Levitation Control of Maglev Systems Based on Cascade Control

Jie Wen[1,2], Jikuo Wu[1], and Yukai Tian[2]

[1]Department of Automation, North University of China

[2]School of Electrical and Control Engineering, North University of China

wenjie015@gmail.com

August 30, 2022, Datong, China

Outline

Maglev trains rely on electromagnetic suction or electromagnetic repulsion to levitate and guide the train on the track, achieving no mechanical contact between the train and the ground track, such that maglev trains become a new type of transportation tool.

The levitation system of maglev trains is a complex nonlinear system with open-loop instability, susceptibility to interference, strong coupling.

The traditional PID control has been difficult to meet the requirements of accuracy and robustness of levitation control for the increasing train speed.

Maglev trains rely on electromagnetic suction or electromagnetic repulsion to levitate and guide the train on the track, achieving no mechanical contact between the train and the ground track, such that maglev trains become a new type of transportation tool.

The levitation system of maglev trains is a complex nonlinear system with open-loop instability, susceptibility to interference, strong coupling.

The traditional PID control has been difficult to meet the requirements of accuracy and robustness of levitation control for the increasing train speed.

Maglev trains rely on electromagnetic suction or electromagnetic repulsion to levitate and guide the train on the track, achieving no mechanical contact between the train and the ground track, such that maglev trains become a new type of transportation tool.

The levitation system of maglev trains is a complex nonlinear system with open-loop instability, susceptibility to interference, strong coupling.

The traditional PID control has been difficult to meet the requirements of accuracy and robustness of levitation control for the increasing train speed.

The method of designing controllers for maglev systems

- Local linearization near the equilibrium point, and applying the design approach for linear systems
  - Fuzzy control
  - Model-free adaptive control
  - Stochastic linear quadratic optimal control
- Nonlinear control methods
  - Neural network
  - Backstepping control
  - H_∞ control

The method of designing controllers for maglev systems

- Local linearization near the equilibrium point, and applying the design approach for linear systems
    - Fuzzy control
    - Model-free adaptive control
    - Stochastic linear quadratic optimal control
- Nonlinear control methods
    - Neural network
    - Backstepping control
    - H_∞ control

Mathematical model

The dynamic equation of the electromagnet and the electrical equation of the electromagnet coil are

$$\begin{aligned} m\ddot{x} &= mg - F \\ U &= Ri + \frac{2C}{x}\dot{i} - \frac{2Ci}{x^2}\dot{x} \end{aligned} \tag{1}$$

where, $F = C\frac{i^2}{x^2}$, $C = \frac{\mu_0 N^2 A}{4}$.

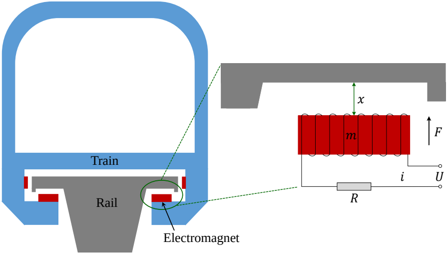

Figure 1: Schematic diagram of levitation systems for maglev train.

Control structure

The levitation system is divided into **electromagnetic system** and **motion system**, and the **cascade control strategy** is used.

- Use sliding mode control to obtain the desired current i_d according to the desired gap x_d and actual gap x
- Apply fuzzy PID control to regulate the control voltage U based on the error between i_d and actual current i to make i tend to i_d

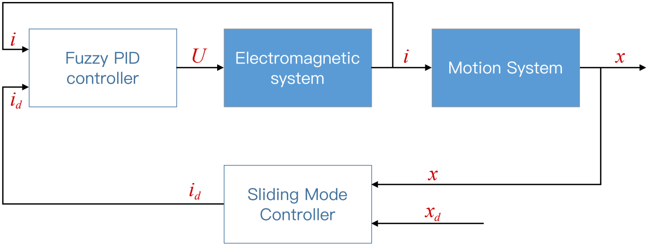

Figure 2: Diagram of control structure for levitation systems.

