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Adaptive High Order Neural Network Identification and Control for Hysteresis Nonlinear System with Bouc-Wen Model

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ABSTRACT

An adaptive high order neural network (HONN) identification approach and control strategy are proposed for hysteresis nonlinear system with the Bouc-Wen model. Firstly, a new identification scheme using HONN is presented to estimate the unknown parameters of the Bouc-Wen hysteresis nonlinear system. Compared with other widely used gradient-descent updating algorithms, the new identification approach utilized adaptively updating law that has acquired faster convergence speed and short training process. Then, a new scalar tracking error is defined which transformed from the vector tracking error between the identified system states and reference states. The transformed scalar tracking error simplifies the controller design and obtains satisfying control results with appropriately adjusted transform vector g. Finally, the Lyapunov function guarantees the stability of all the signals in the closed-loop system and simulations demonstrates the effectiveness of the proposed identification and control strategies.

1. Introduction

Hysteresis systems become more important since the control performance is required higher in electromechanical system (Gao(2018);Gao and Liu(2018);Wang et al(2018); Gao et al(2018a);Gao et al(2018b)), robots(Na et al(2017a);Na et al(2014);Na et al(2018);Na et al(2017b);Wang et al(2017b);Wang et al(2017a);Wang et al(2016a);Wang et al(2016b);Chen et al(2018c);Chen et al(2017)), and smart materials(Chen et al(2018b);Wei et al(2018);Yang et al(2018b)),etc. The existence of the hysteresis will degrade the precision of the control strategy and the serious hysteresis even results in the instability. Therefore, the models of the hysteresis have been investigated for many years.

The Bouc-Wen model (Bouc(1971); Wen(1976); Xu and Zhou(2017); Jin et al(2018);Gao et al(2016); Xuehui and Bo(2017)) is one of the excellent hysteresis models which gets lots of scholars' attention. The Bouc-Wen model is proposed by Bouc(1971) and Wen(1976). In recent years, that becomes one of the important hysteresis models and many researchers focus on this model. Ahmad (2018) proposed a two degree-of-freedom robust digital feedback controller with a simple Bouc-Wen hysteresis feed-forward compensator to deal with the modeling complexity and modeling errors. The experimental results verify the effectiveness of the proposed control scheme. Otherwise, a class of switched stochastic nonlinear pure-feedback systems with unknown direction Bouc-Wen hysteresis model was handled by an adaptive neural network (NN) tracking control strategy in Namadchian and Rouhani (2018). The Nussbaum function and the back-stepping techniques were applied to deal with the unknown hysteresis direction and universal approximation capability of radial basis function NNs and Lyapunov function method was synthesized to develop an adaptive NN tracking control scheme which guaranteed that all signals in the closed-loop system are semi-globally uniformly ultimately bounded (UUB). Xu et al (2018) used a bat-inspired optimization algorithm to identify the Bouc-Wen model and sliding mode control suppressed the hysteresis nonlinearity and achieves high precision tracking control for the piezo-actuated stages. But high order neural network (HONN) rarely utilized the Bouc-Wen model hysteresis systems.

HONN has fast convergence speed and short training process such that many scholars focus on this NN structure. For instance, Na et al (2013) presented a novel adaptive NN control design for nonlinear pure-feedback systems without using back-stepping. The proposed HONN with only a scalar weight updated online was

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constructed to further reduce the computational costs. Furthermore, multi-time-scale recurrent HONN was proposed for the singularly perturbed nonlinear system to identify the unknown parameters in li Zheng et al (2017b). Compared with other widely used gradient-descent updating algorithms, the new method could achieve faster convergence, due to its adaptively adjusted learning rate. Different from Zheng et al(2017b), Zheng et al(2017a) applied multi-time scale recurrent HONN to identify and control the singularly perturbed nonlinear systems with uncertainties. The identification scheme using modified optimal bounded ellipsoid based weights updating laws to achieve high convergence speed and the experimental results demonstrated the effectiveness of the identification and control scheme.

In this paper, we propose a new adaptive HONN identification approach and control strategy to deal with hysteresis nonlinear system with the Bouc-Wen model. A new identification scheme for the Bouc-Wen hysteresis nonlinear system using HONN is proposed firstly. Compared with other widely used gradient-descent updating algorithms, the proposed HONN updating law adopts adaptively adjusted learning rate, which has faster convergence speed and short training process. Then, we define a new scalar tracking error that transformed from the vector tracking error between the system states and the reference states. It is important that the transformed scalar tracking error can simplify the controller design. Selecting suitable adjusted vector *g*, we can get satisfying performance control results as well as simplified controller design. Finally, a Lyapunov function candidate guarantees the stability of the closed-loop system.

The paper is organized as follows. Section II describes the problem formulations. The identification and control design are provided in Section III. Section IV gives the simulations and Section V concludes the paper.

