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Adaptive Control of Nonlinear Systems with Hysteresis and Unknown Control Direction

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Abstract

An adaptive backstepping controller is proposed for a class of nonlinear systems with hysteresis and unknown control direction. As the unknown gain sign is combined with multi-valued non-smooth hysteresis together, it is more challengeable to mitigate hysteresis effects and meanwhile guarantee stability of the dynamic systems. In this paper, Bouc-Wen model is adopted to describe the hysteresis. Then RBF neural networks are applied to approximate the unknown functions. The unknown control direction is solved by Nussbaum function. The adaptive backstepping controller is developed using prescribed performance function to confine the error to a predefined residual set. It is proved that all the closed-loop signals are bounded and the tracking error converges to an arbitrarily small field. Finally, the simulation result shows the feasibility of the control scheme.

Keywords: *hysteresis, Nussbaum function, neural network, Adaptive control*

1. Introduction

Hysteresis nonlinearities appear in many smart-material-based systems. Smart materials such as magnetostrictive materials, piezoceramics and shape memory alloys hold high promise for the design of a new generation of actuation systems. Hysteresis inherent in smart-material-based actuator severely limits systems' performance. It may lead to undesirable accuracy or oscillations, even instability [1]. However, it is difficult to control accurately hysteresis systems by using conventional schemes due to the non-smooth and multi-valued mapping property of hysteresis.

The development of control techniques to mitigate effects of unknown hysteresis has recently attracted significant attention. The control strategies of hysteresis systems can generally be classified as two categories. The first is the use of inverse hysteresis as a compensator and the second is without using the inverse construction.

In the first category, different inverse hysteresis models are constructed, including inverse Preisach model [2], inverse PI model [3], inverse KP model [4] and inverse Bouc-Wen model [5]. By implement the inverse model as part of the closed controller or as a feed-forward compensator, the hysteresis was approximately compensated and a feedback controller was used to reduce residual error due to inaccurate inverse hysteresis model and system uncertainties. In order to construct the hysteresis inverse to cancel hysteresis effect, the most schemes assume that hysteresis output is measurable directly. In practice, the hysteresis hides in the plants so that it usually cannot be measured directly. Hence, the controller dependent upon the measured hysteresis output is very difficult to implement. Moreover, it is difficult to demonstrate the stability of resulting closed-loop system with the inverse model. This explains the reason why the second group of controller was developed. In the second category, the controller schemes without constructing inverse hysteresis to mitigate the effect of hysteresis include adaptive control [6], sliding mode control [7] and variable structure control [8]. The merit of these schemes is to fuse the

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hysteresis models with the available control techniques directly. Moreover, the system stability is guaranteed without necessarily constructing inverse hysteresis.

As hysteresis is combined with unknown control direction, it is more challengeable to mitigate hysteresis effects and meanwhile guarantee stability of the dynamic systems. In this paper, we focus the discussion on control of nonlinear systems with hysteresis and unknown control directions. Nussbaum function is employed to deal with the unknown direction gains. By utilizing Bouc-Wen model to describe hysteresis, an adaptive backstepping controller combined with error transformation is proposed for the nonlinear hysteresis system together with unknown control direction.

2. System Description

Consider a class of nonlinear systems with hysteresis and unknown control direction:

$$\begin{cases} \dot{x}_1 = f_1(\bar{x}_1) + g_1(\bar{x}_1)x_2 \\ \vdots \\ \dot{x}_n = f_n(\bar{x}_n) + g_n(\bar{x}_n)v \\ y = x_1 \\ v = H(u) \end{cases} \tag{1}$$

where $\bar{x}_i = [x_1,\dots x_i]^T$ is the state, $2 \le i \le n$, u is the control input, y is the system output, v is the hysteresis output and H is the hysteretic operator, $f_i(\bar{x}_i)$, $g_i(\bar{x}_i)$ are the unknown functions.

Bouc-Wen model is taken to describe hysteresis and can be expressed as:

$$v = H(u) = d_p u - h \tag{2}$$

$$\dot{h} = A_{bw}\dot{u} - \beta|\dot{u}|h|h|^{n-1} - \gamma\dot{u}|h|^n \tag{3}$$

where parameter d_p is the piezoelectric coefficient, u is the input, v is the hysteresis output, h is the state variable, A_{bw} controls the restoring force amplitude, β and γ control the shape of the hysteresis loop.

