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Robust levitation control for maglev systems with guaranteed bounded airgap

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ABSTRACT

The robust control design problem for the levitation control of a nonlinear uncertain maglev system is considered. The uncertainty is (possibly) fast time-varying. The system has magnitude limitation on the airgap between the suspended chassis and the guideway in order to prevent undesirable contact. Furthermore, the (global) matching condition is not satisfied. After a three-step state transformation, a robust control scheme for the maglev vehicle is proposed, which is able to guarantee the uniform boundedness and uniform ultimate boundedness of the system, regardless of the uncertainty. The magnitude limitation of the airgap is guaranteed, regardless of the uncertainty.

1. Introduction

With the advantages of low cost, less environmental impact, and high speed performance, the magnetic levitation (maglev) is becoming an attractive technology in many engineering applications, such as high-speed train [1–3], magnetic bearing [4–6], photolithography steppers, and magnetic launch [7–9]. In the past, the majority of the efforts in the levitation technology can be divided into two categories [10–12]: the electro-dynamic suspension (EDS) technology and the electro-magnetic suspension (EMS) technology. In the electro-dynamic suspension technology, the levitation is accomplished based on a repulsive force. This system is inherently stable that it is not necessary to control the airgap between the suspended chassis and the guideway. Therefore, it is very suitable for high-speed operations. Many important contributions have been made [13–15]. However, there are some key issues need to be addressed, such as the absence of high-powered permanent magnets or the generated heat problem of the induced current. As a result, these limit the practicality of the electro-dynamic suspension technology.

In the electro-magnetic suspension technology, the magnetic attractive force is used for the levitation. This method is more easily to implement and is able to levitate in zero or low speed, which is impossible for the electro-dynamic suspension. Therefore, it is applied more widely. However, due to the characteristic of the magnet circuit, the electro-magnetic suspension is inherently unstable. As a result, precise airgap control is indispensable. Many contributions have been made based on the precise model [16,17]. There are also preliminary efforts which deal with unknown system parameters and load disturbances [18,19]. However, one key issue which has never been addressed before is that the airgap must be limited to be in certain range, which is associated with the safety concern. So far, there is no literature that has considered this control problem.

The scope of this paper falls into the electro-magnetic suspension technology. We consider the control problem for the levitation of a nonlinear maglev system. The system contains uncertainty, which may be due to unknown parameters and external load disturbances. The uncertainty is possibly fast time-varying. No information other than its possible bound is known. From the control design point of view, there are three major difficulties, which prevent all past research work from being directly applied. First, this is a bounded state problem. The airgap of the maglev system needs to be confined within a specified range. Second, the control input (the current) is one-sided; that is, its sign is definitive and cannot be reversed. Third, the system does not satisfy the (global) matching condition [20,21].

Judging from these difficulties, the main contributions of this paper are fourfold. First, for the bounded state (airgap) constraint, a creative one-to-one state transformation is proposed to convert

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it into an unbounded state. Second, a transformation of the control input is proposed so that the transformed control is unbounded. Third, for the mismatched uncertainty, another state transformation is proposed to convert the system to be locally matched. Fourth, after this three-step transformation, we propose a robust control for the transformed system, which is under nonlinear control input. Both uniform boundedness and uniform ultimate boundedness of the uncertain system are proved. The simulation shows that the proposed robust control is able to guarantee the system performance, regardless of the uncertainty. This control is believed to be the first to render the maglev system to be within the strict state limitation even under arbitrary uncertainty.

2. Maglev vehicle dynamical system

A complete maglev system consists of three subsystems: the spring system, guideway system, and electromagnet system, as shown in Fig. 1. Since the inherent frequency of the spring system is much less than that of the rest of the system, we ignore the influence of the spring system. In addition, we assume that the system is stiff, rather than flexible. Therefore, the maglev vehicle dynamical system can be represented as follows [22]:

$$\begin{cases} m\ddot{x} = f + mg - \dfrac{ki^2}{x^2}, \\ \dfrac{2k}{x}\dot{i} = u - Ri + \dfrac{2ki}{x^2}\dot{x}. \end{cases} \tag{1}$$

Here x denotes the airgap between the suspended chassis and the guideway, $x \in [x_m, x_M]$, m denotes the mass of the suspended system, f denotes the disturbance force, g is the gravitational constant, k is the magnetic constant, i is the current in the coil, R is the resistance of the coil, and u is the applied voltage of the coil, which is the only control input.

