Journal of Robotics and Control (JRC)
Volume 3, Issue 6, November 2022
ISSN: 2715-5072, DOI: 10.18196/jrc.v3i6.12389

Sliding Mode Control Design for Magnetic Levitation System

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Abstract— **This paper presents a control system design for a magnetic levitation system (Maglev) or MLS using sliding mode control (SMC). The MLS problem of levitating the object in the air will be solved using the controller. Inductors used in MLS make the system have nonlinear characteristics. Thus, a nonlinear controller is the most suitable control design for MLS. SMC is one of the nonlinear controllers with good robustness and can handle any model mismatch. Based on simulation results with a step as input reference, MLS provided good system performances: 0.0991s rise time, 0.1712s settling time, and 0.0159 overshoot. Moreover, a prominent tracking control for sine wave reference was also shown. Although the augmented system had a chattering effect on the control signal, the chattering control signal did not affect MLS performances.**

Keywords—Magnetic levitation system; sliding mode control; nonlinear system; nonlinear control

I. INTRODUCTION

Magnetic Levitation System (Maglev) or MLS is a system that levitates an object (usually iron-made objects) using an electromagnetic force [1]–[3]. MLS can be considered a futuristic technology [4] that has broad applications, such as in wind turbines [5], bearings [6][7], suspensions [8], precision motion systems [9], biomedical [10][11], Maglev fan [12], chemical [13], robotics [14] and maglev trains [15]–[18]. This technology makes the system highly efficient since no friction is made between the object and the system [19].

The simplest design of MLS is shown in Fig. 1 [20]. The system consists of an iron object, an inductor to generate the electromagnetic force, a controller (Microcontroller), and a driver [21]. The electromagnetic and gravity forces must have the same value so that the object can levitate [22][23].

Due to its nature, MLS has nonlinear [24], unstable [25], and fast dynamics characteristics [26]. Thus, a suitable controller is needed to control MLS [27]. The nonlinearity is caused by the inductor changing its inductance when the temperature increases [28]. Meanwhile, MLS has unstable and fast dynamics characteristics because the levitating object is easy to fall.

Because of these characteristics, nonlinear controllers are the most suitable for MLSs [29]. Besides, a linear controller, such as PID and FOPID, needs a linear model, although it is plausible to be obtained from a linearization [30]–[38]. Another controller that needs the system to be modeled in a linear one is the widely known state feedback [39]–[42]. Meanwhile, a controller based on fuzzy logic control is not easy to design [43], needs practical data reference or additional knowledge from other controllers [44] and requires high computation to run the fuzzy [45]. Likewise, as proposed in [46], neural network control for MLS needs training data from other controllers [47][48].

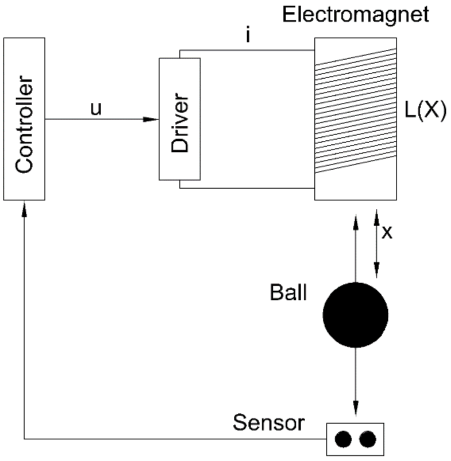

Fig. 1. MLS design

The sliding mode control is a robust nonlinear controller which can easily handle a system's nonlinearity, uncertainty and model mismatch [49]–[52]. It has been implemented to control both linear and nonlinear systems: hydraulic [53][54], single machine infinite bus system [55], inverted pendulum [56]–[58], DC motor [59], induction motor [60], suspension [61], permanent magnet synchronous generator [62], hyperchaotic system [63], quadcopter [64], mobile robot [65][66], stepper motor [67], tank system [68] and robot manipulator [69]. According to study findings, SMC has been reported to give promising results. Hence, this paper's contribution is to present SMC implementation in controlling MLS.

There is some section in the paper. The first section is the introduction. The second section is the modeling of the magnetic levitation system. The third system is a sliding mode control design. The fourth section is the result and discussion. The last section is a conclusion and future work.