2. Problem formulations

2.1 System representation

Considering the hysteresis system with Bouc-Wen model is represented as follows:

$$\begin{cases} \dot{x} = f(x,u) = h(x) + Bv \\ v = \Gamma(x,u) = \tau_1 u + \tau_2 w \end{cases} \tag{1}$$

where $x \in \mathbb{R}^n$ are the system states, $h(x) \in \mathbb{C}^\infty$ represents a unknown general nonlinear smooth function, $u \in \mathbb{R}^m$ is the control signal vector, $v = \Gamma(x,u)$ means unknown hysteresis nonlinearity, which is described by the Bouc-Wen model. It has $sign(\tau_1) = sign(\tau_2)$, $\omega(t_0) = 0$ and

$$\begin{aligned} \dot{w} &= \dot{u} - \alpha|\dot{u}||w|^{n-1} w - \beta \dot{u} |w|^n \\ &= \dot{u} - G(\dot{u}, w) \end{aligned} \tag{2}$$

where $\alpha > |\beta|$.

In order to simplify the control design, the system (1) can be rewritten as

$$\dot{x} = h(x) + B\tau_1 u + B\tau_2 w \tag{3}$$

In this paper, the hysteresis $B\tau_2\omega$ is looked as unknown external disturbance. Then we utilize high order neural network (HONN) to estimate $h(x)$ and the disturbance $B\tau_2\omega$. One of the main contributions in this paper is that a HONN is proposed to identify the unknown $h(x)$ and $B\tau_2\omega$. For this purpose, the following assumption is desired:

Assumption 1. The unknown general nonlinear smooth function h(x) is Lipschitz with Lipschitz constant K as

$$\|h(x_1) - h(x_2)\| \le K\|x_1 - x_2\| \tag{4}$$

Otherwise, from the definition of the Bouc-Wen hysteresis model, we can obvious obtain that the Bouc-Wen model is bounded (see Fig. 1). After Assumption 1, if the input *u* is bounded signal, then, the system (1) is a bounded-input and bounded-output system. In fact, most actual systems satisfy the Assumption 1 and it's a reasonable assumption.

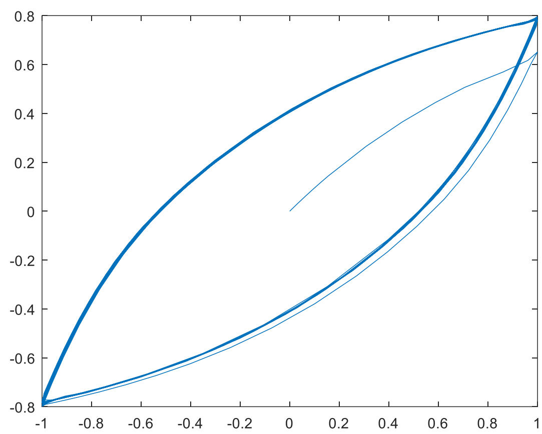

Fig. 1. The curve of the Bouc-Wen hysteresis model.

2.2 High order neural network

To identify the hysteresis system (3), a new HONN is designed estimating the unknown function $h(x)$ and $B\tau_2\omega$. Define the activation function vector $\Phi(\cdot)$ as:

$$\begin{aligned} &\Phi(\cdot) = \left[\Phi_1, \Phi_2, \cdots, \Phi_p\right]^T \in R^{p\times 1} \\ &\Phi_k(\cdot) = \prod_{k\in J_k} \left[\phi_k(\cdot)\right]^{z_k(k)}, k = 1, 2, \cdots, p \end{aligned} \tag{5}$$

where J_k are the collections of the subsets of $1, 2, \cdots n$ and

$Z_k(k)$ are designed unknown nonnegative parameters. In this paper, the activation function $\phi_k(\cdot)$ is chosen as

$$\phi_k(x) = \frac{c_1}{1+e^{-c_2 x}} + c_3 \tag{6}$$

where $\forall c_{1,}, c_2 \in \mathbb{R}^+$ are positive integers and $c_3 \in \mathbb{R}, c_3 \le \gamma\varpi$ is bounded, where γ, ϖ are known parameters.

Assuming the hysteresis nonlinear system (3) can be approximated by the HONN as follows:

$$\dot{x} = A\hat{x} + Du + W\Phi(x) + \varepsilon \tag{7}$$

where $A \in \mathbb{R}^{n\times n}$ is designed diagonal stable matrix, $D \in \mathbb{R}^{n\times 1}$ is designed vector, ε represents the identification error, and which is bounded such that $\varepsilon \le \varepsilon_M$ holds, where ε_M is a positive constant, $W \in \mathbb{R}^{n\times p}$ means the weight matrix of the HONN. Then, the hysteresis system (1) can be estimated by (7) with HONN.

3. Identification and control design

3.1 System identification

Since defined the identification system (7) to estimate the hysteresis system (1), we can assume the hysteresis system is described by HONN as follows:

$$\dot{x} = Ax + Du + W^*\Phi(x) \tag{8}$$

Define the error *e* as follows:

$$e = x - \hat{x} \tag{9}$$

Then, the derivative of *e* is deduced as

$$\dot{e} = Ae + \tilde{W}\Phi(x) + \varepsilon \tag{10}$$

where the weight matrix error $\tilde{W}$ is defined as $\tilde{W} = W^* - W$.