Remark. Besides the disturbance force f, there are also other uncertainties in the maglev system. The mass m is uncertain due to the variation of the train load. The resistance R typically varies as the temperature of the coil fluctuates.

Remark. The airgap x is limited to the interval $[x_m, x_M]$, $x_M > x_m$, which is associated with the safety of the maglev system. It will cause serous accident if the airgap value exceeds the desired interval. However, despite the seriousness of the consequence, the past research could not take this interval condition into account. In the next section, we propose a state transformation to overcome this difficulty.

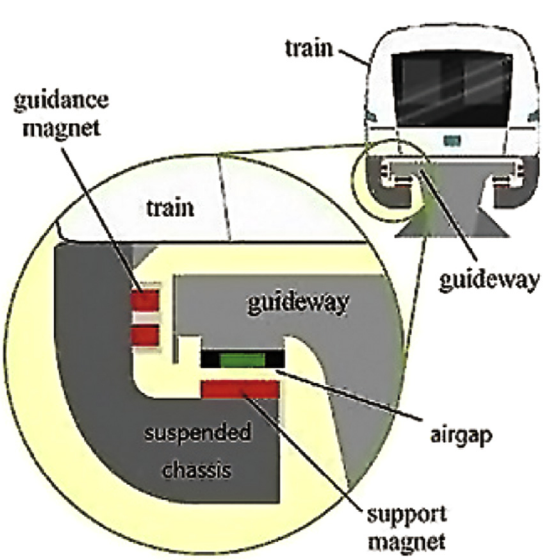

Fig. 1. The maglev system.

3. The state transformations

Previous analysis has shown that the limited airgap x defines the safety of the maglev system. In this section, we propose a three-step state transformation procedure to convert the airgap x into a new state without limitation, which is able to assure that the airgap can not exceed the limitation $[x_m, x_M]$.

3.1. First step

Since the airgap $x \in [x_m, x_M]$, we take the state transformation for the airgap x via the use of tangent function as follows:

$$y = \tan\left[\frac{\pi}{x_M - x_m}(x - x_m) - \frac{\pi}{2}\right] - y_r \tag{2}$$

with

$$y_r = \tan\left[\frac{\pi}{x_M - x_m}(x_r - x_m) - \frac{\pi}{2}\right], \tag{3}$$

where $y \in (-\infty, +\infty)$ is the transformed state from x, $x_r \in [x_m, x_M]$ is the (constant) target airgap. Therefore, $x \to x_M$ as $y \to +\infty$ and $x \to x_m$ as $y \to -\infty$. That is, the boundedness of transformed state is able to assure that the airgap cannot exceed the limitation. Upon using (2), we have

$$x = \frac{x_M - x_m}{\pi}\arctan(y + y_r) + \frac{x_M + x_m}{2}. \tag{4}$$

Taking the first order derivative of (4) yields

$$\dot{x} = \frac{x_M - x_m}{\pi}\frac{\dot{y}}{1 + (y + y_r)^2}. \tag{5}$$

Taking the second order derivative of (4) yields

$$\ddot{x} = \frac{x_M - x_m}{\pi}\frac{[1 + (y + y_r)^2]\ddot{y} - 2(y + y_r)\dot{y}^2}{[1(y + y_r)^2]^2}. \tag{6}$$

3.2. Second step

Since the current $i > 0$, upon using the first equation of (1), we take the state transformation for i as follows:

$$e^v = \frac{ki^2}{x^2} \tag{7}$$

or

$$v = \ln\frac{ki^2}{x^2} = \ln k + 2\ln i - 2\ln x, \tag{8}$$

where $v \in (-\infty, +\infty)$ is the transformed state from i. As a result,

$$i = \sqrt{\frac{x^2 e^v}{k}} \tag{9}$$

Taking the first order derivative of (8)

$$\dot{v} = \frac{2}{i}\dot{i} - \frac{2}{x}\dot{x}. \tag{10}$$

By (1) and (9),

$$\dot{v} = \frac{2}{i}\left(u - Ri + \frac{2ki}{x^2}\dot{x}\right)\frac{x}{2k} - \frac{2}{x}\dot{x} = \frac{x}{ki}u - \frac{R}{k}x = -\frac{R}{k}x + \sqrt{\frac{1}{ke^v}}u. \tag{11}$$