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Redundant unbalance compensation of an active magnetic bearing system

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ABSTRACT

To achieve a good running behavior of a magnetic levitated rotor, a well-developed position controller and different compensation methods are required. Two very important structures in this context are the reduction of the gyroscopic effect and the unbalance vibration. Both structures have in common that they need the angular velocity information for calculation. For industrial applications this information is normally provided by an angle sensor which is fixed on the rotor. The angle information is also necessary for the field oriented control of the electrical drive. The main drawback of external position sensors are the case of a breakdown or an error of the motor controller. Therefore, the magnetic bearing can get unstable, because no angular velocity information is provided. To overcome this problem the presented paper describes the development of a selfsensing unbalance rejection in combination with a selfsensing speed control of the motor controller. Selfsensing means in this context that no angle sensor is required for the unbalance or torque control. With such structures two redundant speed and angle information sources are available and can be used for the magnetic bearing and the motor controller without the usage of an angle sensor.

1. Introduction

In recent years, active magnetic bearings (AMB) have got increasing importance in rotating machinery, because of several attractive advantages, such as no friction losses, wearless, the ability of long-term high speed running, and the possibility to affect the mechanical properties [1,2]. They do not need lubricant and are maintenance free. A so-called active magnetic bearing generates the electro-magnetic force totally by electro magnets compared to hybrid or passive magnetic bearings. Magnetic bearings are unstable systems and they require a control structure for a stable levitation of the rotor. For closed loop operation a radial and axial position informations of AMBs are required. The position information is typically provided by external position sensors, but in the last years also sensorless position strategies were developed, like the INFORM method, which is described in [3,4]. For higher speeds, vibrations caused by mass unbalance are a common problem in magnetic bearing applications. Unbalance occurs if the principal axis of inertia of the rotor is not coincident with its axis of geometry. For real systems it is almost impossible to manufacture an ideal balanced rotor. With conventional mechanical bearings, reaction forces occur due to the unbalance [5]. These reaction forces excites unwanted vibrations at the machine housing. However, with active magnetic bearings it is possible to provide an unbalance compensation to minimize the resulting vibra-

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tion or to reduce the rotor orbit. Such an unbalance compensation allows the rotor to spin around its inertial axis. This additional component of the control structure can have the following tasks:

- Rejection of synchronous bearing forces: The synchronous bearing current is approximately a quadratic function of the rotational speed. So an upper limit of the angular velocity of an AMB is the actuator saturation caused by the unbalance force. Therefore, the aim of this compensation technique is to reject the synchronous bearing current. This can be done by making the controller "blind" for the unbalance frequency. With this unbalance control the upper limit caused by the angular velocity can be significantly increased.
- Rejection of the unbalance vibration: The aim is to reject the vibration due to the reaction forces of the unbalance and the housing. To get a suitable rejection the system requires high damping forces which can also lead to a saturation of the amplifiers. Thus, this balancing technique is a converse approach to the first one, because of the high damping instead of no gain for the unbalance frequency.

The focus of this paper is the rejection of the synchronous bearing forces and the reduction of the gyroscopic effect using redundant angular velocity information. For both structures the knowledge of the angular velocity is required. This information can be provided from the motor controller or from an unbalance observer like it was described in [6]. For the motor controller it is possible to get the speed information from an external sensor or from a sensorless method. The acceleration of the rotor is provided by a permanent magnet synchronous machine (PSM). A problem in critical applications with respect to costs, space and reliability is the rotor position sensor, which reduces the robustness of the drive considerably. In this paper, the INFORM method for sensorless torque- and speed-control down to standstill is used to realize cost effective sensorless drives for reliable transient operation [7]. With these methods two different redundant structures to estimate the speed information can be implemented in the motor controller and the magnetic bearing controller. If the magnetic bearing controller and the motor controller are connected (Fig. 1), both structures are able to use different angle or angular velocity sources for control. This leads to a high robustness of the system because it is possible to provide a stable levitation of the rotor even in the case of a damaged motor controller. With this structure, different critical conditions for the usage of the angular velocities can be defined.

For the tracking of the unbalance frequency, [8] uses an adaptive observer method. A simpler and more straightforward way was shown by [9], where a phase locked loop (PLL) was used in combination with an atan-calculation. However, the lack of this method is the atan-calculation, which shows problems regarding to measuring noise.

The contributions of the presented paper can be summarized as follows:

- A selfsensing unbalance control (no external angle sensor is required) is developed for a five degree of freedom active magnetic bearing. Thus, the magnetic bearing controller can run independent from the motor controller.
- A redundancy of the speed information is given by an unbalance observer of the magnetic bearing in combination with a sensorless motor control strategy. Therefore, no angle or speed sensor is necessary in the whole operating range.