Since *A* is diagonal stable matrix, given a Positive definite symmetric matrix $P = P^T > 0$, that exists a positive definite symmetric matrix $Q = Q^T > 0$ such that the matrix inequality holds:

$$A^T P + PA \le -Q \tag{11}$$

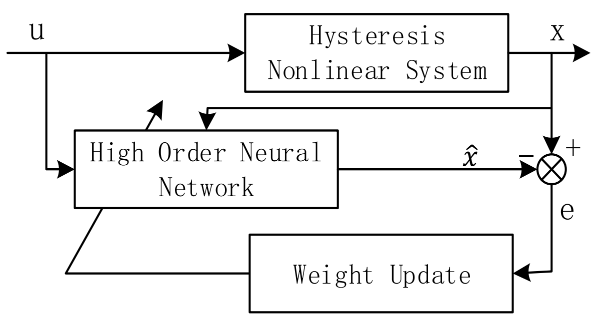

Fig. 2. The HONN identification structure

Then, the identification structure can be illustrated by Fig.2. The hysteresis nonlinear system (1) is identified by (7) with HONN $W\Phi(x)$, the weight matrix can be updated online in the identification structure.

Considering the Assumption 1 and the bounded hysteresis Bouc-Wen model, the error *e* and the weight matrix error $\tilde{W}$ obviously also are bounded, thus, it has

$$\begin{aligned} &\|e\| \le e_M \\ &\|\tilde{W}\Phi(x)\| \le W_M \phi_M \end{aligned} \tag{12}$$

where e_M, W_M, ϕ_M are positive constants.

Define the Lyapunov function as

$$V = \frac{1}{2} e^T P e \tag{13}$$

Then, considering equation (10), the derivative of V can be deduced as

$$\begin{aligned} \dot{V} &= \frac{1}{2}\dot{e}^T P e + \frac{1}{2} e^T P \dot{e} \\ &= \frac{1}{2}\left(e^T A^T + \Phi^T(x)\tilde{W}^T + \varepsilon\right) P e \\ &\quad + \frac{1}{2} e^T P\left(Ae + \tilde{W}\Phi(x) + \varepsilon\right) \\ &= \frac{1}{2} e^T A^P e + \frac{1}{2}\Phi(x)\tilde{W}^T P e + \frac{1}{2} P e \\ &\quad + \frac{1}{2} e^T P A e + \frac{1}{2} e^T P \tilde{W}\Phi(x) + \frac{1}{2} e^T P \varepsilon \end{aligned} \tag{14}$$

According to (11), (12), that has

$$\dot{V} \le -e^T Q e + e^T P\left(W_M \phi_M + \varepsilon_M\right) \tag{15}$$

By applying (13), we have

$$\dot{V} = -\gamma_1 V + \gamma_2 \tag{16}$$

where γ_1 can be obtained by inequation (11), $\gamma_2 = e^T P\left(W_M \phi_M + \varepsilon_M\right)$. According to Lyapunov theorem, *V* is semi-globally uniformly ultimately bounded (UUB) thus the identification error e is bounded. Considering (16), integrating both sides of (16) over $[0, t]$, the following holds:

$$V \le V(0)e^{-\gamma_1 t} + \frac{\gamma_2}{\gamma_1}\left(1 - e^{-\gamma_1 t}\right) \le \frac{\gamma_2}{\gamma_1} + V(0)e^{-\gamma_1 t} \tag{17}$$

where $V(0)$ means the initial value of *V* at time *0*. Moreover, the identification error *e* can be deduced as

$$|e| \le \sqrt{2\left(\frac{\gamma_2}{\gamma_1}+V(0)e^{-\gamma_1 t}\right)} \tag{18}$$

So that

$$\begin{aligned}\lim_{t\to\infty}|e| &\le \lim_{t\to\infty}\sqrt{2\left(\frac{\gamma_2}{\gamma_1}+V(0)e^{-\gamma_1 t}\right)} \\ &= \sqrt{2\frac{\gamma_2}{\gamma_1}}\end{aligned} \tag{19}$$

holds. That means the identification results converge to a small compact set over the zero, which are bounded. Then, the proposed HONN identification approach can effectively estimate the Bouc-Wen hysteresis nonlinear system.

3.2 Error Transformation

Since the HONN can estimated the hysteresis system (1) with $\dot{\hat{x}} = A\hat{x}+Du+W\Phi(x)+\varepsilon$ where A is diagonal stable matrix. Without loss of generality, the reference model can be defined as

$$\dot{x}_r = A_r x_r + B_r u_r \tag{20}$$

where $A_r \in \mathbb{R}^{n\times n}$, $B_r \in \mathbb{R}^{n\times 1}$ are reference model states coefficients matrixes, u_r is the reference input. The state matrix A_r is asymptotically stale and it satisfies

$$\det(sI - A_r) = (s+l)H(s) \tag{21}$$

where $l>0$, $H(s)$ is Hurwitz polynomial.

Define the tracking error as

$$e_t = x - x_r \tag{22}$$

The tracking error will be transformed into a scalar error to simply the control design in this paper. Therefore, according to reference Annaswamy et al (1998), we assume the following assumption:

Assumption 2. $A\in\mathbb{R}^{n\times n}$ is unknown matrix, $D\in\mathbb{R}^{n\times 1}$ is known vector, Then, it exists unknown vector $\delta\in\mathbb{R}^{n\times 1}$ which satisfies

$$\begin{aligned}A + D\delta &= A_r \\ D\delta_r &= B_r\end{aligned} \tag{23}$$

where (A,D) are controllable.

