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Disturbance Observer Based Cascade Fuzzy - SlidingMode Controlfor Nonlinear Systems

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Abstract *–In this article, a robust control scheme based on sliding mode control is proposed for a nonlinear system. First, a nonlinear disturbance observer (NDOB) is incorporated to estimate and reject unknown disturbances. Subsequently, sliding mode control is employed to design the outer loop of the cascade control structure. In this stage, a fuzzy logic controller with Gaussian membership functions for both inputs and outputs is introduced to reduce the chattering caused by the switching term of the sliding mode controller. Finally, an inner-loop sliding mode controller is developed to regulate the electrical variables.*

In essence, the cascade control structure is designed to drive the system states toward the predefined desired states through two subcontrol loops. In the proposed approach, the mechanical variables are regulated by the outer loop, whereas the electrical variables are controlled by the inner loop. Simulation results demonstrate that the proposed control strategy provides good tracking performance for the sign reference signal. The transient response is very fast, reflecting the effectiveness of sliding mode control. In addition, the distance tracking error remains satisfactorily small.

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

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I. Introduction

In practical control systems, disturbances and measurement noise are inevitably present and often degrade system performance. Over the past few decades, disturbance estimation and rejection for nonlinear systems have attracted considerable attention and remain challenging topics in control engineering. Among the available approaches, the nonlinear disturbance observer (NDOB), originally introduced by Ohnishi in 1987 [1], has been recognized as an effective tool for estimating and compensating unknown disturbances. Since then, NDOB-based methods have been further developed and applied in various nonlinear control problems [2]–[4].

Sliding mode control (SMC) is well known as a robust control technique due to its strong insensitivity to matched uncertainties and external disturbances [5]. Over the past several decades, SMC has been successfully applied to a wide range of engineering systems. In general, the design of an SMC scheme involves two main steps: defining an appropriate sliding surface and selecting controller parameters such that the stability of the closed-loop system can be guaranteed, typically through Lyapunov analysis. Once the sliding condition is satisfied, the system states are driven toward and maintained on the predefined sliding manifold [5], [9]. Various SMC-based approaches have been reported in the literature. For example, Lin et al. [6] proposed an intelligent double-integral sliding-mode controller, Chen et al. [7] developed a robust nonsingular terminal sliding-mode control strategy for an active magnetic bearing system, and Su et al. [8] presented a proportional-integral-derivative/fuzzy sliding-mode control approach for the suspension control of an active magnetic bearing system.

Despite its robustness advantages, one of the main drawbacks of conventional SMC is the chattering phenomenon caused by the discontinuous switching term. In most cases, the control law consists of two components: an equivalent control term and a switching control term. Although the switching term improves robustness, it may also induce high-frequency oscillations, which can degrade control quality and adversely affect actuators. To alleviate this problem, several techniques, such as saturation functions and fuzzy logic control, have been introduced to smooth the switching action while preserving robustness.

Motivated by the advantages of both cascade control and sliding mode control, this study proposes a double sliding-mode cascade control structure for a nonlinear system. In the proposed scheme, the outer-loop controller is designed to regulate the mechanical part of the system. Specifically, the displacement is controlled by a PID-type sliding surface combined with an equivalent control term, while a fuzzy logic controller is incorporated to reduce the chattering induced by the switching component. Meanwhile, the inner loop is implemented using sliding mode control to regulate the electrical part of the system. In contrast to the outer loop, the sliding surface in the inner loop is constructed directly from the difference between the reference signal and the measured signal, which enables effective current control. Because the electrical subsystem typically exhibits faster dynamics, it serves as an appropriate inner control loop within the cascade structure.

Cascade control has been widely used for many years because of its ability to improve disturbance rejection and compensate for time-delay effects [10], [11]. In such a structure, the inner loop ensures fast stabilization and enforces the intermediate control objective generated by the outer loop. In this work, the considered plant is an active magnetic bearing system, similar to those investigated in [7] and [8], which has important practical applications in modern electromechanical systems. Finally, the effectiveness of the proposed method is evaluated through comparison with the approaches reported in [7] and [8]. Although the comparison is not entirely equivalent due to differences in controller structures, the obtained results indicate that the proposed method provides satisfactory reference-tracking performance.

