Observer-based Self-Sensing Techniques for Hybrid Active-Passive Self-Bearing Machines

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Abstract

Passive magnetic levitation offers advantages in terms of compactness, reliability and cost thanks to the absence of position sensors, controllers and power electronics dedicated to the rotor suspension. Among these passively levitated systems, those based on a self-bearing machine relying on electrodynamic effects show an operating speed range limited to the high speeds given that the restoring forces are created by induced currents. To address this issue, hybrid active-passive actuation approaches have recently been introduced and consists in actively controlling the axial position of the rotor through the direct-axis component of the currents flowing in the combined winding until reaching the threshold speed beyond which passive levitation can be achieved. However, this active operation requires the addition of an axial position sensor, affecting the benefits related to passive suspension. In this context, this paper proposes self-sensing techniques relying on state observers to estimate the rotor axial position and speed on the basis of the machine electromechanical model. Their performance and robustness are then assessed by means of dynamic simulations.

Keywords: Self-sensing, Sensorless, Observer, Self-bearing, Bearingless

1. Introduction

The demand for high power density magnetically levitated systems has led to the development of self-bearing machines, the latter ensuring both the rotor guidance and drive within a single structure. Generally, the rotor position is actively regulated on the basis of the currents flowing in the armature winding. Although this offers advantages in terms vibration management, sensors and power electronics dedicated to the rotor levitation are required compared to a conventional machine, impacting the cost, compactness and reliability of the system. The current trend is therefore to replace actively controlled degrees of freedom with passive solutions.

In this regard, recent research have investigated passively levitated self-bearing machines relying on a combined armature winding both at the theoretical and experimental levels (Van Verdeghem et al. 2019, Rubio et al. 2023). Nevertheless, the rotor axial levitation arises from induced currents, implying that the restoring force and the underlying stiffness are small at low speeds and even null at rest. Two different approaches have been proposed to allow the rotor suspension in the complete speed range, at the expense of lower drive torque and force capabilities. (Van Verdeghem et al. 2021, Rubio et al. 2021). In both cases, the direct-axis motor current is regulated to control the axial position of the rotor. A position sensor is therefore necessary to operate the machine in this active mode, affecting its reliability, compactness and cost.

Self-sensing techniques can be implemented to prevent the addition of this sensor. Among them, high frequency signal injection is well suited for the start-up and stop phases but observers are preferred at medium and high speeds to prevent interferences between the injected signal and the force and torque currents.

In this context, this paper introduces observer-based self-sensing techniques, derived from the machine electromechanical model, to evaluate the rotor axial position and speed. Dynamic simulations are carried out to validate them and analyse their robustness to parameter errors.

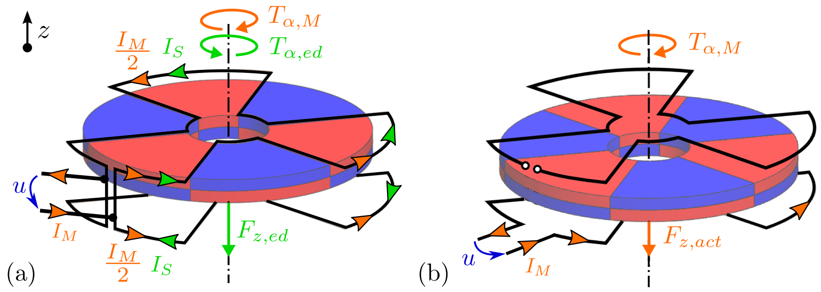

Figure 1: Self-bearing machine (only one phase represented with $p = 3$). (a) Passive operation at high speeds. (b) Active operation at low speeds.

2. Machine Description

This section first describes the structure and the operation principle of the self-bearing machine under study. The electromechanical model predicting its rotor dynamics in active suspension mode is then presented.

2.1 Structure & Principle

As illustrated in Fig. 1, the rotor of the self-bearing machine is composed of axially magnetised permanent magnets creating a magnetic field with p pole pairs. The stator consists of two three-phase windings, placed on both sides of the rotor, whose connection depends on the suspension operation mode.

At high rotor spin speeds, the machine operates in passive mode. As shown in Fig. 1(a), both windings are connected in parallel to the power supply. In case of rotor decentring z, circulating suspension currents I_S are passively induced in the windings due to an unbalance between their permanent magnet flux linkages, creating a restoring force, and add to the conventional motor currents I_M that generate the drive torque.