Then, the following Lemma is introduced to perform the error transforming based on the reference Annaswamy et al (1998):

Lemma 1. If asymptotically stable system $\dot{x} = Ax + Du$ is controllable, there characteristic polynomial $\lambda(s)$ is described by $\lambda(s) = \det(sI - A) = (s+l)H(s)$, where $l>0$, $H(s)$ is Hurwitz polynomial. Then, $\exists g$, it satisfies

$$g^T(sI-A)^{-1}D = \frac{1}{s+l} \tag{24}$$

Define the scalar tracking error e_s as

$$e_s = g^T e_t \tag{25}$$

According to the definition (22) and the equation (8), (20), we have

$$\begin{aligned}\dot{e}_t &= \dot{x} - \dot{x}_r \\ &= Ax + Du + W^*\Phi(x) - A_r X_r - B_r u_r\end{aligned} \tag{26}$$

Considering the assumption 2, the derivative of e_t can be deduced as

$$\begin{aligned}\dot{e}_t &= A_r e_t + D(u - \delta x - \delta_r u_r) \\ &+W^*\Phi(x)\end{aligned} \tag{27}$$

According to the scalar error definition (25), the Lemma 1 and the Laplace transformation, we have

$$\begin{aligned}\dot{e}_s &= -le_s + u - \delta x - \delta_r u_r \\ &+(l-c_2)W^*\Phi(x)\end{aligned} \tag{28}$$

3.3 Control Design

The controller can be designed as follows:

$$u = \hat{\delta}\hat{x} + \hat{\delta}_r u_r + (l-c_2)W\Phi(x) \tag{29}$$

where $\hat{\delta},\hat{\delta}_r$ are the estimations of the δ,δ_r.

To design the adaptive NN control, we define the auxiliary errors as:

$$\begin{aligned}\tilde{\delta} &= \delta - \hat{\delta} \\ \tilde{\delta}_r &= \delta_r - \hat{\delta}_r\end{aligned} \tag{30}$$

Then, the following theorem holds:

Theorem 1. Considering the hysteresis system (1) can be identified by (7); The reference model is defined as (20).According to the assumption 2, the transformed scalar tracking error, the auxiliary error $\delta,\tilde{\delta}_r,u$ we can stabilized control the hysteresis nonlinear system with the controller u as (29) by using the following update laws:

$$\begin{aligned} \dot{\hat{\delta}} &= \rho_1 e_s e \\ \dot{\hat{\delta}}_r &= \rho_2 e_s u_r \\ \dot{\hat{W}} &= \rho_3 e_s (l - c_2)\Phi(x) \end{aligned} \tag{31}$$

where ρ_1, ρ_2, ρ_3 are positive constants.

Proof: Define the Lyapunov function candidate as

$$V_t = \frac{1}{2}e_s^2 + \frac{1}{2\rho_1}\tilde{\delta}^2 + \frac{1}{2\rho_2}\tilde{\delta}_r^2 + \frac{1}{2\rho_3}tr\left\{\tilde{W}^T\tilde{W}\right\} \tag{32}$$

Then, the derivative of V_t is deduced as

$$\dot{V}_t = e_s\dot{e}_s + \frac{1}{\rho_1}\tilde{\delta}\dot{\tilde{\delta}} + \frac{1}{\rho_2}\tilde{\delta}_r\dot{\tilde{\delta}}_r + \frac{1}{\rho_3}tr\left\{\tilde{W}^T\dot{\tilde{W}}\right\} \tag{33}$$

According to equation (28), (29), (30), (31), the equation (33) yields

$$\begin{aligned} \dot{V}_t &= e_s(-le_s + u - \delta x - \delta_r u_r \\ &\quad + (l - c_2)W\Phi(x)) \\ &\quad + \frac{1}{\rho_1}\tilde{\delta}\dot{\tilde{\delta}} + \frac{1}{\rho_2}\tilde{\delta}_r\dot{\tilde{\delta}}_r + \frac{1}{\rho_3}tr\left\{\tilde{W}^T\dot{\tilde{W}}\right\} \\ &= -le_s^2 + e_s(\hat{\delta}\hat{x} + \hat{\delta}_r u_r + (l - c_2)W\Phi(x) \\ &\quad - \delta x - \delta_r u_r + (l - c_2)W\Phi(x)) \\ &\quad + \frac{1}{\rho_1}\tilde{\delta}\dot{\tilde{\delta}} + \frac{1}{\rho_2}\tilde{\delta}_r\dot{\tilde{\delta}}_r + \frac{1}{\rho_3}tr\left\{\tilde{W}^T\dot{\tilde{W}}\right\} \\ &= -le_s^2 - W_M\phi_M \\ &\le -le_s^2. \end{aligned} \tag{34}$$

