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A self-tuning robust full-state feedback control design for the magnetic levitation system

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ABSTRACT

In this study, a self-tuning robust integral of signum of error (RISE) based controller is designed and used to control a magnetic levitation (maglev) system. In the control design, unlike the classical RISE controller, '*tanh*' function is used instead of '*signum*' function to obtain a more smooth control signal. The gains of the controller are updated according to a time-varying update rule. Convergence of the error under the closed-loop operation is proven via Lyapunov-based stability analysis. The controller is tested on an experimental maglev system and successful results are obtained.

1. Introduction

Magnetic levitation (maglev) systems provide that a ferromagnetic object to be levitated and/or held in a desired position in the air with the help of an electromagnet. Since they remove friction problems, these systems are used in many industrial areas such as magnetic trains, vibration isolation in sensitive devices, and high precision positioning of chip plates in photolithography (Eroglu & Ablay, 2016; Karacam & Bayrak, 2017). However, these systems have unstable equilibrium point and nonlinear dynamic structure which make it a challenging problem to control them (Eroglu & Ablay, 2016; Karacam & Bayrak, 2017). These features also make the maglev system a good test bed for control strategies. As a result of these, there are so many studies on the control of maglev systems in the control literature. Karacam and Bayrak used robust integral of signum of error (RISE) controller with a cascade structure to control maglev systems and had successful simulation results (Karacam & Bayrak, 2017). Eroglu and Gunyaz, used a sliding mode controller with a cascade structure to control an experimental maglev system (Eroglu & Ablay, 2016). In Benomair, Firdaus, and Tokhi (2016), Benomair et al. proposed a fuzzy sliding-mode controller with a nonlinear observer that was used to estimate the unmeasured states to provide the tracking control of the maglev system. Al-Araji, proposed a position-tracking control algorithm for maglev systems by utilizing the backstepping technique based on the cognitive online auto-tune algorithm (Al-Araji, 2015). Tran and Kang presented an arbitrary finite-time tracking control method for maglev systems having uncertain dynamics and external disturbances (Tran & Kang, 2014). Nayak and Subudhi presented an output feedback discrete robust control design for the tracking control of maglev systems (Nayak & Subudhi, 2016). In the mentioned study, position of the iron ball was the only needed measurement and the lack of the measurement of the other state was compensated by utilizing Kreisselmeier filter. Adiguzel et al. used a backstepping controller to get an iron ball track a desired trajectory (Adiguzel, Dokumacilar, & Turker, 2016). Lee et al. presented a self-tuning controller with a mass estimator for controlling the maglev systems (Lee, Sung, Lim, & Bien, 2000). In Bächle, Hentzelt, and Graichen (2013), Bachle et al. used a fast nonlinear model predictive control scheme to control maglev systems. In Assis and Galvao (2017), Asis and Galvao used sliding mode predictive controller to control an experimental maglev system. Sun et al. presented a saturated continuous adaptive control strategy for maglev systems with actuator saturation constraints and unknown ball mass (Sun, Fang, & Chen, 2017). Pati et al., proposed a systematic 2 degree-of-freedom control scheme for reference input tracking and load disturbance rejection for maglev systems (Pati, Pal, & Negi, 2017). In Zhao and Gao (2014), Zhao and Gao combined a neural network adaptive control method and a state feedback control method based on radial basis function neural network to control maglev systems. Pallav et al. presented a proportional–integral–derivative (PID) controller with and without derivative filter for maglev systems (Pallav, Pandey, & Laxmi, 2014). Ahmad et al. used a PID controller, of which parameters are tuned by genetic algorithm, for the control of maglev systems (Ahmad, Shahzad, & Palensky, 2014). Kumar and Jerome used a PID controller whose gains were adjusted via

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linear quadratic regulator approach for the tracking control of maglev system (Vinodh Kumar & Jerome, 2013). Gandhi and Adhyaru designed and implemented a pre-fuzzy-PID controller for current controlled mode of the maglev system (Gandhi & Adhyaru, 2018). In Lin, Lin, and Chen (2011), Lin et al. developed an adaptive PID control system for the control of a maglev system. Sahoo et al. presented the design and real time implementation of fuzzy logic control for maglev system (Sahoo, Tripathy, & Sharma, 2018). Rubio et al. utilized a neural network controller design for the trajectory tracking of maglev system (de Jesús Rubio et al., 2017).