At low rotor spin speeds, the machine operates in active mode. Only one three-phase winding is supplied whereas the other is left open, as represented in Fig. 1(b). In this way, the rotor axial position can, similarly to the drive torque, be regulated through the motor current I_M thanks to the asymmetric structure. Self-sensing techniques are derived to provide an estimation of the axial position z required to its control while maintaining the advantages of passive suspension.

2.2 Electromechanical Model

The electrical and mechanical equations governing the axial and spin dynamic behaviour of the self-bearing machine when operating in active suspension mode are given by:

$$
\begin{aligned}
u_d &= R i_{M,d} + L_c(\dot{i}_{M,d} - p\omega i_{M,q}) + \dot{z} K_z \sqrt{\frac{3}{2}} \qquad & m\ddot{z} &= K_z \sqrt{\frac{3}{2}} i_{M,d} - k_z z - C_z \dot{z} + F_e \\
u_q &= R i_{M,q} + L_c(\dot{i}_{M,q} + p\omega i_{M,d}) + p\omega(K_\alpha + z K_z)\sqrt{\frac{3}{2}} \qquad & J_p \dot{\omega} &= p(K_\alpha + z K_z)\sqrt{\frac{3}{2}} i_{M,q} + T_e
\end{aligned}
\tag{1}
$$

where u_d and u_q are the direct and quadrature-axis components of the voltage supplied to the armature, R and L_c are the resistance and the synchronous self inductance coefficient of the windings, K_α is the flux constant, i.e. the amplitude of the permanent magnet flux linked by the windings in centred position, K_z is the flux gradient, namely the proportionality factor between the amplitude of the PM flux linkage and the rotor axial position z, m and J_p are the rotor mass and polar moment of inertia, k_z is the axial external stiffness, e.g. generated by centring bearings ensuring the radial magnetic suspension, C_z is the axial external damping, F_e and T_e are the load force and torque applied on the rotor.

The electrical equations highlight the linear dependence of the direct and quadrature axis back-electromotive force terms to the rotor axial speed $\dot{z}$ and position z respectively. The latter can therefore be extracted from the measurements of the currents and the voltage supplied to the armature winding.

3. State Observers

This section describes the state observers developed based on the machine electromechanical model to estimate the rotor axial position z and speed $\dot{z}$ at low and medium spin speeds without any dedicated sensor.

3.1 Axial Position

The proposed position observer structure relies on the electrical equations of a three-phase RL load in the Park reference frame. Hence, compared to the model (1) governing the self-bearing machine electrical behaviour, the direct and quadrature electromotive force terms are not taken in consideration:

$$\begin{aligned} u_d &= R i_{M,d} + L_c(\dot{i_{M,d}} - p\omega i_{M,q}) \\ u_q &= R i_{M,q} + L_c(\dot{i_{M,q}} + p\omega i_{M,d}) \end{aligned} \tag{2}$$

These equations can be rewritten in a linear time-variant state-space form as follows:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} \end{aligned} \tag{3}$$

where the input vector $\mathbf{u}$ includes the direct and quadrature voltages, u_d and u_q, and the state vector $\mathbf{x}$ comprises the corresponding current components, $i_{M,d}$ and $i_{M,q}$. The latter are measured and thus also constitutes the output vector $\mathbf{y}$. The matrices $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are given by:

$$\mathbf{A} = \begin{bmatrix} -\frac{R}{L_c} & p\omega \\ -p\omega & -\frac{R}{L_c} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \frac{1}{L_c} & 0 \\ 0 & \frac{1}{L_c} \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{4}$$

A conventional Luenberger observer can then be established based on this simplified electrical model to provide estimates of the state and output vectors, denoted $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ respectively:

$$\begin{aligned} \dot{\hat{\mathbf{x}}} &= \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} + \mathbf{f}(\mathbf{y} - \hat{\mathbf{y}}) \\ \hat{\mathbf{y}} &= \mathbf{C}\hat{\mathbf{x}} \end{aligned} \tag{5}$$