2. Unbalance control using a two modulation step approach

A simple unbalance control technique is the insertion of a Notch filter in the feedback path. However, this method has stability problems using open loop designed filters [10]. This lack of Notch filters is eliminated by an observer-based design [11]. The observer based method requires much computing power and a very accurate plant model, which is often not preferable in industrial applications. A converse approach is an adaptive feedforward method [12,13]. This technique cannot introduce instability, if the adaption process itself is stable. However, such methods often uses complex nonlinear adaption

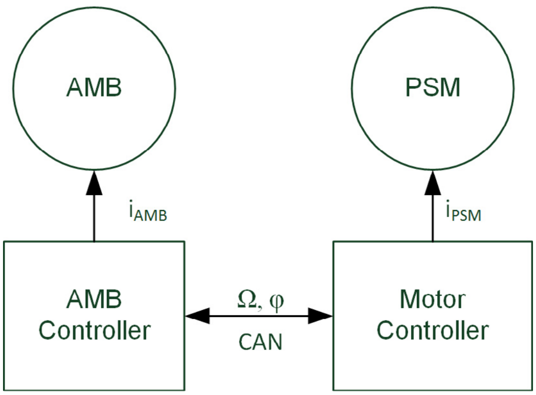

Fig. 1. Communication of the controllers.

processes and convergence could not be proven in all cases. In this paper a multi variable Notch filter is used which is designed for the closed loop system like it was demonstrated in [14].

In this paper only rotors are considered, which fulfill:

$$I_r > I_p \tag{1}$$

where I_p is the polar moment of inertia and I_r is the equatorial moment of inertia. Using this assumption stability can achieved in the whole operating range. Otherwise the rotor has an unstable resonance for operation with unbalance control [15]. For unbalance control the angle of unbalance or the synchronous rotation frequency is needed. This information is provided using an unbalance observer. Because the unbalance frequency runs synchronously with the angular velocity, the estimated variables can also be used for speed- or torque control of an electrical drive.

The structure of the two modulation step approach is shown in Fig. 2. The closed loop system with $\mathbf{C}(s)$ and $\mathbf{G}(s)$ is assumed to be stable. The unbalance of the rotor causes a sinusoidal signal with the frequency Ω in the sensor signal $\mathbf{y}(t)$, which corresponds to the unbalance of the signal. The idea of this compensation is the subtraction of a compensation signal $\mathbf{c}(t)$ from the sensor signal $\mathbf{y}(t)$. This compensation signal corresponds with the unbalance part of the sensor signal and has the same phase, frequency and amplitude. To generate the compensation signal the sensor signal is multiplied by $\sin\Omega t$ and $\cos\Omega t$ to shift the frequency Ω down to zero. Afterwards the signal is integrated and shifted back to the frequency Ω by multiplying with $\sin\Omega t$ and $\cos\Omega t$. Because of the integration action constant signal part of the modulated signal is canceled. This constant value corresponds with the amplitude of the unbalance signal. The value ε affect the convergence speed of the compensation. The multiplications with the trigonometric functions can also be substituted by a transformation in a rotating frame. However, this transformation cannot handle oval rotor orbits, due to a possible anisotropy of the magnetic bearings. The compensation signal $\mathbf{c}(t)$ is:

$$\mathbf{c}(t) = [\sin(\Omega t)\mathbf{I} \quad \cos(\Omega t)\mathbf{I}] \begin{bmatrix} \mathbf{T}_R & -\mathbf{T}_J \\ \mathbf{T}_J & \mathbf{T}_R \end{bmatrix} \cdot \int \begin{bmatrix} \sin(\Omega t)\mathbf{w}(t) \\ \cos(\Omega t)\mathbf{w}(t) \end{bmatrix} dt \tag{2}$$

The bold symbols denote multi-variable matrices and $\mathbf{I}$ is an identity matrix. Transformation of Eq. (2) into the s-domain leads to the open loop input output equivalent:

$$\mathbf{N}_{ol} = \frac{1}{s^2 + \Omega^2}(s\mathbf{T}_R - \Omega\mathbf{T}_J) \tag{3}$$

Closing the feedback loop leads to:

$$\mathbf{N}_{cl} = \frac{\mathbf{e}}{\mathbf{y}} = \left(s^2 + \Omega^2\right)\left(s^2\mathbf{I} + s\mathbf{A}_1 + \mathbf{A}_0\right)^{-1} \tag{4}$$

with

$$\mathbf{A}_1 = \varepsilon\mathbf{T}_R, \quad \mathbf{A}_0 = \Omega^2\mathbf{I} - \varepsilon\Omega\mathbf{T}_J \tag{5}$$

Eq. (4) shows the Notch characteristic if $s = j\Omega$. ε defines in this context the bandwidth of the compensation. It can be concluded that the two modulation Notch filter and the LTI Notch filter have the same input output description. Nevertheless, the two modulation step approach has some advantages compared to the common LTI implementation.

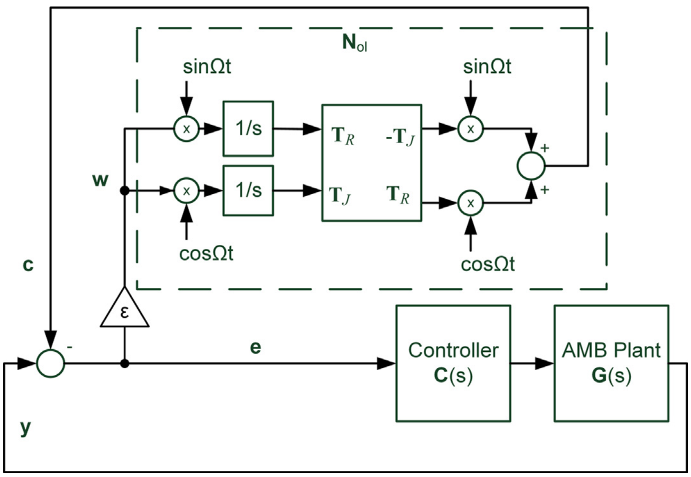

Fig. 2. Two modulation step Notch filter.

