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Brief paper

A state observer for sensorless control of magnetic levitation systems[☆]

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ABSTRACT

In this paper we address the problem of state observation for sensorless control of magnetic levitation systems, that is, the regulation of the position of a levitated object measuring only the voltage and current of the electrical supply. Instrumental for the development of the theory is the use of parameter estimation-based observers, which combined with the dynamic regressor extension and mixing parameter estimation technique, allow the reconstruction of the magnetic flux. With the knowledge of the latter it is shown that the mechanical coordinates can be estimated with suitably tailored nonlinear observers. Replacing the observed states, in a certainty equivalent manner, with a full-state feedback stabilising law completes the sensorless controller design. In the interest of brevity the result is presented only for a two-degree-of-freedom system but the approach is applicable also for the more familiar case of one-degree-of-freedom. Simulation results are used to illustrate the transient performance and robustness of the proposed scheme.

1. Introduction

The use of magnetically levitated (MagLev) technology eliminates mechanical contact between moving and stationary parts in the system, attenuating the cumbersome friction problem. An additional benefit is the possibility of actively changing the position of the levitated object and to change the stiffness of the levitation system. Therefore, it finds many application areas such as magnetic bearings (Samanta & Hirani, 2008), vibration isolation (Tsuda et al., 2009), bearingless motors (Lin, Shieh, Teng, & Shieh, 2005), bearingless pumps (Raggl, Warberger, Nussbaumer, Burger, & Kolar, 2009), microelectromechanical systems (Komori & Yamane, 2001), and high speed rail transportation (Yan, 2008). In addition, MagLev can also control a floating object which is performing linear or rotary motion (Ohji, Hara, Amei, & Sakui, 2008). See Han and Kim (2016) and Schweitzer and Maslen (2009) for recent overview of MagLev systems.

Since MagLev systems are inherently unstable, position control of the levitated object is of paramount importance. Clearly, the knowledge of the position is necessary to accomplish this task, making MagLev systems highly expensive because of the cost (and low reliability) of existing position sensors. To overcome this limitation a lot of research has been devoted to the development of sensorless (also called self-sensing) MagLev systems. In these schemes the position sensor is replaced by some kind of estimation algorithm that reconstructs the position from the measurement of voltages and currents. These estimation algorithms may be classified in two groups: (i) technologically-based techniques that exploit the functional relationship between the systems inductance and the position of the levitated object; (ii) theoretically-based designs of state observers proceeding from the mathematical model of the system. The interested reader is referred to Gluck, Kemmetmuller, Tump, and Kugi (2011), Maslen, Meeker, and Knospe (2000) and Mizuno, Araki, and Bleule (1996) for a review of the existing literature on sensorless control of MagLev systems reported in the control community and to Ranjbar, Noboa, and Fahimi (2012) and Schweitzer and Maslen (2009) for results found in the application journals.

The present contribution belongs to the second category mentioned above. Namely, proceeding from the full nonlinear mathematical model derived from physical laws, we design a state observer for the flux, position and velocity of the MagLev system measuring only voltages and currents. Because of space limitations we consider only two-degrees-of-freedom (2-dof) systems, the

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case of 1-dof been treated in Bobtsov, Pyrkin, Ortega, and Vedyakov (0000). As is well-known, the dynamic behaviour of these systems is highly nonlinear. Therefore, to ensure good performance in a wide operating range it is necessary to avoid the use of linearised models that, to the best of the authors' knowledge, is the prevailing approach reported in the literature (Gluck et al., 2011; Mizuno et al., 1996). See Maslen, Montie, and Iwasaki (2006) and Montie (2003) for a detailed analysis of the deleterious implications of linearisation in sensorless Maglev models.

The first step in our design is the reconstruction of the flux, which is done by combining the parameter estimation-based observers (PEBO) recently reported in Ortega, Bobtsov, Pyrkin, and Aranovskiy (2015) with the dynamic regressor extension and mixing (DREM) parameter estimation technique of Aranovskiy, Bobtsov, Ortega, and Pyrkin (2017). The combination of these two new techniques has been proven highly successful in the solution of several complex practical problems (Aranovskiy, Bobtsov, Ortega, & Pyrkin, 2016; Bobtsov et al., 2015; Pyrkin, Mancilla, Ortega, Bobtsov, & Aranovskiy, 2017)—see also Ortega, Praly, Aranovskiy, Yi, and Zhang (2018) for the reformulation of DREM as a functional Luenberger observer. With the knowledge of the flux we propose suitably tailored nonlinear observers for the mechanical coordinates, obtaining in this way an asymptotically convergent solution to the posed observation problem. To complete the sensorless controller design the observed state is then replaced in the full information asymptotically stabilising interconnection and damping assignment passivity-based controller (IDA-PBC) reported in Rodriguez, Ortega, and Siguerdidjane (2000), see also Rodriguez, Ortega, and Mareels (2000).