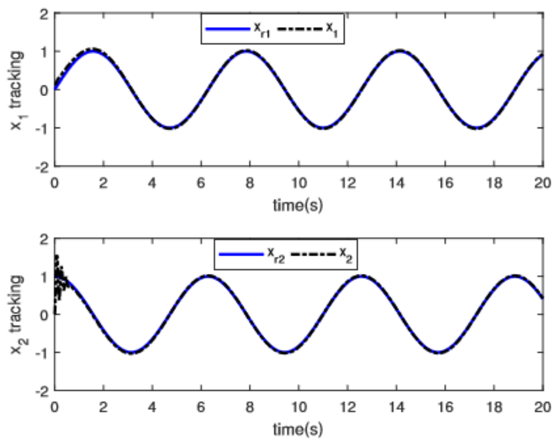

Fig. 3. The adaptive control tracking result with $u_r = sin(t)$

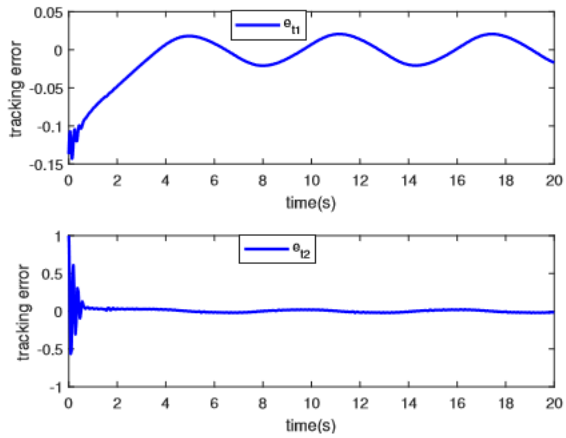

Fig. 4. The vector tracking error of the system with $u_r = sin(t)$

Therefore, according to the Lyapunov theory, the designed controller can be stabilized control the hysteresis nonlinear system with the HONN identification approach. The tracking error e_s is bounded. Since the scalar error e_s is transformed from the vector tracking error e_t, which actually magnifies the vector error e_t, and expends the control precision but simplifies the computation complexity. Select appropriately parameters, we also can get the desired control precision under the simple computation with the transformed scalar error e_s. Since the magnified scalar error e_s is bounded, the vector tracking error e_t also is bounded.

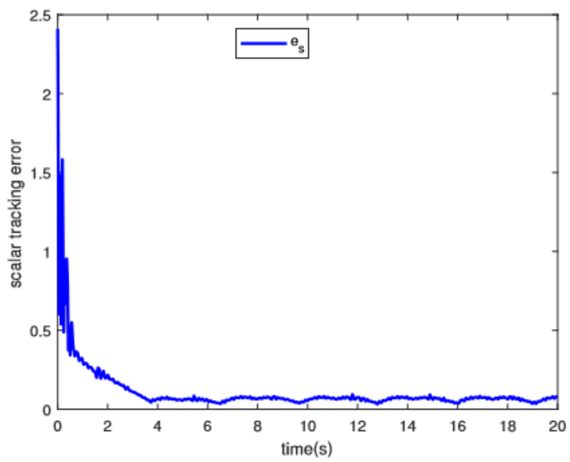

Fig. 5. The scalar tracking error of the system with $u_r = sin(t)$

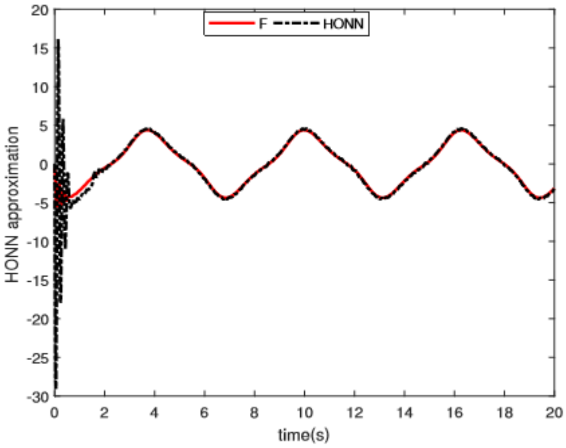

Fig. 6. The HONN identification results with $u_r=sin(t)$

4. Simulations

To verify the proposed identification approach and the adaptive control, the following hysteresis nonlinear system is considered:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -2\sin(0.65\pi x_1) - 3x_2 + v \\ v &= 1.01u + 0.02w \end{aligned} \tag{35}$$

where ω is determined by equation (2), $\alpha = 1.25$, $\beta = 0.2$, $n = 2$, $\omega(0) = 0$. The reference model is chosen as:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -x_1 - 3x_2 + 1.2u_r, \end{aligned} \tag{36}$$

where $u_r = \sin(x)$.

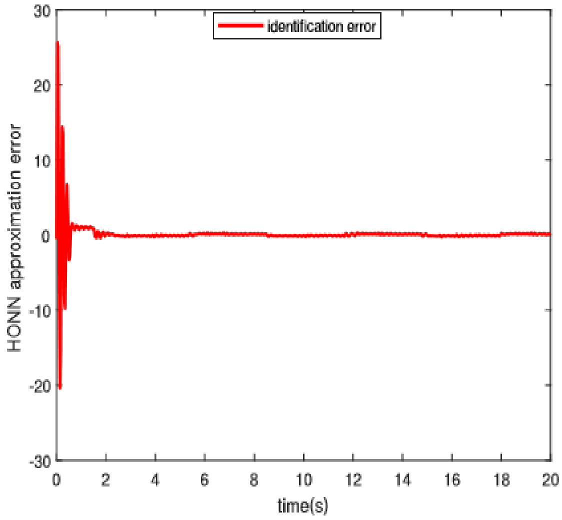

Fig. 7. The identification error of the system with $u_r=sin(t)$

The aim is to design a HONN and an adaptive controller tracking the reference model with $u_r = sin(x)$. In the simulation, the parameters of the equation (6) are chosen as $c_1 = 2, c_2 = 8, c_3 = 1$ and $p = 5$ for the equation (5).