- The two modulation Notch filter can be used as an ideal feed forward compensation if ε is kept to zero. This operation is impossible with the LTI implementation.
- With the integrator outputs the amplitude of the unbalance of the rotor can be calculated.
- In the narrow band case the two modulation Notch filter shows no numerical errors compared to the classical LTI implementation.

In [14] a detailed stability analysis of the two modulation step Notch filter is made. A decentralized approach of the two modulation step Notch filter can be used if the cross couplings are not too high. In this context "decentralized" means that the transfer function matrix of the Notch filter has only diagonal terms. However, this decentralized step approach can also be used for systems with cross coupling, if this cross coupling is considered in the controller.

3. Reduction of the gyroscopic effect

The gyroscopic effect influences the performance of an AMB system in two ways.

- A high gyroscopic effect causes high cross couplings. Thus, the fast decentralized Notch filter cannot be used and has to be replaced by a more complex method.
- The gyroscopic effect splits up the rigid body modes. For such a parameter-variant system either the performance decreases or a complex controller is required.

Possible control structures to reduce the gyroscopic effect are described in [16,17]. A magnetically levitated rotor can be describes in the following linearized form [1]:

$$\begin{aligned} \mathbf{M}\ddot{\mathbf{x}} + \mathbf{G}(\Omega)\dot{\mathbf{x}} + \mathbf{B}\mathbf{K}_S\mathbf{B}^T\mathbf{x} &= \mathbf{B}\mathbf{K}_i\mathbf{i} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} \end{aligned} \tag{6}$$

with the mass matrix $\mathbf{M}$, the gyroscopic matrix $\mathbf{G}(\Omega)$, the matrix of the negative stiffness $\mathbf{K}_S$, the matrix of the force to current factors $\mathbf{K}_i$, the input matrix $\mathbf{B}$, the output matrix $\mathbf{C}$, the center of gravity (COG) coordinates $\mathbf{x}$, the sensor coordinates $\mathbf{y}$ and the current vector $\mathbf{i}$. It is straightforward to show that the control structure

$$\mathbf{i}_{komp} = ((\mathbf{B}\mathbf{K}_i)^{-1}\mathbf{G}(\Omega)\dot{\mathbf{x}} + \mathbf{v}) \tag{7}$$

cancels the parameter-variant term $\mathbf{G}(\Omega)$ for the virtual input $\mathbf{v}$ (more details are given in [16]). Therefore, the straightforward LTI control theory can be used for the new input $\mathbf{v}$. As can be seen from Eq. (7) the reduction of the gyroscopic effect requires the angular velocity information Ω. If the angular velocity information gets lost, the system will get unstable.

4. Unbalance observer

As stated in the previous sections the unbalance compensation and the reduction of the gyroscopic effect requires the information of the angular velocity. To achieve a stable levitation independent of the motor controller information, an unbalance observer is used. For the system which is presented in this paper the angular velocity Ω, the angle of the synchronous unbalance φ and the magnitude of the unbalance A is estimated using a special observer. The output equation of the unbalance for a forward rotating system has the following form:

$$\begin{aligned} x &= A\cos(\varphi) \\ y &= A\sin(\varphi) \end{aligned} \tag{8}$$

Using the following observer model the unbalance information can be estimated.

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\Omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \varphi \\ \Omega \end{bmatrix} + \begin{bmatrix} k_{1\varphi} & k_{2\varphi} \\ k_{1\Omega} & k_{2\Omega} \end{bmatrix}\begin{bmatrix} x - \hat{x} \\ y - \hat{y} \end{bmatrix} \tag{9}$$

where φ is the angle of the maximum elongation caused by the unbalance and Ω is the angular velocity. This observer model assumes a constant angular velocity. But such an observer can also be used for systems with a slow acceleration in comparison to the system dynamic of the observer, because of the correction terms $k_{1\varphi}, k_{2\varphi}, k_{1\omega}$ and $k_{2\omega}$. This slow acceleration can be assumed in many applications of active magnetic bearings, because also the linearized model (6) requires this assumption. The advantage of such an observer, which only uses the kinematics compared to an observer which also uses the principle of momentum is the independence of system parameters. Therefore, this observer can be used with the same parameters for different AMB systems. When the measuring Eq. (8) are inserted into the observer model Eq. (9) the failure dynamic is nonlinear.

$$\begin{bmatrix} \dot{e}_\varphi \\ \dot{e}_\Omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_\varphi \\ e_\Omega \end{bmatrix} + \begin{bmatrix} k_{1\varphi} & k_{2\varphi} \\ k_{1\Omega} & k_{2\Omega} \end{bmatrix} \cdot \begin{bmatrix} A\left(\cos(\varphi) - \cos(\hat{\varphi})\right) \\ A\left(\sin(\varphi) - \sin(\hat{\varphi})\right) \end{bmatrix} \tag{10}$$

