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Fuzzy Disturbance Observer-Based Cascaded Controller for Suspension of the Active Magnetic Bearing System

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Abstract:
Normally, the fuzzy logic control is well known as an approximate control methodology. In this paper, the fuzzy logic system is used to do other work that is the filter for the estimated disturbance signal, which can be considered that the fuzzy logic control was applied to regulated the control input signal with the appearance of the disturbance value. The stability is constructed following the Lyapunov law. Due to unable to measure the outside disturbance and uncertainty directly, this part presents a robust controller for the suspension active magnetic bearing system (SAMB), which combine the sliding mode control (SMC), and a disturbance observer (DOB) is presented. The DOB is use system control signal and system output to construct the disturbance value, the high frequency term of estimate will be reason for noise, and this part proposed the fuzzy logic controller to deal with the high frequency. The operation of the Fuzzy rules are a filter. The unmeasurable disturbance and uncertainty are reduce by a term is called disturbance and uncertainty estimation, the estimated value is given by low-pass-filter and convolution operation. The inner loop is constructed by the switching controller to force the control current to desired value. The archived results are given out by Matlab Simulink.
This paper is organized as following:
- Overview of this part is give firstly.
- The disturbance observer-based control law.
1. Nonlinear disturbance observer-based control law is constructed first.
2. The disturbance and uncertainty estimation is constructed completely.
The system output response is smooth, the disturbance and uncertainty are completely rejected. The overshoot, settling time, rise time, and steady-state are good performed.

Keywords: *Active magnetic bearing system (AMB),Suspension active magnetic bearing (SAMB), sliding mode control (SMC), disturbance observer (DOB), nonlinear disturbance observer, fuzzy logic controller.*

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I. Disturbance observer-based control law

A highly unstable system as AMB cannot be presented as a dynamical system or the lump of the uncertainty value is unmeasured. Furthermore, the unexpected disturbance is unable to observer, then an observer is required.

1.1Nonlinear disturbance observer-based Control Law

The Equation of system is represented as

$$\dot{x} = \begin{bmatrix} 0 & I \\ B & A \end{bmatrix} x + \begin{bmatrix} 0 \\ C \end{bmatrix} i + \begin{bmatrix} 0 \\ 1 \end{bmatrix} m_d \quad (1.1)$$

or $$\dot{x} = G_1 x + G_2 i + G_3 m_d \quad (1.2)$$

where $x = [z(t) \quad \dot{z}(t)]^T$ is the system state vector.

This section presents the nonlinear disturbance observer as

$$\begin{cases} \dot{y} = -L(x) \cdot G_3 \cdot \left[y + \rho(z) \right] - L(x) \cdot \left[G_1 \cdot x + G_2 \cdot i \right] \\ \hat{m}_d = y + \rho(x) \end{cases} \quad (1.3)$$

where z is an internal state vector of the DOB, $p(x)$ is auxiliary vector of DOB, nonlinear function to make is, $L(x)=\partial\rho(x)/\partial x$ is observer gain, and $\hat{m}_d$ is estimated value of disturbance from mechanical part of the 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 l to y for all system states $x(t)$. The $\rho(x)$, and $\mathrm{L}(x)$ are chosen as

$$L(X)=\rho_0\frac{\partial L_f^{\rho-1}H(X)}{\partial X} \qquad (1.4)$$

$$\rho(X)=\rho_0\partial L_f^{\rho-1}H(X)$$

Respectively, where p_0 is positive constant for tuning the bound of errors. Let $n_0=\left|\min_z L_{G_4}L_{G_1X}H(X)\right|$ is positive scalar.

