DISTURBANCE OBSERVER BASED CASCADE FUZZY - SLIDING MODE CONTROL FOR NONLINEAR SYSTEMS

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ABSTRACT:

In this article, a robust control scheme based sliding mode control for nonlinear system is proposed. Firstly, the nonlinear disturbance observer (NDOB) is equipped to eliminate and reject the unknown disturbance. Subsequently, sliding mode control is used to construct outer-loop of cascade control. In this step, fuzzy logic control is presented with Gaussmf input and output membership function to reduce chattering from switching value part of sliding mode controller. Finally, inner-loop of sliding mode control (SMC) method is employed to control electrical value. Basically, cascade control is used to force system states on pre-defined states within two sub-control-loop. This study give proposal mechanical value will be controlled by outer-loop, and electrical value will be controlled by inner-loop, respectively. Simulation results shown that proposed control method is good track for sign reference signal. The transient respond very fast like sliding mode control effective. And distance tracking error is quite good also.

Keywords: Nonlinear disturbance observer NDOB, sliding mode control (SMC), proportional-integral-derivative (PID).

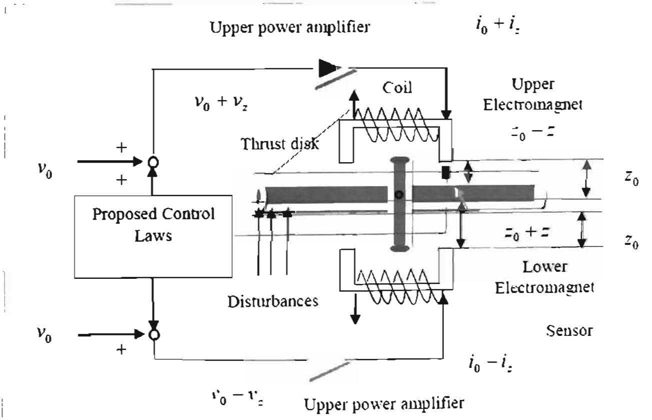
I. Introduction

In every practical system always exist disturbances, and noises. In pass few decades, the disturbance estimation, and rejection for nonlinear system has been interesting, and challenging many scientists in control field. NDOB was originally described by Ohnish in 1987 [1]. NDOB has been developed by many scientists in over pass two decades. Xiao et al. (2014) [2], Ginoya et al. (2014) [3], and Yang et al. (2013) [4], etc.

Sliding mode control (SMC) is a robustness controller [5]. For over almost a half century, SMC has been widely applied in many systems. There are always consist two step to achieve desired goal with SMC. Firstly, the researchers have to design sliding surface. Secondly, how much values for SMC surface parameters are determined to satisfy Lyapunov law. Every system states will be forced to converge on pre-defined sliding surface. In [6] Lin et al. gave intelligent double integral sliding-mode control, Chen et al. [7] has implemented robust nonsingular terminal sliding-mode control for active magnetic bearing system, and Su et al. [8] was used Proportional–integral–derivative/fuzzy sliding mode control for suspension of active magnetic bearing system, etc. SMC was developed in the Soviet Union in the mid-1950s [5]. SMC input equal to the difference between reference value, and measure value. The main problems in designing sliding controller are which SMC surface is, and how much SMC surface parameters are determined correctly. This job is also considered world-wide for many scientists, and researchers, there is they can self-design the surface for suitable systems. Every system states will be forced to converge on the SMC surface [9]. SMC surface function has to satisfy Hurwitz polynomial [9]. All kinds of SMC surface is designed always gives system input control value two catholic parts, there are equivalent, and switching value. Chattering phenomenon always occurs from switching control part. Based on this characteristic many researchers used Saturation function, or Fuzzy logic control to eliminate chattering values. Take advantages of cascade control, this study use double sliding mode controller to design cascade controller. Outer-loop sliding controller will be designed to control mechanical part, there is displacement of nonlinear system will be controlled by proportional-integral-derivative (PID) surface sliding controller, under equivalent, in this stage, Fuzzy controller is used to reduce chattering from switching control value. After all, the inner-loop is employed by sliding mode controller also. But the different of this SMC is the sliding surface just only equal to difference from reference signal and measurement signal. This part the current value from electrical part will be controlled effectively. In nonlinear system, electrical part is considered effective control part. Cascade controller have been using for more than 60 years [10]. These structures are able to compensate of disturbances and time delays [11]. The inner-loop guaranty that the system will be stabilized follows predetermined from outer-loop. This study system is referred to Chen et al. [7], and Su et al. [8], there is active magnetic bearing system with many practical applications. After all, our results compare to Chen, and Su et al [7], and [8] respectively. Although this compare is not fair, but our results figure out that the prosed method is good track reference input signal enough.