With the estimated angle $\hat{\varphi}$. For a nonlinear failure dynamic, stability cannot be proven in all cases. Therefore, the feedback variables k_φ and k_Ω are chosen as a function of the states and the input [18]. Using non-linear observer parameters a linear failure dynamic can be achieved. The first step is to insert substitute variables according to Fig. 3

$$\begin{aligned} \varphi_M &= \hat{\varphi} + \delta \\ \delta &= \frac{\varphi - \hat{\varphi}}{2} \end{aligned} \tag{11}$$

in the feedback term.

$$x - \hat{x} = A\left(\cos(\varphi) - \cos(\hat{\varphi})\right) \tag{12}$$

With these variables the failure can be formulated as:

$$\begin{aligned} x - \hat{x} &= A(\cos(\varphi_M + \delta) - \cos(\varphi_M - \delta)) \\ &= -2A\sin(\varphi_M)\sin(\delta) \end{aligned} \tag{13}$$

If δ is assumed to be small, then $\varphi_M \approx \varphi$ and the Taylor expansion can be used for $\sin(\delta)$. Therefore, the failure can be written as:

$$x - \hat{x} = -A\sin(\varphi)(\varphi - \hat{\varphi}) \tag{14}$$

For the y direction the derivation is the same and the result is:

$$y - \hat{y} = A\cos(\varphi)(\varphi - \hat{\varphi}) \tag{15}$$

For $|e_\Omega| > 0,\ \varphi$ and $\hat{\varphi}$ rotate with different angular velocities Ω and $\hat{\Omega}$. Therefore, the assumption for a small δ is always fulfilled for a certain time. The observer requires a high enough settling time to converge in the time slot, where the assumption of a small δ is given. The aim of the presented design procedure is to get a resulting linear failure dynamic. A simple approach is to divide by sine or cosine. However, this method shows numerical problems at the zero crossing of the sine and cosine functions. Thus, another method of calculating the observer parameters:

$$\begin{aligned} k_{1\varphi} &= -\frac{\tilde{k}_\varphi}{A}\sin(\varphi) \quad k_{2\varphi} = \frac{\tilde{k}_\varphi}{A}\cos(\varphi) \\ k_{1\Omega} &= -\frac{\tilde{k}_\Omega}{A}\sin(\varphi) \quad k_{2\Omega} = \frac{\tilde{k}_\Omega}{A}\cos(\varphi) \end{aligned} \tag{16}$$

With these feedback variables the following failure dynamic is achieved after some algebraic steps is

$$\begin{bmatrix} \dot{e}_\varphi \\ \dot{e}_\Omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_\varphi \\ e_\Omega \end{bmatrix} + \begin{bmatrix} \tilde{k}_\varphi & \tilde{k}_\varphi \\ \tilde{k}_\Omega & \tilde{k}_\Omega \end{bmatrix} \cdot \begin{bmatrix} e_\varphi \\ e_\varphi \end{bmatrix}. \tag{17}$$

This resulting failure dynamic is linear and time invariant. Thus, stability can be proven by the calculation of the eigenvalues of the resulting dynamic matrix. With the presented method it is possible to estimate the angle and angular velocity of the synchronous unbalance from the sensor signal. The correction terms $\tilde{k}_\varphi$ and $\tilde{k}_\Omega$ can be determined using pole place-

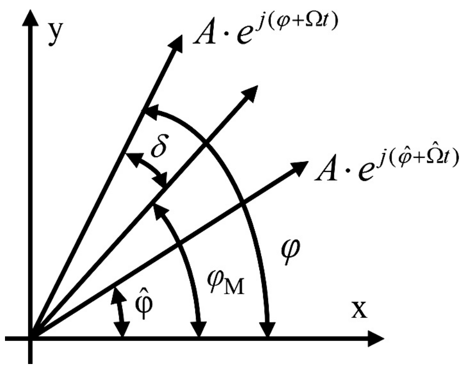

Fig. 3. Substitute variables.

ment methods. Sometimes a parameter tuning depending on the noise level by experiments is required. This unbalance observer in combination with an unbalance controller does not need information from external devices (like the motor controller) to get the angular velocity. Finally, this combination is a selfsensing unbalance rejection method.

5. Selfsensing angle estimation of the electrical motor

On the motor side there are also selfsensing methods developed in the literature. The selfsensing method which is used in this paper is based on [19]. In the high speed range the back EMF method is used, which calculates the actual angle of the rotor from the inducted voltage in the stator winding of the rotating permanent magnet. At standstill and in the low speed range the back EMF method does not work, because the inducted voltage depends on the angular velocity. Therefore the system is unobservable for standstill. To solve that problem, the INFORM method is used for low speeds. Because the INFORM method uses reluctance or saturation effects, the gradient of the coil currents is used to detect the rotor position, the system is observable using the INFORM method.

5.1. The back EMF method

The classical voltage model utilizes the stator voltage equation and the flux linkage equation:

$$\begin{aligned} \underline{u}_s(\tau) &= \underline{i}_s(\tau) r_s + \frac{d\underline{\psi}_s}{d\tau} \\ \underline{\psi}_s &= l_s \underline{i}_s + \underline{\psi}_m \end{aligned} \tag{18}$$

where $\underline{u}_s$ describes the stator voltage space phasor, $\underline{i}_s$ the stator current space phasor, r_s the stator resistance, l_s the stator inductance, $\underline{\psi}_s$ the stator flux linkage space phasor and $\underline{\psi}_m$ the permanent flux linkage space phasor.