The error of the estimated disturbance and disturbance is $\tilde{m}_d=m_d-\hat{m}_d$.

or

$$\begin{aligned}\dot{\tilde{m}}_d &= \dot{m}_d+L(x)\cdot G_4\cdot\left[y+\rho(x)\right]\\ &+L(x)\cdot\left[G_1\cdot x-L(x)\cdot\dot{z}\right] \qquad (1.5)\\ &=\dot{m}_d-L(x)\cdot G_4\cdot\tilde{m}_d\end{aligned}$$

Suppose that $|m_d|\le k$ where k is positive constant given by system lump of uncertainties. The Lyapunov function are

$$V(\tilde{d})=\tilde{m}_d{}^T\tilde{m}_d \qquad (1.6)$$

Taking the derivative Eq. (1.6) will leads to

$$\begin{aligned}\dot{V}(\tilde{d}) &= 2\tilde{m}_d{}^T\left[\dot{m}_d-L(x)G_4\tilde{m}_d\right]\\ &=-2\tilde{m}_d{}^T L(x)G_4\tilde{m}_d+2\tilde{m}_d{}^T\dot{\tilde{m}}_d\\ &\le -2n_0\rho_0\|\tilde{m}_d\|^2+2\|\tilde{m}_d\|k\\ &\le -\rho_0 n_0\|\tilde{m}_d\|^2+\frac{k}{\rho_0 n_0} \qquad (1.7)\end{aligned}$$

Then, we have

$$\|\tilde{m}_d(t)\|\le\|\tilde{m}_d(0)\|\exp\left(-\rho_0 n_0 t\right)+\frac{k}{\rho_0 n_0^2} \quad (1.8)$$

$$I_{control}=I_c+\alpha\hat{m}_d \qquad (1.9)$$

where I_c is the conventional control value

$$\begin{aligned}\dot{x} &= G_1\cdot x+G_2\cdot\left[I_c+\alpha\cdot\left(l-\tilde{l}\right)\right]+G_3\cdot m_d\\ &=G_1\cdot x+G_2\cdot I_c+\left(G_2\cdot\alpha+G_3\right)m_d-G_2\cdot\alpha\cdot\tilde{m}_d \qquad (1.10)\end{aligned}$$

Based on the matching condition α is chosen as $\alpha=-G_2^{-1}G_4$ is in the sense that input-to-state stable.

1.2Nonlinear Disturbance Observer and uncertainty estimation based control law

Due to unable directly to estimate the uncertainty of the system, this paper proposes the uncertainty estimator based on the sliding mode surface. Firstly, the system from Eq. (1.1) need to be modified as

$\dot{x} = (G_{1n} + \Delta G_1)\cdot x + (G_{2n} + \Delta G_2)\cdot i + G_3 m_d$ (2.1)

or

$\dot{x} = (G_{1n})\cdot x + (G_{2n})\cdot i + L + G_3 m_d$ (2.2)

where lump of the uncertainty is $L = \Delta G_1 \cdot x + \Delta G_2 \cdot i.$ basically, the derivative of the sliding mode surface is

$\dot{s}_{in} = -k\cdot sat(s_{in})$ (2.3)

or $\dot{s}_{in} = -L - u_L(\mathrm{t}) - k\cdot sat(s_{in})$ (2.4)

where $L = -u_L(\mathrm{t}).$ The lump of uncertainty can be observed by a filter. A suggestion of strictly proper low-pass-filter is $G_f(\mathrm{s}),$ the lump of the uncertainty can be approximated by

$\hat{L} = L^{-1}\left\{G_f(\mathrm{s})\right\}\times\left(-u_L(\mathrm{t}) - k\cdot sat(s_{in}) - \dot{s}_{in}\right)$ (2.5)

where $L^{-1}\{\bullet\}$ is the inverse Laplace transfer function, and $\times$ sign is convolution operator. Substituting $\hat{L} = -u_L(\mathrm{t})$ to Eq. 2.5) yields

$u_L(\mathrm{t}) = L^{-1}\left\{\dfrac{G_f(\mathrm{s})}{1 - G_f(\mathrm{s})}\right\}\times\left(k\cdot sat(s_{in}) + \dot{s}_{in}\right)$ (2.6)

$V_C(\mathrm{t}) = V_{0c} + L^{-1}\left\{\dfrac{G_f(\mathrm{s})}{1 - G_f(\mathrm{s})}\right\}\times\left(k\cdot sat(s_{in}) + \dot{s}_{in}\right)$ (2.7)

