SLIDING-MODE-PID CONTROLLER DESIGN FOR MAGNETIC LEVITATION SYSTEM

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Abstract - Emission from vehicles is one of causes of environmental pollution and threat to human health. Magnetic levitation (Maglev) train with high speed, comfort, low energy consumption and low emission is a good solution to this problem. This paper studies Maglev system as a foundation to develop Maglev trains. The paper also presents a sliding mode control (SMC) combining PID (PID-SMC) control for issues of regulation and tracking of a Maglev system with uncertainty. First, nonlinear dynamics model of magnetic levitation system is built. Second, a PID controller, whose gains are chosen suitably in order to guarantee the stability is applied. Next, to increase the robustness of the system and requirement of uncertainty bound in the design, a SMC controller is proposed to compensate the uncertainties of the dynamics system. All gains of sliding mode control system are generated by experimental method. Finally, a composite controller consisting of a PID plus a SMC algorithm is proposed to enhance overall tracking performance. The effectiveness of controllers is verified through experiment results.

Key words - magnetic levitation (Maglev); sliding mode control (SMC); PID combined SMC (PID-SMC).

1. Introduction

Traffic congestion has been one of problems on theworld in recent years [1, 2]. This congestion status also happens in Vietnam [3]. The congestion causes much waste of fuel, time, especially environmental pollution [1, 2, 3]. To solve this issue, a new type of mass transportation has been studiedin the past few decades. This transportation is known as Maglev, or magnetic levitation system. Maglev (Magnetic Levitation) train is a late-model railway vehicle with many good performances such as high speed, comfort, low energy consumption and low emission.Lots of countries have started up the engineering study of maglev train [4, 5].

In Vietnam, one of the first Maglev Systems has been constructed in Hanoi capital and Ho Chi Minh City. Therefore, studies about control algorithm of Maglev System are very necessary in current time. To understand the complexity of this control system, a Maglev system has been designed by Educational Control Products (ECP), which is model 730 Maglev of ECP based on the control of magnetic systems. The Model 730 is useful for the development of studies in control theory applications. It is the magnetic control system complexity outlining the importance of control theory to the precision control of magnetic levitation systems [6]. Research on Magnetic Levitation System – ECP model 730 will lead application into the world of complex control designs so a lot of researches have been done for controlling the Maglev in recent years.

In few years, a lot of research has been conducted for controlling the magnetic levitation (Maglev) system. It is very difficult to control magnetic levitation system because the dynamics of the system is described by a high order nonlinear equation and it is unstable in the open-loop operations. In [7-9], the feedback linearization method has been proposed to design a controller for magnetic levitation system. There are some problems for stability, accuracy and robustness of system because these designs only use nominal parameters of the system. Uncertainty of system also arises because the parameters vary due to environment conditions. Next, a sensorless control using second order sliding mode control was proposed to control magnetic levitation system [10]. This technique was a nonlinear control method being robust to parameter variation and external disturbances. An adaptive robust nonlinear controller was proposed to control magnetic levitation system [11]. This designed controller based on nonlinear system model having parameter uncertainties. This approach helps to overcome practical problems such as poor transient performance and high-gain feedback of the adaptive controller. Among others, PID controller is widely used widely in industrial applications for its ease of implementation. However, it is not robust to variation of parameter and disturbances [12].

To alleviate such difficulty, a SMC is proposed to increase the robustness of system. SMC is a nonlinear control method being robust to parameter variation and external disturbances. However, the SMC gain must be large enough to satisfy requirement of uncertainty bound and guarantee closed-loop stability over the entire operating space [13, 14]. On the other hand, larger control gains are more possible to ignite chattering behaviors. Therefore, the SMC gain must be chosen to bargain the robustness of the controller and the chattering behaviors.

