Introduction of a Novel Highly Dynamic Thrust Bearing Control Based on a Fractional–Order Flux Estimator

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Abstract

The dynamic forces of nonlaminated magnetic thrust bearings are highly impaired by the magnetic skin effect inside the solid core. As the modification of the core design only offers limited room for improvement at a high financial cost, control–based measures are desired. Currently, advanced control topologies try to overcome the problem with complex controllers and observers but hardly maintain the direct physical reference to essential bearing parameters like stiffness and damping, required for a simple bearing operation. This is one major reason why most of them are not established sustainably and the common decentralized and cascaded position control with subordinated current control remains the industry standard. The inability to cope with the skin effect and the accompanying loss of stability, dynamic and bandwidth is merely tolerated. Here we propose a new model–based control scheme based on a pre–calculated fractional–order flux estimator. It allows us to compensate the skin effect within the inner control loop by means of a simple IIR–filter–cascade in the feedback path and maintains all physical references and the simplicity of the standard topology. We show that it is possible to stably implement the known high–fidelity eddy current models, based on the diffusion equation, as real–time application on a microprocessor. Unlike other voltage–based flux estimators, our approach is based on the measured coil current as a more reliable true feedback signal. We conclude with a proof of concept of our new digital flux control, which significantly improved stiffness and damping and at least quadrupled the bandwidth of the axial position control over the industry standard.

Disclaimer

This digest is a brief summary of the experimental results shown in our publication titled *"Highly Dynamic Thrust Bearing Control Based on a Fractional–Order Flux Estimator"* in the IEEE IAS Special Issue on Magnetically Levitated Motor Systems [1, doi: 10.1109/TIA.2021.3076421].

1 Introduction and Control Concept

Over the last decades, research in magnetic bearing control has led to a multitude of manifold control algorithms. However, in most cases bearing manufacturers still rely on a rarely questioned industry standard: the common decentralized cascaded position control with subordinated current control [2] (X–I–control, Fig. 1b+d), even though it is impaired by an undesirable positive feedback and prone to perturbations like leakage and fringing fluxes, core saturation, hysteresis and especially eddy currents. But unlike most alternative topologies [2], it preserves the physical analogy to the mass–spring–damper–system, which generally describes all forms of bearings and simple tuning parameters like the stiffness k and damping d are available. Regarding radial bearings, there are no apparent issues with this standard approach, as the employed cores with dedicated electrical sheets are less susceptible for the mentioned perturbations. Thrust bearings, on the other hand, are commonly built from solid general–purpose steel compounds, as any lamination of the core is practically ineffective due to a 3D flux propagation.

Therefore, they suffer from high eddy current flows inside the iron core, resulting in a magnetic skin effect. As a consequence, one observes a substantial damping of the thrust force caused by a significant lag between the force–generating magnetic flux Φ_x and the measurable coil current i_{meas}, which hampers the dynamic, stability and bandwidth of the control. Flux–based topologies, which

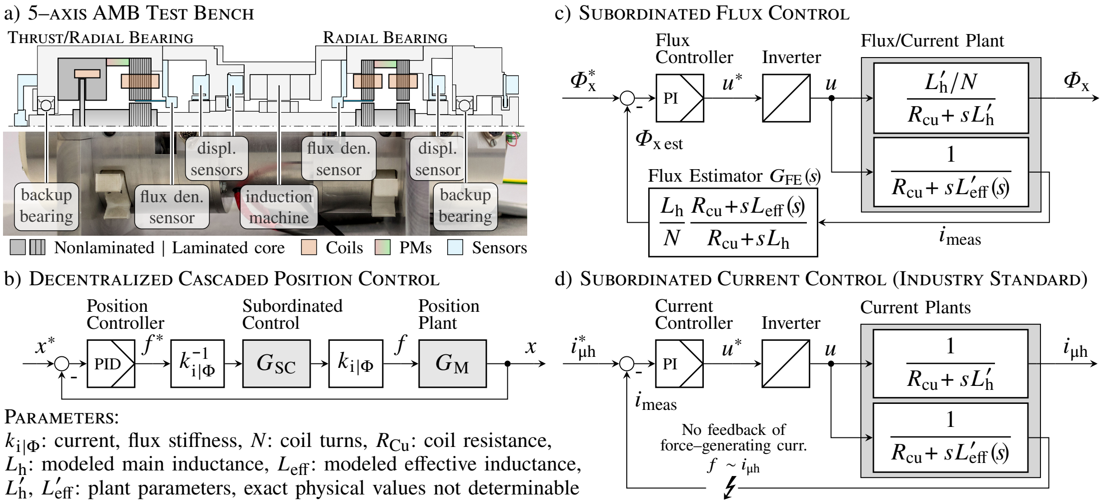

Figure 1: Drive and control concept: a) Test bench with radial bearings and solid thrust bearing controlled by b) Decentralized cascaded position control with subordinated c) flux control and d) current control, adapted from [1]

are mainly similar to the X–I–control, are known to effectively overcome these problems in theory, by directly using the force–generating flux as feedback signal. However, commercially available Hall sensors neither fit into the thin air gaps of modern magnetic bearings nor can they measure the actual total flux in the inhomogeneous air gap field of thrust bearings. To resolve this problem, we estimate the flux by employing the known analytical eddy current models in the feedback path. These models were established for thrust bearings by [3], but have not been used in magnetic bearing control yet.