Then choose $G_f(\mathrm{s}) = \dfrac{1}{1 + Ts}$ as a filter, then

$V_C(\mathrm{t}) = V_{original} + \left(\dfrac{k}{T}\cdot sat(s) + k\cdot\int_0^t sat(s(\mathrm{t}))\,\mathrm{dt}\right)$ (2.8)

This section the sliding mode control for system current is presented, the output voltage is choose as

$V_{0c} = \chi\cdot(\mathrm{sat(s)} + \sqrt{|\mathrm{s}|}) + \sigma\int(\mathrm{sat(s)} + \sqrt{|\mathrm{s}|}),$ (2.9)

The term of condition is determined as

$\dot{s}_{in} = (\dot{I}_{cref} - \dot{I}_c)$

$= \dot{I}\cdot A_{cref}(\mathrm{t}) - (A_n\cdot I_c(\mathrm{t}) + B_n\cdot V_c(\mathrm{t}) + d)$

$= \dot{I}\cdot A_{cref}(\mathrm{t}) - (A_n\cdot I_c(\mathrm{t}) + B_n\cdot V_c(\mathrm{t})) - d$ (2.10)

1.3Stability analysis

The stability of the uncertainty estimation as following

$s\cdot s(\mathrm{s}) = -\mathrm{k}\cdot s(\mathrm{s}) - \left[1 - G_f(\mathrm{s})\right]\cdot L(\mathrm{s})$ (3.1)

or

$s(s) = k_d\cdot s\cdot e(s) + k_p\cdot e(s) + k_i\cdot\dfrac{1}{s}\cdot e(s)$ (3.2)

Substituting Eq. (4.21) to Eq. (3.2) yields

$$e(s) = \frac{s}{s+k} \cdot \frac{G_f(s)-1}{k_d \cdot s^2 + k_p \cdot s + k_i} \cdot L(s) \quad (3.3)$$

On the time domain the distance tracking error are

$$\lim_{t\to\infty}(e(t)) = \lim_{s\to 0} s \cdot \frac{s}{s+k} \cdot \frac{G_f(s)-1}{k_d \cdot s^2 + k_p \cdot s + k_i} \cdot L(s) \quad (3.4)$$
$$= 0$$

Fuzzy control Fuzzy logic is widely used in many industrial machine control. Fuzzy logic was first proposed by Lotfi A. Zadeh of the University of California at Berkeley in a 1965. This chapter is apply the fuzzy with the following rules