II. MAGNETIC LEVITATION MODEL

The maglev system diagram is shown in Fig. 2, where R denotes the resistance, L is inductance, F_g is gravity force, F_e is the electromagnetic force, x is the object position from the inductor, e is the source voltage, m is the object mass, and i is the current.

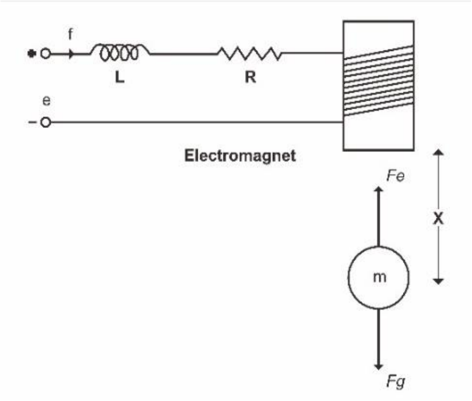

Fig. 2. MLS dynamics diagram

Based on the mechanical analysis using the second Newton law, the dynamics of MLS can be written as

$$m\ddot{x} = mg - f_e \tag{1}$$

where the electromagnetic force is expressed as

$$f_e = -\frac{1}{2} i^2 \frac{d}{dx}(L(x)) \tag{2}$$

The inductance $L(x)$ is a nonlinear component that can be represented as

$$L(x) = L + L_0 x_0 \tag{3}$$

Thus, the electromagnetic force can be rewritten as

$$f_e = k\frac{i^2}{x^2} \tag{4}$$

where

$$k = \frac{L_0 x_0}{2} \tag{5}$$

Concisely, a mathematical expression of MLS dynamics based on the mechanical analysis in (1) can be stated as

$$\frac{d^2x}{dt^2} = g - \frac{k}{m}\left(\frac{i}{x}\right)^2 \tag{6}$$

Aside from mechanical analysis, an equation can be derived based on electrical analysis using the Kirchhoff law on voltage, as in (7).

$$e = iR + \frac{d}{dt}L(x)i \tag{7}$$

Using simple mathematical operations, the equation can be rewritten as

$$\frac{di}{dt} = -\frac{R}{L}i - \frac{2k}{L}\frac{i}{x^2}\frac{dx}{dt} + \frac{1}{L}e \tag{8}$$

Therefore, the dynamics of MLS can be built and represented as a state-space model by assuming $x_1 = x$, $x_2 = \dot{x}$, $x_3 = i$, and by referring to (6) and (8). The dynamics of MLS in a state-space representation are written as follows

$$\dot{x}_1 = x_2 \tag{9}$$

$$\dot{x}_2 = g - \frac{kx_3^2}{mx_1^2} \tag{10}$$

$$\dot{x}_3 = -\frac{Rx_3}{L} + \frac{2kx_2x_3}{Lx_1^2} + \frac{u}{L} \tag{11}$$

with the output of the system defined as

$$y = x_1 \tag{12}$$

As can be seen in the dynamics of MLS, the nonlinearity characteristics can be observed in (10) and (11). A simpler model with only one dynamics equation that shows the nonlinearity can be achieved by transforming the model into an equivalent canonical form. The nonlinear transform in coordinates can be defined as follows

$$z_1 = x_1 \tag{13}$$

$$z_2 = x_2 \tag{14}$$

$$z_3 = g - \frac{kx_3^2}{mx_1^2} \tag{15}$$

where $x_1 > 0$ and $x_3 > 0$.

Thus, an equivalent model in new coordinates can be expressed as

$$\dot{z}_1 = z_2 \tag{16}$$

$$\dot{z}_2 = z_3 \tag{17}$$

$$\dot{z}_3 = f(z) + g(z)u \tag{18}$$

where

$$f(z) = -\frac{4k^2x_2x_3^2}{mLx_1^4} + \frac{2kRx_3^2}{mLx_1^2} + \frac{2kx_3^2x_2}{mx_1^3} \tag{19}$$

$$g(z) = \frac{2kx_3}{mx_1^2L}u \tag{20}$$

and $x_1 > 0$.

III. SLIDING MODE CONTROL DESIGN

The first step in designing sliding mode control is designing the switching surface [70]. The switching surface is defined as

$$s = c_1e + c_2\dot{e} + \ddot{e} \tag{21}$$

where c_1, c_2 must fulfill the Hurwitz condition, $c_1, c_2 > 0$.