Due to non-contact between rotor and stator, working without lubrication, nonfrictionless active magnetic bearing system promising many application such wind turbine, helicopter, flywheel engine, vacuum pump, etc. (Su, and Chen et al.). The most important control objective is the controlled rotor adapt to predefined position, this propose just only focus on control one axial AMB such follows Figure. 1 below.

Fig. 1. The structure of active magnetic bearing system



This study divides into five parts. Firstly, introduction is given some simple information about our works. Secondly, problem formulation gives us system mathematical. and problems need to solve. Thirdly, controller is proposed, after that construct subsystem for whole system, and prove that the proposed method is satisfied some control rules. Subsequently, some simulation results figure out our method is good better than Su, and Chen et al. at the same system, and same situation. Finally, conclusion is make a statement for our proposed control method.

II. Problem formulation

References from Su, and Chen et al. the system mathematical model is described as single input and single output, there are reference signal is pre-defined position of rotor, and output measurement signal is displacement value. System mathematical model is presented follows.

$$m\ddot{x}(t) = -c\dot{z} + k_p.z(t) + k_i.i_{z(t)} - f_{d_{z(t)}} \quad (1)$$

or

$$\ddot{z}(t) = -\frac{c}{m} + \frac{k_p}{m}.z(t) + \frac{k_i}{m}.i_{z(t)} - \frac{1}{m}f_{dz}(t) \quad (2)$$

Denote,

$$A = -\frac{c}{m}, B = k_p / m, C = k_i / m, D = -\gamma$$

Eq.(2) can be re-written as

$$\ddot{z}(t) = A.\dot{z}(t) + B.z(t) + C.i_z(t) + D.f_{dz}(t) \quad (3)$$

System states can be separated by

$$\ddot{z}(t) = (A_n + \Delta A)\dot{z}(t) + (B_n + \Delta B)z(t) + (C_n + \Delta C).i_z(t) + D.f_{dz}(t) \quad (4)$$

Or denote

$$\Xi(t) = (\Delta A.\dot{z}(t) + \Delta B.z(t) + \Delta C.i_z(t) + D.f_{dz}(t)),$$

then Eq.(4) equal to

$$\ddot{z}(t) = A.\dot{z}(t) + B.z(t) + C.i_z(t) + \Xi(t) + D.f_{dz}(t) \quad (5)$$

$\Delta = \Xi(t) + D.f_{dz}(t)$ is lumped uncertainties and give k is positive constant used as hitting gains and required $|\Delta| < k$.

Denote $X = [z(t).\dot{z}(t)]^T, I = i_z(t). W = f_{dz}(t)$ where X is system states value, U is current value, an W is unknown disturbances value. then Eq. (5) can be written such as

$$\dot{X} = \begin{bmatrix} 0 & I \\ B & A \end{bmatrix} X + \begin{bmatrix} 0 \\ C \end{bmatrix} I + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \Xi + \begin{bmatrix} 0 \\ D \end{bmatrix} W \quad (6)$$

Now, redefine above compact form to get dynamic equation of the mentioned system as

$$\dot{X} = G_1X + G_2I + G_3\Xi + G_4W$$

Cascade controller is used sliding mode control in this propose, there are system position, and system current will be controlled by outer-loop, and inner-loop, respectively. The innerloop will make system stable more than outer-loop.

From requires of cascade controller, the system mathematical is divided by two part. There are mechanical, and electrical part. The current value of mechanical will be supplied by the outer c l from electrical part [12]. The model of electrical part is presented as

$$\frac{dI_c}{dt} = -\frac{R_c + R_s}{L_c} I_c + \frac{1}{L_c} V_c \quad (7)$$

where R_c is coil resistance, R_s is current sense resistance, V_c is supply voltage, L_c is coil inductance. V_c is converted through upper, and lower power amplifiers. Based on Eq. (7-8) we construct cascade controller in next section

III. Proposed approach

The design procedure is presented as follows. Firstly, nonlinear disturbance observer to construct the open-loop. Subsequently, cascade sliding mode outer-control-loop is used to construct for system states stable on one pre-defined values, and Fuzzy logic control is used to eliminate chattering value occurs from switching control part of the sliding mode control. Finally, cascade inner-control-loop is used to control electrical value. To archive the desired goal, some subsystem are briefly summarized in the following.