The fuzzy rule is following

IF $\hat{m}_d$ is NB Then $u_{\hat{m}_d}$ is PB

IF $\hat{m}_d$ is NM Then $u_{\hat{m}_d}$ is PM

IF $\hat{m}_d$ is ZO Then $u_{\hat{m}_d}$ is ZO

IF $\hat{m}_d$ is PM Then $u_{\hat{m}_d}$ is NM

IF $\hat{m}_d$ is PB Then $u_{\hat{m}_d}$ is NB

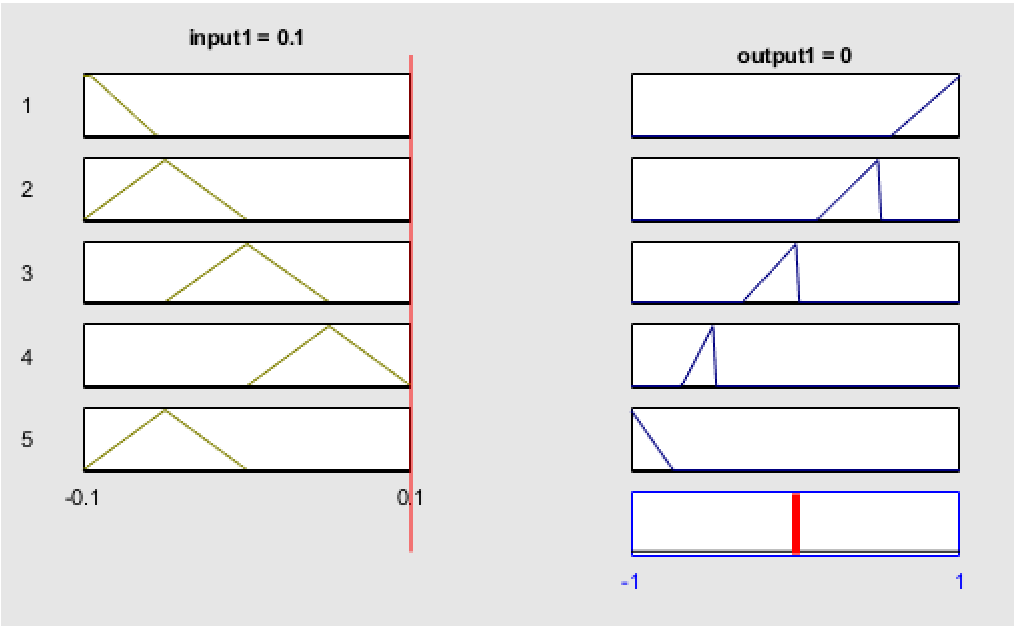


***Figure. 3**.1Fuzzy rule*

Fuzzy surface is

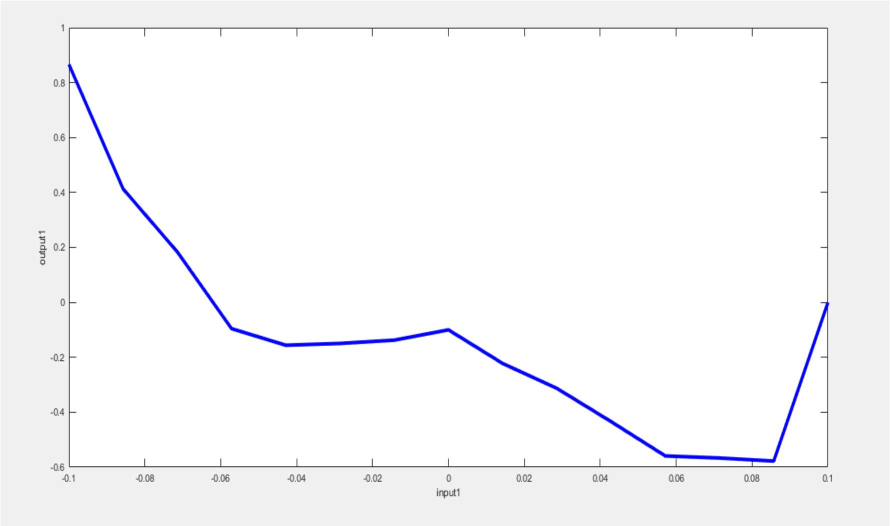


Figure. 3.2Fuzzy surface

We chose the $G_f(s)-1 \rightarrow 0$ by selecting the suitable T. then the T is small enough to implement in the real system. The proposed controller and some advanced technics are applied to construct to the active magnetic bearing system are construct as the Figure 3.3 below.