Owing to the absence of physical contact between the rotor and the stator, active magnetic bearings (AMBs) operate without lubrication and mechanical friction, which makes them attractive for various applications, including wind turbines, helicopters, flywheel energy storage systems, and vacuum pumps [7], [8]. The main control objective is to maintain the rotor at a predefined reference position. In this work, the study is restricted to the control of a single-axis axial AMB, as shown in Fig. 1.

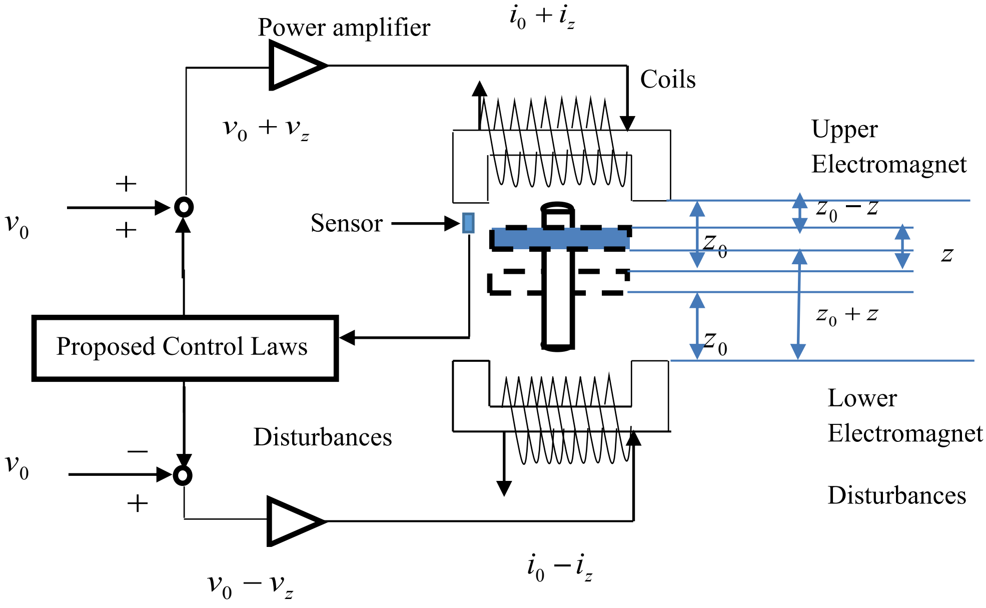


Fig. 1. The structure of active magnetic bearing system.

This article is organized into five sections. Section I provides a brief introduction to the research background and motivation. Section II presents the problem formulation, including the mathematical model of the system and the control objectives to be addressed. Section III proposes the control strategy, develops the corresponding subsystem structure for the overall system, and proves that the proposed method satisfies the required stability conditions. Section IV presents simulation results to demonstrate the effectiveness of the proposed method in comparison with the approaches of Su et al. and Chen et al. under the same system and operating conditions. Finally, Section V concludes the article and summarizes the main findings of the proposed control method.

II. Problem formulation

Following Su et al. and Chen et al., the system is modeled as a single-input single-output (SISO) system, where the reference input is the predefined rotor position and the measured output is the rotor displacement. The mathematical model of the system is given as follows.

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

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 $X = [z(t), \dot{z}(t)]^T, I = i_z(t), \mathrm{W} = \mathrm{f}_{dz}(t)$ 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 $\dot{X} = G_1 X + G_2 I + G_3 \Xi + G_4 W$

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 innerloopwill 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 suppliedby the outer *c I* 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 coilinductance. $V_c$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 summarized as follows. First, a nonlinear disturbance observer is developed to estimate and compensate for the disturbances in the open-loop system. Subsequently, an outer-loop cascade sliding mode controller is designed to drive the system states toward the predefined desired values, while a fuzzy logic controller is incorporated to reduce the chattering caused by the switching component of the sliding mode controller. Finally, an inner-loop cascade controller is employed to regulate the electrical variable. To achieve the desired control objective, the main subsystems are briefly described 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

$$\begin{cases} \dot{y} = -l(X).G_4[y + p(z)] - l(X).[G_1 + G_2 I] \\ \hat{W} = y + p(X) \end{cases} \quad (8)$$

where *p(X)* is a nonlinear need to make, $l\left(X\right)=\partial p\left(X\right)/\partial X$ is observer gain, $\hat{W}$ isestimated value of disturbance from system.

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

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

Respectively, where p₀ is positive constant for tuning the bound of errors. Let $n_0=\left|\min_z L_{G_4}L_{G_1X}H\left(X\right)\right|$ is positive scalar.