The change of the permanent flux linkage space phasor can be calculated with

$$\frac{d\underline{\psi}_m}{d\tau} = \underline{u}_s(\tau) - \underline{i}_s(\tau) r_s - l_s \frac{d\underline{i}_s}{d\tau} \tag{19}$$

according to Eq. (18). In the special case of a PSM the rotor magnetic flux linkage $\underline{\psi}_m$ is constant and its angular position coincides with the rotor angular position γ_m.

$$\underline{\psi}_m(\tau) = |\underline{\psi}_m| e^{j\gamma_m(\tau)} \tag{20}$$

Differentiating Eq. (20) yields

$$\frac{d\underline{\psi}_m}{d\tau} = j\omega_m \underline{\psi}_m(\tau) \tag{21}$$

Combining Eq. (19) with Eq. (21) and building the argument yield

$$\gamma_m(\tau) = \mp\frac{\pi}{2} + \arg\left[\underline{u}_s(\tau) - \underline{i}_s(\tau) r_s - l_s \frac{d\underline{i}_s}{d\tau}\right] \tag{22}$$

With this mathematical expression it is already possible to calculate the rotor position. Compared to many other types of electrical machines the angle can be calculated without an integration process for PSMs. If for the calculation of the actual angle Eq. (22) is used, the armature voltage has to be measured. This measurement can be saved by short-circuiting the machine terminals according to [20]. In this case all inverter branches have either positive or negative DC link potential. In this case the armature voltage is zero and the angle γ_m can be calculated by:

$$\gamma_m(\tau) = \mp\frac{\pi}{2} + \arg\left[-\underline{i}_s(\tau) r_s - l_s \frac{d\underline{i}_s}{d\tau}\right] \tag{23}$$

If it is possible neglect the stator resistance r_s, Eq. (23) gets independent of the machine parameters:

$$\gamma_m(\tau) = \pm\frac{\pi}{2} + \arg\left[\frac{d\underline{i}_s}{d\tau}\right] \tag{24}$$

With this method a very robust rotor position detection is possible in the high speed range. It is clear that the back-EMF method can only be used for high speeds. For the low speed range or even standstill another method has to be developed.

5.2. The INFORM method

The INFORM method was introduced in [19] and optimized in (e.g. [21]). This method uses the angular dependence of magnetic conductivity to detect the rotor position. This measuring procedure uses test algorithms by utilizing voltage steps and measuring the current response. These voltage steps are applied to the system by a special measuring sequence inter-

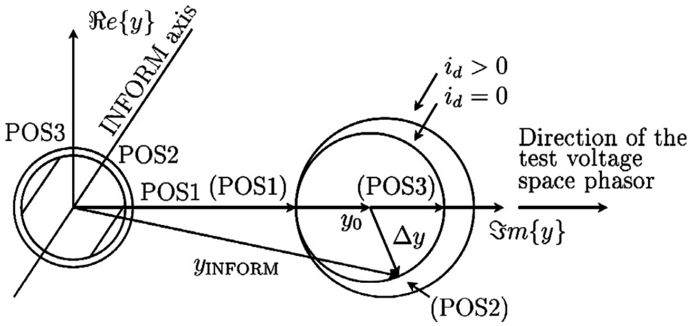

Fig. 4. Complex function $\underline{y}_{\mathrm{INFORM}}$ at two different saturation levels.

rupting the PWM control, or the excitation is provided by an intelligent current control loop. We define an INFORM parameter (complex reactance)

$$\underline{y}_{\mathrm{INFORM}} = \frac{d\underline{i}_s/d\tau}{\underline{u}_s} \tag{25}$$

Due to saturation effects $\underline{y}_{\mathrm{INFORM}}$ is a 180°-periodic function. This function can be modeled with a good approximation as:

$$\underline{y}_{\mathrm{INFORM}} = \underline{y}_0 - \Delta\underline{y} \cdot \exp\left(j(2\gamma_{\mathrm{INFORM}} - 2\gamma_u)\right) \tag{26}$$

This complex function describes a circle with the parameter $\arg(\underline{u}_s) = \gamma_u$, the rotor angle γ_m, the offset y_0 and the radius Δy (more details are given in [19,22]). Fig. 4 shows this context. For the measurement of $\underline{y}_{\mathrm{INFORM}}$, test voltage space phasors $\underline{u}_s$ are applied to the system during operation. $\underline{y}_{\mathrm{INFORM}}$ can be identified by measuring the current changes $di_s/d\tau$. Turning the rotor from POS1 to POS3 according to Fig. 4 will change the argument of $\underline{y}_{\mathrm{INFORM}}$ from π to 0. If different measurements $\underline{y}_{\mathrm{INFORM}}$ in different directions of $\underline{u}_s$ are combined the resulting circle $\underline{c}_{\mathrm{INFORM}}$ gets offset-free.

$$\underline{c}_{\mathrm{INFORM}} = \Delta y \cdot \exp\left[j(2\gamma_m)\right] \tag{27}$$

With the evaluation of $\underline{c}_{\mathrm{INFORM}}$, it is possible to estimate the angle of the PSM even for standstill. With the combination of the back EMF method and the INFORM method a sensorless control of the PSM in the whole operating range is possible. The INFORM method is used up to approximately 10% of the rated speed. For higher speed above the angle of the INFORM method and the back EMF are merged using weighing factors. The weighing factor of the INFORM method decreases for higher speeds. Therefore a soft switching action between both methods are realized.

