High-gain Output Feedback Control for Linear Stepping Motor Based on Fuzzy Approximation

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***Abstract*—In this paper, a *d-q* linear stepping motor model is converted into a standard form for backstepping control design. Due to the tracking control problem of mover, a high-gain fuzzy observer is designed to estimate the unknown system states. According to the "differential explosion" problem existed in backstepping design process, a class of command filters are introduced to avoid complex partial derivatives of the backstepping controller. The advantages of the designed control scheme are simple and flexible by comparing with the traditional control schemes. Finally, the simulation results verify the feasibility and effectiveness of the controller.**

***Index Terms*—Linear stepping motor control, Adaptive backstepping approach, High-gain fuzzy observer, Command filters**

I. INTRODUCTION

Currently, linear stepping motor (LSM) is widely used in engineering applications with its high accuracy and simple model structure. The control of LSM is a key point for the applications of LSM [1-3].

Nowadays, adaptive backstepping control has become an effective tool to deal with nonlinear system problems with its universality [4-5], and LSM model can be seen as a nonlinear system. Therefore, an adaptive controller design of LSM is reasonable and feasible. In actual research environment, most of system states are unavailable. In view of this problem, an adaptive neural network was used to estimate the unknown states, so as to realize the cooperative compound tracking control of the system [6]. In addition, fuzzy observer is also an effective method to estimate the unknown states [7-8], and the fuzzy logic systems were adopted to achieve the control goal. Subsequently, a high-gain observer was proposed to improve the performance of the observer design [9], which is characterized by strong robustness and good anti-interference ability.

In backstepping design process of LSM controller, the "differential explosion" problem caused by derivatives of virtual control laws makes design process very complicated and the calculation is huge, which is not conducive to the design of controller. Hence, a command filtering technique was proposed to solve this problem [10-12]. Command filtering technique has also been widely used because of its universality, and the controller design scheme can ensure the stability and safety of the system.

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Motivated by above analysis, the mover tracking problem is considered in this paper. By combining high-gain fuzzy observer and command filtering technique, a backstepping controller design scheme is carried out. The proposed control scheme ensures that all signals in LSM are uniformly ultimately bounded.

II. MATHEMATICAL DESCRIPTION OF LSM

The *d-q* axis equations of LSM are described as follows [3]:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_1(\breve{x}_1) + b_1 x_3 \\ \dot{x}_3 = f_2(\breve{x}_2) + b_2 V_q \\ \dot{x}_4 = -b_3 x_4 + f_3(\breve{x}_3) + b_2 V_d \end{cases} \tag{1}$$

where $f_1(\breve{x}_1) = -Bx_2/m - F_c \sin(8\pi x_1/p)/m$, $\breve{x}_1 = [x_1, x_2]^T$, $f_2(\breve{x}_2) = -k_f x_2/L - Rx_3/L - 2\pi x_2 x_4/p$, $\breve{x}_2 = [x_2, x_3, x_4]^T$, $b_1 = k_f/m$, $b_2 = 1/L$, $b_3 = R/L$, $f_3(\breve{x}_3) = 2\pi x_2 x_3/p$ and $\breve{x}_3 = [x_2, x_3]^T$. The physical meanings of other symbols are shown in TABLE I:

TABLE I
PHYSICAL MEANINGS OF SYMBOLS

Physical significance	Symbolic representation
Mover position	$x_1(m)$
Mover speed	$x_2(m/s)$
q -axis current I_q	$x_3(A)$
d -axis current I_d	$x_4(A)$
q -axis voltage	$V_q(V)$
d -axis voltage	$V_d(V)$
Back electromotive force constant	k_m
Mover mass	$m(kg)$
Coefficient of viscous friction	$B(N/m/s)$
Pitch	$p(mm)$
Cogging force constant	$F_c(N)$
Resistance of each winding	$R(\Omega)$
Inductance of each winding	$L_l(mH)$
Transformation coefficient	$k_f = 2k_m/p$

For LSM (1), the control objective is that the mover of LSM can track a continuous and smooth reference signal within a small error area. In another words, all signals in LSM are uniformly ultimately bounded. To achieve the control objective, the following assumption and lemma are described as follows:

Assumption 1: The reference signal $y_d(t)$ is known with continuous and smooth property, and its first-order derivative is bounded.