Since there are several full-state controllers that achieve the stabilisation objective, see *e.g.*, Maslen et al. (2000), Ortega, Loria, Nicklasson, and Sira-Ramirez (2013) and Torres and Ortega (1998), our main contribution is the solution of the – until now open – problem of state observation that, as shown below, turns out to be significantly involved. In Yi, Ortega, and Zhang (2018) injection of high-frequency sinusoidal probing signals in the voltage is used to generate a virtual output and be able to design a PEBO for a 1-dof MagLev system, see also Yi, Ortega, Siguerdidjane, and Zhang (2018). The invasive injection of probing signals is avoided in the present contribution. On the other hand, as always for observer based controller designs for nonlinear systems, some excitation condition needs to be imposed on the signals of the system (Aranovskiy et al., 2017). It should be pointed out that the proposed observer can be combined with other controllers, for instance, the well-known "complementarity control" (Bonivento, Gentili, & Marconi, 2005; Levine, Lottin, & Ponsart, 1996) in which the two magnetic forces are never simultaneously activated yielding a more efficient energy consumption.

The remainder of the paper is organised as follows. The model of a 2-dof MagLev system is presented in Section 2. In Section 3 the observer design for the vertical dynamics is presented and in Section 4 we give the corresponding sensorless control. The transient performance and robustness of the proposed observer and sensorless controller are validated in Section 5 via simulations. The paper is wrapped-up with some conclusions and future work in Section 6.

2. Model of the MagLev systems and problem formulation

The model of the 2-dof MagLev system depicted in Fig. 1 is obtained from Faraday's and Newton's laws as

$$\dot{\lambda}_i = -RI_i + u_i, \quad i = 1, \dots, 4 \tag{1}$$

$$m\ddot{Y} = f_1 - f_2 - mg, \tag{2}$$

$$m\ddot{X} = f_3 - f_4, \tag{3}$$

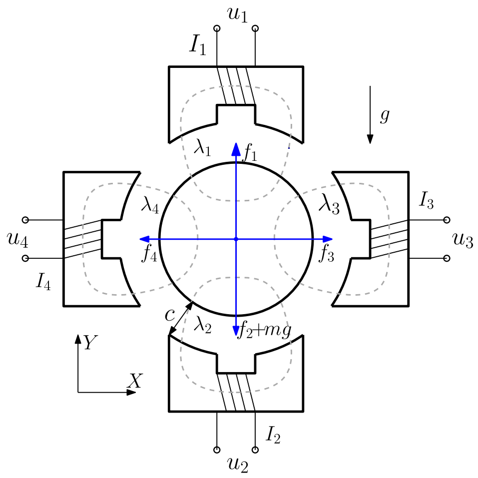

Fig. 1. 2-dof MagLev system.

where X, Y are the rotor positions in the horizontal and vertical directions, respectively, R are the coils resistances, m is the mass of the rotor, g is the acceleration of gravity, and λ_i, I_i, f_i, u_i, $i = 1, \dots, 4$ denote the total magnetic flux, the current in the coil, the force and the control voltage associated with the ith actuator, respectively. The following assumptions on the magnetic device are made:

(A1) The magnetic forces of the vertical and horizontal motions are decoupled.

(A2) The total flux, rotor position and coil current are related as

$$\begin{aligned} I_j &= \frac{1}{k}(c + (-1)^j Y)\lambda_j, \quad j = 1, 2 \\ I_j &= \frac{1}{k}(c + (-1)^j X)\lambda_j, \quad j = 3, 4 \end{aligned} \tag{4}$$

for some positive constants c and k.

(A3) The forces produced by the actuators satisfy

$$f_i = \frac{1}{2k}\lambda_i^2, \quad i = 1, \dots, 4, \tag{5}$$

and they are bounded.

From the equations above it is clear that, due to Assumption **(A1)**, the dynamics of the horizontal and vertical motions are decoupled, with independent control signals. This fact allows us to carry out the design of the observers and sensorless controllers for the horizontal and vertical motions in an independent way. For the sake of brevity, we present here only the one corresponding to the latter one—since both dynamics are, up to the constant gm, identical, the design of the observer for the horizontal dynamics is obtained *verbatim* from the one of the vertical one. In any case, the reader is referred to Bobtsov et al. (0000) where the design for both motions is presented.

Problem formulation. Consider the vertical dynamics of the MaGLev system (1)–(5). Assume that all the systems parameters are known and that the only signals available for measurement are the currents I_i, $i = 1, 2$, that we arrange in a vector $I := \mathrm{col}(I_1, I_2)$. The control objective is to design a dynamic output feedback controller

$$\begin{aligned} \dot{\zeta} &= F(\zeta, I) \\ U &= H(\zeta, I), \end{aligned}$$