6. Simulation results

In order to explain the physical effects and show the behavior of the system for different parameters, simulations are necessary. For the modeling of the system the rigid body model according to [1] is used:

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{x}} + \mathbf{G}(\omega)\dot{\mathbf{x}} + \mathbf{B}\mathbf{K}_S\mathbf{B}^T\mathbf{x} = \mathbf{B}\mathbf{K}_i\mathbf{i} + \mathbf{Us} \\ &\mathbf{y} = \mathbf{C}\mathbf{x} \end{aligned} \tag{28}$$

with the mass matrix $\mathbf{M}$, the matrix of the gyroscopic effect $\mathbf{G}(\omega)$, the input matrix $\mathbf{B}$, the output matrix $\mathbf{C}$, the negative stiffness matrix $\mathbf{K}_x$, the matrix of the current-force factor $\mathbf{K}_i$, the current vector $\mathbf{i}$, the rotor unbalance $\mathbf{Us}$ and the coordinate vector $\mathbf{x}$.

The parameters of the unbalance observer are:

$$\begin{aligned} \tilde{k}_\varphi &= 0.0002 \\ \tilde{k}_\omega &= 0.4 \end{aligned}$$

For the simulation the observer the controller and the AMB system was implemented on Matlab/Simulink. The rigid body model is designed as continuous time model. The controller and the observer are implemented as a discrete time model with a sampling frequency of 10 kHz. To simulate a measuring noise a white noise with an amplitude of 10 μm and a sampling frequency of 10 kHz is applied on the sensor signals. Fig. 5 shows the performance of the unbalance observer for a constant angular velocity. The result of the observer shows an almost ideal sine shape even for a quite noisy output signal. This proves that the observer works very well for constant angular velocities.

The next simulation shows the performance and the impact of different starting points of the unbalance observer for an accelerating system. In Fig. 6 the performance of the observer can be seen for different starting points. Because the linearization is done under a few assumptions, the system needs a long time to estimate the right value of the angular velocity

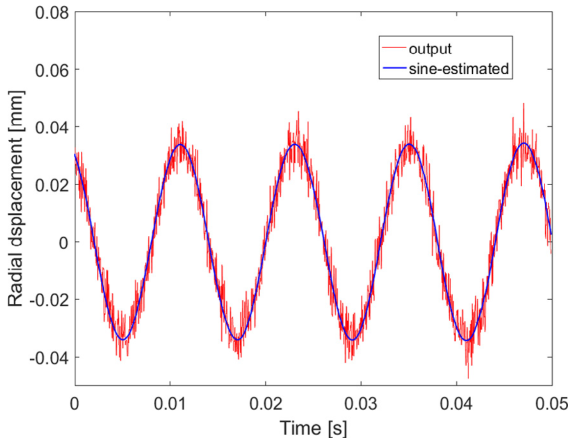

Fig. 5. Simulated estimation of the unbalance for a constant angular velocity of 5000 rpm.

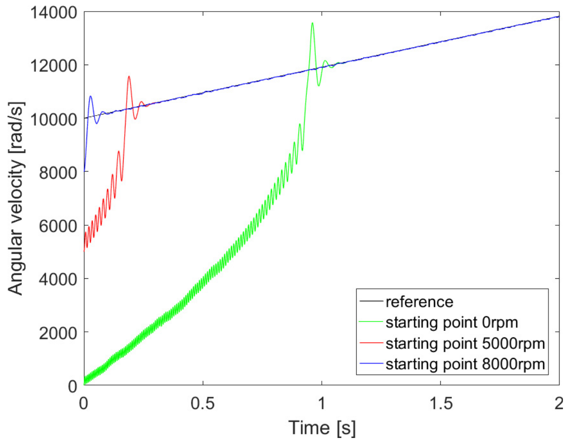

Fig. 6. Simulated estimation of the unbalance for a different starting points.

(green[1] line). Such a long time is not acceptable in the case of a failure of the motor controller, because the system will get unstable before the right value is reached. If the starting value is near the real value the observer is much faster (blue line). For industrial applications it is necessary to synchronize the starting value with the estimated value of the motor controller. Thus, this method provides a sufficient settling time of the estimated angular velocity in the case of an error in the motor controller. Another method to be fast enough in the case of a failure is to run the observer and the INFORM/EMF method always simultaneously.

7. Experimental results

To proof the functionality of the designed estimation and control algorithm, the system was tested on an industrial application with high polar moment of inertia. The control system was implemented on a digital signal processor (TMS320DM335) of a state of the art hardware for magnetic bearings. The geometry of the levitated rotor can be seen in Fig. 7. The aluminum part illustrates a more complex structure (blade wheel), which is not implemented in the simulation. The parameters of the system are shown in Table 1. For the position measurement inductive sensors, which are excited with a 40 kHz signal, were used. The actuators are active magnetic bearings using the "differential driving mode" for operation. The measurements were made and stored in the digital signal processor. Afterwards the variables were sent to the personal computer using a communication software.