Lemma 1 [8,9]: Suppose that there exists a compact set Ω. If the fuzzy logic system $\kappa^T\phi(x)$ is utilized to approximate an unknown function $f(x)$, then the approximation error ε satisfies:

$$\sup_{x\in\Omega} | f(x)-\kappa^T\phi(x)| \le \varepsilon \tag{2}$$

where κ is called a weight vector, and $\phi(x)$ is usually chosen as a vector composed by Gaussian functions.

III. HIGH-GAIN OBSERVER DESIGN

According to **Lemma 1**, a nonlinear function $f_i(\breve{x}_i)$ in system (1) can be approximated by fuzzy logic system $f_i(\bar{x}_i | \hat{\kappa}_i)$, which is defined by

$$f_i(\bar{x}_i | \hat{\kappa}_i) = \hat{\kappa}_i^T \phi_i(\bar{x}_i) \tag{3}$$

where $\bar{x}_1 = [\hat{x}_1, \hat{x}_2]^T$, $\bar{x}_2 = [\hat{x}_2, \hat{x}_3, \hat{x}_4]^T$ and $\bar{x}_3 = [\hat{x}_2, \hat{x}_3]^T$ are the estimation vectors of the state x_i.

Then, define an optimal parameter vector as

$$\kappa_i^* = \arg\min_{\kappa_i\in\bar{U}_i}\left\{\sup_{(\hat{x}_i,\breve{x}_i)\in U_i} | \hat{f}_i(\bar{x}_i | \hat{\kappa}_i) - f_i(\breve{x}_i)|\right\}, \tag{4}$$

where $\bar{U}_i$ and U_i are bounded sets of κ_i and $\hat{x}_i$, respectively. Therefore, the minimum approximate error can be expressed by

$$\xi_i = f_i(\breve{x}_i) - \kappa_i^{*T}\phi_i(\bar{x}_i) \tag{5}$$

where $|\xi_i| \le \xi_i^*\ (i=1,2,3)$ and ξ_i^* is a positive constant. In the subsequent design, $\phi_i(\bar{x}_i)$ is abbreviated as ϕ_i.

Next, a high-gain fuzzy observer is design as follows:

$$\dot{\hat{X}} = A'\hat{X} + W'y + \sum_{j=1}^{3} H_j\hat{\kappa}_i\phi_i + b_2 u, \tag{6}$$

where $\hat{X} = [\hat{x}_1,...,\hat{x}_4]^T$, $W' = [w_1L, w_2L^2, w_3L^3, w_4L^4]^T$ is gain vector, $H_i = \Big[\underbrace{0,0,...,1}_{i},0\Big]_{1\times4}$, $A' = \begin{bmatrix} -w_1L & 1 & 0 & 0 \\ -w_2L^2 & 0 & b_1 & 0 \\ -w_3L^3 & 0 & 0 & 0 \\ -w_4L^4 & 0 & 0 & -b_3/L \end{bmatrix}^T$, $u = [0,0,V_q,V_d]^T$. Meanwhile, define positive definite matrix $Q = Q^T$ such that the positive definite matrix $P = P^T$ satisfies:

$$A^T P + PA = -2Q < 0. \tag{7}$$

Define the observation error vector e_i and scaling error $\varsigma_i\ (i=1,2,3,4)$ as follows:

$$e_i = x_i - \hat{x}_i, \tag{8}$$

$$\varsigma_i = \frac{e_i}{L^{i-1}}. \tag{9}$$

where $L>1$ is a constant. The time-derivative of (9) can be expressed as:

$$\dot{\varsigma} = LA\varsigma + \varepsilon' + \sum_{i=1}^{3}\frac{1}{L^{i-1}}H\tilde{\kappa}_i^T\phi_i, \tag{10}$$

where $\varepsilon' = \left[0, \frac{\varepsilon_1}{L}, \frac{\varepsilon_2}{L^2}, \frac{\varepsilon_3}{L^3}\right]^T$ satisfies $|\varepsilon'| \le \bar{\varepsilon}$ and $\bar{\varepsilon} > 0$.