According to the authors' best knowledge, Karacam and Bayrak (2017) is the first study that the RISE type controller was used for the control of maglev system. Simulation studies presented in the mentioned study show that this type of controller can successfully control the maglev system. In this study, unlike the controller in Karacam and Bayrak (2017), '*tanh*' function is utilized instead of '*signum*' function to obtain more smooth control signal. This control design is very similar to the controller structure in Dasdemir and Zergeroglu (2015) except the gain which is added to the parameter of '*tanh*' function. Also the stability analysis differs from the one in Dasdemir and Zergeroglu (2015). The proposed controller is combined with a newly designed self-tuning rule to cope with difficulties of adjusting the control gains. The self-tuning rule in this study is designed by utilizing the approach presented in Bidikli, Tatlicioglu, and Zergeroglu (2014). However, since the structure of the controller proposed in this study different from the one given in the mentioned study, the approximation used in the self-tuning rule is completely different and novel. Then, the proposed controller is applied to an experimental maglev system by considering the success of this type of controller on maglev systems presented in Karacam and Bayrak (2017). Convergence of the error in the closed-loop operation was shown via a Lyapunov-based stability analysis while the performance demonstration is realized via experimental results. Proposing a self-tuning continuous RISE based controller for the control of nonlinear systems and utilizing from it for the control of experimental maglev system can be considered as the main contributions of this study.

2. System model and its properties

In this section, mathematical model of a maglev system is examined. It should be noted that, the robust structure of the proposed controller makes the knowledge of the system model unnecessary. However, the system model is given by considering the completeness of the study. The maglev system shown in Fig. 1 is constructed as a combination of electrical and electromechanical subsystems. In the following subsections, structure and model of these subsystems are examined in a detailed manner.

2.1. Electrical subsystem

The electrical subsystem of the maglev system is constructed and modeled as a serial RL circuit having an alternative current voltage source and a variable inductor. In Fig. 1 inductance of the electromagnet denoted by $L(x) \in \mathbb{R}$ while the position of the ball is denoted by $x(t) \in \mathbb{R}$. Inductance of the electromagnet equals to $L_1 \in \mathbb{R}$ when the iron ball is removed from the system and equals to $L_0 + L_1 \in \mathbb{R}$ when the iron ball is in contact with the electromagnet. It varies according to the position of the ball except these issues and this situation can mathematically be expressed as Eroglu and Ablay (2016)

$$L = L_1 + \frac{k}{x} \tag{1}$$

where $k \in \mathbb{R}$ is defined as

$$k \triangleq x_0 L_0 \tag{2}$$

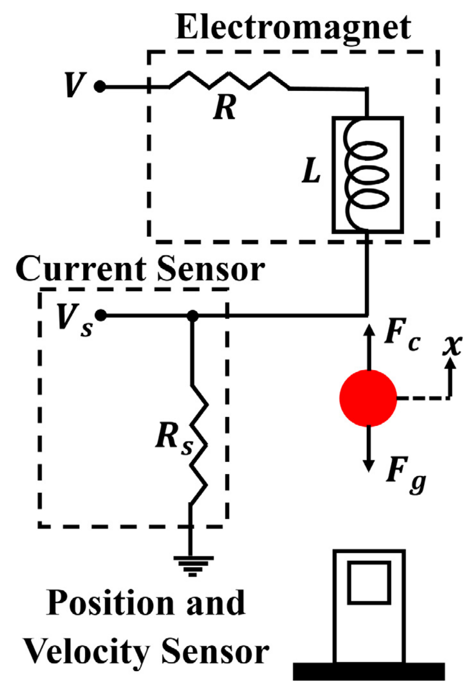

Fig. 1. Maglev System.

where $x_0 \in \mathbb{R}$ denotes the working point where the inductance value equals to $L_0 \in \mathbb{R}$. The mathematical model of the electrical subsystem is given as

$$V = I\left(R + R_s\right) + L\dot{I} + I\dot{L} \tag{3}$$

where the voltage, current and resistor values of the electromagnet and the resistor value of the current sensor are denoted by V, I, R and R_s, respectively. The final form of the model of the electrical subsystem can be rearranged as follows by substituting (1) into (3)

$$\dot{I} = \frac{1}{L}V - \frac{\left(R + R_s\right)}{L}I + \frac{k}{L}\frac{\dot{x}}{x^2}I. \tag{4}$$

2.2. Electromechanical subsystem

The mathematical model of the electromechanical subsystem can be obtained according to the Newton's second law via the free- body diagram of the iron ball shown in Fig. 1. The electromagnet and gravitational forces are denoted by $F_c(t)$ and $F_g(t) \in \mathbb{R}$, respectively. The gravitational force is expressed as

$$F_g = Mg \tag{5}$$

where the mass of the iron ball and the acceleration due to gravity are denoted by M and $g \in \mathbb{R}$, respectively. The electromagnet force is expressed as

$$F_c = -\frac{I^2}{2}\frac{dL}{dx} \tag{6}$$

and the equivalent force that is effective on the ball can be obtained as

$$F = F_c - F_g = \frac{k}{2}\left(\frac{I}{2}\right)^2 - Mg \tag{7}$$

where (1), (5) and (6) are utilized. The final form of the model can be obtained as follows according to the Newton's second law by considering the equivalent force in (7)

$$m(x)\ddot{x} + f(x) = u \tag{8}$$

where $m(x) \triangleq \frac{2Mx^2}{k}$, $f(x) \triangleq \frac{2Mgx^2}{k}$ and $u \triangleq I^2$.