3.1 Nonlinear disturbance observer design

* Nonlinear disturbance observer equation

This section, the disturbance observer will be constructed for open-loop, Based on Eq. (7) the observer model is described as:

$$\begin{cases} \dot{y} = -l(X).G_4[y + p(z)] - l(X).[G_1 + G_2I] \\ \hat{W} = y + p(X) \end{cases} \quad (8)$$

where $p(X)$ is a nonlinear need to make.

$$l(X) = \partial p(X) / \partial X$$

is observer gain, $\hat{W}$ is estimated value of disturbance from system.

Nonlinear disturbance observer is used to estimate uncertain unknown disturbance under operating process. There exists a sub-function $y = H(X) \in R^m$, where $H(X)$ is smooth function, related to degree from disturbance W to y for all system states $X(t)$. Then $p(X)$, $l(X)$ are chosen as

$$l(X) = p_0 \frac{\partial L_f^{\rho-1} h(X)}{\partial X} \qquad (9)$$
$$p(X) = p_0 \partial L_f^{\rho-1} h(X)$$

Respectively, where p_0 is positive constant for tuning the bound of errors.

Let $n_0 = |\min_z L_{G4} L_{G1X} H(X)|$ is positive scalar.

Define $\tilde{W} = W - \hat{W}$ Under Eq.(7) and Eq.(10) error value can be verified as:

$$\dot{\hat{W}} = \dot{W} + l(X)G_4\left[y + p(X)\right] + l(X)\left[G_1 X - l(X)\dot{z}\right] = \dot{W} - l(X)G_4\tilde{W} \qquad (10)$$

Suppose that $|\dot{W}| \le k$ where k is positive constant given by system lump of uncertainties.

The select Lyapunov for Eq. (12) as $V(\tilde{W}) = \tilde{W}^T\tilde{W}$ or can be written as:

$$\begin{aligned}\dot{V}(\tilde{W}) &= 2\tilde{W}^T\left[\dot{W} - l(X)G_4\tilde{W}\right] \\ &= -2\tilde{W}^T l(Z)G_4\tilde{W} + 2\tilde{W}^T\dot{W} \\ &\le -2n_0 p_0 \|\tilde{W}\|^2 + 2\|\tilde{W}\|k \\ &\le -p_0 n_0 \|\tilde{W}\|^2 - \left(\sqrt{p_0 n_0}\|\tilde{W}\| - \frac{k}{\sqrt{p_0 n_0}}\right)^2 + \frac{k}{p_0 n_0} \\ &\le -p_0 n_0 \|\tilde{W}\|^2 + \frac{k}{p_0 n_0}\end{aligned} \qquad (11)$$

Then, we have

$$\|\tilde{W}(t)\| \le \|\tilde{W}(0)\| \exp(-p_0 n_0 t) + \frac{k}{p_0 n_0^2} \qquad (12)$$

which figure out that the system of Eq. (12) is bounded.

* Stability analysis of nonlinear disturbance observer.

Disturbance observer brings out two parts given by: $I_{control} = I_c + \alpha\hat{W}$ (13)

where I_c is conventional control value, substitution of Eq. (14) into Eq. (7) gives

$$\begin{aligned}\dot{X} &= G_1 X + G_2\left[I_c + \alpha\left(W - \tilde{W}\right)\right] + G_3\Xi + G_4 W \\ &= G_1 X + G_2 I_c + \left(G_2\alpha + G_4\right)W + G_3\Xi - G_2\alpha\tilde{W}\end{aligned} \qquad (14)$$

There exists NDOB law as Eq. (14) such closed-loop is input-to-state stable, where W and $\tilde{W}$ are bounded, then we construct the α in the procedure following [13]. Based on the matching condition α is chosen as $\alpha = G_2^{-1}G_4$ is in the sense that input-to-state stable. Then this study gives cascade control based on this term to determine controller parameter as following.