In order to analysis the stability of the proposed observer, construct a Lyapunov function as

$$V_0 = \frac{1}{2}\varsigma^T P\varsigma. \tag{11}$$

Then, we have

$$\dot{V}_0 = \varsigma^T P\left(LA\varsigma + \varepsilon' + \sum_{i=1}^{3}\frac{1}{L^{i-1}}H\tilde{\kappa}_i^T\phi_i\right). \tag{12}$$

By introducing the following Young's inequalities

$$\varsigma^T P\varepsilon' \le \frac{1}{2}\|P\|^2\|\bar{\varepsilon}\|^2 + \frac{1}{2}\|\varsigma\|^2, \tag{13}$$

$$\varsigma^T P\sum_{i=1}^{3}\frac{1}{L^{i-1}}H\tilde{\kappa}_i^T\phi_i \le \frac{3}{2}\|\varsigma\|^2 + \frac{1}{2}\|P\|^2\sum_{i=1}^{3}\tilde{\kappa}_i^T\tilde{\kappa}_i. \tag{14}$$

Substituting (13) and (14) into (12) produces that

$$\dot{V}_0 \le -\lambda_0\|\varsigma\|^2 + \frac{1}{2}\|P\|^2\sum_{i=1}^{3}\tilde{\kappa}_i^T\tilde{\kappa}_i + \Delta_0. \tag{15}$$

where $\lambda_0 = \min\{0.5L\lambda_{\min}(Q) - 2\}$ and $\Delta_0 = 0.5\|P\|^2\|\bar{\varepsilon}\|^2$.

IV. BACKSTEPPING CONTROLLER DESIGN

In this section, a backstepping controller design is carried out. First of all, it is necessary to define the following coordinate transformations:

$$\begin{cases} z_1 = x_1 - y_d, \\ z_i = \hat{x}_i - \hat{\alpha}_{i-1}, (i=2,3), \\ M_i = z_i - s_i, (i=1,2,3, s_3=0). \end{cases} \tag{16}$$

where s_i is called compensation signal and $\hat{\alpha}_i$ is the output of the first-order command filter. The definition of the filter is given by

$$l_i\dot{\hat{\alpha}}_i + \hat{\alpha}_i = \alpha_i, \hat{\alpha}_i(0) = \alpha_i(0), i=1,2. \tag{17}$$

where $l_i > 0$ is a design parameter of the command filter. Then, the backstepping control design process is composed by four steps.

Step 1: Select a Lyapunov function for the first subsystem:

$$V_1 = \frac{1}{2}M_1^2. \tag{18}$$

Then, one has

$$\dot{V}_1 = M_1(M_2 + s_2 + \hat{\alpha}_1 + L\varsigma_2 - \dot{y}_d - \dot{s}_1), \tag{19}$$

Next, we design a dynamic compensation dynamic $\dot{s}_1$ and a virtual control law α_1 as follows:

$$\dot{s}_1 = -\left(\bar{c}_1 + \frac{L}{2}\right)s_1 + \hat{\alpha}_1 - \alpha_1 + s_2, \tag{20}$$

$$\alpha_1 = -\left(\bar{c}_1 + \frac{L}{2}\right)z_1 + \dot{y}_d. \tag{21}$$

where $\bar{c}_1 > 0$ is constant.

