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A novel robust position estimator for self-sensing magnetic levitation systems based on least squares identification

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A R T I C L E I N F O

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A B S T R A C T

In this work a novel method is introduced for the estimation of the position of a self-sensing magnetic levitation system, based on a least squares identification strategy. In the first step, a detailed mathematical model of the magnetic levitation system is derived and the properties of this system are analyzed for the case of a pulse-width modulated control. Based on this model, an estimation algorithm for the inductance of the magnetic levitation system is introduced. In classical position estimation schemes known form the literature large estimation errors are typically induced by a deviation of the electric resistance from its nominal value or by a fast motion of the levitated object. In this work it is shown that these errors can be exactly compensated by means of a suitable estimation strategy. Furthermore, it is outlined that the chosen structure of the estimation scheme allows for a very efficient implementation in real-time hardware. Afterwards, the design of a cascaded position controller for the magnetic levitation system is briefly summarized. Finally, the excellent quality and the high robustness of the proposed position estimator is demonstrated by means of simulation studies and measurement results on a test bench.

1. Introduction

Magnetic levitation systems enable an almost frictionless suspension of objects. Only the magnetic force generated by the electromagnets of the magnetic levitation system support the levitated object. In addition to the low friction, further benefits are the possibility to actively change the position of the levitated object and to alter the characteristics (e.g. the stiffness) of the levitation system. Magnetic levitation systems are inherently unstable, so active position control of the levitated object is indispensable. Certainly, the determination of the position is necessary for the implementation of the controller, which makes magnetic levitation systems relatively expensive and causes problems in the case of a failure of the position sensor.

For this reason, so-called sensorless or self-sensing magnetic levitation systems have been developed in the recent years. The position sensor is replaced by an estimation algorithm which makes use of the voltage and current measurement of the magnetic levitation system. The basic idea of all estimation algorithms is to utilize the functional relationship between the inductance of the magnetic levitation system and the position of the levitated object. The numerous works dealing with the development of estimation algorithms for the magnetic levitation systems can basically be divided into two working principles: (i) state observer approach and (ii) parameter estimation approach.

The classical state observer approach uses a Luenberger state observer, which is designed on the basis of a linearized mathematical model of the magnetic levitation system, see, e.g. Vischer (1988). This approach, however, exhibits major shortcomings concerning the robustness with respect to changes of the parameters and external disturbances (Thibeault & Smith, 2002). Furthermore, the linearized treatment significantly limits the operating range of the magnetic levitation system. An improvement of the robustness in the case of a pulse-width modulation (PWM) controlled magnetic levitation system could be obtained in Maslen, Montie, and Iwasaki (2006) and Montie (2003) by formulating the system in form of a linear mathematical model with periodic parameters. However, no practical implementation of the algorithms have been reported in these works. To the author's knowledge, no attempts of applying the theory of nonlinear state observers to magnetic levitation systems have been made. The reason, of course, is the need of very high sampling rates and the resulting computational effort.

By far a larger number of works deal with the parameter estimation approach for the position estimation of the levitated object. These works can again be divided into three categories: (a)

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The first approach is based on the injection of a high frequency sinusoidal voltage test signal. The resulting changes in the amplitude of the current are a measure of the inductance and, therefore, of the position of the levitated object. The appropriate choice of the frequency of the test signal enables the decoupling of the control and the estimation (Sivadasan, 1996). The substantial disadvantage of this approach is the additional hardware effort for supplying and evaluating the test signal. Furthermore, the reported implementations of this approach make use of linear amplifiers with a low energy efficiency (Sivadasan, 1996). (b) The second subgroup makes use of hysteresis amplifiers, switching on and off the supply voltage such that the resulting amplitude of the current ripples is kept constant (Mizuno & Hirasawa, 1998). The position of the levitated object is then inferred from the switching frequency of the hysteresis amplifier, where the frequency is typically measured by a phase-locked loop. This approach lacks in the ability to accurately estimate high-dynamic changes of the position signal.

Due to the increasing demands on energy efficiency nowadays switching amplifiers are almost exclusively used for the control of magnetic levitation systems. The third group (c) of the parameter estimation approaches utilizes pulse-width modulation (PWM) controlled switching amplifiers, where the average value of the voltage can be influenced by the duty ratio. Most of the contributions dealing with the position estimation for this configuration rely on a harmonic analysis of the voltage and the current signals (Kucera, 1997; Noh & Maslen, 1997; Schammass, 2003; Schammass, Herzog, Bühler, & Bleuler, 2005). Although several practical implementations have been reported in literature, the first harmonic is certainly only a rough approximation of the real current and voltage signals. It is well-known that this approach yields inaccurate results if fast changes of the duty ratio or a fast motion of the levitated object do occur. For this reason, e.g. Kucera (1997) uses a look-up table to approximately account for these effects. Furthermore, the influence of the electric resistance of the coil is generally neglected. In contrast to the harmonic analysis a least squares estimation is performed in Pawelczak (2005) in order to obtain the actual value of the inductance. Although the dependence on the electric resistance is systematically included in this approach, a change of the duty ratio and a motion of the levitated object cause inaccuracies in the estimation results. Again a look-up table is used to approximately account for this effect.