Outline

1. Introduction
2. Model of Levitation Systems
3. Controllers Design
   - Design of Sliding Mode Controller
   - Design of Fuzzy PID Controller
4. Numerical Simulations
   - Stable Levitation Experiments
   - Robustness Experiments
5. Conclusions

Design of Sliding Mode Controller

Sliding mode control is a nonlinear control method that alters the dynamics of a nonlinear system by applying a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior.

The design of sliding mode controller contains two steps:

- Design the **switching function** $s(x)$ so that the sliding mode determined by it is asymptotically stable and has good dynamic quality.
- Design the **control law** so that the arrival condition is satisfied, and the sliding mode is formed on the sliding mode surface $s(x) = 0$.

Design of Sliding Mode Controller

Sliding mode control is a nonlinear control method that alters the dynamics of a nonlinear system by applying a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior.

The design of sliding mode controller contains two steps:

- Design the **switching function** $s(\boldsymbol{x})$ so that the sliding mode determined by it is asymptotically stable and has good dynamic quality.
- Design the **control law** so that the arrival condition is satisfied, and the sliding mode is formed on the sliding mode surface $s(\boldsymbol{x}) = 0$.

Design of Sliding Mode Controller

For the electromagnetic system, let $x_1 = x$, $x_2 = \dot{x}$, $u = i^2$, then the electromagnetic system can be described by

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= \mathrm{g} - \frac{C}{m x_1^2} u \end{aligned} \tag{2}$$

The **linear switching function** is selected as $s(\boldsymbol{x})$, i.e.,

$$s(\boldsymbol{x}) = c_1 (x_1 - x_d) + x_2, \;\; \boldsymbol{x} = [x_1, x_2]^{\mathrm{T}} \tag{3}$$

In order to reduce the chattering of sliding mode control, we apply the **exponential reaching law**, i.e.,

$$\dot{s}(\boldsymbol{x}) = -\varepsilon \operatorname{sgn}(s(\boldsymbol{x})) - k s(\boldsymbol{x}) \tag{4}$$

Design of Sliding Mode Controller

Let the Lyapunov function $V(\boldsymbol{x}) = \frac{1}{2}s^2(\boldsymbol{x})$, it is easy to obtain from (4) that

$$\begin{aligned} \dot{V}(\boldsymbol{x}) &= s(\boldsymbol{x})\dot{s}(\boldsymbol{x}) \\ &= -\varepsilon|s(\boldsymbol{x})| - ks^2(\boldsymbol{x}) \\ &< 0 \end{aligned} \tag{5}$$

which means that the system state tends to the sliding mode surface.

On the other hand, from (2) and (3), we have

$$\begin{aligned} \dot{s}(\boldsymbol{x}) &= c_1(\dot{x}_1 - \dot{x}_d) + \dot{x}_2 \\ &= c_1 x_2 + g - \frac{C}{m x_1^2} u \end{aligned} \tag{6}$$

Design of Sliding Mode Controller

Let the Lyapunov function $V(\boldsymbol{x}) = \frac{1}{2}s^2(\boldsymbol{x})$, it is easy to obtain from (4) that

$$\begin{aligned} \dot{V}(\boldsymbol{x}) =& s(\boldsymbol{x})\dot{s}(\boldsymbol{x}) \\ =& -\varepsilon|s(\boldsymbol{x})| - ks^2(\boldsymbol{x}) \\ <& 0 \end{aligned} \tag{5}$$

which means that the system state tends to the sliding mode surface.