By substitute (20) and (21) into (19), it yields that

$$\dot{V}_1 = -\bar{c}_1 M_1^2 + M_1M_2 + \frac{1}{2}\|\varsigma\|^2. \tag{22}$$

Step 2: Construct a Lyapunov function for the second subsystem:

$$V_2 = V_1 + \frac{1}{2}M_2^2 + \frac{1}{2}\tilde{\kappa}_1^T\tilde{\kappa}_1. \tag{23}$$

Similar to Step 1, from $z_2 = \hat{x}_2 - \hat{\alpha}_1$, $M_2 = \hat{x}_2 - s_2$ and (22), we have

$$\dot{V}_2 = \dot{V}_1 + M_2\left(b_1\left(M_3 + s_3 + \hat{\alpha}_2\right) + w_2 L^2\left(y - \hat{x}_1\right)\right) + M_2\left(\hat{\kappa}_1^T\phi_1 - \dot{\hat{\alpha}}_1 - \dot{s}_2\right) - \tilde{\kappa}_1^T\dot{\hat{\kappa}}_1, \tag{24}$$

Then, design a dynamic compensation dynamic $\dot{s}_2$ and a virtual control law α_2 as follows:

$$\dot{s}_2 = -\bar{c}_2 s_2 + b_1\hat{\alpha}_2 - \alpha_2 + b_1 s_3 - s_1, \tag{25}$$

$$\alpha_2 = -\bar{c}_2 z_2 - z_1 - w_2 L^2\left(y - \hat{x}_1\right) - \hat{\kappa}_1^T\phi_1 + \dot{\hat{\alpha}}_1. \tag{26}$$

where $\bar{c}_2 > 0$ is a design parameter.

Substitute (25) and (26) into (24), it produces that

$$\dot{V}_2 \le \dot{V}_1 - \bar{c}_2 M_2^{\ 2} + b_1 M_2 M_3 - M_2\tilde{\kappa}_1\phi_1 - \tilde{\kappa}_1^T\left(\dot{\hat{\kappa}}_1 - M_2\phi_1\right), \tag{27}$$

Next, design an adaptive law $\dot{\hat{\kappa}}_1$ as

$$\dot{\hat{\kappa}}_1 = M_2\phi_1 - \rho_1\hat{\kappa}_1, \tag{28}$$

where $\rho_1 > 0$ is a design parameter.

From the following Young's inequalities

$$\begin{cases} M_2\tilde{\kappa}_1\phi_1 \le \frac{1}{2}M_2^{\ 2} + \frac{1}{2}\tilde{\kappa}_1^T\tilde{\kappa}_1, \\ \tilde{\kappa}_1^T\hat{\kappa}_1 \le -\frac{1}{2}\tilde{\kappa}_1^T\tilde{\kappa}_1 + \frac{1}{2}\|\kappa_1^*\|^2, \end{cases} \tag{29}$$

one has

$$\dot{V}_2 = -\sum_{j=1}^{2}C_j M_1^{\ 2} + \frac{1}{2}\|\varsigma\|^2 - \Xi_1\tilde{\kappa}_1^T\tilde{\kappa}_1 + b_1 M_2 M_3 + \frac{\rho_1}{2}\|\kappa_1^*\|^2, \tag{30}$$

where $C_1 = \bar{c}_1$, $C_2 = \left(\bar{c}_2 - \frac{1}{2}\right) > 0$ and $\Xi_1 = \left(\frac{\rho_1 - 1}{2}\right) > 0$.

