Control Engineering Practice 82 (2019) 24–35

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

On disturbance rejection in magnetic levitation

Wei Wei[a], Wenchao Xue[b,c,*], Donghai Li[d]

[a] *School of Computer and Information Engineering, Beijing Key Laboratory of Big Data Technology for Food Safety, Beijing Technology and Business University, 100048, Beijing, China*
[b] *LSC, NCMIS, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China*
[c] *School of Mathematical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[d] *Department of Thermal Engineering, Tsinghua University, 10084, Beijing, China*

ARTICLE INFO

Keywords:
Magnetic levitation system
Open-loop instability
Time-varying extended state observer
Sensor noise attenuation

ABSTRACT

Magnetic levitation systems belong to an important and challenging class of control engineering problems with nonlinear uncertain dynamics, multiple disturbances and large sensor noise. To obtain a simple and practical solution that does not depends on the exact model information, a time-varying active disturbance rejection solution is proposed and validated in both numerical and experimental results. The proposed method is confirmed with rigorous analysis of transient performance and noise attenuation. Moreover, the proposed solution is tested in a magnetic levitation ball system with disturbances and measurement noise. The results show that the proposed solution is effective and practical.

1. Introduction

Magnetic levitation is a technique to suspend an object via a non-contact pattern. Such a method enables frictionless levitation of objects, and offers numerous advantages, such as elimination of lubrication system, lowering rotating losses, providing higher speed and long-life service. Due to its great potential in engineering applications, including magnetic bearings, high-speed magnetically levitating trains, micro-manipulation of levitating objects, nanoscale positioning systems, and vibration isolation systems (see Ref. Golob & Tovornik, 2003; Khamesee & Shameli, 2005; Kim, Verma, & Shakir, 2007; Kummer et al., 2010; Lanzara, D'Ovidio, & Crisi, 2014; Phuah, Lu, & Yahagi, 2005; Schuhmann, Hofmann, & Werner, 2012 and the references therein for details), magnetic levitation has attracted much attention and becomes increasingly popular in industries. However, inherently nonlinear, open-loop unstable, time-varying self-inductance and mutual coefficients, nonlinear and time-varying electromagnetic force, coupled with the nonlinear actuators make the control of magnetic levitation system be a challenge.

With an attempt to achieve desired performance, numerous magnetic levitation control techniques have been proposed. By combining linear quadratic Gaussian control, fault tolerant control and multi-objective optimization, Michail et al. proposed a linear controller to get optimum performance (Michail, Zolotas, Goodall, & Whidborne, 2012). Nonlinear feedback linearization (Torres, Schnitman, Junior, & Felippe de Souza, 2012; Trumper, Olson, & Subrahmanyan, 1997), feed-forward linearization (Morales & Sira-Ramirez, 2010), lead compensator (Weng, Lu, & Trumper, 2002), and model predictive control (Bächle, Hentzelt, & Graichen, 2013) have also been designed to stabilize the magnetic levitation systems. A nonlinear magnetic levitation system model is transformed into a set of piecewise linear model, and then an explicit nonlinear predictive control has been established (Ulbig, Olaru, Dumur, & Boucher, 2010). Additionally, based on nonlinear models, different approaches have also been proposed (Bonivento, Gentili, & Marconi, 2005; Glueck, Kemmetmueller, Tump, & Kugi, 2011; Xu, Hwa Chen, & Guo, 2015; Yang, Fukushima, Kanae, & Wada, 2009). Most reported approaches emphasize that, if better performance is expected, an accurate mathematical model is of necessity. However, it is hard to obtain an accurate model for a complex magnetic levitation system. PID, a model free control approach, commonly used in control engineering practice, is also employed (Abdel-Hady & Abuelenin, 2008; Berkelman & Dzadovsky, 2013; Golob & Tovornik, 2003). Especially, for improving tracking performance, fuzzy logic based PID control (Golob & Tovornik, 2003) and fuzzy-supervised PID control (Abdel-Hady & Abuelenin, 2008) have been proposed. However, fuzzy rules largely depend on experience, which limits applications of such approaches more or less. Besides the approaches mentioned above, advanced control techniques, such as sliding mode control (Elahi & Nekoubin, 2011), neuronal control (Chen, Lin, & Shyu, 2009; Pan and Liu et al., 2016; Rubio et al., 2017), and data-driven approach (Qin, Peng, Ruan, Wu, & Gao, 2014) have also been proposed and implemented successfully.

In this paper, we still focus on the control of magnetic levitation system. By estimating and canceling the generalized disturbance, which includes both internal uncertainties and external disturbances, in real-time, active disturbance rejection control (ADRC) is capable of achieving

---

[*] Corresponding author at: LSC, NCMIS, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China.
E-mail address: wenchaoxue@amss.ac.cn (W. Xue).

https://doi.org/10.1016/j.conengprac.2018.09.018
Received 22 January 2018; Received in revised form 21 July 2018; Accepted 16 September 2018