7.1. Behavior of the unbalance control structure

To test the functionality and the performance of the unbalance controller in combination with the unbalance observer the position signal is measured during the switching on action at 6000 rpm (Fig. 8). The amplitude of the unbalance is near the

[1] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

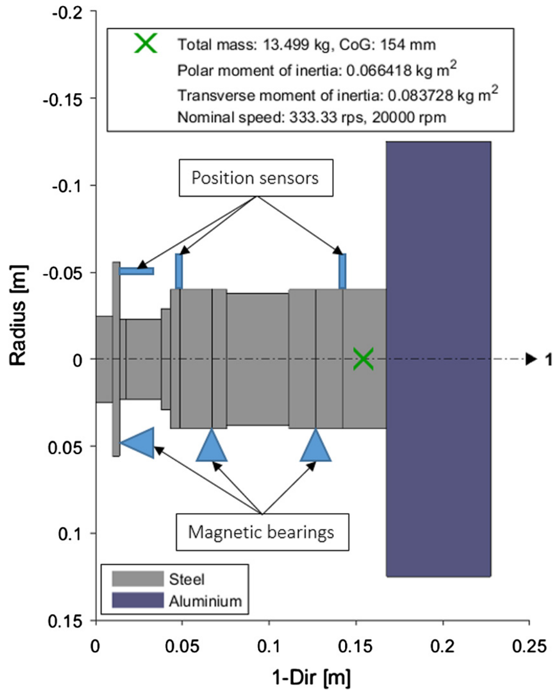

Fig. 7. Geometry of the levitated rotor.

Table 1
System parameters.

Polar moment of inertia	I_p	0.066418 kg mm^2
Equatorial moment of inertia	I_r	0.083728 kg mm^2
Mass of the rotor	m	13.499 kg
Sampling time	T_S	100 µs
Sensor bandwidth	BW_S	3.2 kHz
Actuator bandwidth	BW_A	1.3 kHz
Mechanical air-gap	A_G	165 µm
Negative stiffness of the AMB	k_x	120.000 N/m
Force/current factor of the AMB	k_i	110 N/A

boarders of the mechanical airgap (165 µm) at the beginning of the measurement. Without an unbalance compensation this high amplitude of the unbalance oscillation will limit the operation for higher speed. After switching on the unbalance controller, the amplitude of the unbalance was significantly reduced compared to the system before the switching action. With the demonstrated unbalance rejection method, the upper limit of the speed is not defined by the unbalance oscillation anymore. It has to be considered that only the unbalance part of the current signal is eliminated. This elimination makes the controller blind for the unbalance frequency, but the unbalance at the position signal is only reduced. The state of the art also presents methods to reject the whole unbalance. However, this rejection requires a high current and is not necessary for many industrial applications. Furthermore, the unbalance observer would not work if the unbalance is fully suppressed. Fig. 9 shows the current of one magnetic bearing coil before and after the unbalanced control is switched on. The synchronous signal part is fully suppressed in the current signal. The AC part of the current signal after switching on the unbalance control consists only of noise caused by the feedback path. Without this compensation the actuator will saturate for higher angular velocities.

7.2. Angular estimation using three different methods

The unbalance controller requires a synchronous angle (Ωt) for calculation (DC angle errors do not affect the result). Therefore, the estimated angular velocity is integrated in the DSP or the estimated angle can be used directly for unbalance control. The angle signal is available from three different redundant sources: Back-EMF, INFORM and unbalance observer angle information and can be compared. Fig. 10 shows the measured angle errors using the Back-EMF method, the INFORM method and the unbalance observer.

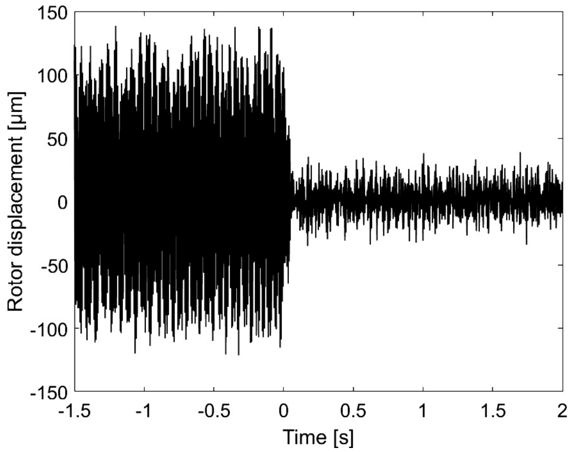

Fig. 8. Measured displacement of the rotor using unbalance control (unbalance control activated at 6000 rpm).

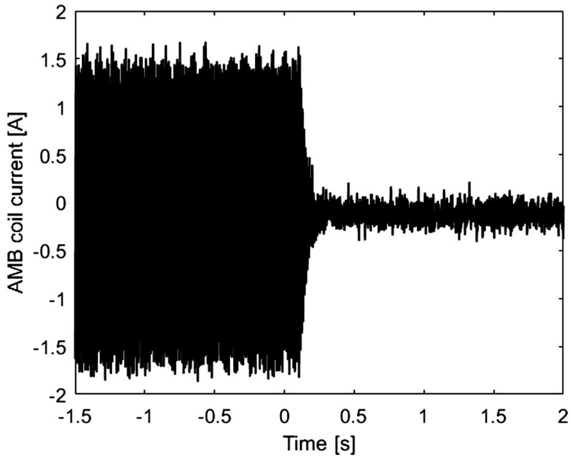

Fig. 9. Measured coil current of one magnetic bearing (unbalance control activated at 6000 rpm).