Regarding this, it is then natural to formulate a composite controller possessing the advantages of the above-mentioned two controllers while avoiding their disadvantages at the same time. Basically the SMC dominates when the tracking errors are large while in the region with smaller tracking errors the control authority is switched to the PID controller to avoid possible chattering behaviors. Experimental results demonstrate its validity of the proposed control algorithm.

The remainder of the paper is organized as follows: a derivation of the system's dynamical model based on the Newton's method is presented in next section. The central part of this paper, namely, the control design, is detailed in after this section. To demonstrate the usefulness of the proposed designs, simulation and experimental results doneon Magnetic Levitator - Model 730 of ECP are given in experiment section. Conclusion is drawn in final section.

2. Dynamics of Magnetic Levitation System

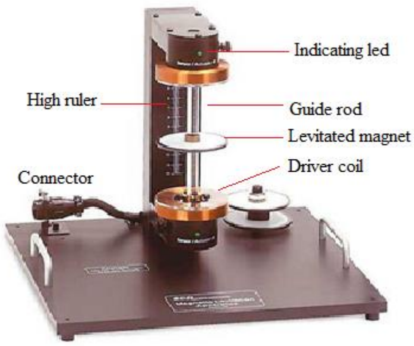

Figure 1. *Magnetic Plant*

The physical structure of a typical Maglev is shown in Figure 1. The plant consists of a drive coil that generates a magnetic field; a magnetic levitated permanent magnet that can be moved along a grounded glass rod; and a laser-based position sensor. The forces from coil, gravity, and friction act upon the magnet. From Newton's second law of motion, the system dynamics can be written as:

$$F_m - mg - c\dot{x}_r - F_L = m\ddot{x}_r \tag{1}$$

Where x_r is the distance between the coil and the magnet, m is the weight of the magnet, F_m is the magnetic force, c is the friction constant, and g is the gravitational constant, F_L is the external force disturbance. The magnetic force can be calculated as [10].

$$F_m = \frac{u}{a(x_r+b)^N} \tag{2}$$

Where u is the control effort. N, a and b can be determined by experimental methods (typically 3<N <4.5) [15]. These parameters can be estimated by constant values in the desired region of operation. However, because of the intrinsic nonlinearity of the magnetic fields, these constants will vary when the dynamics goes out of parameter determination region.

3. Control Design

Replacing (2) into (1), we get:

$$\ddot{x}_r = -\frac{c}{m}\dot{x}_r - \frac{u}{ma(x_r+b)^N} - g - \frac{F_L}{m} \tag{3}$$

The dynamic magnetic levitation is rewritten following:

$$\ddot{x}_r = f(X;t) + G(X;t)U(t) + d(X;t) \tag{4}$$

where

$$X = [x_r, \dot{x}_r]^T;\ G(X;t) = \frac{1}{ma(x_r+b)^N}$$

$$d(X;t) = -g - \frac{F_L}{m};\ f(X;t) = -\frac{c}{m}\dot{x}_r$$

U(t)=u(t) is the control effort and X is the state vector. To separate the nominal system and the uncertainties (in which the external disturbance F_L=0), the dynamics equation can be shown as:

$$\ddot{x}_r(t) = [f_n(X;t) + \Delta f] + [G_n(X;t) + \Delta G]U(t) + [d_n(X;t) + \Delta d] \tag{5}$$

The equation (5) can be modified as

$$\ddot{x}_r(t) = f_n(X;t) + G_n(X;t)U(t) + d_n(X;t) + L(X;t) \tag{6}$$

where the index of n present nominal part of the equation term and L(X;t) is call the lumped uncertainty and is defined as:

$$(X;t) = \Delta f + \Delta GU(t) + \Delta d \tag{7}$$

It is assumed that the bound of L is known in advance:

$$L(X;t) < \delta \tag{8}$$

whereδ is a given positive constant

3.1. PID control

The design of PID controller consists of two steps. The first is to simulate the real plant (it is presented by transfer function G(s)). The second is to choose gains of PID controller (G_{PID} (s)) suitably. Function G_{PID} is given by

$$G_{PID} = K_p * e(t) + k_d\dot{e}(t) + K_i\int_0^t e(\tau)d\tau \tag{9}$$

where e is errors, K_p is proportional gain, K_i is integral gain, K_d is derivative gain. The stability and robustness of system depend on K_i, K_p, K_d gain.