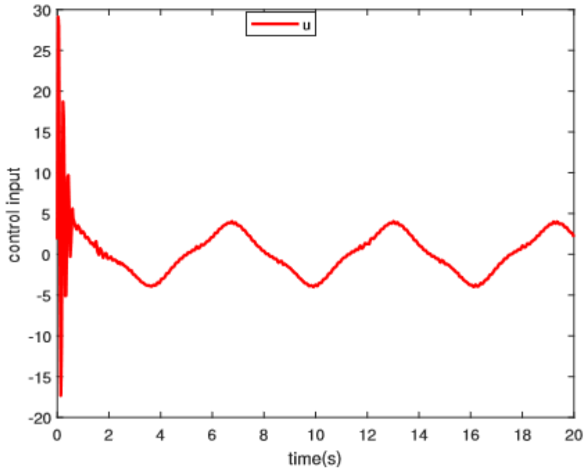

Fig. 8. The adaptive controller of the system with $u_r=sin(t)$

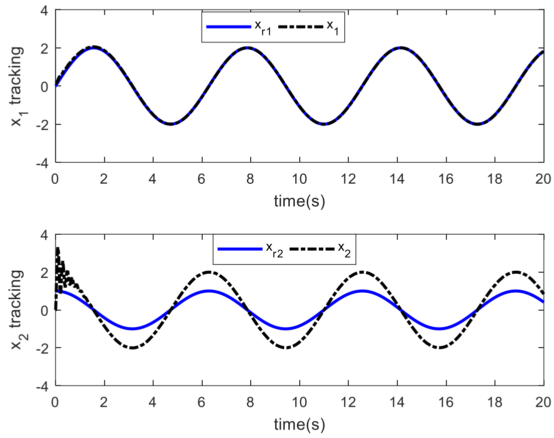

Fig. 9. The adaptive control tracking result with $u_r=2sin(t)$

To demonstrate the relationship of the vector tracking error e_t and the transformed scalar error e_s, we chose $g = [3 \quad 2]^T$. Then, the simulation results are illustrated in Fig.3-Fig.8.

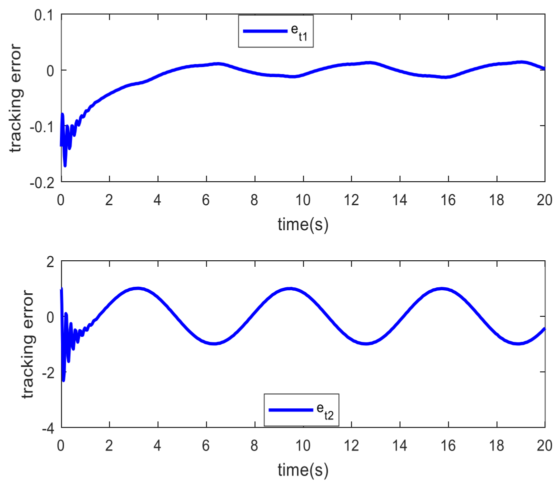

Fig. 10. The vector tracking error of the system with $u_r=2sin(t)$

Fig.3 illustrates the simulation results of control (29) with the initial conditions $x_1(0)=0$ $x_2(0)=0$ and $\hat{W}(0)=[0,0,\ldots,0]^T$.

It is illustrated that the controller can commendably track the reference model. Fig.4 shows the vector tracking error of the states and the scalar tracking error is shown in Fig.5. The mean average error (MAE) of $e_{t1}=0.0178$, MAE of $e_{t2}=0.0339$, but MAE of $e_s=0.2003$.

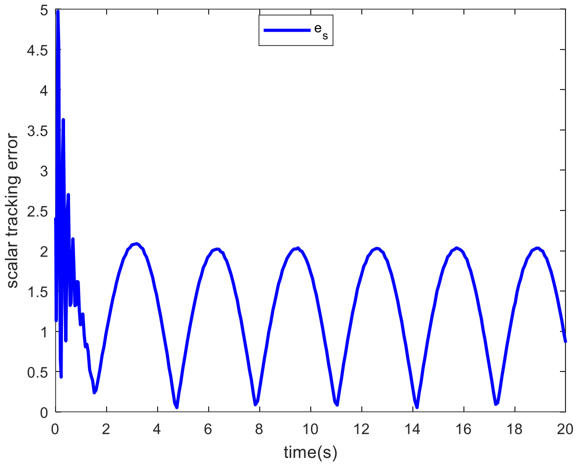

Fig. 11. The scalar tracking error of the system with $u_r=2sin(t)$

To compare the vector tracking error with the scalar error, one can obviously indertify that the scalar error magnifies the vector error. That means the transformed scalar error simplify the computation but degrade the control performance.

Fig.6 and Fig.7 illustrate the identification results and the identification error. In the Fig.6, the unknown section of the hysteresis system F is defined as $F=W\Phi(x)$. It is shown that the proposed identification approach can performance estimate the unknown function of the hysteresis system. The controller is shown in Fig.8.