Meanwhile, the tracking error and its derivative can be determined as in the following equations

$$e(t) = z_1(t) - z_{1d}(t) \tag{22}$$

$$\dot{e}(t) = \dot{z}_1(t) - \dot{z}_{1d}(t) \tag{24}$$

$$\ddot{e}(t) = \ddot{z}_1(t) - \ddot{z}_{1d}(t) \tag{25}$$

where z_{1d} is the referenced value.

Then, the Lyapunov theorem is applied to determine the equation of the sliding mode controller. The Lyapunov function is written as follows

$$V = \frac{1}{2}s^2 \tag{26}$$

In order to guarantee the system’s stability, the first derivative of (26) must be a negative value, as in

$$\dot{V} = s\dot{s} < 0 \tag{27}$$

Meanwhile, the derivative of the sliding function can be derived from (21), as written in the following equations

$$\dot{s} = c_1\dot{e}(t) + c_2\ddot{e}(t) + \dddot{e}(t) \tag{28}$$

$$= c_1\dot{e}(t) + c_2\ddot{e}(t) + [\dot{z}_3(t) - z_{3d}(t)] \tag{29}$$

$$= c_1\dot{e}(t) + c_2\ddot{e}(t) + f(x) + g(x)u - z_{3d}(t) \tag{30}$$

While the derivative of the Lyapunov function can be defined as

$$s\dot{s} = s[c_1\dot{e}(t) + c_2\ddot{e}(t) + f(x) + g(x)u - z_{3d}(t)] \tag{31}$$

Finally, the equation of SMC, which is the control signal, can be determined by considering equation (27). The control signal can be expressed as in the following equations.

$$u(t) = \frac{1}{g(x)}(-f(x) - c_1\dot{e}(t) - c_2\ddot{e}(t) + z_{3d}(t) - \eta\ sgn(s)) \tag{32}$$

$$sgn(s) = \begin{cases} 1, & s > 0 \\ 0, & s = 0 \\ -1, & s < 0 \end{cases} \tag{33}$$

The equations can be proven to fulfill the stability condition as in (27) by substituting (32) into (31). The result of the substitution, which is the mathematical proof, is expressed in the equation as

$$s\dot{s} = -\eta|s| < 0 \tag{34}$$

Thus, the controller is guaranteed to fulfill the stability condition.

IV. RESULT AND DISCUSSION

The simulation was done in Simulink MATLAB 2018. The parameters of MLS used in the research are listed in Table 1.

TABLE I. PARAMETERS OF MLS

Parameter	Value
Coil Resistance	9Ω
Coil Inductance	0.12H
Gravity Acceleration	9.8m/s2
Object Mass	0.36kg
Force Constant	0.00013Nm2/A2

This study implemented the SMC to control MLS with two input references: step and sine wave signals. Step and sine as signals had distinctive characteristics; each signal represented a different difficulty to be controlled or tracked.

A step signal with an amplitude of 0.01m was given to the augmented system in the first simulation. The system response is shown in Fig. 3. Based on the figure, the augmented system can reach the reference; the steady-state error was not found. The system’s performances were: 0.0991 rise time, 0.1712 settling time, and 0.0159 overshoot. In other words, the applied MSC could control MLS when given a step as the reference with satisfactory performances: zero steady-state error and reasonably fast system response. Meanwhile, the control signal given by the SMC is provided in Fig. 4. It can be seen that the control signal had a chattering effect.