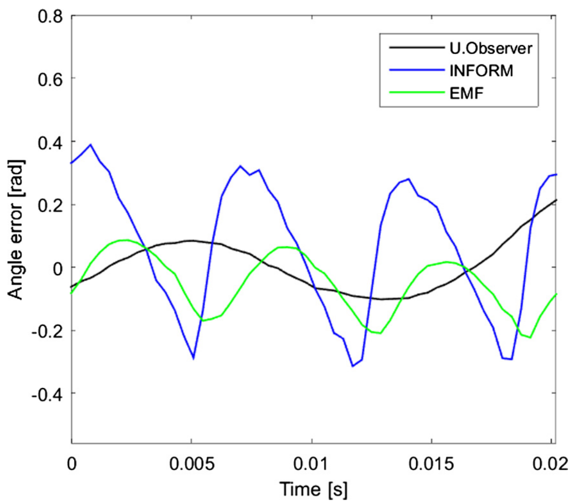

Fig. 10. Error of the angle estimation using three different methods.

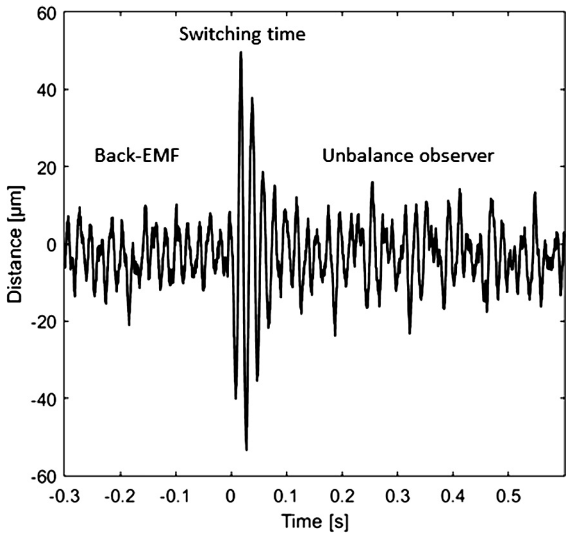

Fig. 11. Switching between two different sources of the angular velocity with a defined dead time.

Because the INFORM method is only used up to 1000 rpm the comparison of the angle errors is done at about 750 rpm. Fig. 10 shows that all the estimated angles have an acceptable quality. The angle which is estimated from the unbalance observer has normally a constant phase shift to the other angles. This phase shift is caused by the fact, that the unbalance vector is not collinear with the flux space vector of the PSM. As a consequence this phase shift needs to be eliminated if the angle of the unbalance vector is used for the vector control of the electrical machine. However, this phase shift shows no problem for the unbalance compensation. It can also be seen that the angle of the Back-EMF method shows the highest quality. Therefore, the angle of the unbalance observer will only be used in the case of a failure of the Back-EMF method for this speed range. As stated in previous sections the Back-EMF method cannot be used for standstill or very low rotational speeds. Also the unbalance observer cannot be used for standstill. For controller design it has to be figured out by measurements at different speeds, which estimation principle should be used for a specified speed range.

7.3. Switching between both estimation methods

To test the magnetic bearing system in the case of a fault or a breakdown of the motor controller, the source of the angular velocity is switched during operation. Therefore, the rotor runs with a defined angular velocity using the angle of the motor controller as source for unbalance compensation. For testing an information loss, the angle is set to zero for about 10 ms. After this "blind" time the estimated angular velocity of the unbalance observer is used. The unbalance observer is running during the whole experiment. The left side of Fig. 11 shows the system using the angle of the motor controller (Back-EMF range). In the range of the high amplitudes the angle information is zero for 10 ms. This time should simulate the detection of an error and switching between the angle-sources. After this switching action the AMB controller uses the angular velocity of the unbalance observer. From this experiment can concluded that it is possible to stabilize the rotor in the case of an error of the motor controller even for a loss of the angular velocity information.

8. Conclusion

Unbalance control is an essential part of the control structure for magnetically levitating rotors to provide a good running behavior even in the high speed range. The main drawback of this method is the potential instability, if the angular velocity information gets lost. Also the reduction of the gyroscopic effect requires this important information to provide a robust control system. To cancel this lack of both compensation methods, selfsensing methods at the AMB and at the motor controller side were developed. At the AMB side the synchronous unbalance oscillation can be used to estimate the unbalance angle and the angular velocity of the rotor. This estimation is done by a non-linear observer. At the motor controller side for low speed or standstill the INFORM method is used, which utilizes the angular dependence of the stator inductance. For higher speeds the back EMF method is used, which is based on the inducted voltage of the running electrical drive. With these two independent information sources it is possible to run both systems without a communication between them. It is further possible to use the communication of both systems if a failure occurs. This fact provides a safe system based on the redundant angular velocity information.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ymssp.2017.02.040.

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