In this work a position estimation algorithm based on least squares identification is proposed, which, in contrast to existing works, is capable of systematically accounting for the influence of the electric resistance, the (rapid) change of the duty ratio, and for the motion of the levitated object. Section 2 is devoted to the deviation and the analysis of the mathematical model of the considered magnetic levitation system. The development of the position estimation scheme is outlined in Section 3, where first only a stationary object is considered. The position estimation algorithm is then generalized for the case of a moving levitated object. Here, it is also shown that the proposed position estimation algorithm is very robust to changes of the electric resistance. Furthermore, information on an efficient implementation of the algorithm is given in this section. Section 4 deals with the development of a basic position control algorithm. The results of simulation studies and measurements on a test bench are summarized in Section 5. The paper concludes with a short summary and an outlook to further research activities.

2. Mathematical model

The mathematical model of the magnetic levitation system forms the basis of the subsequent position estimation algorithm and the design of a position controller. Clearly, an exact model of the magnetic levitation system is necessary in order to achieve a good estimation and control performance. In Fig. 1, a sketch of the

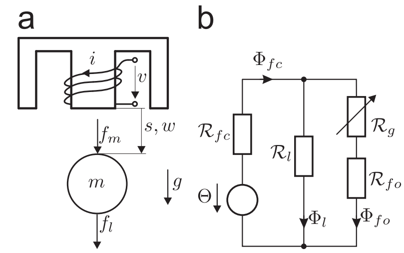

Fig. 1. Schematic diagram of the magnetic levitation system and equivalent magnetic circuit: (a) Schematic diagram; (b) Equivalent magnetic circuit.

considered magnetic suspension system is given. It basically comprises the levitated object, which, in the considered case, is a ball, and the magnetic core. Both, the levitated object and the magnetic core are made of highly permeable material with a relative permeability $\mu_r \gg 1$. The coil of the electromagnet is included in the core and has N turns. Applying a voltage v to the terminals of the coil results in a current i which in turn yields a magnetic field in the air gap between the core and the levitated object. By means of the resulting magnetic force f_m the position s of the levitated object can be controlled. The mathematical model of the magnetic levitation system is based on the equivalent magnetic circuit given in Fig. 1b. It comprises the effective reluctance $\mathcal{R}_{fc}$ of the core, the effective reluctance $\mathcal{R}_{fo}$ of the levitated object, the effective reluctance $\mathcal{R}_g$ of the air gap between the core and the levitated object, and the reluctance $\mathcal{R}_l$, which accounts for the leakage fluxes. The reluctances are given as functions of the geometrical and magnetic parameters in the form:

$$\mathcal{R}_{fc} = \frac{l_{fc}}{\mu_0 \mu_r A_{fc}} \tag{1a}$$

$$\mathcal{R}_{fo} = \frac{l_{fo}}{\mu_0 \mu_r A_{fo}} \tag{1b}$$

$$\mathcal{R}_g = \frac{s}{\mu_0 A_g} \tag{1c}$$

$$\mathcal{R}_l = \frac{l_l}{\mu_0 A_l}. \tag{1d}$$

Here l_{fc}, l_{fo} and l_l are the effective lengths and A_{fc}, A_{fo}, A_l are the effective areas of the corresponding elements. The effective length of the air gap is given by the position s of the levitated object and the corresponding area is denoted by A_g. Furthermore, μ_0 denotes the permeability of air and μ_r is the relative permeability of the material of the core and the levitated object.

Using the electromotive force $\Theta = Ni$, the flux through the coil Φ_{fc} is given in the form:

$$\Phi_{fc} = \frac{\Theta}{\mathcal{R}}, \tag{2}$$

with the equivalent reluctance $\mathcal{R}$ of the overall system given by

$$\mathcal{R} = \mathcal{R}_{fc} + \frac{\mathcal{R}_l(\mathcal{R}_g + \mathcal{R}_{fo})}{\mathcal{R}_l + \mathcal{R}_g + \mathcal{R}_{fo}}. \tag{3}$$

Based on the flux linkage $\psi = N\Phi_{fc}$ of the coil, Faraday's law yields

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi = -Ri + v, \tag{4}$$

where R is the electric resistance, i denotes the current and v is the voltage applied to the coil. The flux linkage is a function of the current i and the position s of the levitated object. Using

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi = \frac{\partial\psi}{\partial i}\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\partial\psi}{\partial s}w = L(s)\frac{\mathrm{d}i}{\mathrm{d}t} + \frac{\partial L(s)}{\partial s}wi, \tag{5}$$