Hybrid Active-Passive Operation of a Passively Levitated Self-Bearing Machine

Joachim Van Verdeghem[1,2], Eric L. Severson[2], and Bruno Dehez[1]

[1] Dept. of Mechatronic, Electrical Energy and Dynamic Systems, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[2] Dept. of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison (WI), USA

Abstract

Passively levitated self-bearing machines relying on a combined armature winding have been recently developed so as to allow the systems that implement them to reach higher reliability and compactness while lowering their cost and complexity. The axial guidance being achieved through electrodynamic phenomena based on induced suspension currents, the restoring force is small at low speeds. External loads may therefore prevent the rotor from being magnetically suspended below a threshold speed. In this context, this extended abstract introduces and validates an innovative hybrid active-passive operation of these self-bearing machines. It consists in regulating the rotor axial position, and thence the restoring force, through the direct-axis component of the currents flowing in the combined winding until the threshold speed beyond which passive levitation can be achieved is reached. The proposed active operation solely requires an additional axial position sensor. As a result, the benefits offered by passive suspension are not significantly impacted.

1 Introduction

Self-bearing machines gather the motor function and rotor magnetic levitation within a single structure, improving the power density of the systems that integrate them. The position sensors, controllers and power electronics linked to the actively stabilised degrees of freedom may be restrictive in applications calling for high compactness and reliability as well as low cost. This set the trend towards the adoption of alternative solutions based on passive phenomena.

Recent researches disclosed that electrodynamic thrust bearings can produce both the passive axial restoring force and the drive torque through a single armature winding thanks to an appropriate connection to the power supply [1, 2]. An electromechanical model allowing to predict the rotor axial and spin dynamics of these novel self-bearing machines was derived and experimentally validated [1]. Their combination with passive permanent magnet bearings ensuring the rotor radial and tilt stabilisations conduced to the first fully passively levitated self-bearing machines relying on a combined winding [3]. However, the axial suspension resulting from passively induced currents, the restoring force and the underlying stiffness are small at low speeds and even null at standstill. Hence, the rotor can not be levitated below a threshold speed, determined by the axial load and the destabilising stiffness exerted on the machine, which may represent an issue for applications necessitating frequent start-up and stop phases.

This extended abstract of the paper [4], accepted for publication in the IEEE-IAS Special Issue on Magnetically Levitated Motor Systems, proposes and validates a hybrid active-passive actuation approach enabling these thrust self-bearing machines to levitate in their entire speed range. Specifically, at low spin speeds, the restoring force, and thus the rotor axial position, is actively controlled through the currents flowing in the combined armature winding and supplied by the same N-phase inverter as that employed for the drive. Beyond the levitation threshold speed, the axial suspension is switched from active to passive operation.

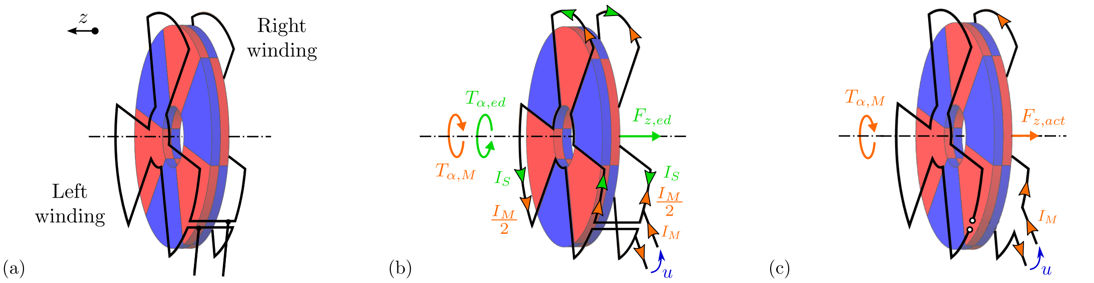

Figure 1: Self-bearing machine under study (only one phase represented and $p = 3$). (a) Structure. (b) Passive axial levitation operation. (b) Active axial levitation operation.

2 Structure & Principle

The machine under study, depicted in Fig. 1(a), ensures both the drive torque and axial restoring force production. The rotor consists of a permanent magnet arrangement creating an axial magnetic field with p pole pairs. The stator encompasses three phases constituted by the parallel connection of a left and a right winding that each includes p coils connected in series.

2.1 Suspension passive operation

In centred position, i.e. $z = 0$, the machine behaves as a conventional double-sided permanent magnet motor, thus only developing a drive torque $T_{\alpha,M}$ through the quadrature-axis current $I_{M,q}$. As soon as the rotor leaves its nominal position, i.e. $z \neq 0$, a passively induced suspension current I_S, circulating in the short-circuited path formed by the series connection of the upper and lower windings, adds to the classic motor current I_M supplied by the voltage source u, as illustrated in Fig. 1(b). The former current generates the axial restoring force $F_{z,ed}$ and a drag torque $T_{\alpha,ed}$ whereas the motor current solely produces the drive torque $T_{\alpha,M}$. At low speeds, the axial force $F_{z,ed}$ may not be sufficient to compensate for an axial load or destabilising stiffness, precluding the rotor from being magnetically suspended below a threshold speed ω^*.