Step 3: The following Lyapunov function is designed:

$$V_3 = V_2 + \frac{1}{2}M_3^{\ 2} + \frac{1}{2}\tilde{\kappa}_2^T\tilde{\kappa}_2 + \frac{1}{2}\tilde{\kappa}_3^T\tilde{\kappa}_3. \tag{31}$$

Then, we have

$$\dot{V}_3 = \dot{V}_2 + M_3\left(w_3 L^3\left(y - \hat{x}_1\right) + \hat{\kappa}_2^T\phi_2\right) M_3\left(b_2 V_q - \dot{\hat{\alpha}}_3 - \dot{s}_3\right) - \tilde{\kappa}_2^T\dot{\hat{\kappa}}_2 - \tilde{\kappa}_3^T\dot{\hat{\kappa}}_3, \tag{32}$$

According to (32), design an actual control signal V_q as

$$V_q = -\frac{1}{b_2}\left(\bar{c}_3 M_3 + b_1 M_2 + w_3 L^3\left(y - \hat{x}_1\right) + \dot{\hat{\alpha}}_3 - \hat{\kappa}_2^T\phi_2\right), \tag{33}$$

where $\bar{c}_3 > 0$ is a design parameter.

Substituting (33) into (31) produces that

$$\dot{V}_3 \le \dot{V}_2 - b_1 M_2 M_3 - \bar{c}_3 M_3^{\ 2} - \sum_{j=2}^{3}\tilde{\kappa}_j^T\left(\dot{\hat{\kappa}}_j - M_3\phi_j\right) - \sum_{j=2}^{3}M_3\tilde{\kappa}_j\phi_j, \tag{34}$$

Next, design two adaptive laws $\dot{\hat{\kappa}}_2$ and $\dot{\hat{\kappa}}_3$ as

$$\dot{\hat{\kappa}}_2 = M_3\phi_2 - \rho_2\hat{\kappa}_2, \tag{35}$$

$$\dot{\hat{\kappa}}_3 = M_3\phi_3 - \rho_3\hat{\kappa}_3. \tag{36}$$

where $\rho_2 > 0$ and $\rho_3 > 0$ are design parameters.

By using Young's inequalities

$$\begin{cases} M_3\tilde{\kappa}_i\phi_i \le \frac{1}{2}M_3^{\ 2} + \frac{1}{2}\tilde{\kappa}_i^T\tilde{\kappa}_i, \\ \tilde{\kappa}_i^T\hat{\kappa}_i \le -\frac{1}{2}\tilde{\kappa}_i^T\tilde{\kappa}_i + \frac{1}{2}\|\kappa_i^*\|^2, \end{cases} \tag{37}$$

the following results hold.

$$\dot{V}_3 = -\sum_{j=1}^{3}C_j M_1^{\ 2} + \frac{1}{2}\|\varsigma\|^2 - \sum_{j=1}^{3}\Xi_j\tilde{\kappa}_j^T\tilde{\kappa}_j + \sum_{j=1}^{3}\frac{\rho_j}{2}\|\kappa_j^*\|^2, \tag{38}$$

where $C_3 = \left(\bar{c}_3 - \frac{1}{2}\right) > 0$, $\Xi_j = \left(\frac{\rho_j - 1}{2}\right) > 0, \left(j = 1, 2, 3\right)$.

Step 4: It is worth noting that state x_4 can converge into a neighborhood of the origin by directly designing the control signal V_d, so here we design a specific form of V_d as follows:

$$V_d = -\frac{1}{b_2}\left(w_4 L^4\left(y - \hat{x}_1\right) + \hat{\kappa}_3\phi_3\right), \tag{39}$$

where $\hat{\kappa}_3$ is obtained through the adaptive law $\dot{\hat{\kappa}}_3$ in (36).

Finally, by both considering high-gain observer and backstepping controllers, we define

$$V = V_0 + V_3. \tag{40}$$

Then, one has

$$\dot{V} \le -\left(\lambda_0 - \frac{1}{2}\right)\|\varsigma\|^2 - \sum_{j=1}^{3}C_j M_j^{\ 2} - \Xi\tilde{\kappa}_j^T\tilde{\kappa}_j + \Delta, \tag{41}$$

where Ξ and Δ are defined by $\Xi = \sum_{j=1}^{3}\Xi_j + \frac{1}{2}\|P\|^2$ and $\Delta = \sum_{j=1}^{3}0.5\rho_j\|\kappa_j^*\|^2 + 0.5\|P\|^2\|\bar{\varepsilon}\|^2$, respectively.