The observer equations include an additional feedback term that involves a function $\mathbf{f}$ of the error between the measured $\mathbf{y}$ and estimated $\hat{\mathbf{y}}$ output vectors. This function usually applies a significant gain $\mathbf{G}$, the stability of the corresponding observer being analysed through the analysis of the eigenvalues of the matrix $\mathbf{A} - \mathbf{G}\mathbf{C}$. Other forms can also be used, adding e.g. an integral term or including a sign function (sliding mode). In all cases, this feedback term aims to compensate for errors on parameters of the observed system, on the one hand, but also for unmodelled phenomena and disturbances, on the other hand. Regarding the machine under study and assuming that the winding impedance is properly determined, this term therefore provides estimates for both electromotive forces, denoted $\hat{e}_d$ and $\hat{e}_q$. The rotor axial position z and speed $\dot{z}$ can then be evaluated on the basis of these estimates by direct identification with respect to the complete model (1):

$$\hat{z} = \frac{1}{K_z}\left(\frac{\hat{e}_q}{\sqrt{\frac{3}{2}}p\omega} - K_\alpha\right), \qquad \hat{\dot{z}} = \frac{\hat{e}_d}{\sqrt{\frac{3}{2}}K_z}. \tag{6}$$

This method requires an accurate identification of the machine parameters, notably the flux constant K_α and gradient K_z, to produce precise estimations. In addition, the direct-axis electromotive force e_d, that results from the rotor axial speed $\dot{z}$, is expected to be small due to the low frequency of the axial mechanical oscillations, leading to an unfavourable signal-to-noise ratio. A specific axial speed observer is then developed in Section 3.2

3.2 Axial Speed

The speed observer leans on the following simplified mechanical model predicting the rotor dynamics:

$$m\ddot{z} = K_z\sqrt{\frac{3}{2}}i_{M,d} - k_z z - C_z\dot{z} \tag{7}$$

This equation does not integrate the axial load force F_e, the latter being considered as an unmodelled disturbance. The system under study can be expressed in the state-space form (3) where the state vector $\mathbf{x}$ consists of the rotor axial position z and speed $\dot{z}$ while the input vector $\mathbf{u}$ solely encompasses the measured d-axis motor current $i_{M,d}$. Assuming that the observer (6) properly evaluates the axial position z, its estimate $\hat{z}$ can be seen as an indirect measurement and thus constitutes the output vector $\mathbf{y}$. The matrices $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are given by:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 \\ -\frac{k_z}{m} & -\frac{C_z}{m} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ \frac{K_z}{m}\sqrt{\frac{3}{2}} \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 0 & 1 \end{bmatrix}. \tag{8}$$

Pursuing an approach identical to that adopted for the position, an observer can be constructed based on this state-space model. In this case, the rotor axial speed $\dot{z}$ is an internal state of the observer and is consequently directly accessible whereas the feedback term provides an estimate for the unmodelled disturbance force F_e.

4. Case Study

This section aims to validate the operation principle of the proposed observers and to assess their robustness to parameter errors. To that end, dynamic simulations are performed on MATLAB SIMULINK in the Park reference frame on the basis of the electromechanical model (1). A two-level scheme is implemented to control the machine. On the high level, the rotor axial position z and spin speed ω are regulated based on a PID and a PI controller respectively. On the low level, PI controllers allow to regulate the direct and quadrature axis components of the motor current i_M. The case study is conducted on the basis of the reaction wheel demonstrator described and characterised in (Van Verdeghem & Dehez 2021).

4.1 Principle Validation

Assuming an accurate knowledge of the machine parameters, the validation of the observers is carried out based on a specific sequence aiming to verify their tracking capabilities. More precisely, the rotor spin speed ω is first fixed to 1200 (rpm) and then increases up to 1350 (rpm), as shown in Fig. 2(d), while a sinusoidal axial position setpoint characterised by an amplitude of 0.1 (mm) and a frequency of 20 (Hz), equivalent to a synchronous disturbance, is imposed. The rotor is subjected to a step of axial disturbance force F_e at 0.125 (s) as well as to a constant load torque of 50 (mNm).

Analysing first the position observer, Figs. 2(a) and 2(b) illustrate the evolution with time of the direct and quadrature-axis electromotive forces, e_d and e_q, and currents, $i_{M,d}$ and $i_{M,q}$, the dotted and solid lines corresponding to the actual and estimated values respectively. The agreement between them highlights the proper compensation of the machine electromotive forces provided by the feedback term of the observer and confirms its operation principle. It can also be noted that, as expected, the direct component e_d of the electromotive forces is extremely low and would therefore be difficult to exploit in a physical system due to noise. Fig. 2(c) depicts the time evolution of the rotor axial displacement z and its estimate $\hat{z}$, calculated through (6), underlining their accordance and therefore validating the position observer.