3.2. Sliding Mode Control

The design of the sliding mode controller consists of two stages. The first is to define the error $e=x_r-x_m$ (the error between the desired position x_m, and the real position x_r). The second is to design sliding surface in the state variable space to ensure good control performance. The third is to formulate a control law to reach the state of the system on the desired predefined surface and to maintain its position on it. The sliding surface is defined as:

$$S(t) = \dot{e}(t) + \lambda_1 e(t) + \lambda_2\int_0^t e(\tau)d\tau \tag{10}$$

where λ_1 and λ_2 are positive constants. Differentiating S(t) with respect time

$$\begin{aligned}\dot{S}(t) &= \ddot{e}(t) + \lambda_1\dot{e}(t) + \lambda_2 e(t)\\ &= x(t) - \dot{x}_m(t) + \lambda_1\dot{e}(t) + \lambda_2 e(t)\\ &= f_n(X;t) + G_n(X;t)U(t) + d_n(X;t)\\ &+L(X;t) - \ddot{x}_m(t) + \lambda_1\dot{e}(t) + \lambda_2 e(t)\end{aligned} \tag{11}$$

By choosing the value λ_1 and λ_2 properly, the feature of system dynamic such as rise time, overshoot, and setting time can be changed by the second-order system. It is important to find a control law u(t) so that the state x_r remains on the surface S(t)=0, for all t. The globally asymptotic stability of (11) is guaranteed when the following control law is applied to the magnetic levitation system. Control law is given by

$$U_{SMC}(t) = G_n(X;t)^{-1}[-f_n((X;t) - d_n(X;t) + \ddot{x}_m(t) - \lambda_1\dot{e}(t) - \lambda_2 e(t) - \delta sgn(S(t))] \tag{12}$$

wheresgn is the sign function

Lyapunov function candidate is defined as:

$$\mathrm{V} = \frac{1}{2}\mathrm{S}^2 \tag{13}$$

Differentiating V with respect to time using (11), we get:

$$\dot{V} = S\dot{S} = S(t)[f_n(X;t) + G_n(X;t)U(t) + d_n(X;t) + L(X;t) - \ddot{x}_m(t) + \lambda_1\dot{e}(t) + \lambda_2 e(t)] \tag{14}$$

Replacing control law from (12) into (14) results in the following:

$$\dot{V} = S(t)\{ f_n(X;t) + G_n(X;t)G_n(X;t)^{-1}[f_n(X;t) -d_n(X;t) + \ddot{x}_m(t) - \lambda_1\dot{e}(t) - \lambda_2 e(t) - \delta sgn(S(t))] + d_n(X;t) + L(X;t) - \ddot{x}_m(t) + \lambda_1\dot{e}(t) + \lambda_2 e(t)\}$$
$$= S(t)\{L(X;t) - \delta sgn(S(t))\} \quad (15)$$

The time derivative of the candidateLyapunov function can be separated as:

$$1)\ S(t) < 0 \to sgn(S(t)) = -1$$
$$\to L(X;t) - \delta sgn(S(t)) > 0$$
$$\dot{V} = S(t)\{L(X;t) - \delta sgn(S(t))\} < 0$$
$$2) S(t) = 0 \to \dot{V} = 0$$
$$3) S(t) > 0 \to sgn(S) = +1$$
$$\to L(X;t) - \delta sgn(S(t)) < 0$$
$$\dot{V} = S(t)\{L(X;t) - \delta sgn(S(t))\} < 0$$
$$(1),(2),(3) \to \dot{V} \le 0$$