In this digest and the main article [1], we present the proof of concept of a novel control approach: a decentralized cascaded position control with a subordinated flux control, based on a fractional–order flux estimator (X–Φ_{EST}–control, Fig. 1b+c). It allows us to eliminate the force–damping caused by the eddy currents and maintains the advantageous cascaded structure of the X–I–control. There is no need for additional sensors apart from the common displacement and current sensors (Fig. 1a). Additionally, our method preserves the physical reference of all control variables and compensates the eddy currents effects in the inner control loop in real–time, where they physically occur. The approach also significantly differs from voltage–based flux observers and hybrid forms known in the literature as discussed in [1].

The concept of the proposed flux estimator $G_{FE}(s)$ in Fig. 1c is simple and derives naturally from a proper modeling of the subordinated control loop. The term *"fractional"* illustrates the characteristic properties of the system, described by the effective inductance $L_{eff}(s)$, containing the Laplace–variable s with a fractional exponent $\gamma \in \mathbb{Q}$. The whole procedure from the analytical modeling of $L_{eff}(s)$, its rational integer–order approximation and the digital implementation of the estimator is thoroughly explained in [1]. We only briefly present the experimental results for the outer position control here.

2 Experimental Results and Conclusion

By means of frequency and step responses in Fig. 2, we compare the classic X–I–control with the novel X–Φ_{EST}–control for selected stiffness k/k_x and damping ratios D [1]. Furthermore, we use the analytical model to derive a *trend* for a range of parameters to illustrate the whole potential of our new approach, based on the following characteristic control properties:

The phase margin φ_{PR}, an important stability criterion, shows a significant limitation of the parameter range for the X–I–control, although the maximum achievable 20° are hardly sufficient for a robust controller design. The X–Φ_{EST}–control increases the phase margin by an average of 30 – 40° and therefore allows a securer bearing operation over the entire parameter range.

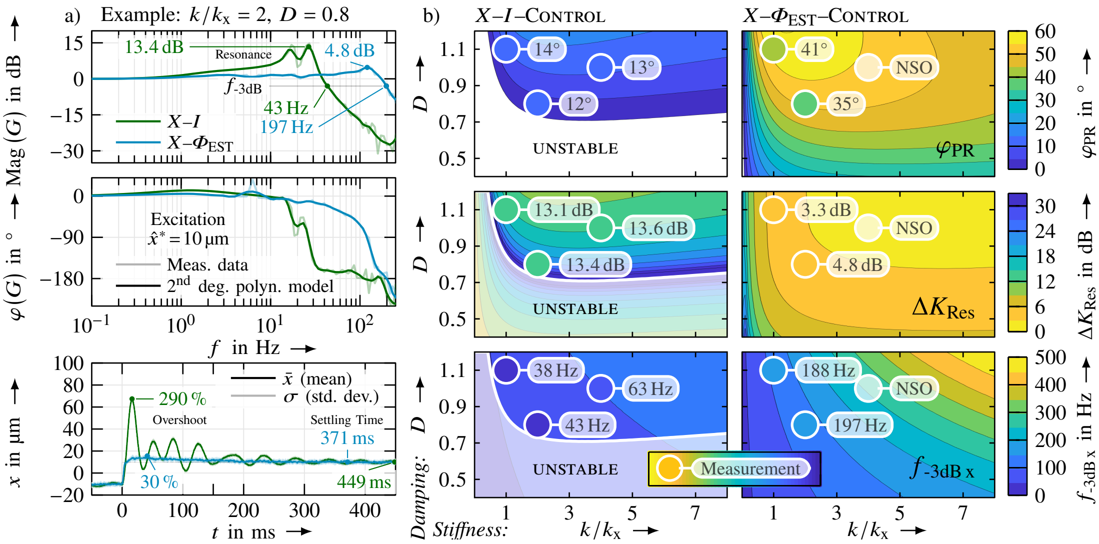

Figure 2: Control attributes derived from analytical model for various stiffness/damping parameters, validation by measurement for example parameters — NSO: No stable operation at resonance for $\hat{x}^* = 10\,\mu\text{m}$, adapted from [1]

The resonance amplitude ΔK_{Res} at the resonance frequency f_0 is a measure of the degree of oscillation occurring with an excitation of the reference position $\hat{x}^*$. The X–Φ_{EST}–control allows a much higher damping compared to the X–I–control by reducing the resonance amplitude by at least 5 – 25 dB.

The overshoot ϵ_{OS} is closely related to ΔK_{Res} in the time domain. It is partly caused by the unavoidable derivative gain and limited integral gain of the controller. While the X–Φ_{EST}–control with 30 – 40 % almost reaches the attainable minimum, the X–I–control yields an unacceptable overshoot of 150 – 400 %.

The cutoff frequency $f_{\text{-3dB}}$ of the position control is the attribute with the greatest potential of improvement. For the X–Φ_{EST}–control we observe at least a duplication if not even more than a quadruplication compared to the X–I–control. With a more potent inverter (here we are limited to $U_{\text{dc}} = 48\,\text{V}$), allowing higher voltages and stiffness ratios $k/k_x > 7$, a bandwidth up to 500 Hz is feasible.

From this proof of concept, we can conclude that the novel X–Φ_{EST}–control achieves significantly improved control properties compared to the industry standard, by compensating the eddy current effects in the inner control loop. A drawback of our approach is the increased voltage demand to compensate the magnetic skin effect, which may require an upgrade of the bearing supply to fully utilize the potential of this control. However, additional measures to reduce the actual causative eddy currents or the regulated control variant proposed in [1] mitigate the problem. Hence. the X–Φ_{EST}–control is a cost–efficient, possibly pure software–based measure to improve the dynamic behavior of magnetic thrust bearings. It neither requires additional sensors, nor state observers or an online parameter identification and is readily applicable even to existing magnetic bearing control implementations.

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