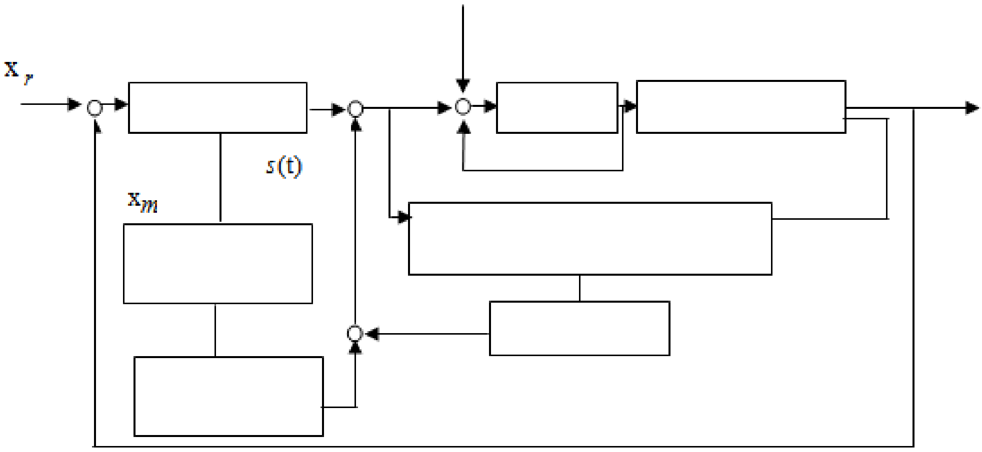
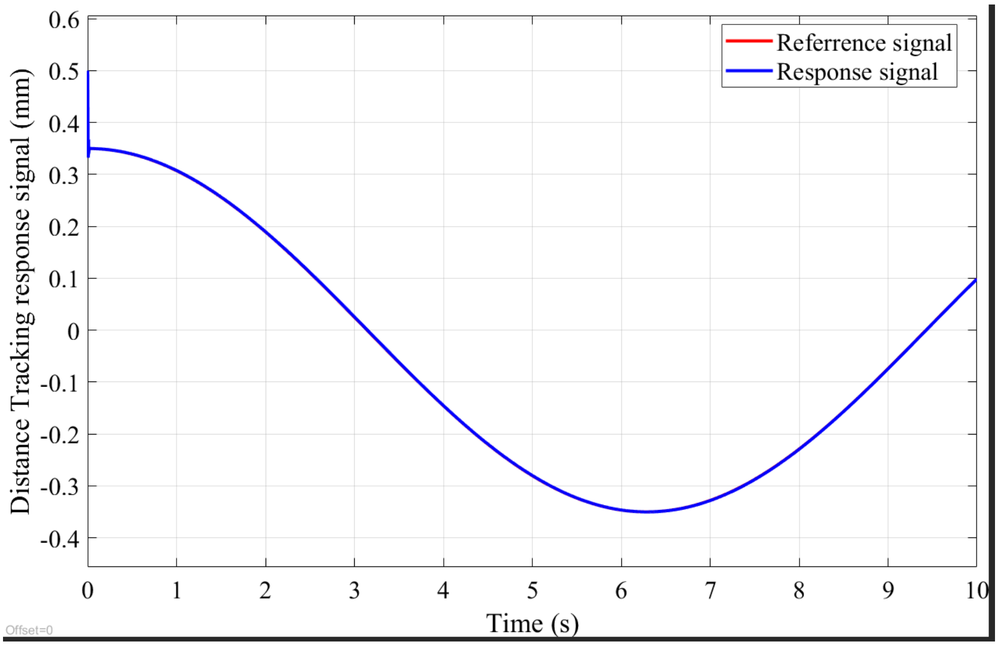
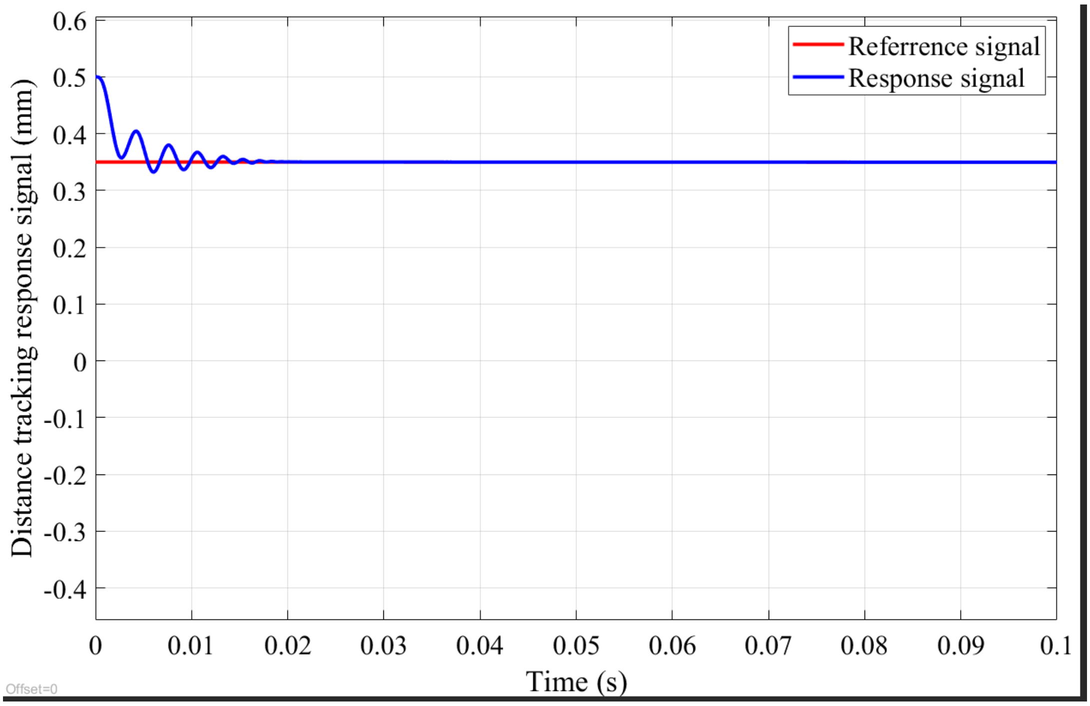