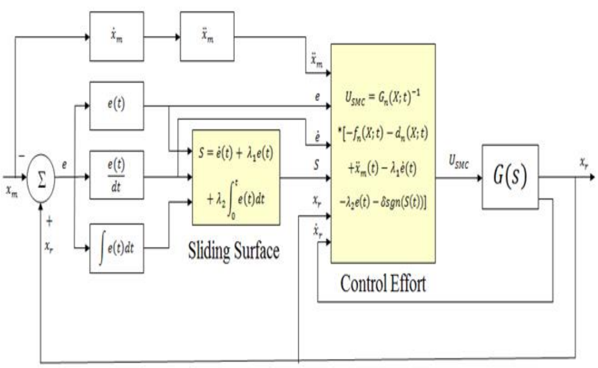

Figure 2. *SMC Control*

Thus, the designed control law is completely satisfied the asymptotic stability. Moreover, the SMC guarantees that the state trajectory of the system reaches the sliding surface in a finite time and stays on it, with any initial condition. The model was show in Figure 2. A large control gain δ is often required in order to minimize the time required to reach the switching surface from the initial, and the selection of the control gain δ relative to the magnitude of uncertainties to keep the trajectory on the sliding surface.

3.3. PID-SMC controller

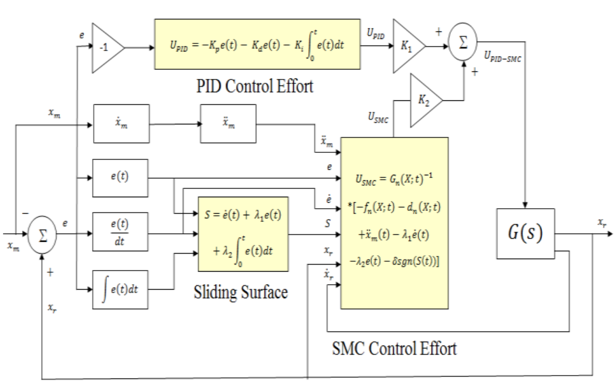

Figure 3. *PID-SMC Control*

In practice, the control gainδmight be too conservative which might ignite chattering behavior. Regarding this, we propose a combination controller between PID and SMC to reduce chattering as well as maintain robustness at the same time. The block diagram of the proposed controller is shown in Figure 3 and control effort of PID-SMC is given by:

$$U_{PID-SMC} = K_1 U_{PID} + K_2 U_{SMC} \quad (16)$$

where: K_1 and K_2, which are positive constants,are chosen empirically.

4. Experimental Results

Experimental works for verifying the validity of the proposed controller are conducted here. Parameter identification using curve-fitting technique is done first andthe results are m=0.121 (kg); c=2.69; a=1.65; b=6.2; N=4. Initial conditions of this experiment are that the initial magnet position (x_r) is 20mm in all experiments and the controlled stroke of the disk (Δx) is 10mm. The chosen PID gain are K_p=1.72, K_d=0.065, K_i=0.5, the chosen SMC gains are λ_1=30; λ_2=10; δ=10 and the chosen PID-SMC constants are K_1=0.5; K_2=0.5. The errors are calculated by the sum of squared tracking errors (SSTE).

$$SSTE = \sum_{k=1}^{n} (error(kT))^2$$

where t=kT is time from 0 to 4s, and T=0.002562.

To explore the adaptability of the proposed design to variation of parameters, two case studies are considered in the following:

- Case 1: magnet weight is 0.121 kg (m=0.121 kg).

- Case 2: magnet is added a disk weighing 0.03 kg. Total weight of disk is 0.151 kg (m=0.151kg).

In case 1, testsare implemented with sinusoidal command and the experimental results are displayed in Figure 4, Figure 5 and Figure 6. The error measure is calculated by SSTE method and shown in Table 1.

