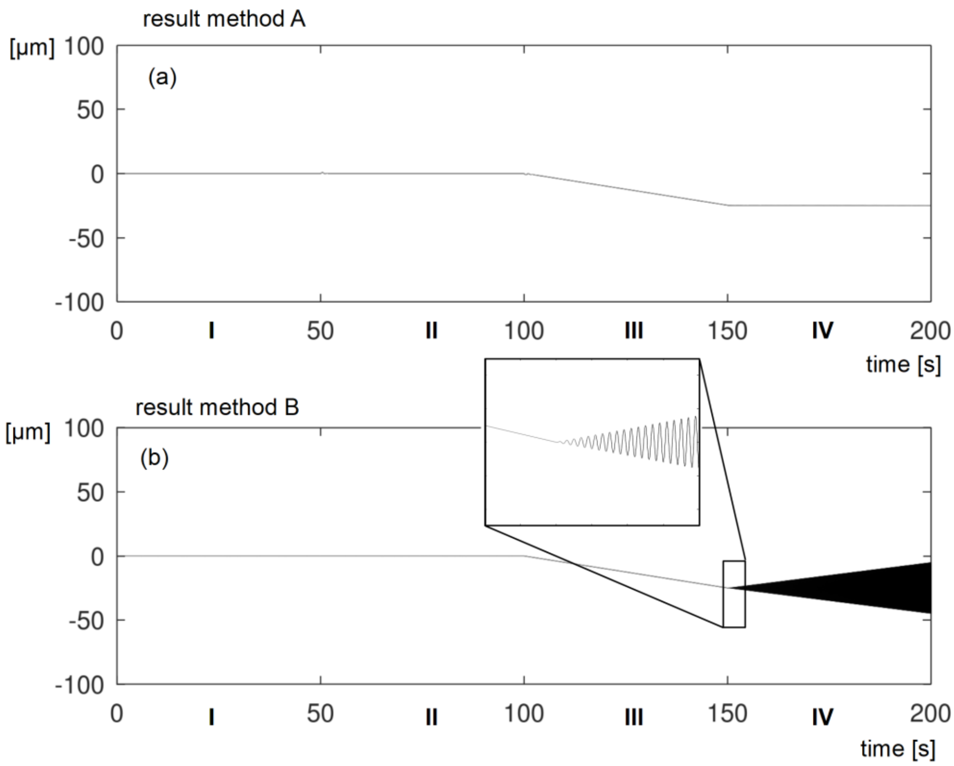

Figure 5: (a) Simulation result for method A, the depicted function graph is the difference $\bar{\boldsymbol{d}}_3 - \bar{\boldsymbol{d}}_1$. **(b)** simulation result for method B $\Delta \boldsymbol{d}_y - \Delta \boldsymbol{d}_x$

4 Discussion

Both, method A and method B are based on the same principle, that is, a comparison of the transducer signals of the different control axes. In general, method B seems to be more flexible than method A and provides a means to detect, in addition to a transducer offset drift, a transducer amplification drift.

The offset drift, for example as simulated in setups II and III, may comprise low frequency components in case of a slow offset drift and a broad band component including high frequencies in case of offset steps. In particular low frequency offset drifts may be detected with method A, wherein method B may, due to the absence of low pass filtering, detect both low and high frequency components of the offset drift.

Offset drift may be due to a movement of one or more of the transducers. Such a transducer movement may occur, for example, in case of a thermal expansion of a machine part to which the transducer is attached. Such a thermally induced movement of the transducer position may cause different drifts in all four transducer locations. In this sense, it is important to make the transducer fixation as stationary as possible.

In general, offset drift may also be related to a transducer amplification drift. In this paper we have neglected this effect for the sake of simplicity of the analysis by limiting the transducer amplification drift to AC components. The simulation results of setup IV show that AC amplification drift is detectable only with method B. In addition, from Figure 5b one may conclude that a detection of an oscillation or a changing oscillation in the signal Δd_x alone (i.e. without comparison to Δd_y) may indicate an amplification drift in the x axis.

With the proposed methods A and B, it is not possible to determine which of the transducers is defective. In order to obtain this kind of information, further tests would be required. However, it is at least possible to detect inconsistencies within the sensorial information. Since, in general, more than one transducer could be defective, it is not possible to estimate the extent of the defectiveness without an uncertainty. This uncertainty, however, would, due to closed loop control, also occur in a similar way if a completely independent monitoring system for monitoring the transducer integrity were in use.

It should also be noted that information about a temperature of the rotor may be obtained with method B. In particular, it is possible to estimate the thermal expansion of the rotor (relative to the stator, wherein a thermal expansion of the stator may be estimated independently) in the plane where the transducers are located. Since machine temperatures (including the rotor temperature) are usually monitored in order to detect abnormal situations, method B gives additional information that can be used in general machine operation monitoring.

5 Conclusion

The methods proposed in this paper provide simple and efficient means to protect machinery against non-obvious malfunctions of magnetic bearing position transducers such as offset drift, amplification drift and sporadic dropouts. It is possible to recognize a potential problem of the transducers and to bring, if necessary, the machinery into a safe state. Further investigations about a root cause of the detected problem may be started subsequently. For the implementation of the method there is no need for extra hardware. By solely a small software routine it is hence possible to increase the robustness, reliability and safety level of the machinery.

6 References

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