3.2 Cascade sliding mode control

This section is given by cascade with two control loops, it is the same type of controller, based on sliding mode control. The inner-loop will be designed to reach pre-defined current from outer-loop, in the outer-loop the desire goal is control system position. Otherwise, this work is designed when system consist disturbance sub-system inside as

$$\dot{X} = G_1 X + G_2\left(I_c + \alpha\hat{W}\right) + G_3\Xi + G_4 W \qquad (15)$$

Eq.(16) can be written as

$$\begin{bmatrix} z(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} 0 & I \\ B & A \end{bmatrix}\begin{bmatrix} z(t) \\ \dot{z}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ C \end{bmatrix}\left(I_c + \alpha\hat{W}\right) + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\Xi + \begin{bmatrix} 0 \\ D \end{bmatrix}W \qquad (16)$$

This study propose outer-loop to force system states converge to pre-defined position, then SMC can be described as

Step 1: Cascade outer-loop design

Sliding mode control is robust control method, it can be apply for many kind of system, such nonlinear or linear systems. Where SMC system is presented such Eq. (18)

$$\begin{cases} \ddot{z}(t) = f(t, z, i) \\ s = s(t, z) \end{cases} \qquad (17)$$

Sliding mode surface is selected as

$$s_{out}(t) = \dot{z}_m(t) - \dot{z}_r(t) + \lambda_1\left(z_m(t) - z_r(t)\right) + \lambda_2\int_0^t \left(z_m(\tau) - z_r(\tau)\right)d\tau \qquad (18)$$

where z_r is reference distance and z_m is measured distance $\lambda_1\lambda_2 > 0$ is chosen such that the real parts of the roots of

$P(S_{out}) = S^2_{out} + \lambda_1 S_{out} + \lambda_2 < 0$, then sliding surface is satisfied Lyapunov law as:

$$\begin{aligned}\dot{V}(t) &= \dot{s}_{out}(t)s_{out}(t) < 0 \\ \dot{s}_{out}(t) &= \ddot{z}_m(t) - \ddot{z}_r(t) + \lambda_1\left(\dot{z}_m(t) - \dot{z}_r(t)\right) + \lambda_2\int_0^t \left(\dot{z}_m(\tau) - \dot{z}_r(\tau)\right)d\tau\end{aligned} \qquad (19)$$

$$= \ddot{z}_m(t) - A\dot{z}(t) + Bz(t) + C\left(I_{out}(t) + \alpha\hat{W}\right) + \lambda_1\left(\dot{z}_m(t) - \dot{z}_r(t)\right) + \lambda_2\int_0^t\left(\dot{z}_m(\tau) - \dot{z}_r(\tau)\right)d\tau \quad (19)$$

The current is calculated as

$$I_{cref}(t) = \frac{1}{C}\left[\ddot{z}_r(t) - \left(A\dot{z}(t) + Bz(t)\right) + \lambda_1\left(z_r(t) - z_m(t)\right) + \lambda_2\int_0^t\left(\dot{z}_r(\tau) - \dot{z}_m(\tau)\right) + ksat\left(s_{out}(t)\right) + \alpha\hat{W}\right] \quad (20)$$

where I_{out} is reference signal of inner-loop.

In order to system states reach more precise to pre-defined position, Fuzzy is proposed to reduce chattering from switching control part

Step 2: Fuzzy logic controller

Fuzzy logic is a practical mathematical addition to classic Boolean logic [15]. Under sliding mode control condition, chattering value is occurred in switching control, then this study propose the power toll to eliminate this unwell value. Fuzzy membership function are Gaussmf, and we considered NB denotes "Negative Big", NM denotes "Negative Middle", ZO denotes "Zero", PB denotes "Positive Big", and PM denotes "Positive Middle", then

Rule 1: IF (s_1) is NB THEN Δy_1 is NB.

Rule 2: IF (s_2) is NM THEN Δy_2 is NM.

Rule 3: IF (s_3) is ZO THEN Δy_3 is ZO.

Rule 4: IF (s_4) is PM THEN Δy_4 is PM.

Rule 5: IF (s_5) is PB THEN Δy_5 is PB.

Output of fuzzy system can be designed as

$\Delta_t = K.\Delta y.sat(s)$, (where K=400).