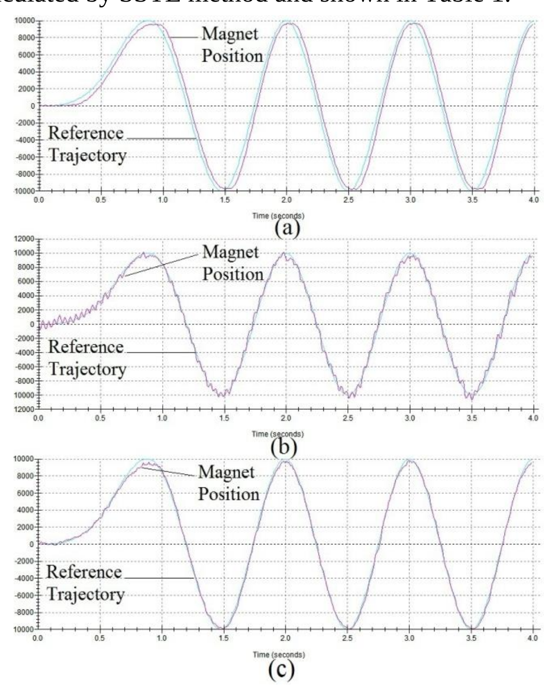

Figure 4. *Performance of PID (a), SMC (b), PID-SMC (c) in case 1*

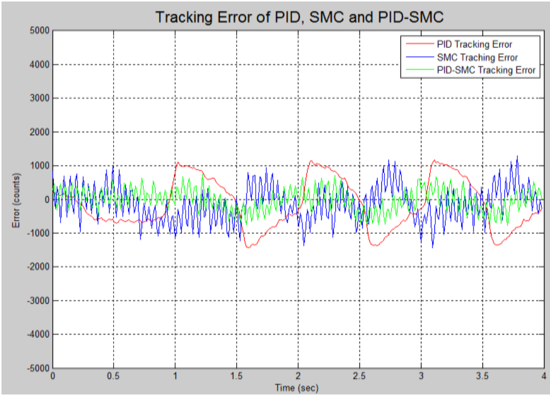

Figure5. *Error of PID, SMC, PID-SMC in case 1*

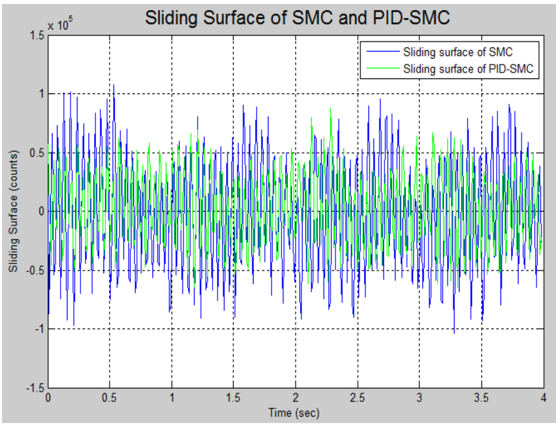

Figure 6. *Sliding surface of SMC, PID-SMC in case 1*

Table 1. *Error measures of PID, SMC, PID-SMC in case 1*

Performance / Reference Trajectory	Sum of Squared Tracking Error [mm^2] (SSTE)		
	PID	SMC	PID_SMC
Sinusoidal trajectory	$7.6x10^2$	$3.4x10^2$	$1.3x10^2$

The Figure 4 shows that performance of PID-SMC is better than PID and SMC. Besides, Figure 5 and Table 1 illustrate that error of PID-SMC is the smallest. In addition, chattering in operation of PID-SMC decreases dramatically and be show in Figure 6.

In case 2, tests are implemented with sinusoidal command and the experimental results are displayed in Figure 7, Figure 8 and Figure 9. The error measure is calculated by SSTE method and shown in Table 2.

In this case, the error of PID increases drastically so its tracking performance is poor. In contrast, SMC errors do not grow up significantly due to the robustness of SMC to the variation of system parameters and disturbances. Similarly, the PID-SMC controller has the same characteristics but without igniting chattering behaviors and sliding surface is less.