The following result can be found from in[9]:

$$|h(t)| \le \sqrt[n]{\frac{A_{bw}}{\beta + \gamma}} = h_M \tag{4}$$

where $A_{bw} > 0$, $\beta + \gamma > 0$ and $\beta - \gamma \ge 0$.

The control objective is to design a control input u such that:

P1. The output y tracks the desired output $y_d(t)$.

P2. The tracking error $e(t) = y(t) - y_d(t)$ of both transient and steady-state performance should be limited to prescribed field.

Assumption 1) the desired output $y_d(t)$ and its derivative are both known bounded function of time.

3. Controller Design

Consider the nonlinear system described by (1),we make the following assumptions:

Assumption 2) There exists a compact region $\Omega_x \in R^n$ such that $\bar{x}_n \in \Omega_x$.

Assumption 3) The signs of $g_i(\bar{x}_i)$, $i = 1,\cdots,n$ are unknown to be either strictly positive or strictly negative, and there exist positive constants g_i^* and smooth functions $g_i(\bar{x}_i)$ such that $0 < g_i^* \le |g_i(\bar{x}_i)| \le \bar{g}_i(\bar{x}_i)$.

3.1. Nussbaum Function

In order to solve the unknown control direction, in this paper we adopt Nussbaum function $N(k) = k^2 \cos(k)$.

Lemma 1) Let $V(\cdot)$, $k(\cdot)$ be smooth functions defined on $\left[0, t_f\right)$ with $V(t) \geq 0$, $\forall t \in \left[0, t_f\right)$, and $N(\cdot)$ be an even smooth Nussbaum function. If the following inequality holds:

$$V(t) \leq \int_0^t \left[N(k(\tau)) + 1\right] \dot{k}(\tau) d\tau + c_0, \forall t \in \left[0, t_f\right) \quad (5)$$

where $c_1 > 0$, c_0 is a suitable constant, then $\int_0^t \left[N(k(\tau)) + 1\right] \dot{k}(\tau) d\tau$, $V(t)$ and $k(t)$ must be bounded on $[0, t)$.

3.2. Error Transformation

For the sake of translating the prescribed performance characteristics into tracking error constraint, firstly the performance function $\rho(t)$ is introduced[10].

Definition 1) if $\rho(t)$ is positive, decreasing and $\lim_{t \to \infty} \rho(t) = \rho_\infty > 0$, a smooth function $\rho(t)$ is called a performance function.

To guarantee P2, the tracking error must satisfy the following condition:

$$-\delta\rho(t) < e(t) < \rho(t), e(0) > 0 \quad (6)$$

or

$$-\rho(t) < e(t) < \delta\rho(t), e(0) < 0 \quad (7)$$

for all $t \geq 0$, where $0 \leq \delta \leq 1$. In this paper we choose $\rho(t) = (\rho_0 - \rho_\infty)e^{-lt} + \rho_\infty$, where l controls the decreasing rate of $\rho(t)$, The constant $\rho_0 = \rho(0)$ expresses the maximum expected initial error. The constant ρ_∞ represents the maximum allowable size of the tracking error at the steady state.

To satisfy P1 and P2, we incorporate an error transformation, more specifically, we define:

$$e(t) = \rho(t) S(z_1) \quad (8)$$

where z_1 is the transformed error and $S(\cdot)$ is a smooth, strictly increasing and invertible function with the following properties:

$$\begin{cases} -\delta < S(z_1) < 1, e(0) > 0 \\ -1 < S(z_1) < \delta, e(0) < 0 \end{cases} \quad (9)$$

and

$$\left.\begin{aligned} \lim_{z_1 \to -\infty} S(z_1) = -\delta \\ \lim_{z_1 \to +\infty} S(z_1) = 1 \end{aligned}\right\}, e(0) > 0 \quad (10)$$

$$\left.\begin{aligned} \lim_{z_1 \to -\infty} S(z_1) = -1 \\ \lim_{z_1 \to +\infty} S(z_1) = \delta \end{aligned}\right\}, e(0) < 0 \quad (11)$$

Due to the properties of $S(z_1)$, $\rho(t) \geq \rho_\infty > 0$, the inverse transformation of (8):

$$z_1 = S^{-1}\left(\frac{e(t)}{\rho(t)}\right) \tag{12}$$

Differentiating (12) with respect to time, we obtain:

$$\dot{z}_1 = \eta(-\upsilon + f_1(\bar{x}_1) + g_1(\bar{x}_1)x_2) \tag{13}$$

where $\eta = \frac{\partial S^{-1}}{\partial\left(\frac{e(t)}{\rho(t)}\right)}\frac{1}{\rho(t)}$, $\upsilon = \dot{y}_d + \frac{e(t)\dot{\rho}(t)}{\rho(t)}$, $\eta > 0$.

