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Tracking control for magnetic-suspension systems with online unknown mass identification

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ABSTRACT

This paper proposes a new nonlinear tracking control scheme with simultaneous unknown mass identification for magnetic suspension systems. Specifically, an amplitude-saturated adaptive control law is developed to achieve stable tracking and accurately estimate the unknown suspended mass simultaneously. The stability is assured with rigorous Lyapunov-based analysis. As far as we know, this is the *first continuous* control method for magnetic suspension systems with unknown levitated ball mass and actuator saturation, yielding an asymptotic result to achieve simultaneous tracking control and mass identification. Through hardware experiments, we verify the performance of the proposed method and compare it with existing methods.

1. Introduction

Magnetic suspension systems can realize non-contact supports for objects by employing the magnetic forces existing between electromagnets and ferromagnetic materials (e.g., iron, cobalt, nickel), which present many advantages in engineering applications (Glück, Kemmetmüller, Tump, & Kugi, 2011; Karimi, Mišković, & Bonvin, 2003; Matsumoto, Arai, & Nakagawa, 2014, pp. 8600304–1-4; Mizuno, Takasaki, Kishita, & Hirakawa, 2007; Shiakolas & Piyabongkarn, 2003; Yang, Li, & Yu, 2013; Yang, Su, Li, & Yu, 2014; Zhou & Duan, 2011). For instance, unexpected friction forces can be eliminated to reduce unnecessary energy consumption, and mechanical attrition can be avoided. These merits make magnetic suspension systems find a surge of real-world applications in practice, such as gravity compensation (Zhang, Kou, Jin, & Zhang, 2015), magnetic bearings (Cole, Keogh, Sahinkaya, & Burrows, 2004; Grochmal & Lynch, 2007; Shi, Zmood, & Qin, 2004), high-speed maglev trains (Hasirci, Balikci, Zabar, & Birenbaum, 2011), actively positioned bearingless motors (Sugimoto & Chiba, 2014), maglev carriers (Li, Park, Lim, & Ahn, 2015), electromagnetic chucks, and so forth. The control problem is interesting, nontrivial, and much more complicated than it might appear, due to such reasons as only unidirectional control inputs, ever-present mass uncertainty to be completely canceled out, actuator saturation, and so on. Therefore, the problem of generating proper magnetic force to achieve rapid, accurate, and stable suspension control is of important significance.

In the past decades, studies on magnetic suspension systems have received a lot of interests. Specifically, in Yang et al. (2013, 2014), two novel disturbance observer-based controllers are presented for a class of systems and successfully applied to magnetic suspension systems. Through an approximate mapping, Ulbig, Olaru, Dumur, and Boucher (2010) develop a new nonlinear predictive strategy to achieve regulation control. Later, in Morales, Feliu, and Sira-Ramírez (2011), a generalized proportional integral control method is designed for magnetic suspension systems using the differential flat theory. Feemster, Fang, and Dawson (2006) propose a repetitive learning-based control law that can achieve regulation control for the levitated ball subject to disturbances. Bonivento, Gentili, and Marconi (2005) derive an observer-based controller for a modified suspension system that can provide both attractive and repulsive forces. A robust regulation control law is designed in Gentili and Marconi (2003), which is demonstrated to be effective in the presence of perturbations. Ghosh, Krishnan, Tejaswy, Mandal, Pradhan, and Ranasingh (2014) propose a 2-degrees of freedom (DOF) proportional-integral-derivative (PID) method for controlling magnetic suspension systems. Bächle, Hentzelt, and Graichen (2013) present a novel nonlinear model predictive control strategy for magnetic suspension systems,

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which can achieve high control performance for both stabilization and fast set-point changes. To achieve enhanced robustness, some *discontinuous* variable structure control schemes are elaborately designed. For instance, Shieh, Siao, and Liu (2010) combine feedback linearization and optimal sliding mode control (SMC) techniques to realize robust control. By using a modified sliding condition, a novel controller is presented for magnetic suspension control in Gutierrez and Ro (2005). One dynamic and two static SMC methods are developed in Al-Muthairi and Zribi (2004) and demonstrated to be effective. Besides the above-mentioned methods, some intelligent strategies are also introduced to control magnetic suspension systems. Specifically, in Lin, Teng, and Shieh (2007), a radial basis function network is incorporated into the design of an SMC law to improve the transient control performance. In Hassanzadeh, Mobayen, and Sedaghat (2008), a novel genetic algorithm-based optimal mechanism is introduced to determine the control parameters for magnetic suspension systems, whose effectiveness is validated by experiments. Wai and Lee (2009)) design a neural network-based strategy to achieve model-free control for magnetic suspension systems. In Chen, Chiang, and Shen (2009) and Lin and Li (2015), fuzzy logic frameworks are incorporated into controller design to improve the overall control performance.