Focusing then on the speed observer, Fig. 3(a) represents the time evolution of the axial disturbance force F_e and its estimate $\hat{F}_e$. It can be concluded that the observer feedback term correctly evaluates the axial load force throughout the sequence, even though a small overshoot occurs upon the step. Hence, the estimate $\hat{F}_e$ can be exploited for active disturbance rejection control, through a feedforward action in the position regulator

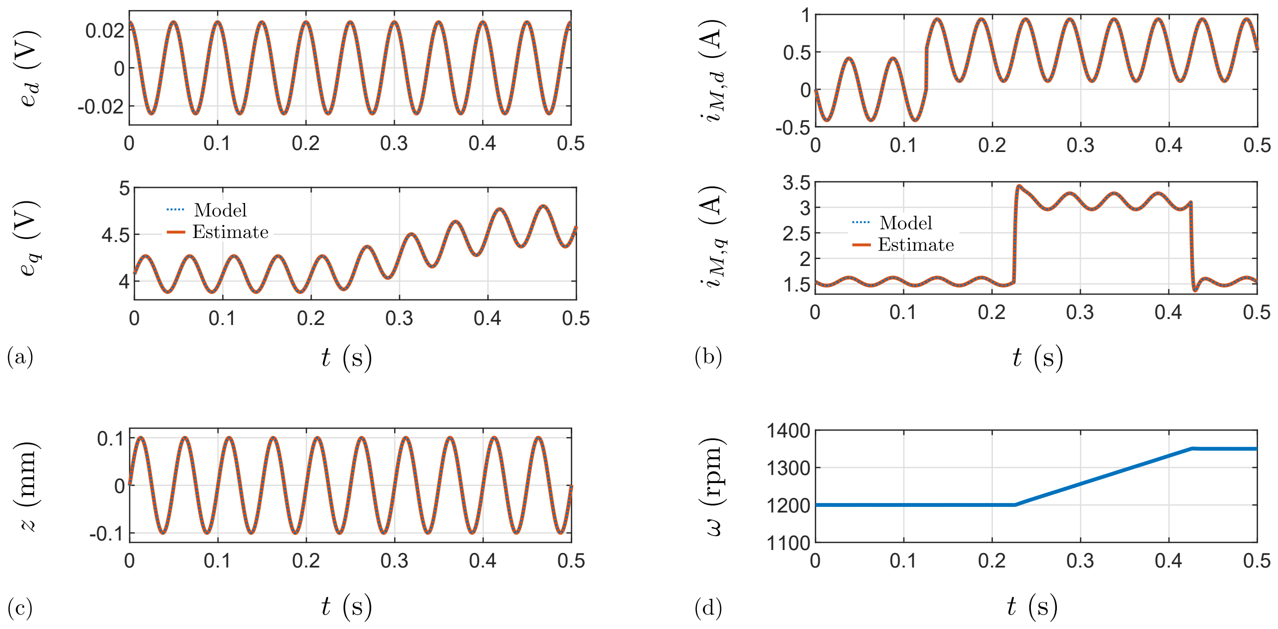

Figure 2: Position observer validation. (a) Direct and quadrature axis electromotives forces, e_d and e_q. (b) Direct and quadrature axis currents, $i_{M,d}$ and $i_{M,q}$. (c) Rotor axial position z. (d) Rotor spin speed ω.

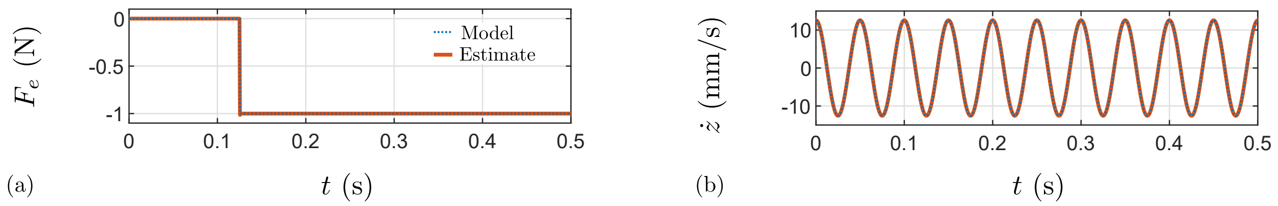

Figure 3: Speed observer validation. (a) Axial load force F_e. (b) Rotor axial speed $\dot{z}$.