By selecting appropriate parameters, make λ_0, C_j and Ξ be greater than 0, and define

$$\bar{A} = \min\left\{\left(2\lambda_0 - 1\right)/\lambda_{\max}\left(P\right), 2C_j, 2\Xi\right\}, j = 1, 2, 3. \tag{42}$$

where $\lambda_{\max}\left(P\right)$ is a maximum eigenvalue of matrix P. Therefore, $\dot{V}$ can be written as: $\dot{V} \le -\bar{A}V + \Delta$. According to the conclusion in [11-12], the compensation signal is bounded. By combining **Assumption 1** with coordinate transformation (16), the control signal composed of bounded function shows that all signals in the closed-loop LSM system are uniformly ultimately bounded.

V. SIMULATION

In this section, the simulation experiments are established to verify that the proposed scheme can achieve the following control objective: the mover position of LSM can follow a reference signal $y_d\left(t\right) = \sin\left(t\right)$ within a small error area. In order to achieve the control objective, the parameters are selected and shown in TABLE II, and the running time is set to T =30s. The initial conditions of the states are chosen as follows: $x_1\left(0\right)$ = 1 and $x_2\left(0\right) = x_3\left(0\right) = x_4\left(0\right)$ =0.

By using the parameters in TABLE II, virtual control laws (21) and (26), dynamic compensation dynamics (20) and (25) and actual control laws (33) and (39), the control performance results of the proposed scheme are achieved and shown in Fig. 1-Fig. 4. The tracking performance of the mover is shown in Fig. 1. From the simulation results, it can be seen that the mover starts from the initial position of 1m and can follow the reference signal well after 1s. In order to further investigate the effect of the proposed controller, it can be analyzed from the perspective of tracking error. If the tracking error is as small as possible, it will prove that the tracking control of LSM is better, hence the tracking error of the proposed scheme is shown in Fig. 2. From the results in Fig. 2. The tracking error initially fluctuates slightly, but quickly returns to a small neighborhood around the origin, which also shows that a good steady-state performance has been achieved.

TABLE II
TABLE OF PARAMETERS

Motor System	Adaptive and control laws	Observer
$m=$ 0.65 kg	$\rho_1=1$	$w_1=1$
$B=$ 0.01 $N/m/s$	$\rho_2=1$	$w_2=1$
$F_c=$ 2.4 N	$\rho_3=1$	$w_3=12$
$p=$ 1.28 mm	$\bar{c}_1=5$	$w_2=1$
$k_f=$ 27.83	$\bar{c}_2=8$	$L=2.5$
$R=$ 3 Ω	$\bar{c}_3=15$	
$L_l=$ 0.5 mH	$l_1=l_2=0.1$	