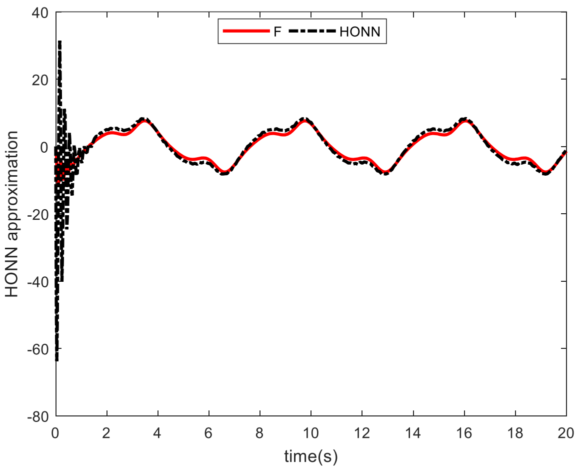

Fig. 12. The HONN identification results with $u_r=2sin(t)$

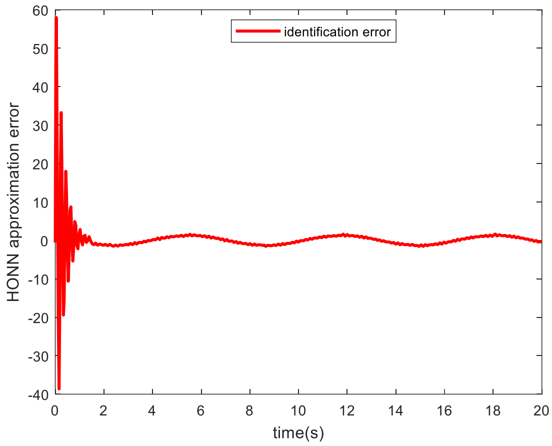

Fig. 13. The identification error of the system with $u_r=2sin(t)$

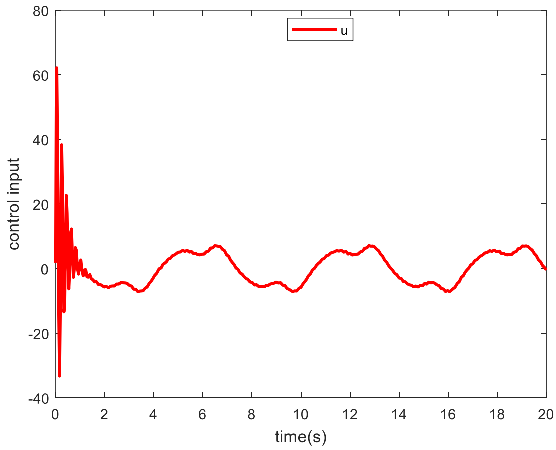

Fig. 14. The adaptive controller of the system with $u_r=2sin(t)$

Increase the amplitude of the reference input u_r to $u_r=2sin(t)$. Then, the identification and control results are shown in Fig.9.-Fig.14.

It is obviously shown that the identification precision and control precision are degraded. From Fig.9, the control results of x_2 can track the reference state x_{r2}, and the error between x_2 and x_{r2} is illustrated in Fing.10 as e_{t2}. Then, MAE of e_{t2}=0.0572, MAE of e_{t1}=0.0206, compared with 0.0339 and 0.0178, the vector tracking error with the reference input $u_r=2sin(t)$ greater than the error with reference input $u_r=sin(t)$. The scalar tracking error e_s=1.4119 with the reference input $u_r=2sin(t)$. It is far greater than e_s= 0.2003 with the reference input $u_r=sin(t)$.

The same conclusion can be deduced from the identification results. Compared with the Fig.6 and Fig.12, one can find that the identification performance is degraded with the reference input amplitude magnifying. The maximum error of the identification is increased more than one times from Fig.7 and Fig.13. But from the Fig.6 and Fig.12, the proposed identification approach has accurately estimated the unknown function of the system.

From the tracking error Fig.4, Fig.10 and the controller Fig.8, Fig.14, it is demonstrated that the proposed adaptive control strategy can track the reference model, where the HONN identification approach can estimate the unknown system function and the unknown hysteresis nonlinearity.

5. Conclusion

A new adaptive HONN identification scheme and control strategy were presented for the unknown Bouc-Wen hysteresis nonlinear system. a HONN with adaptively updating law was firstly applied to identify the unknown Bouc-wen model and the unknown system function. Compared with other widely used gradient-descent updating rates, the new online HONN identification approach had faster convergence speed. To simplify the control design, the vector tracking error was transformed into a new scalar tracking error, which not only could simplify the control design with the less computational burden, but also could get approving control precision for selecting suitable transform vector g. Finally, the stability of the closed-loop was guaranteed by a Lyapunov function. The simulation results have verified the validity of the proposed identification scheme and the control strategy.

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References

Ahmad I (2018) Two degree-of-freedom robust digital controller design with bouc-wen hysteresis compensator for piezoelectric positioning stage. IEEE Access 6:17,275-283.

Annaswamy AM, Skantze FP, Loh AP (1998) Adaptive control of continuous time systems with convex/concave parametrization. Automatica 34(1):33-49.

Bouc R (1971) Modle mathmatique d'hystrsis: application aux systmes undegr de libert. Acustica(in French) 24:16-25.

Chen Q, Ren X, Na J, Zheng D (2017) Adaptive robust finite-time neural control of uncertain pmsm servo system with nonlinear dead zone. Neural Computing and Applications 28(12):3725 -3736.

Chen Q, Shi L, Na J, Ren X, Nan Y (2018c) Adaptive echo state network control for a class of pure-feedback systems with input and output constraints. Neurocomputing, 275:1370 -1382.