(Petersen et al. 2023), but also to adapt to the rotor axial position setpoint in active suspension mode so as to limit oscillations due to the transition to passive operation (Van Verdeghem et al. 2021). Finally, as shown in Fig. 3(b), the rotor axial speed $\dot{z}$ is properly estimated, validating the proposed observer.

4.2 Robustness Analysis

The observer robustness is analysed by studying the impact on the estimates of errors on the self-bearing machine parameters. The spin speed reference is set to 1200 (rpm) and a sinusoidal axial position setpoint is imposed. Constant axial load force F_e and torque T_e, amounting to 1 (N) and 50 (mNm), are exerted on the rotor.

Figs. 4(a) and 4(b) present the time evolution of the estimated axial position $\hat{z}$ and the estimation error $|z - \hat{z}|$ for $\pm 5\%$ variations of the machine parameters. As expected, deviations on the winding impedance directly affect the estimate $\hat{e}_q$ of the quadrature-axis electromotive force and hence conduces to an offset on the position. Specifically, an error on the synchronous inductance coefficient L_c has a low influence on the observer accuracy given that this parameter is small for the ironless structure under study. On the other hand, the resistive term creates a non-negligible estimation discrepancy due to its dependence to the quadrature axis current $i_{M,q}$ and the underlying commanded torque, arising from the load T_e and spin speed reference modifications. The incorrect evaluation of the flux constant K_α also generates a significant offset since the variation with the position of the flux linkages and thus of the resulting electromotive forces, based on which the estimate is established, is of the same order of magnitude as the error. In contrast, as stated in (6), a deviation of the flux gradient K_z

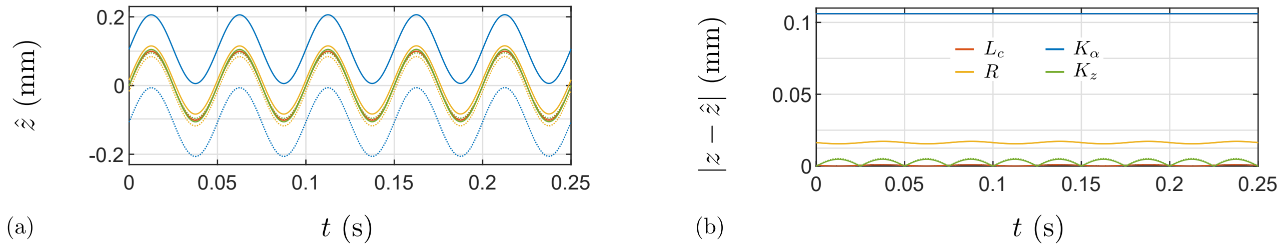

Figure 4: Observer robustness to $\pm 5\%$ parameter variations. (a) Position estimate $\hat{z}$. (b) Estimation error.

solely leads to a scaling error on the estimate $\hat{z}$, thence still allowing to regulate the rotor position in the airgap centre. Regarding the speed observer, inaccuracies in the machine mechanical parameters do not compromise the estimate $\hat{\dot{z}}$ but directly impact that of the disturbance force $\hat{F}_e$. Similarly, the improper estimation of the axial position z due to parameter errors has almost no influence on the speed estimate.

It should be noted that the errors considered in this analysis are substantial when the machine parameters are experimentally identified in the commissioning phase. Moreover, the effect of the temperature on the winding resistance R as well as the flux gradient K_z and constant K_α can be taken into account in the observer.

5. Conclusion

This paper introduces observer-based self-sensing techniques to estimate the rotor axial position and speed of self-bearing machines. The former relies on the motor electrical model and more specifically on the induced electromotive forces whereas the latter takes advantage of the rotor mechanical equation, providing in addition an estimate for the axial load force. Their operation principle and tracking capability are validated through the analysis of a specific sequence including speed, load and position setpoint variations. Furthermore, the study of their robustness reveals in particular that errors on the flux constant and the winding electrical resistance have a significant impact on the position estimate, highlighting the importance of a proper identification of the machine parameters. In contrast, parameter errors have a very small impact on the axial speed estimate.

Future works will include the development of a differential control strategy based on the machine electromotive forces, estimated through the proposed observer for the supplied winding and measured for the winding left open, to regulate the rotor in centred position while suppressing the influence of the flux constant and gradient.

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