Figure. 3.3Nonlinear disturbance observer for AMB system

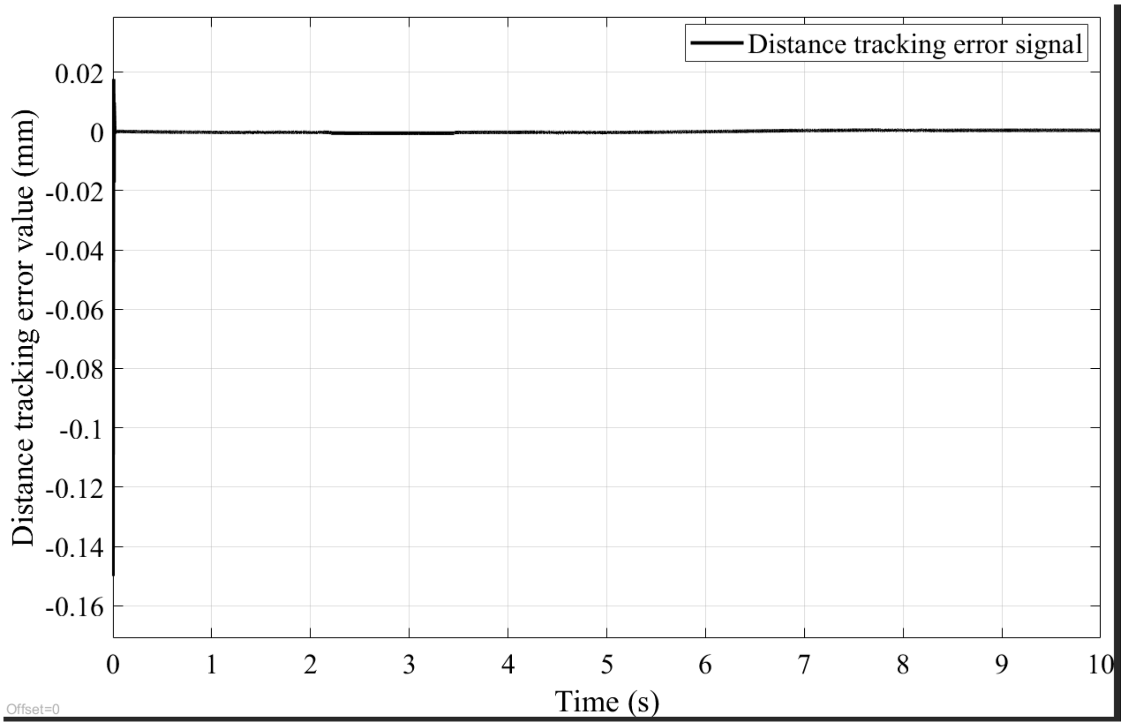
The proposed method results are given by the next part