Therefore the transformed system dynamics can be described as:

$$\begin{cases} \dot{z}_1 = \eta\left(-\upsilon + f_1(\bar{x}_1) + g_1(\bar{x}_1)x_2\right) \\ \dot{x}_2 = f_2(\bar{x}_2) + g_2(\bar{x}_2)x_3 \\ \vdots \\ \dot{x}_n = f_n(\bar{x}_n) + g_n(\bar{x}_n)v \end{cases} \tag{14}$$

Remark 1) the transient and steady state tracking error behavioral bounds are given via performance function $\rho(t)$. System (1) is invariant under the error transformation (8).

3.3. Adaptive Neural Network Control

The following change of coordinates is defined as:

$$\begin{cases} z_1 = S^{-1}\left(\frac{e(t)}{\rho(t)}\right) \\ z_2 = x_2 - \alpha_1 \\ \vdots \\ z_n = x_n - \alpha_{n-1} \end{cases} \tag{15}$$

Where $\alpha_i, i = 1,\dots n$ are virtual controls.

The controller design includes n steps and the design process is as follows:

Step 1: Expected virtual control α_1 is chosen by (12) and (13):

$$\alpha_1 = \frac{N(k_1)\zeta_1}{\bar{g}_1(\bar{x}_1)} \tag{16}$$

$$\zeta_1 = \frac{c_1}{2\eta}z_1 - \upsilon + \hat{f}_1 + b_1 z_1 \eta\left(1 + \bar{g}_1^{-2}\right) \tag{17}$$

$$\dot{k}_1 = z_1\eta\zeta_1 \tag{18}$$

$$\dot{\hat{\theta}}_{f_1} = z_1\eta\varphi_{f_1}(x_1) - \delta\hat{\theta}_{f_1} \tag{19}$$

where c_1 and δ are both positive constants.

RBF neural network is used to approximate the unknown function $f_1(x_1)$. $\hat{f}_1$ is the estimated value of $f_1(x_1)$:

$$f_1(x_1) = \theta_{f_1}^{*T}\phi_{f_1}(x_1) + \Delta_1(x_1) \tag{20}$$

where $\Delta_1(x_1)$ is the reconstruction error, $\left|\Delta_1(x_1)\right| < \Delta_{1m}$, $\theta_{f_1}^{*}$ is the ideal weight vector and $\hat{\theta}_{f_1}$ is the estimated value.

We choose a positive Lyapunov function as

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} \tilde{\theta}_{f_1}^T \tilde{\theta}_{f_1} \tag{21}$$

where $\tilde{\theta}_{f_1} = \hat{\theta}_{f_1} - \theta_{f_1}^*$ is the estimation error.

The derivative of V_1 yields:

$$\begin{aligned} \dot{V}_1 &= z_1 \dot{z}_1 + \tilde{\theta}_{f_1}^T \dot{\hat{\theta}}_{f_1} \\ &= z_1 \eta \left(-\upsilon + f_1 + g_1 x_2 \right) + \tilde{\theta}_{f_1}^T \dot{\hat{\theta}}_{f_1} \\ &\le | z_1 | \eta \left(-\upsilon + f_1 + g_1 z_2 + N(k_1) \zeta_1 \right) + \tilde{\theta}_{f_1}^T \dot{\hat{\theta}}_{f_1} \end{aligned} \tag{22}$$