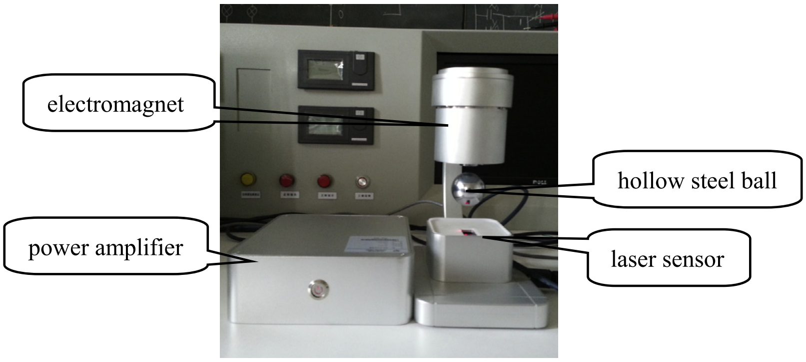

Fig. 1. A magnetic levitation ball system.

satisfactory performance (Han, 1995, 1998, 2009). However, relatively complex structure and more parameters limit the applications of ADRC. For simplifying structure and reducing the number of tunable parameters, linear active disturbance rejection control (LADRC) has been proposed (Gao, 2003). It is proved that LADRC is able to obtain desired closed-loop system performance with only two tunable parameters. Besides, those tunable parameters can be determined by an easily acceptable bandwidth-parameterization approach (Gao, 2003). So far, LADRC has been successfully used in several industrial sectors and does help the extensive applications of ADRC. Recently, LADRC has also been utilized in the control of magnetic levitation system (Zhang & Zhang, 2017).

Actually, as we known, extended state observer (ESO) is the key part of ADRC to promote control performance. In order to improve the system performance further, numerous modified ESOs (Pu, Yuan, Yi, & Tan, 2015; Xue et al., 2015; Zhao & Guo, 2015) have been proposed. Guo and Zhao propose a special kind of nonlinear ESO to ensure desired estimation error (Zhao & Guo, 2015). Pu et al. also suggest a particular time varying gain of nonlinear ESO to avoid the output of ESO being large (Pu et al., 2015). But those results pay litter attention to the performance analysis of ESO when system output is corrupted by sensor noise, which is inevitable in practice. Xue et al. (2015) start the point of using dynamic gain of ESO such that certain index of estimation error can be minimized in sense of stochastic. Nevertheless, the solution of optimized problem usually needs some statistic information of measurement noise. Also, there are other approaches to deal with the sensor noise, such as adding a dimension of ESO (Martinez-Vazquez, Rodriguez-Angeles, & Sira-Ramirez, 2009), providing a low-pass filter (Wei, Liang, Li, & Su, 2016), but the cost is making a higher order ESO or generating phase-delays.

In this paper, in order to improve the system performance one step further, noise attenuation, a commonly discussed problem in practice, is also taken into consideration in the design of ESO. The main objective of this work is to propose a new ESO for ADRC in order to optimize the closed-loop system performance. Main contributions are

- The time varying ESO (TESO) is proposed so as to deal with both generalized disturbance and measurement noise.
- The convergence of TESO is confirmed theoretically, and the upper bound of estimation error for TESO is depicted by the upper bound of generalized disturbance and measurement noise.
- The transient performance of TESO is verified, and it can be arbitrarily close to LESO. Moreover, better filtering performance of TESO than that of LESO is proved.
- Performance comparison and evaluation under different scenarios between time-varying ADRC (TADRC) and LADRC are performed in both numerical and experimental cases.

The magnetic levitation ball control system with a contactless laser position measure system is taken as the experimental platform. LADRC and TADRC are both designed. It is shown that TESO can guarantee both fast estimation of generalized disturbance and desired noise filtering.

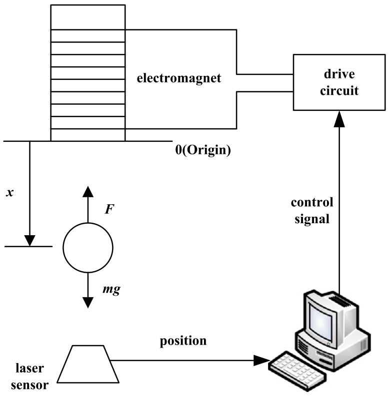

Fig. 2. Structure of magnetic levitation ball control system.

The rest of this paper is organized as follows. In Section 2, a magnetic levitation ball system, including its physical model and mathematical model, is described. TADRC is designed and analyzed in Section 3. Numerical results have been provided in Section 4. Experimental results and discussions are presented in Section 5. In the end, Section 6 concludes the paper.

2. Magnetic levitation ball system

2.1. System description

Magnetic levitation ball control system is a platform to investigate magnetic levitation technique in laboratory. Physical system of a magnetic levitation ball system is shown in Fig. 1.

The magnetic levitation device, shown in Fig. 1, is composed of an electromagnet, a power amplifier, a laser sensor, and a hollow steel ball. The experimental device is a single-axis magnetic levitation system, i.e. the steel ball can just move up and down along the vertical direction. Current of the electromagnet can be adjusted so as to make the steel ball be stable in a given position or to drive the ball to track a desired trajectory. It is worth pointing out that, limited by the device itself, it is only able to control the steel ball to move up and down. There will be no movements in other directions, since, in the laboratory, there is no velocity and no force from other directions.

The magnetic levitation ball control system consists of two parts: the magnetic levitation device and a computer. Structure of magnetic levitation ball control system is shown in Fig. 2.

In Fig. 2, variable x is the distance between the steel ball and the electromagnet surface, i.e. the position of the steel ball. We pick the origin to be the electromagnet surface, and the whole motion range is