Referrence signal
Response signal
Distance Tracking response signal (mm)
Time (s)
Offset=0

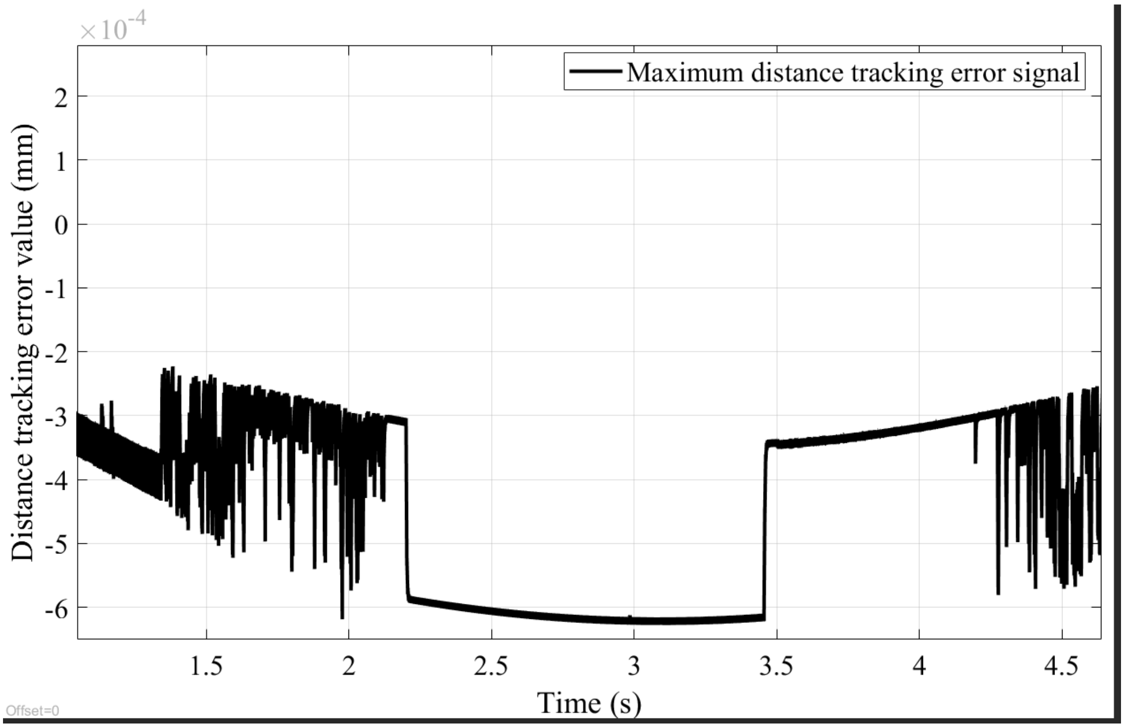
(a)


Referrence signal
Response signal
Distance tracking response signal (mm)
Time (s)
Offset=0