On the other hand, from (2) and (3), we have

$$\begin{aligned} \dot{s}(\boldsymbol{x}) =& c_1(\dot{x}_1 - \dot{x}_d) + \dot{x}_2 \\ =& c_1x_2 + \mathrm{g} - \frac{C}{mx_1^2}u \end{aligned} \tag{6}$$

Design of Sliding Mode Controller

According to (4) and (6), we design the sliding mode control u as

$$u = \frac{mx_1^2}{C}\left(c_1 x_2 + \mathrm{g} + \varepsilon \operatorname{sgn}\left(s\left(\boldsymbol{x}\right)\right) + ks\left(\boldsymbol{x}\right)\right) \tag{7}$$

i.e.,

$$\begin{aligned} i_d =& \sqrt{\frac{mx_1^2}{C}\left(c_1 x_2 + \mathrm{g} + \varepsilon \operatorname{sgn}\left(s\left(\boldsymbol{x}\right)\right) + ks\left(\boldsymbol{x}\right)\right)} \\ =& \sqrt{\frac{mx^2}{C}\left(c_1 \dot{x} + \mathrm{g} + \varepsilon \operatorname{sgn}\left(c_1\left(x - x_d\right) + \dot{x}\right) + k\left(c_1\left(x - x_d\right) + \dot{x}\right)\right)} \end{aligned} \tag{8}$$

Outline

1. Introduction
2. Model of Levitation Systems
3. Controllers Design
   - Design of Sliding Mode Controller
   - Design of Fuzzy PID Controller
4. Numerical Simulations
   - Stable Levitation Experiments
   - Robustness Experiments
5. Conclusions

Design of Fuzzy PID Controller

The diagram of fuzzy PID controller is shown in Fig. 3, where $\triangle K = \{\triangle K_p, \triangle K_i, \triangle K_d\}$ represents the variation values of K_p, K_i, K_d obtained by fuzzy inference in the standard PID controller.

From Fig. 3, e, $\dot{e}$ and $\triangle K$ are the input and output of fuzzy control, while $\triangle K$ is one of the inputs of the standard PID controller to regulate the parameters K_p, K_i, K_d.

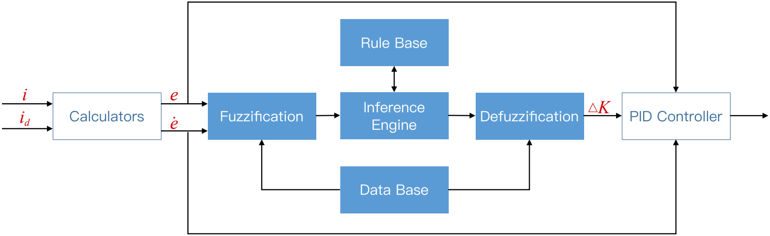

Figure 3: Diagram of fuzzy PID controller.

Design of Fuzzy PID Controller

According to the variation ranges of e and $\dot{e}$ when the standard PID controller is used to control the single-point levitation system, the relevant parameters of the fuzzy PID controller are shown in Table 1.

Table 1: Parameters setting of fuzzy PID controller

Variable	e	$\dot{e}$	$\triangle K_p$	$\triangle K_i$	$\triangle K_d$
Linguistic Variable	E	E_c	K_p	K_i	K_d
Basic Domain	$[-0.01, 0.01]$	$[-30, 30]$	$[-6, 6]$	$[-0.1, 0.1]$	$[-0.1, 0.1]$
Fuzzy Domain	$[-3, -3]$	$[-3, -3]$	$[-6, -6]$	$[-1, -1]$	$[-1, -1]$
Fuzzy Subset	[NB NM NS ZO PS PM PB]				
Membership Function	Triangular function				
Quantization Factor	300	0.1	1	0.1	0.1

Design of Fuzzy PID Controller

The fuzzy rule table for K_p is shown in Table 2.

Table 2: Fuzzy rule tables for K_p

e $\dot{e}$	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PM	PM	PS	ZO
NM	PB	PB	PB	PM	PM	PS	ZO
NS	PB	PM	PM	ZO	PS	ZO	PS
ZO	PM	PS	PS	NS	ZO	NS	NS
PS	PS	ZO	ZO	NS	NS	NM	NM
PM	ZO	ZO	NS	NM	NM	NM	NB
PB	ZO	NS	NM	NM	NB	NB	NB

Design of Fuzzy PID Controller

The fuzzy rule table for K_i is shown in Table 3.