Table 2. *Error measures of PID, SMC, PID-SMC in case 2*

Performance / Reference Trajectory	Sum of Squared Tracking Error [mm^2] (SSTE)		
	PID	SMC	PID_SMC
Sinusoidal trajectory	$1.2x10^3$	$4.2x10^2$	$1.7x10^2$

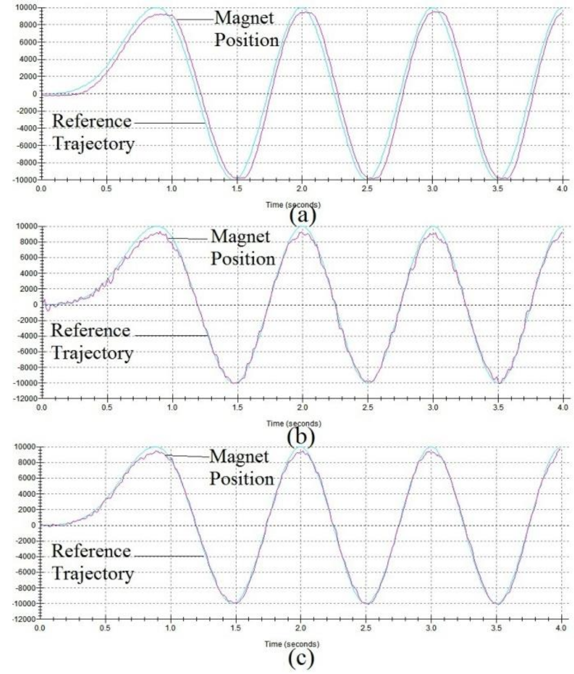

Figure 7. *Performance PID (a), SMC (b), PID-SMC (c) in case 2*

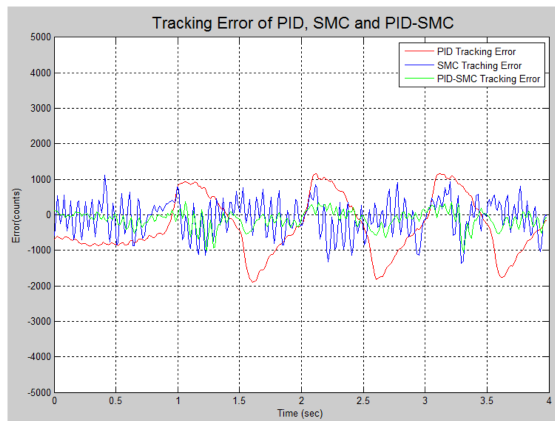

Figure 8. *Tracking error of PID, SMC, PID-SMC in case 2*

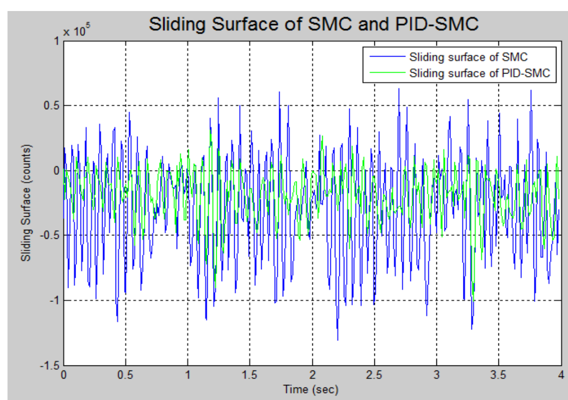

Figure 9. *Sliding surface SMC, PID-SMC in case 2*

5. Conclusion

This paper has successfully demonstrated the effectiveness SMC and PID-SMC to control the position of a magnetic levitated object. As expected, the SMC exhibits good tracking performances robustness to parameter variation and disturbances. However, it creates larger chattering behaviors. The proposed PID-SMC algorithm retains the advantages of SMC algorithm while avoids chattering at the same time. The experimental results confirm these features clearly.

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