Substituting (16)-(20) into (22), we can obtain that

$$\dot{V}_1 \le \eta g_1 | z_1 | z_2 + \left[N(k_1) + 1 \right] \dot{k}_1 - \left[\frac{c_1}{2} + b_1 z_1^2 \eta^2 \left(1 + \bar{g}_1^2 \right) \right] z_1^2 - \delta \tilde{\theta}_{f_1}^T \hat{\theta}_{f_1} + | z_1 | \eta \Delta_1 \tag{23}$$

for $-\delta \tilde{\theta}_{f_1}^T \hat{\theta}_{f_1} \le \frac{\delta}{2} \left\| \theta_{f_1}^* \right\|^2 - \frac{\delta}{2} \left\| \tilde{\theta}_{f_1} \right\|^2$, $-\frac{1}{4} \eta^2 z_1^2 + |z_1| \eta \Delta_{1m} \le \Delta_{1m}^2$, (23) can be written as:

$$\begin{aligned} \dot{V}_1 &\le -\left[\frac{c_1}{2} + b_1 \eta^2 \left(1 + \bar{g}_1^2 \right) - \frac{\eta}{4} \right] z_1^2 + \eta g_1 | z_1 | z_2 + \left[N(k_1) + 1 \right] \dot{k}_1 + \frac{\delta}{2} \left\| \theta_{f_1}^* \right\|^2 - \frac{\delta}{2} \left\| \tilde{\theta}_{f_1} \right\|^2 + \Delta_{1m}^2 \\ &= -\left[\frac{c_1}{2} + b_1 \eta^2 \left(1 + \bar{g}_1^2 \right) - \frac{\eta}{4} \right] z_1^2 - \frac{\delta}{2} \left\| \tilde{\theta}_{f_1} \right\|^2 + \left[N(k_1) + 1 \right] \dot{k}_1 + q_1 + \eta g_1 | z_1 | z_2 \end{aligned} \tag{24}$$

where $q_1 = \frac{\delta}{2} \left\| \theta_{f_1}^* \right\|^2 + \Delta_{1m}^2$.

We should further transform (24) in the next step owing to remove the item $\eta g_1 | z_1 | z_2$:

$$\begin{aligned} \dot{V}_1 &\le -\left[\frac{c_1}{2} + b_1 \eta^2 \left(1 + \bar{g}_1^2 \right) - \frac{\eta + \eta^2}{4} \right] z_1^2 - \frac{\delta}{2} \left\| \tilde{\theta}_{f_1} \right\|^2 + \left[N(k_1) + 1 \right] \dot{k}_1 + q_1 + g_1^2 z_2^2 - \left(\frac{\eta z_1}{2} - g_1 z_2 \right)^2 \\ &\le -\lambda_1 V_1 + \left[N(k_1) + 1 \right] \dot{k}_1 + q_1 + g_1^2 z_2^2 \end{aligned} \tag{25}$$

where $\lambda_1 = \min \left\{ 2 \left[\frac{c_1}{2} + b_1 \eta^2 \left(1 + \bar{g}_1^2 \right) - \frac{\eta + \eta^2}{4} \right], \delta \right\}$.

Multiplying (25) by $e^{\lambda_1 t}$, we have

$$\frac{d}{dt} \left(V_1 e^{\lambda_1 t} \right) \le q_1 e^{\lambda_1 t} + \left[N(k_n) + 1 \right] \dot{k}_n e^{\lambda_1 t} + g_1^2 z_2^2 e^{\lambda_1 t} \tag{26}$$

Then integrating (26), it becomes

$$\begin{aligned} V_1(t) &\le \frac{q_1}{\lambda_1} + \left[V_1(0) - \frac{q_1}{\lambda_1} \right] e^{-\lambda_1 t} + e^{-\lambda_1 t} \int_0^t \left[N(k_1) + 1 \right] \dot{k}_1 e^{\lambda_1 \tau} d\tau + e^{-\lambda_1 t} \int_0^t g_1^2 z_2^2 e^{\lambda_1 \tau} dt \\ &\le \frac{q_1}{\lambda_1} + e^{-\lambda_1 t} \int_0^t \left[N(k_1) + 1 \right] \dot{k}_1 e^{\lambda_1 \tau} d\tau + e^{-\lambda_1 t} \int_0^t g_1^2 z_2^2 e^{\lambda_1 \tau} dt \end{aligned} \tag{27}$$

If z_2 can be regulated as bounded, z_1 can also be regulated as bounded from Lamma 1).

Step $i (2 \le i \le n-1)$: The time derivative of z_i

$$\dot{z}_i = f_i + g_i x_{i+1} - \dot{\alpha}_{i-1} \tag{28}$$

Similarly RBFNN is used to approximate the unknown function f_i:

$$f_i(x_i) = \theta_{f_i}^{*T} \phi_{f_i}(x_i) + \Delta_i(x_i) \tag{29}$$

where $\Delta_i(x_i)$ is the reconstruction error, $\left|\Delta_i(x_i)\right| < \Delta_{im}$, $\theta_{f_i}^*$ is the ideal weight vector, $\hat{\theta}_{f_i}$ is the estimated value.