Table 3: Fuzzy rule tables for K_i

$\dot{e}$ \ e	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NM	NM	NM	NS	ZO	ZO
NS	NM	NM	NS	ZO	ZO	PS	PS
ZO	NM	NS	ZO	ZO	PS	PS	PM
PS	NS	ZO	ZO	PS	PS	PM	PM
PM	ZO	ZO	PS	PM	PM	PB	PB
PB	ZO	ZO	PM	PM	PB	PB	PB

Design of Fuzzy PID Controller

The fuzzy rule table for K_d is shown in Table 4.

Table 4: Fuzzy rule tables for K_d

e $\dot{e}$	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PS	NS	NM	NB	NM	NM	PS
NM	PS	NS	NS	NM	NS	NM	ZO
NS	ZO	NS	ZO	NS	NS	NS	ZO
ZO	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PS	ZO	PS	PS	PS	ZO	PS	PM
PM	ZO	PS	PS	PM	PS	PS	PB
PB	ZO	PS	PM	PB	PS	PM	PB

Outline

1. Introduction
2. Model of Levitation Systems
3. Controllers Design
   - Design of Sliding Mode Controller
   - Design of Fuzzy PID Controller
4. Numerical Simulations
   - Stable Levitation Experiments
   - Robustness Experiments
5. Conclusions

Stable Levitation Experiments

The initial gap x_0 is set as 7 mm, the desired gap x_d is set as 3 mm. The system parameters of the levitation system are set as $R = 3.1\ \Omega$, $m = 14\ \mathrm{Kg}$ and $C = 7.8 \times 10^{-4}$, respectively.

The control parameters in switching mode controller are set as $c_1 = 1.5$, $\varepsilon = 0.001$ and $k = 10$, respectively.

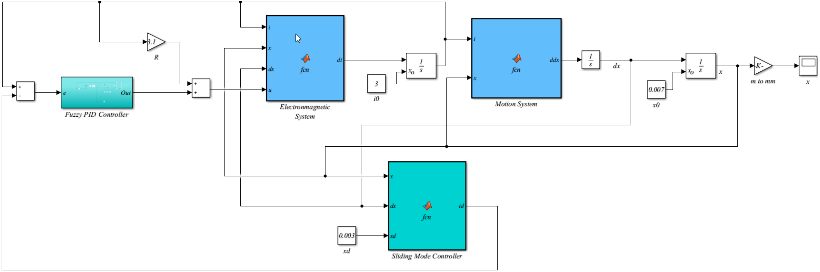

Figure 4: Simulation model in Simulink.

Stable Levitation Experiments

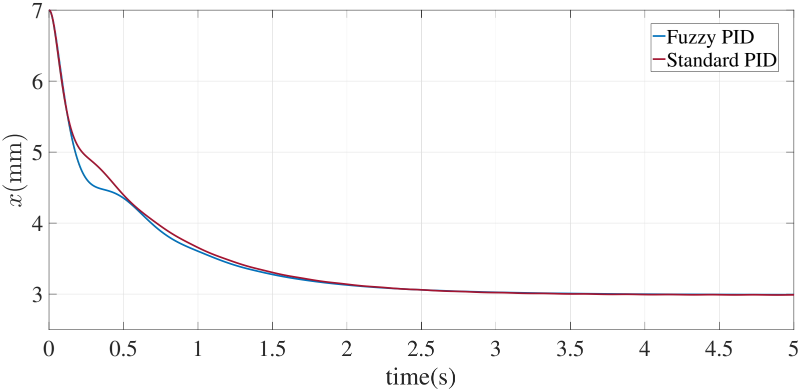

Figure 5: Curves of the actual gap x.