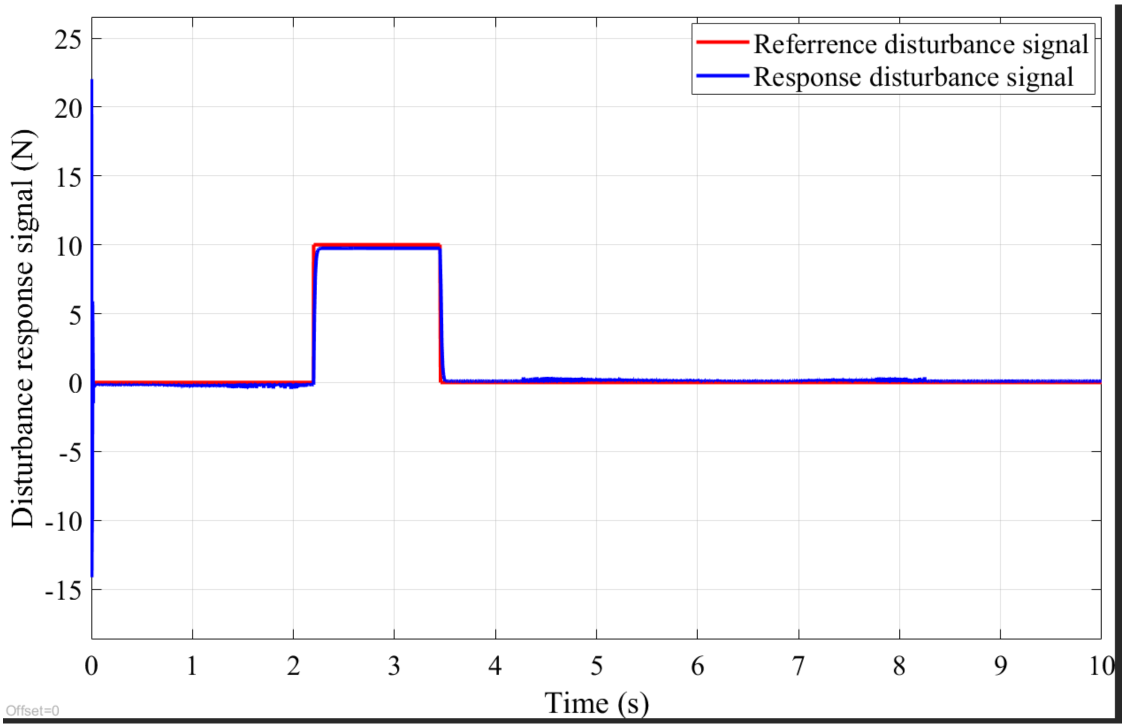
(b)


Distance tracking error signal
Distance tracking error value (mm)
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
0
1
2
3
4
5
6
7
8
9
10
Time (s)
Offset=0

c)


×10^-4
Maximum distance tracking error signal
Distance tracking error value (mm)
2
1
0
-1
-2
-3
-4
-5
-6
1.5
2
2.5
3
3.5
4
4.5
Time (s)
Offset=0

(d)



(e)

Figure. 3.4The given output signal (a) The distance response signal in first 20s,
(b) The distance response signal at first 0.1s, (c) The distance tracking error value,
(d) The top value of the distance tracking error value, (e) The disturbance response signal.

The given output signals proved that the proposed controller with an observer is suitable to control the active magnetic bearing system. The settling time very small, it equal to $0.02s,$ the top of the distance tracking error value is $0.6 \cdot 10^{-3} mm,$ and the average of the distance tracking error value is $3.152 \cdot 10^{-4} mm,$. In order to improve the performance of the proposed control method, this paper applied an uncertainty estimation by a sliding mode surface. A PI-filter is applied to guarantee the system distance tracking error value is force to zero.

II. Summary

A design methodology for active magnetic bearing system with many unexpected value is given out, the achieved results proved that the proposed method are very good at tracking flexible input signal. The chattering and the disturbance is reduced by an uncertainty estimator, the distance tracking error value is significantly reduced, and a top of the distance tracking value in two case very difference.
Comparison to previous published paper.

Research	Top error	Average error
This proposed method	$0.6 \cdot 10^{-3} mm,$	$3.152 \cdot 10^{-4} mm,$
Lin et al. [6]	$0.908.10^{-3} mm$	$5.666.10^{-3} mm$

Table 2.1 The controller parameters

Parameter	Description	Value
λ	Sliding surface coefficient	500
κ	Hitting control gain	100
ε	Saturation function coefficient	0.0016
χ	Cascade inner output voltage parameter	800
δ	Cascade inner output voltage parameter	0.05
T_{out}	Low-pass filter parameter	0.01

T_{in}	Low-pass filter parameter	0.0952

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