$\mu(s_1) = [3,-15]$, $\mu(s_2) = [3,-7.5]$, $\mu(s_3) = [3,0]$, $\mu(s_4) = [3,7.5]$, $\mu(s_5)$ [3,15], and output membership function as Δy_i $0.1.s_r$. Defuzzification uses center of gravity method. Combine to outer-loop yeild $I_{cref} = I_{out} + \Delta_t$, where Icref is reference signal of inner-loop.

Step 3: Cascade inner-loop design

Usually, electrical control part is more effective than mechanical part. This study inner-loop is based on outer-loop and fuzzy system, and then the sliding mode inner-control-loop is proposed as

$s_{in} = I_{cref} - I_c$ (21)

combine with Eq. (8), we have

$$\dot{s}_{in} = \dot{I}_{cref} + \frac{R_c + R_s}{L_c} I_c - V_c \quad (22)$$

To achieve the desire goal $\dot{s}_{in} = s_{in} = 0$, where V_c is control input, and to be designed as

$$V_c = \chi\sqrt{|s_{in}|}sat(s_{in}) + \sigma\int\sqrt{|s_{in}|}sat(s_{in})dt \text{ [14]}.$$

All above original signum function is replaced by sat function.

Remark: Design saturation function

This propose is replace signum function by saturation function, the function is presented as

$sat(s) = sign(s)\min\{1,|s|\}$ (23)

$$sat(s) = \begin{cases} 1 & if\ s > \varepsilon \\ \frac{1}{\varepsilon}s & if\ s \in [-\varepsilon;\varepsilon] \\ -1 & if\ s < -\varepsilon \end{cases} \quad (24)$$

Then, structure of system is constructed as follows.

The simulation results illustrate that our proposed is good track enough under signum reference signal scenarios. With thrust disk equal to 0.38 kg is forced on the rotor during running process. Our result is used to compare with Su and Chen et al. [7], and [8]. With the same parameters, same system. The parameters is follow as Table. 1 below.

Table. 1 Controller parameters

Controller parameters	$k_1 = 5, \lambda_1 = 2200, \lambda_2 = 600, \chi = 800$ $\sigma = 400, L = [0, 0.1], \alpha = -1$
System parameters	$m = 2.565kg$, $k_{ai} = 40N/A$, $k_{\varphi} = 25200N/m$, $z_0 = 1mm$, $T = 0.38kg$, $c = 0.001$ $R_c = 10\Omega$, $R_s = 1\Omega$, $L_c = 412.5mH$,

IV. An illustrative example

Corresponding to the design procedure presented in the paper, some simulation result are given to demonstrate how much effectiveness of the proposed control method for active magnetic bearing system. First of all, distance tracking as

Average of distance tracking error is equal to $0.3850\mu m$ and maximum error value is equal $1.6125\mu m$ at 1500 (ms). Fast transient responses (within 80ms).

The main result performed that the nonlinear observer control based cascade fuzzy control is good track with reference signal as F[illegible] nd the

Fig. 3. Nonlinear disturbance observer-based fuzzy CSMC

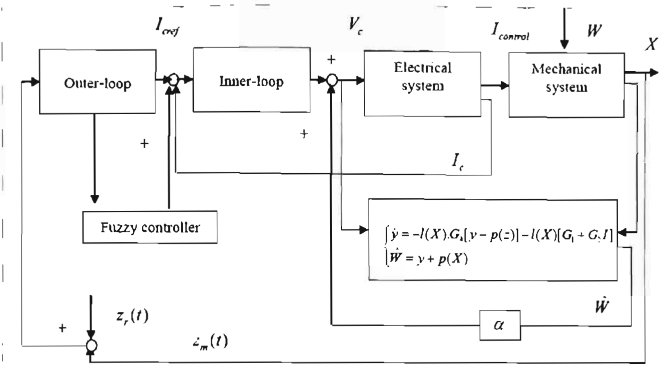
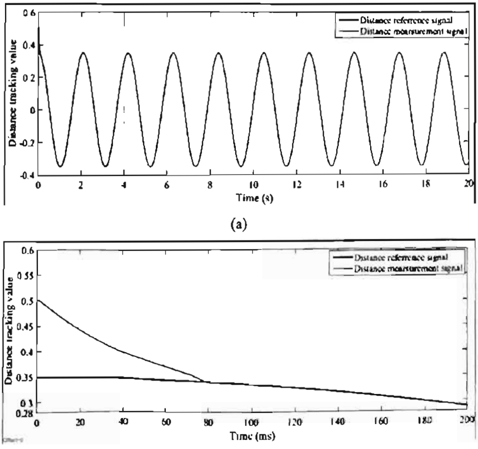


Fig. 4 Distance tracking value (a) in 20s and (b) in (0 to 200 ms) running process



chattering is converged to zero with sat (.) Function and fuzzy controller. Otherwise NDOB is good in eliminate and reject disturbance.