Set the control function and adaptive laws as follows:

$$\alpha_i = \frac{N(k_i)\zeta_i}{\bar{g}_i(\bar{x}_i)} \tag{30}$$

$$\zeta_i = \frac{c_i}{2} z_i + \hat{f}_i - \dot{\alpha}_{i-1} + b_i z_i\left(1 + \bar{g}_i^2\right) \tag{31}$$

$$\dot{k}_i = z_i \zeta_i \tag{32}$$

$$\dot{\hat{\theta}}_{f_i} = z_i \phi_{f_i}(x_i) - \delta \hat{\theta}_{f_i} \tag{33}$$

Then, Lyapunov function can be selected as:

$$V_i = \frac{1}{2} z_i^2 + \frac{1}{2} \tilde{\theta}_{f_i}^T \tilde{\theta}_{f_i} \tag{34}$$

Applying the similar method as step 1, we obtain:

$$\dot{V}_i \le -\lambda_i V_i + \left[N(k_i) + 1\right]\dot{k}_i + q_i + g_i^2 z_{i+1}^2 \tag{35}$$

If z_{i+1} is bounded, we can conclude that V_i, $k_i(t)$ are both bounded by Lamma 1). Thus z_i, $\hat{\theta}_{f_i}$ are also bounded from (34).

Step n : Considering the n -th subsystem

$$\begin{cases} \dot{z}_n = f_n + g_n v - \alpha_{n-1} \\ v = d_p u - h \\ \dot{h} = A_{bw}\dot{u} - \beta\left|\dot{u}\right| h \left|h\right|^{n-1} - \gamma \dot{u}\left|h\right|^n \end{cases} \tag{36}$$

The final control law is designed:

$$\alpha_n = u = \frac{N(k_n)\zeta_n}{d_p \bar{g}_n(\bar{x}_n)} \tag{37}$$

$$\zeta_n = \frac{c_n}{2} z_n + \hat{f}_n + sgn(z_n)\hat{D} - \dot{\alpha}_{n-1} + b_n z_n\left(1 + \bar{g}_n^2\right) \tag{38}$$

$$\dot{k}_n = z_n \zeta_n \tag{39}$$

$$\dot{\hat{\theta}}_{f_n} = z_n \phi_{f_n}(x_n) - \delta \hat{\theta}_{f_n} \tag{40}$$

$$\dot{\hat{D}} = d\left|z_n\right| \tag{41}$$

where $D = \bar{g}_n h_M$, $\hat{D}$ is the estimate value of D, c_n and b_n are positive constant.

$$f_n(x_n) = \theta_{f_n}^{*T} \varphi_{f_n}(x_n) + \Delta_n(x_n) \tag{42}$$

where $\left|\Delta_n(x_n)\right| < \Delta_{nm}$, $\theta_{f_n}^*$ is the ideal weight vector and $\hat{\theta}_{f_n}$ is the estimated value.

Theorem 1) For the system (1) and Bouc-Wen model (2),(3),the adaptive control laws (37)-(41)guarantee that all signals in the closed-loop system remain bounded and the tracking error converges to arbitrarily small area by (12) under Assumptions 1-3.

Proof:

Set the Lyapunov function

$$V_n = \frac{1}{2} z_n^2 + \frac{1}{2} \tilde{\theta}_{f_n}^T \tilde{\theta}_{f_n} + \frac{1}{2d} \tilde{D}^T \tilde{D} \tag{43}$$

where $\tilde{\theta}_{f_n} = \hat{\theta}_{f_n} - \theta_{f_n}^*$, $\tilde{D} = \hat{D} - D$.