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

$$\tilde{W}=\dot{W}+l\left(X\right)G_4\left[y+p\left(X\right)\right]+l\left(X\right)\left[G_1X-l\left(X\right)\dot{z}\right]=\dot{W}-l\left(X\right)G_4\tilde{W} \tag{10}$$

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

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

$$\begin{aligned}\dot{V}\left(\tilde{W}\right)&=2\tilde{W}^T\left[\dot{W}-l\left(X\right)G_4\tilde{W}\right]\\&=-2\tilde{W}^Tl\left(Z\right)G_4\tilde{W}+2\tilde{W}^T\dot{W}\\&\le-2n_0p_0\left\|\tilde{W}\right\|^2+2\left\|\tilde{W}\right\|k\\&\le-p_0n_0\left\|\tilde{W}\right\|^2-\left(\sqrt{p_0n_0}\left\|\tilde{W}\right\|-\frac{k}{\sqrt{p_0n_0}}\right)^2+\frac{k}{p_0n_0}\\&\le-p_0n_0\left\|\tilde{W}\right\|^2+\frac{k}{p_0n_0}\end{aligned} \tag{11}$$

Then, we have

$$\left\|\tilde{W}\left(t\right)\right\|\le\left\|\tilde{W}\left(0\right)\right\|\exp\left(-p_0n_0t\right)+\frac{k}{p_0n_0^2} \tag{12}$$

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

$$I_{control}=I_c+\alpha\hat{W} \tag{13}$$

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

$$\begin{aligned}\dot{X}&=G_1X+G_2\left[I_c+\alpha\left(W-\tilde{W}\right)\right]+G_3\Xi+G_4W\\&=G_1X+G_2I_c+\left(G_2\alpha+G_4\right)W+G_3\Xi-G_2\alpha\tilde{W}\end{aligned} \tag{14}$$

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 onthe 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 asfollowing.

3.2 Cascade sliding mode control

This section presents a cascade control structure consisting of two control loops, both designed based on the sliding mode control principle. The inner loop is developed to force the current to track the reference generated by the outer loop, while the outer loop is designed to regulate the system position. In addition, the controller is formulated by taking into account the presence of an internal disturbance subsystem, as described below.

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

Eq.(16) can be written as

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

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

<u>Step 1</u>: *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)

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

Sliding mode surface is selected as

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

where *zr* is reference distance and *zm* is measured distance $\lambda_1, \lambda_2 > 0$ is chosen such that the real parts of the roots of $P(s_{out}) = s_{out}^2 + \lambda_1 s_{out} + \lambda_2 < 0$, then sliding surface is satisfied Lyapunov law as

$$\dot{V}(t) = \dot{s}_{out}(t)s_{out}(t) < 0$$

$$\dot{s}_{out}(t) = \ddot{z}_m(t) - \ddot{z}_r(t) + \lambda_1\left(\dot{z}_m(t) - \dot{z}_r(t)\right) + \lambda_2\int_0^t\left(\dot{z}_m(\tau) - \dot{z}_r(\tau)\right)d\tau$$

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

The current is calculated as

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

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

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

<u>Step 2</u>: *Fuzzy logic controller*

Fuzzy logic is a practical mathematical addition to classic Boolean logic [15]. Undersliding mode control condition, chattering value is occurred in switching control, then thisstudy propose the power toll to eliminate this unwell value. Fuzzy membership function areGaussmf, 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 $\Delta y_1$is NB.
Rule 2: IF (s_2) is NM THEN $\Delta y_2$is NM.
Rule 3: IF (s_3) is ZO THEN $\Delta y_3$is ZO.
Rule 4: IF (s_4) is PM THEN $\Delta y_4$is PM.
Rule 5: IF (s_5) is PB THEN $\Delta y_5$is PB.

Output of fuzzy system can be designed as $\Delta i = K.\Delta y.sat(s)$, (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 outputmembership function as $\Delta y_t = 0.1.s_t$. Defuzzification uses center of gravity method.Combine to outer-loop yeild $I_{cref} = I_{out} + \Delta i$, where I_{cref} 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-loopis based on outer-loop and fuzzy system, and then the sliding mode inner-control-loopis proposed as

$$s_{in} = I_{cref} - I_c \tag{21}$$

combine with Eq. (8), we have

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

To achieve the desire goal $\dot{s}_{in} = 0$, and $s_{in} = 0$, where $V_c$is control input, and to be designed as $V_c = x\sqrt{|s_{in}|}sat(s_{in}) + \sigma\int\sqrt{|s_{in}|}sat(s_{in})dt$ [14]. All above original signum functionis replaced by sat function.