V. Conclusion

A design methodology nonlinear disturbance observer based cascade fuzzy sliding mode control for active magnetic bearing system with various unknown disturbance values. To achieve the desired goal, nonlinear disturbance observer, sliding outer-loop combined with fuzzy, sliding inner-loop are used together under Lyapunov law. Simulation results is given by Matlab Simulink, some scenarios is well track with time-varying trajectory ■

Fig. 5. Distance tracking error value (a), in 20s running process, (b) top value of tracking value, and (c) average value of distance tracking value (in 12s to 14s)

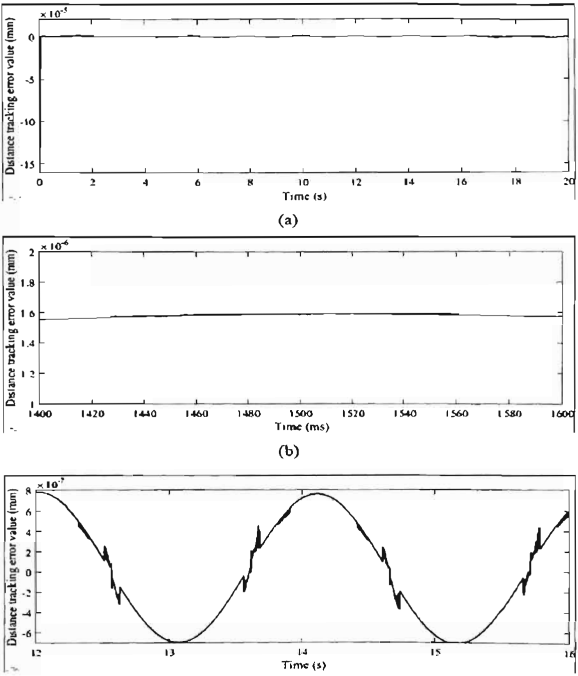


Table 2 : Comparision of this proposed and Lin et al. (3)

Controller	Average of distance tracking value	Top of distance tracking error value
RNTSM Lin et al.	0.908 μm	5 666 μm
RFISMC Su et al.	0.5025 μm	1.964 μm
Our proposed	0.3850 μm	1 6125 μm

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TÓM TẮT:

Bài viết này đề xuất một hệ điều khiển bền vững dựa trên điều khiển trượt cho hệ thống phi tuyến. Đầu tiên, bộ quan sát nhiễu phi tuyến (NDOB) được sử dụng để loại trừ nhiễu không xác định. Sau đó, điều khiển trượt được sử dụng để thiết lập vòng lặp ngoài cho bộ điều khiển tầng. Trong bước này, bộ điều khiển logic mờ được đưa ra với đầu vào Gaussmf và hàm liên thuộc đầu ra để giảm sự nhiễu ồn từ giá trị chuyển đổi của bộ điều khiển trượt. Cuối cùng, vòng lặp bên trong của phương pháp điều khiển trượt (SMC) được sử dụng để điều khiển các giá trị về điện. Về cơ bản, điều khiển tầng được sử dụng để thiết lập trạng thái hệ thống trong hai vòng điều khiển. Nghiên cứu này đề xuất giá trị cơ học sẽ được điều khiển bởi vòng lặp ngoài và giá trị điện sẽ được kiểm soát bởi vòng lặp trong, tương ứng. Kết quả mô phỏng cho thấy phương pháp điều khiển được đề xuất quan sát tốt tín hiệu tham chiếu. Kết quả đáp ứng nhanh cho thấy hiệu quả của điều khiển trượt . Và khoảng cách sai lệch nhiễu là khá tốt.

Từ khóa: Bộ quan sát nhiễu phi tuyến (NDOB), phương pháp điều khiển trượt (SMC), bộ điều khiển PID.