2.2 Suspension active operation

The active operation addresses the levitation issue arising below the threshold speed ω^*. As represented in Fig. 1(c), it relies on the right winding while the left one is disconnected from the voltage source, reducing the machine to a single-sided structure identical to that investigated in [5]. The axial force $F_{z,act}$ and the drive torque $T_{\alpha,M}$ are regulated independently through the direct $I_{M,d}$ and quadrature $I_{M,q}$ axis components of the current supplied by the three-phase inverter. As a result, this operation mode only requires an additional position sensor, thus not substantially affecting the advantages ensuing from the passive levitation.

3 Experimental Setup

Fig. 2 depicts the self-bearing machine prototype, controlled and supplied through an AC driver, within the dedicated test rig. The latter comprises two air bearings that ensure the rotor radial and tilt guidance. A laser displacement sensor provides the measurement of the rotor axial position z. In suspension active operation, electronic switches disconnect the left windings while an axial position control loop, relying on a PID regulator that generates the force reference $F_{z,ref}$ converted into a direct-axis motor current setpoint $I_{M,d,ref}$, is activated. The prototype can be tilted by an angle σ with respect to the frame in order to exert an axial load $F_e = mg \sin\sigma$ on the machine, m being the rotor mass and g the gravitational acceleration.

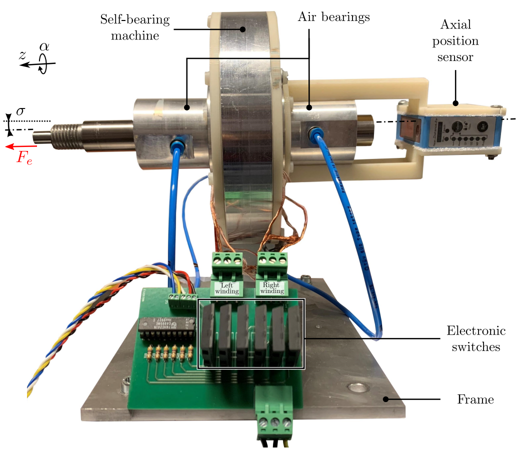

Figure 2: Self-bearing machine prototype and the dedicated test rig.

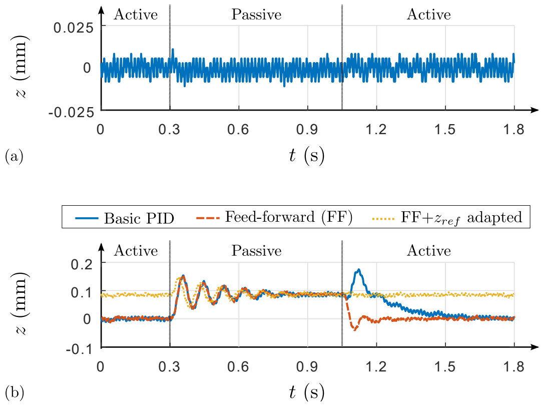

Figure 3: Time evolution of the axial position z during transitions from active to passive operation and vice versa. (a) No axial load ($F_e = 0$). (b) Axial load $F_e = 0.5$ (N).

4 Experimental Results

Fig. 3(a) represents the time evolution of the rotor axial position z during transitions from active to passive operation and vice versa when there is no axial load and the speed setpoint is fixed to 4000 (rpm). Throughout the sequence, the rotor levitates around its centred position ($z = 0$) with a constant amplitude of oscillations, demonstrating that, in these specific conditions, the passages between suspension modes do not affect the rotor axial behavior.

Fig. 3(b) illustrates the transitions when an axial load $F_e = 0.5$ (N) is applied on the rotor ($\sigma = 2.7^\circ$). As shown in solid line, passing from active to passive operation leads to significant transient rotor oscillations. This arises from the step of axial load to which the machine is subjected at the time of the transition due to the sudden disappearance of the active force while the passive one is not yet created. Similarly, the shift from passive to active levitation results in an axial deviation before the controller brings the rotor back to the reference position $z_{ref} = 0$. The transition to active operation can be considerably enhanced by feed-forwarding the axial force exerted on the rotor in the integral term of the position regulator. In this way, as illustrated in dashed line, the axial disturbance affecting the self-bearing machine is limited to the setpoint step towards the centred position ($z = 0$). The axial behavior during the shifts can be further improved by setting the position reference z_{ref} to the axial displacement at which the rotor stabilizes in passive mode. As shown in dotted line, removing the position setpoint step allows to proceed with the shift to active suspension without creating any axial disturbance.

References

[1] J. Van Verdeghem *et al.*, "Experimental investigations on passively levitated electrodynamic thrust self-bearing motors," *IEEE Trans. Ind. App.*, vol. 55, pp. 4743–4753, Sep. 2019.

[2] G. Cavalcante Rubio and A. Chiba, "Design and analysis of a bearingless motor with passive axial suspension through null-flux coils," in *2019 IEEE IEMDC*, pp. 779–786, 2019.

[3] J. Van Verdeghem and B. Dehez, "Fully passively levitated self-bearing machines with combined windings," in *2020 IEEE Energy Conversion Congress and Exposition*, pp. 254–261, 2020.

[4] J. Van Verdeghem, E. L. Severson, and B. Dehez, "Hybrid active-passive actuation approach of passively levitated thrust self-bearing machines," *Accepted in IEEE Trans. Ind. App.*, 2021.

[5] J. Asama *et al.*, "Development of a one-axis actively regulated bearingless motor with a repulsive type passive magnetic bearing," in *2014 IEEE IPEC*, pp. 988–993, May 2014.