Most existing model-based methods are presented with a basic assumption that the levitated iron ball mass is exactly known *a priori*. However, in practice, magnetic suspension systems are used to levitate different objects, whose masses are uncertain or even unavailable. The levitated object always moves vertically, i.e., in the same or opposite direction with its gravitational force, and a complete controller contains both error-related feedback and feedforward compensation terms. More precisely, the aim of including feedforward compensation terms is to compensate for the gravitational force of the levitated object, and *only if* one exactly compensates for the gravity effects, accurate regulation or tracking control can be achieved. Otherwise, due to the fact that the gravitational force is always present, if we cannot completely cancel it out, there will always be steady positioning/tracking errors induced by the mismatch between the actual gravitational force and the nominal compensation force. To overcome this issue, the preliminary task is to estimate the unknown mass for precise compensation. Nonetheless, in this case, traditional model-based adaptive control approaches (designed according to the procedures in Chapter 8 of Slotine & Li, 1991) are not applicable because they cannot ensure the convergence of the parameter estimates to the actual values (a brief explanation can be found in Remark 6 in this paper). Yang and Tateishi (2001) propose a backstepping-based adaptive controller, but the steady positioning error cannot be completely eliminated, i.e., an ultimately uniformly bounded (not asymptotic) result is obtained. In Lin, Liu, and Li (2014), a novel neural network (NN)-based adaptive controller is designed for magnetic suspension systems and it contains a sign-function-related robust term to eliminate the mismatch caused by uncertainties, which make the controller's structure *discontinuous*. Recently, Li, Li, and Cui (2013) propose an effective partial feedback controller and construct an estimator (observer) to online recover the uncertain mass, where the controller and the observer are analyzed separately. Hence, it is both theoretically and practically important to derive an effective *continuous* control method that can overcome the above-mentioned issue to achieve tracking/regulation control in the presence of unknown levitated ball mass.

Additionally, currently available control approaches for magnetic suspension systems, such as those mentioned previously, assume that the actuator can generate any finite-amplitude control force as required. In other words, they can merely ensure that the computed control input is $\mathcal{L}_\infty$ bounded in the sense that the control signal will not tend to infinity. In fact, due to physical constraints, electromagnets can only provide amplitude-saturated attractive force. If the saturation effect is not considered when performing controller design and the calculated control force exceeds the permitted range, the actuator will fall into saturation, badly deteriorating the control performance and even resulting in mission failure. The fact that the electromagnet can only supply attractive force makes the problem even more complicated. Hence, the second challenging issue is how to sufficiently make use of the amplitude-saturated control force to achieve accurate tracking/regulation control.

A PID controller can eliminate steady tracking (positioning) errors resulting from unknown (uncertain) levitated ball mass. However, it can neither guarantee that the saturation constraint is respected nor assure that the computed control force is always attractive from a theoretical viewpoint. Similar to many other systems such as those in Mobayen (2014, 2015), the problem of effective tracking control is important for magnetic suspension systems. To overcome the above-mentioned issues, we suggest in this paper a new nonlinear tracking control strategy for magnetic suspension systems, which can achieve satisfactory control performance in the presence of unknown iron ball mass and actuator limitation. As far as we know, the presented method yields the *first continuous control solution* for the foregoing important practical issues (i.e., unknown/uncertain levitated ball mass, actuator saturation, and only attractive force available) with the benefit of recovering unknown iron ball mass. More precisely, by respecting the amplitude-saturated attractive force constraint, a saturated adaptive control law is designed. By elaborately including tracking error-related terms in the adaptive mechanism, we can prove that the closed-loop system is asymptotically stable at the equilibrium point while the mismatch error between the actual ball mass and its estimate value converges to zero, which is supported by rigorous Lyapunov-based analysis. A series of hardware experimental results are included to examine the proposed method's effectiveness and robustness.

The main contribution of this work is as follows:

1. The proposed method does not require the exact mass of the levitated object, and it can online recover the mass for the unknown levitated object accurately.
2. The designed controller can theoretically ensure the control input to be always attractive and within the permitted range.
3. Experimental results illustrate that it achieves superior control performance over the comparative SMC method in Yang et al. (2013), and it shows robustness w.r.t. uncertainties and disturbances.

The rest of the paper is outlined as follows. In Section 2, we formulate the control problem of interest. The main results, including controller design and closed-loop stability analysis, are provided in Section 3. We exhibit hardware experiments to verify the performance of the designed controller in Section 4. The paper is wrapped up in Section 5 with some summarizing remarks.

2. Problem formulation

The schematic illustration for a magnetic suspension system is shown in Fig. 1, where the iron ball can be levitated, under the action of the attractive force supplied by the electromagnet. A light source emits parallel light, which is received by a silicon photocell, and the iron ball position can then be detected. By treating the vertical downward direction as the *positive direction*, the *nonlinear* model for a magnetic suspension system is represented as

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