Then

$$\dot{V}_n = z_n \dot{z}_n + \tilde{\theta}_{f_n}^T \dot{\hat{\theta}}_{f_n} + \frac{1}{d} \tilde{D}^T \dot{\hat{D}} = z_n \left[f_n + g_n \left(d_p u - h \right) \right] + \tilde{\theta}_{f_n}^T \dot{\hat{\theta}}_{f_n} + \frac{1}{d} \tilde{D}^T \dot{\hat{D}} \tag{44}$$

Substituting (37)-(41) into (44), we have

$$\dot{V}_n \le -\lambda_n V_n + \left[N(k_n) + 1 \right] \dot{k}_n + q_n + \tilde{D}^T \left(\frac{1}{d} \dot{\hat{D}} - |z_n| \right) = -\lambda_n V_n + \left[N(k_n) + 1 \right] \dot{k}_n + q_n \tag{45}$$

where $\lambda_n = \min \left\{ 2 \left[\frac{c_n}{2} + b_n \left(1 + \bar{g}_n^2 \right) - \frac{1}{4} \right], \delta \right\}$, $q_n = \frac{\delta}{2} \left\| \theta_{f_n}^* \right\|^2 + \Delta_{nm}^2$,

Multiplying (45) by $e^{\lambda_n t}$, we obtain

$$\frac{d}{dt} \left(V_n e^{\lambda_n t} \right) \le q_n e^{\lambda_n t} + \left[N(k_n) + 1 \right] \dot{k}_n e^{\lambda_n t} \tag{46}$$

Integrating (46), it becomes

$$\begin{aligned} V_n(t) &\le \frac{q_n}{\lambda_n} + \left[V_n(0) - \frac{q_n}{\lambda_n} \right] e^{-\lambda_n t} + e^{-\lambda_n t} \int_0^t \left[N(k_n) + 1 \right] \dot{k}_n e^{\lambda_n \tau} d\tau \\ &\le \frac{q_n}{\lambda_n} + V_n(0) e^{-\lambda_n t} + e^{-\lambda_n t} \int_0^t \left[N(k_n) + 1 \right] \dot{k}_n e^{\lambda_n \tau} d\tau \end{aligned} \tag{47}$$

With the fact that V_n , k_n are bounded by applying Lamma 1), so $z_n(t)$ and $\hat{\theta}_{f_n}$ are both bounded from (41) .Via employing $n-1$ Lamma 1), V_i , k_i , $\hat{\theta}_{f_i}$, z_i $(1 \le i \le n)$ are all bounded over time $[0, t_f)$. As a consequence, all signals in the closed-loop system are bounded. By utilizing the Barbalat Lamma, we can conclude the tracking error converges to arbitrarily small area.

4. Simulation Results

In this section, a second-order nonlinear system with hysteresis is demonstrated to certify the effectiveness of the proposed adaptive control approach.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -2\left(x_1^2 - 1 \right) x_2 - x_1 + \left(2 + \sin(x_1 x_2) \right) v \\ y = x_1 \\ v = H(u) = d_p u - h \\ \dot{h} = A_{bw} \dot{u} - \beta |\dot{u}| h - \gamma u |h| \end{cases}$$

where $d_p = 1.5$, $A_{bw} = 0.12$, $\beta = 0.02$, $\gamma = -0.02$.

We requested a steady state error of no more than 0.01.The transient and steady state error bounds are prescribed through the performance function $\rho(t) = (0.2 - 0.01) e^{-2.5t} + 0.01$ with $\delta = 0.3$. We initialized at $x_1(0) = 0, x_2(0) = 0$.

Figure 1-3 represent hysteresis characteristics, system output and tracking error respectively. Comparing with control scheme without error transformation, the proposed controller can effectively track the system error and ensure transient and steady-state performance .

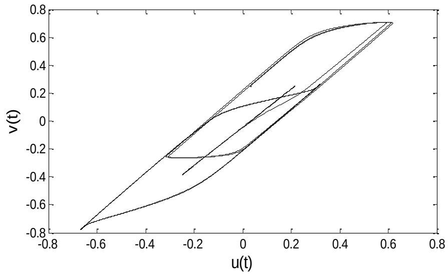

Figure 1. System Hysteresis Characteristics

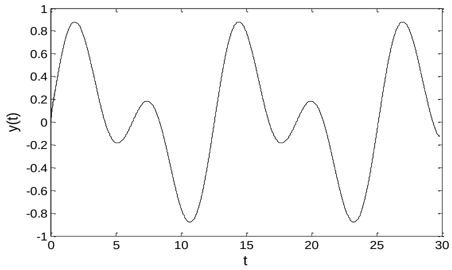

Figure 2. System Output. The Solid Line (-) Indicates the System Output with the Error Transformation. The Dashed Line (--) Indicates the Desired Output