Stable Levitation Experiments

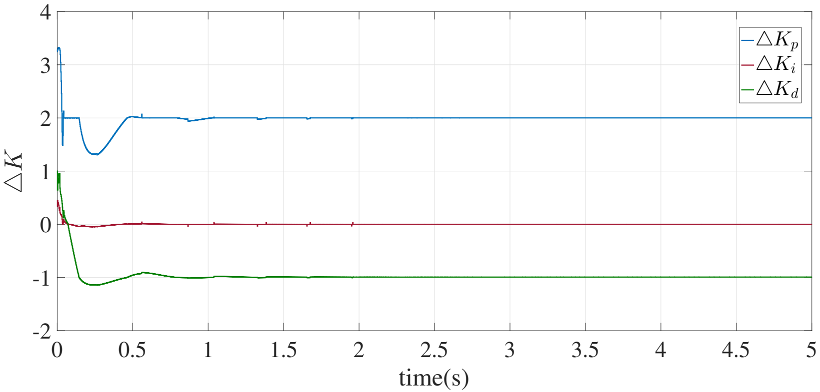

Figure 6: Curves of $\triangle K$.

Outline

1. Introduction
2. Model of Levitation Systems
3. Controllers Design
    - Design of Sliding Mode Controller
    - Design of Fuzzy PID Controller
4. Numerical Simulations
    - Stable Levitation Experiments
    - Robustness Experiments
5. Conclusions

Robustness Experiments

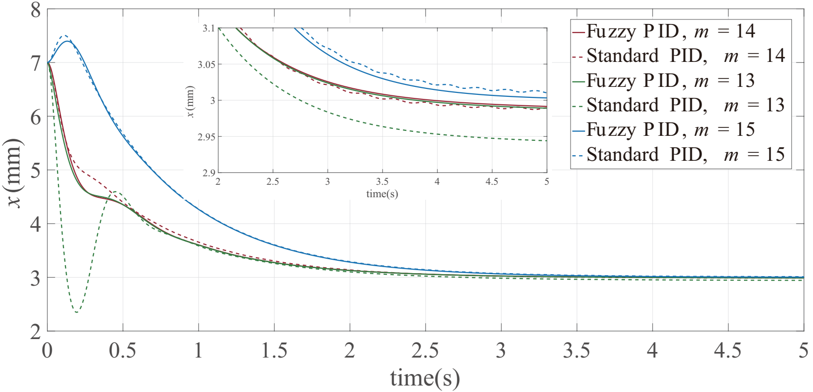

Figure 7: The results for different mass m.

Robustness Experiments

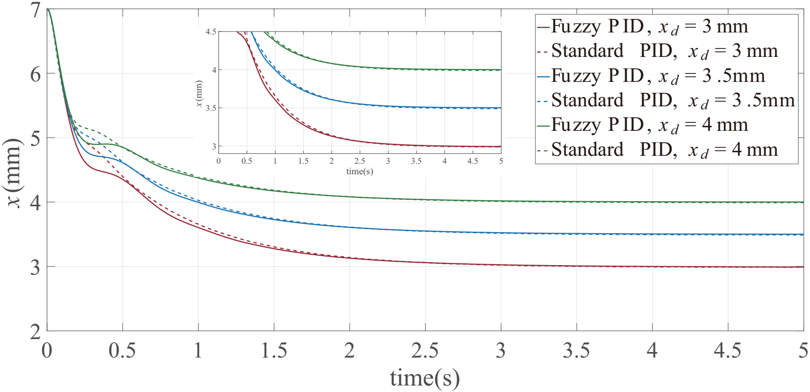

Figure 8: The results for different desired gap x_d.

- Achieve the stable levitation of the single-point levitation system for maglev train by applying the cascade control.
  - Electromagnetic system: switching mode controller
  - Motion system: fuzzy PID controller
- Further works.
  - Cooperative control of multi-point levitation system
  - Improvement of the designed controller for faster stable levitation
  - Robustness analyses in theory

- Achieve the stable levitation of the single-point levitation system for maglev train by applying the cascade control.
  - Electromagnetic system: switching mode controller
  - Motion system: fuzzy PID controller
- Further works.
  - Cooperative control of multi-point levitation system
  - Improvement of the designed controller for faster stable levitation
  - Robustness analyses in theory

Thanks for your attention!

Q&A