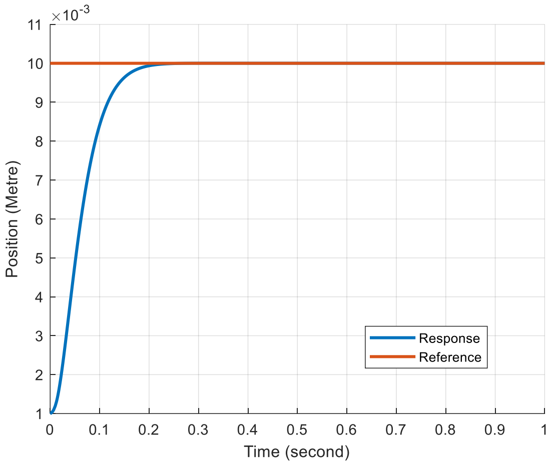

Fig. 3. MLS Response of step reference

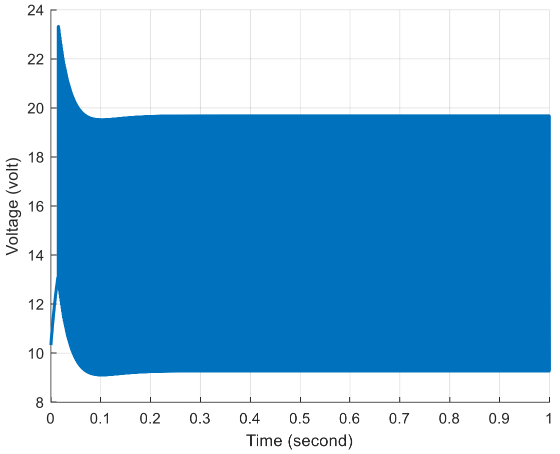

Fig. 4. SMC Control signal of step reference

Then, the augmented system was given with a sine wave reference ($0.5 * sin(pi * t)$) in the next simulation. The system response is shown in Fig. 5, and the control signal given by SMC is shown in Fig. 6. Similarly, according to Fig. 5, it is proven that the SMC can make the MLS track sine wave reference. Also, it can be seen that the control signal had a chattering effect, as presented in Fig. 6.

Both simulation results showed that the applied SMC was successfully controlled MLS with step and sine wave signals as references without any significant issues. Although both control signals had the chattering effect, all system responses were not affected. This phenomenon indicates that the chattering effect in the control signal does not necessarily negatively impact MLS performance specifications.

The chattering effect in the SMC control signal occurred due to the sign function in its equation, as can be seen in (32) and (33). Although the chattering effect did not negatively affect MLS performance, the chattering could be compensated by considering changing the sign function into a saturation/threshold function.

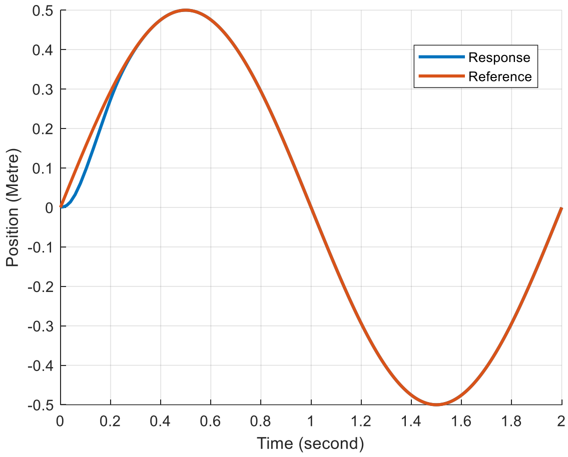

Fig. 5. MLS response of sine reference

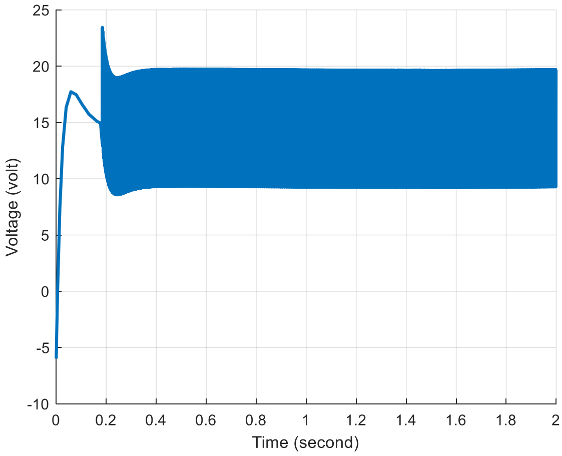

Fig. 6. SMC Control Signal of sine reference

V. CONCLUSION

This paper present about a control system design for Magnetic Levitation System (MLS) using the Sliding Mode Control (SMC). Based on simulation results, SMC performed satisfactorily in tracking control using step and sine signals as reference. However, the SMC control signal had a chattering effect due to the sign function in its equation. Since the augmented system performed well, with a fast system response and no steady-state error, it can be stated that the chattering effect in the SMC control signal did not affect MLS performances. The future research about magnetic levitation is hardware implementation, design another controller and controller optimization.

ACKNOWLEDGMENT

The author would like to thank Universitas Ahmad Dahlan for the grant research funding under PD-050/SP3/LPPM-UAD/VII/2022.

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