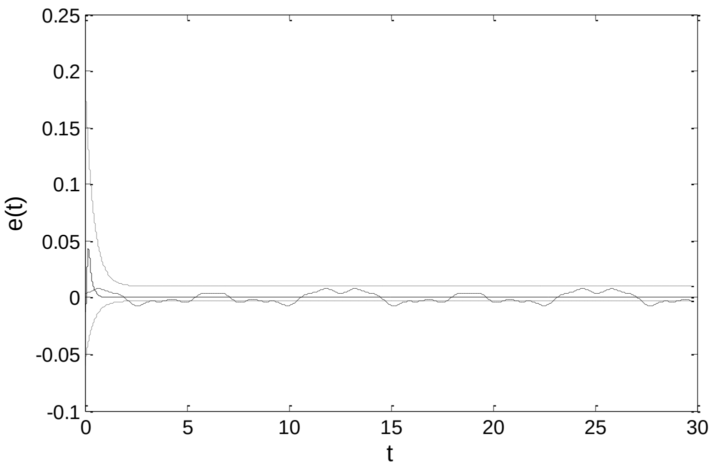

Figure 3. Tracking Error. The Solid Line (-) Indicates the Tracking Error with the Error Transformation. The Dashed Line (--) Indicates The Tracking Error Without The Error Transformation

5. Conclusion

An adaptive backstepping controller is proposed for nonlinear systems with hysteresis and unknown control direction by utilizing error transformation. The hysteresis is described by Bouc-Wen model. Nussbaum function is employed to solve the unknown direction gains. The performance function is used to confine the error to a predefined residual set. The results indicate that all signals in the closed-loop systems are bounded. The proposed scheme can eliminate the effect of hysteresis and meanwhile guarantee the prescribed performance.

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References

[1] G. Tao and P. V. Kolotovic, "Adaptive control of plants with unknown hysteresis", IEEE Transactions on Automatic Control, vol. 40, (**1995)**, pp: 200-212.
[2] G. Ping and M. Jouanen, "Tracking control of a piezoceramic actuator", IEEE Transactions on Control System Technology, vol. 4, **(1996)**, pp: 209-216.
[3] G.Y. Gu, M.J. Yang and L.M. Zhu, "Real-time inverse hysteresis compensation of piezoelectric actuators with a modified Prandtl-Ishlinskii model", Review of Scientific Instruments, vol. 83, **(2012)**, pp:065106 - 065106-8.
[4] G.V. Webb and D.C. Lagoudas, "Hysteresis modeling of SMA actuators for control application", Journal of Intelligent Material Systems and Structures, vol. 9, **(1998)**, pp: 432-448.
[5] M. Rakotondrabe, "Bouc–Wen Modeling and inverse multiplicative structure to compensate hysteresis nonlinearity in piezoelectric actuators", IEEE Transactions on Automation Science and Engineering, vol. 8, **(2011)**, pp: 428-431.
[6] C.Y. Su, Y. Stepanenko and J. Svoboda, "Robust adaptive control of a class of nonlinear systems with unknown backlash-like hysteresis", IEEE Transactions on Automatic Control, vol. 45, **(2000)**, pp: 2427-2432.
[7] Q. Xu and Y. Li, "Model predictive discrete-time sliding mode control of a nanopositioning piezostage without modeling hysteresis", IEEE Transactions on Control Systems Technology, vol. 20, **(2012)**, pp: 983–994.
[8] C.Y. Su, Q.Q. Wang and X.K. Chen "Adaptive variable structure control of a class of nonlinear systems with unknown Prandtl-Ishlinskii hysteresis", IEEE Transactions on Automatic Control, vol. 50, **(2005)**, pp: 2069-2074.
[9] I. Faycal and R. Jose. "Systems with hysteresis:analysis, identification and control using the Bouc-Wen model", England:John Wiley Press, **(2007)**.
[10] C.P. Bechlioulis and G.A. Rovithakis, "Adaptive control with guaranteed transient and steady state tracking error bounds for strict feedback systems", Automatica, vol. 45, **(2009)**, pp: 532-538.

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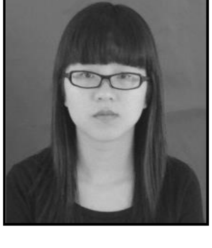

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