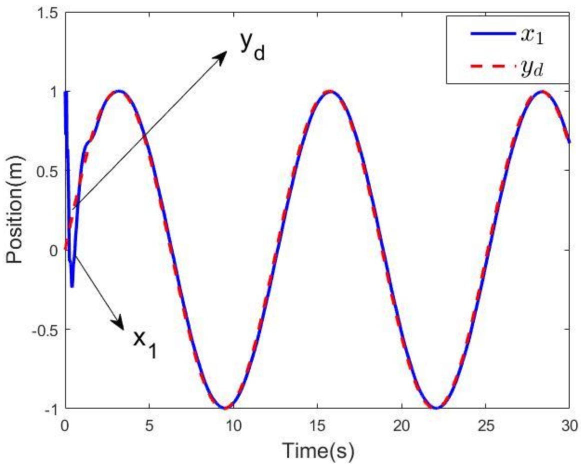

Fig. 1 Tracking performance of motor position

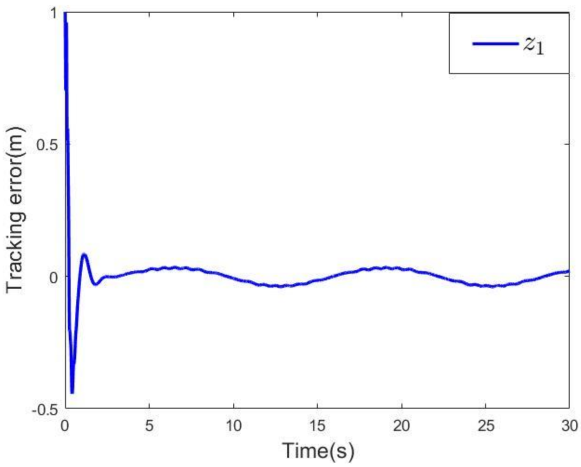

Fig. 2 Tracking error of motor position

It can be seen in Fig. 3 that the control signal V_q and V_d, the control signal V_q ensures that the boundedness of all signals of the first three subsystems, and the control signal V_d guarantees the boundedness of the fourth subsystem. Finally, the adaptive parameter response curve is displayed in Fig. 4. Three curves represent the two-norms of vectors κ_1, κ_2 and κ_3, respectively. It shows that that the adaptive parameters are bounded. In conclusion, the effectiveness and feasibility of the proposed scheme are verified by simulation results.

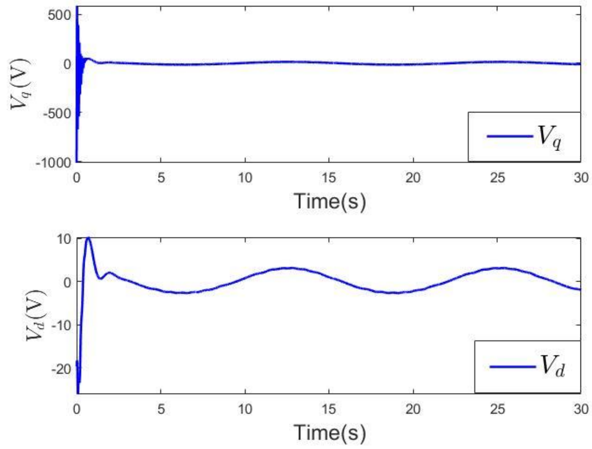

Fig. 3 Control signal V_q and V_d

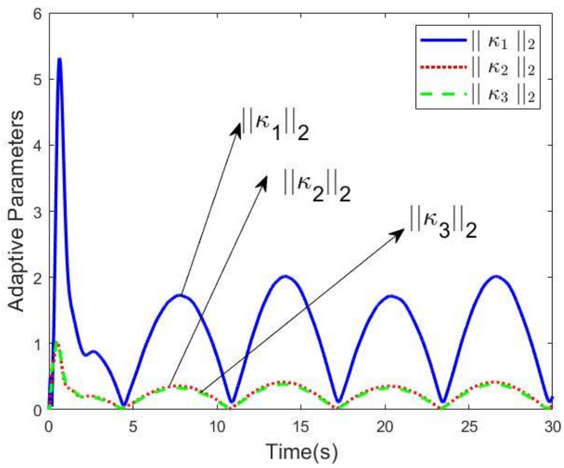

Fig. 4. Response curve of adaptive parameters

VI. CONCLUSION

Due to the tracking control problem of LSM, a novel backstepping controller has been designed by combining high-gain observer and command filtering technique. The application of the proposed scheme has certain advantages by compared with the existing results: in the case of unknown system states, the state estimation can be carried out by high-gain observer, and the introduction of command filters simplifies the calculation amount in the controller design process to make the design of the controller more flexible. Finally, the effectiveness of the controller design is verified by simulation results. The follow-up work can be carried out on the basis of considering possible sensor failures in LSM, and the fault-tolerant control of LSM can be further studied.

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