Chen, Q., Wang, Y. , Hu, Z. (2018b) Finite Time Synergetic Control for Quadrotor UAV with Disturbance Compensation. International Journal of Applied Mathematics in Control Engineering, 1, 31-38.

Gao X (2018) Adaptive Neural Control for Hysteresis Motor Driving Servo System with Bouc-Wen Model. Complexity. DOI 10.1155/2018/9765861.

Gao X, Liu R (2018) Multiscale Chebyshev Neural Network Identification and Adaptive Control for Backlash-Like Hysteresis System. Complexity. DOI 10.1155/2018/1872493

Gao X, Sun B, Wang S (2018a) Hopfield neural network identification for Preisach hysteresis system. In: 2018 37th Chinese Control Conference (CCC), pp 1580-1584.

Gao X, Sun B, Zhang C (2018b) Variable gain super-twisting sliding mode control for preisach hysteresis nonlinearity system. In: 2018 10th International Conference on Modelling, Identification and Control (ICMIC), pp1-5.

Gao X, Li Y, Ren X, Zhu C (2016) Variable gain super-twisting sliding mode control for hammerstein system with bouc-wen hysteresis nonlinearity. In: 2016 35th Chinese Control Conference (CCC), pp 3369–3372.

Jin, X., Xiang, N. , Su, T. (2018) Online Motion Pattern Recognition of Finger Gesture by Inertial Sensor. International Journal of Applied Mathematics in Control Engineering, 1, 39-46.

Na J, Ren X, Zheng D (2013) Adaptive control for nonlinear pure-feedback systems with high-order sliding mode observer. IEEE Transactions on Neural Networks and Learning Systems 24(3):370-382.

Na J, Chen Q, Ren X, Guo Y (2014) Adaptive prescribed performance motion control of servo mechanisms with friction compensation. IEEE Transactions on Industrial Electronics 61(1):486-494.

Na J, Herrmann G, Zhang K (2017a) Improving transient performance of adaptive control via a modified reference model and novel adaptation. International Journal of Robust and Nonlinear Control 27(8):1351-1372.

Na J, Huang Y, Wu X, Gao G, Herrmann G, Jiang JZ (2017b) Active adaptive estimation and control for vehicle suspensions with prescribed performance. IEEE Transactions on Control Systems Technology PP(99):1-15.

Na J, Chen AS, Herrmann G, Burke R, Brace C (2018) Vehicle engine torque estimation via unknown input observer and adaptive parameter estimation. IEEE Transactions on Vehicular Technology 67(1):409-422.

Namadchian Z, Rouhani M (2018) Adaptive neural tracking control of switched stochastic pure-feedback nonlinear systems with unknown bouc-wen hysteresis input. IEEE Transactions on Neural Networks and Learning Systems 29(12):5859-5869.

Wang S, Ren X, Na J (2016a) Adaptive dynamic surface control based on fuzzy disturbance observer for drive system with elastic coupling. Journal of the Franklin Institute 353(8):1899 -1919.

Wang S, Ren X, Na J, Gao X (2016b) Robust tracking and vibration suppression for nonlinear two-inertia system via modified dynamic surface control with error constraint. Neurocomputing 203:73 -85.

Wang S, Na J, Ren X (2017a) Rise-based asymptotic prescribed performance tracking control of nonlinear servo mechanisms. IEEE Transactions on Systems, Man, and Cybernetics: Systems PP (99):1-12.

Wang S, Ren X, Na J, Zeng T (2017b) Extended-state-observer-based funnel control for nonlinear servomechanisms with prescribed tracking performance. IEEE Transactions on Automation Science and Engineering 14(1):98-108.

Wang S, Yu H, Gao X, Wang N (2018) Adaptive Barrier Control for Nonlinear Servomechanisms with Friction Compensation. Complexity. DOI 10.1155/2018/8925838

Wei, W., Liang, B. , Zuo, M. (2018) Linear Active Disturbance Rejection Control for Nanopositioning System. International Journal of Applied Mathematics in Control Engineering, 1, 92-95.

Wen YK (1976) Method for random vibration of hysteretic systems. Journal of Engineering Mechanics 102(2):249 -263.

Xu R, Zhou M (2017) Sliding mode control with sigmoid function for the motion tracking control of the piezo-actuated stages. Electronics Letters 53(2):75-77.

Xu R, Zhang X, Guo H, Zhou M (2018) Sliding mode tracking control with perturbation estimation for hysteresis nonlinearity of piezo-actuated stages. IEEE Access 6:30,617-629.

Xuehui G, Bo S (2017) Identification for bouc-wen hysteresis system with hopfield neural network. In: 2017 9th International Conference on Modelling, Identification and Control (ICMIC), pp 248–253.

Yang Z., Fu J., Wang L., Chen, Z. , Bai, H. (2018b) Back-stepping Sliding Mode with Unidirectional Auxiliary Surfaces for HSV with Attitude Constrains. International Journal of Applied Mathematics in Control Engineering, 1, 77-83

Zheng D, Xie W, Chai T, Fu Z (2017a) Identification and trajectory tracking control of nonlinear singularly perturbed systems. IEEE Transactions on Industrial Electronics 64(5):3737-3747.

Zheng D, Xie WF, Ren X, Na J (2017b) Identification and control for singularly perturbed systems using multi-time-scale neural networks. IEEE Transactions on Neural Networks and Learning Systems 28(2):321-333.

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