Remark: Design saturation function

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

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

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

Then, structure of system is constructed as follows.

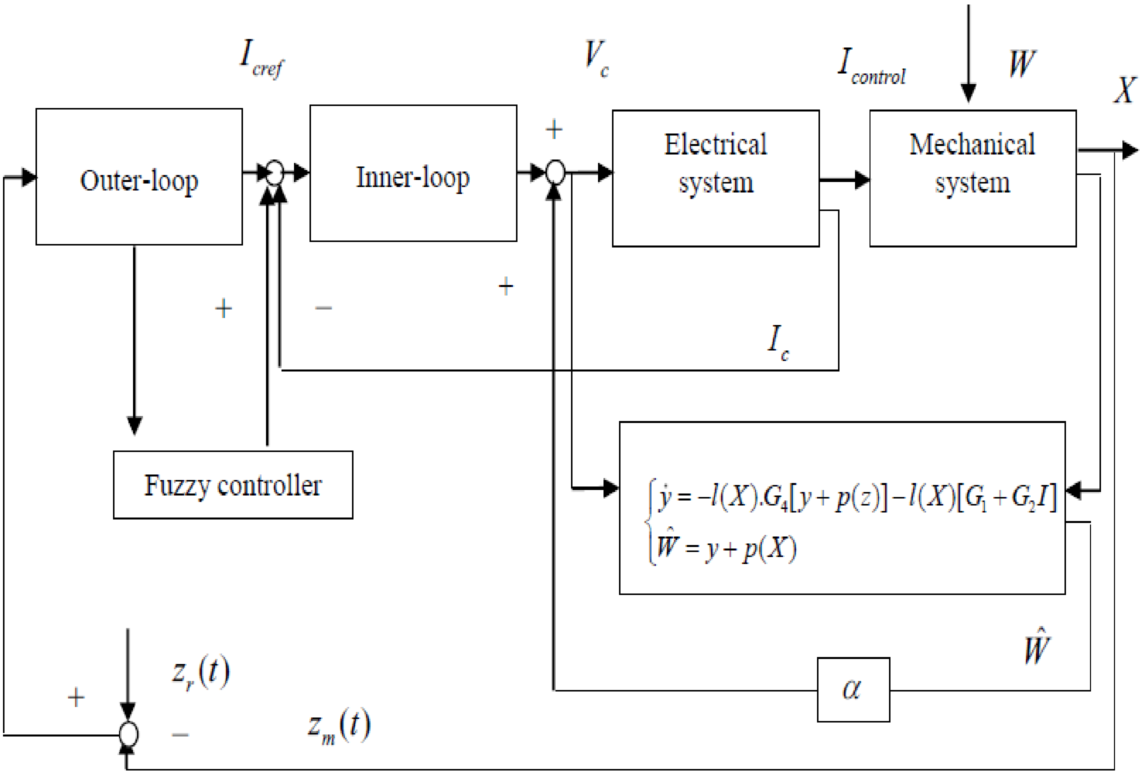


Fig. 2. Nonlinear disturbance observer-based fuzzy CSMC

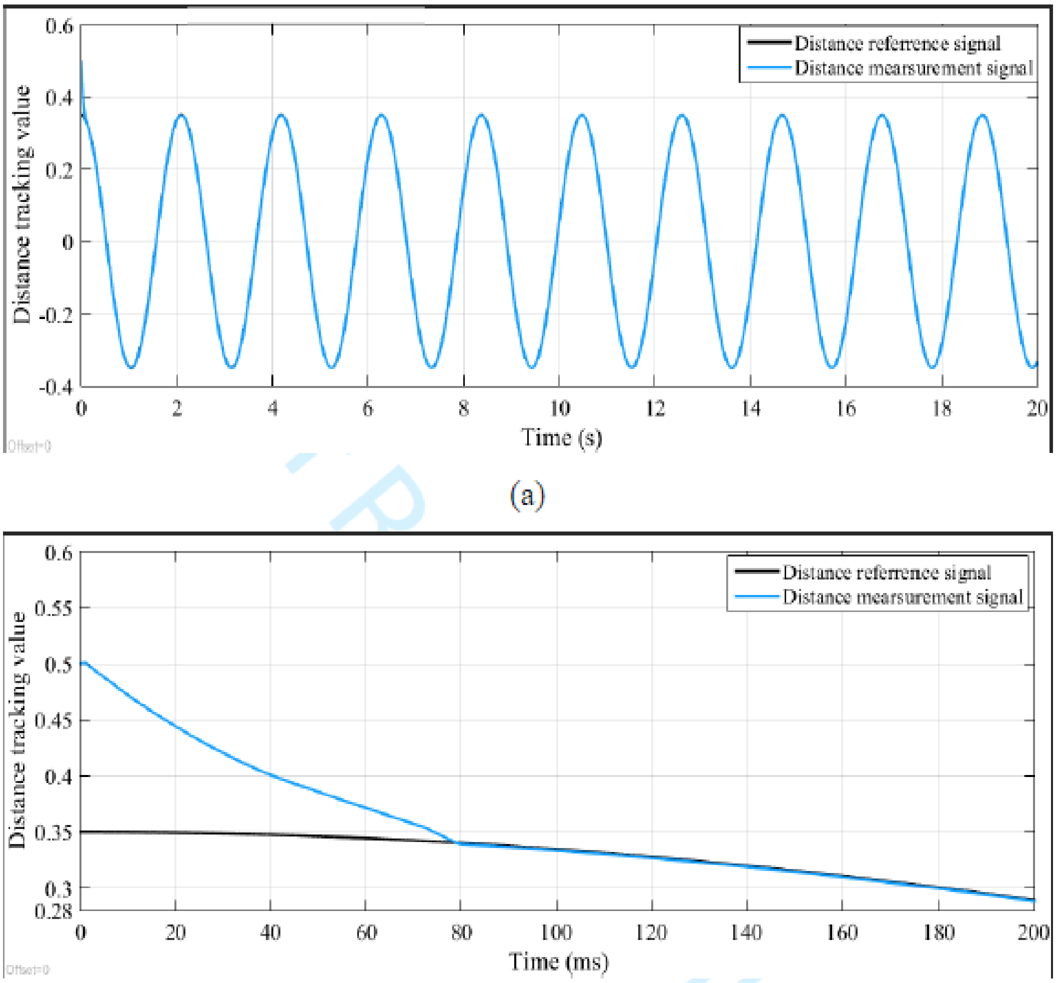
The simulation results show that the proposed method achieves satisfactory tracking performance under signum reference signal scenarios. During the operation, a thrust disk with a mass of 0.38 *kg* is applied to the rotor. The obtained results are compared with those reported by Su et al. and Chen et al. [7], [8] under the same system configuration and parameter settings. The simulation parameters are listed in Table I.

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	$m = 2.565kg,\ k_{ai} = 40N/A,$ $k_{ap} = 25200N/m,\ z_0 = 1mm,$ $T = 0.38kg,\ c = 0.001.\mathrm{R}_c = 10\Omega,$ $\mathrm{R}_s = 1\Omega, \mathrm{L}_c = 412.5mH,$

IV. An illustrative example

In accordance with the design procedure presented in this paper, simulation results are provided to demonstrate the effectiveness of the proposed control method for the active magnetic bearing system. First, the displacement tracking performance is evaluated.



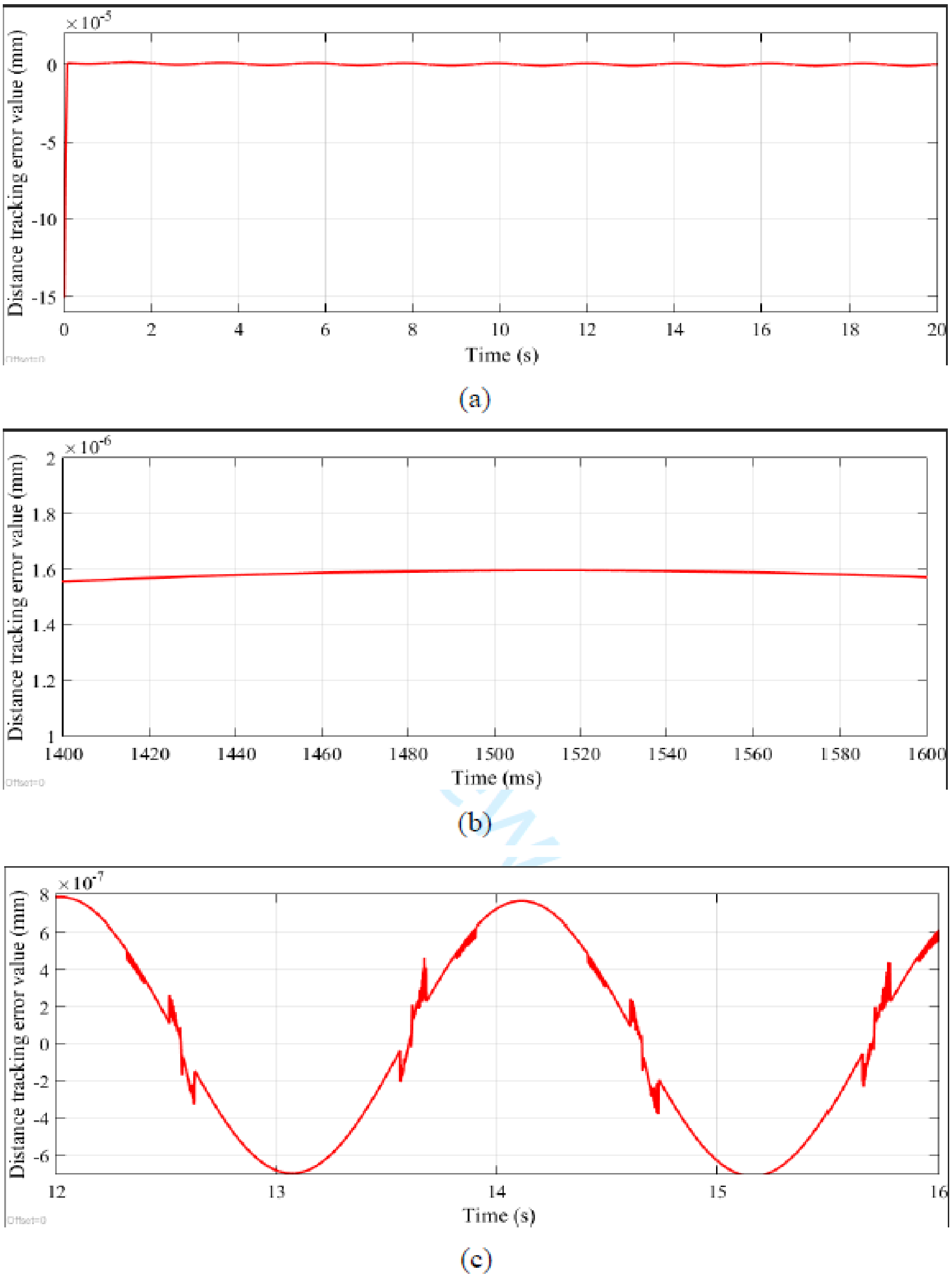
(a)

(b)

Fig. 3. Distance tracking value (a) in 20s and (b) in (0 to 200 ms) running process.

The average displacement tracking error is 0.3850 μm, whereas the maximum tracking error reaches 1.6125 μm at t=1500 (ms). In addition, the system exhibits a fast transient response, with a settling time of approximately 80 (ms).

The main results indicate that the proposed nonlinear disturbance observer-based cascade fuzzy control scheme achieves satisfactory tracking performance with respect to the reference signal, as shown in Fig. 3. Moreover, the chattering effect is significantly reduced and converges to nearly zero through the use of the sat(·) function and the fuzzy controller. In addition, the nonlinear disturbance observer demonstrates good capability in estimating, compensating for, and rejecting disturbances.



(a)

(b)

(c)

Fig. 4. 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.	$0.908\mu m$	$5.666\mu m$
RFISMC Su et al.	$0.5025\mu m$	$1.964\mu m$
Our proposed	$0.3850\mu m$	$1.6125\mu m$

V. Conclusion

This paper proposes a nonlinear disturbance observer-based cascade fuzzy sliding mode control scheme for an active magnetic bearing system in the presence of various unknown disturbances. To accomplish the control objective, a nonlinear disturbance observer, a fuzzy-enhanced outer-loop sliding mode controller, and an inner-loop sliding mode controller are systematically integrated based on Lyapunov stability theory. MATLAB/Simulink simulation results show that the proposed approach achieves satisfactory tracking performance under several time-varying reference trajectory scenarios.

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