Adaptive Controller Design for the Control Systems with Dead-zone

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ABSTRACT
An adaptive tracking control problem is investigated for a class of nonlinear system with non-symmetric actuator dead-zone fault. Based on adaptive compensation algorithm, a new adaptive controller specially designed is employed without constructing the dead-zone inverse. This paper studies the dead-zone fault model is more universal. The restrictions that the dead-zone slopes and the boundaries are equal and symmetrical are removed. The dead-zone model parameters are all unknown and the model of nonlinear system also have unknown parameters. The proposed adaptive controller can eliminate the effect of simulation show the proposed method. The result simulation show the effectiveness of the proposed method.

General Terms
Data Acquisition

Keywords
Actuator fault, Non-symmetric dead-zone, Adaptive compensation.

1. INTRODUCTION
In the process of actual industrial control, the ideal linear system does not exist and there will be non-linear characteristics to a certain extent, due to wear, aging, and other defects of machine components or errors and interference of the system itself. The control systems with dead-zone is the most common in these nonlinear phenomena. The nonlinear systems with dead zone due to the presence of a large number of non-linear characteristics, and internal control systems with uncertain parameters, and actuator dead zone is unknown so that the study of such systems becomes very complicated. In some areas there is a lot of research of nonlinear parameters and uncertain factors, traditional control methods is clearly unable to achieve the performance requirements. Faced with these complexities, how to design a controller to resolve the contradiction between the high-performance and the dead, to achieve system stability, rapidity, accuracy has become the goal of many researchers.

In recent years, with the dead zone more and more attention, emerging new design approach in which the most important is adaptive controller design. Many of existing adaptive approaches use an inverse dead-zone nonlinearity to minimize the effects of dead-zone (zhou, when, &zheng, 2006). As an alternative, a robust adaptive control scheme was developed in Wang, Su, and Hong (2004) without constructing the dead-zone inverse, where the dead-zone is modelled as a combination of a line and a disturbance-like term. However, this scheme requires symmetric dead-zones inputs. In fact, practical systems may be subjected to non-symmetric dead-zone control inputs. To overcome this limitation, a new adaptive control strategy is proposed to deal with non-symmetric dead-zone inputs case without constructing the dead-zone inverse in Ibrir, Xie, and Su (2007). Due to the non –symmetric property of the dead-zone input, the controlled system shall be represented as an uncertain nonlinear system subject to linear input with time-varying coefficient and an external perturbation that depends upon the dead-zone parameters. However, this strategy requires the upper and lower limits of dead-zone is known. To overcome this limitation, this paper design a new Adaptive controller. By introducing parameters, eliminating the limitation that the upper and lower limits of dead-zone is known in Ibrir, Xie, and Su (2007). And by selecting the appropriate parameters can weaken the chattering of controller. This has a more profound practical significance.

2. SYSTEMS WITH DEAD-ZONES
Consider the uncertain nonlinear system subjected to a non-symmetric dead-zone input nonlinearity:

$$\begin{aligned} \dot{x}_i &= x_{i+1}, 1 \le i \le n-1, \\ \dot{x}_n &= \sum_{i=1}^{v} f_i(x)\theta_i + \Gamma(u), \end{aligned} \tag{1}$$

Where $x = (x_1, x_2, \cdots, x_n)^T$ are the system states, $f_i(x)$ are real-valued nonlinear functions, and θ_i are constant unknown parameters. $\Gamma(u)$ is a single dead-zone input nonlinearity defined as follows:

$$\Gamma(u) \triangleq \begin{cases} m_r(u - b_r), u \ge b_r \\ 0, -b_l < u < b_r \\ m_l(u + b_l), u \le -b_l \end{cases} \tag{2}$$

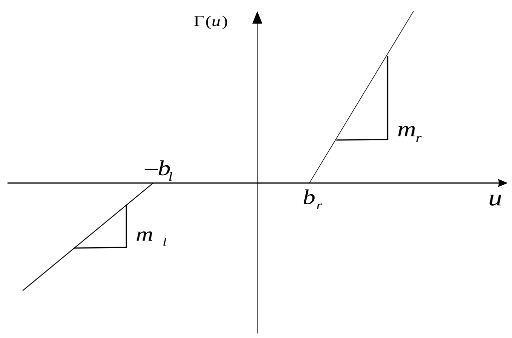

Fig 1: Non-symmetric dead-zone nonlinearity

The non-symmetric dead-zone input is shown in Fig.1. The parameters m_l and m_r stand for the right and the left slope of the dead-zone characteristic b_l and b_r represent the breakpoints of the input nonlinearity. In this section, the following assumptions are considered.

Assumption 1. The system states vector is accessible for measurements.

Assumption 2. The coefficients m_l, m_r, b_l and b_r are strictly positive and unknown. There is a positive constant $\eta > 0$, and

$\eta \le m_r, \eta \le m_l$

According to the above notation, the dead-zone (1) can be redefined as a slowly time-varying input-dependent function of the following form:

$$\Gamma(u) = m(t)u + d(t) \tag{3}$$

Where

$$m(t) \triangleq \begin{cases} m_l, u \le 0 \\ m_r, u > 0 \end{cases} \tag{4}$$

$$d(t) \triangleq \begin{cases} -m_r b_r, u \ge b_r \\ -m(t)u, -b_l < u < b_r \\ m_l b_l, u \le -b_l \end{cases} \tag{5}$$

Based on the new representation (3) of the dead-zone, the controlled system involves an external perturbation $d(t)$ and unknown input coefficient term $m(t)$ that is always positive and bounded. The control objective is to design an adaptive feedback such that for any bounded initial conditions $x_0 \in \mathbb{R}^n$ of system (1), one has

$$\lim_{x\to\infty} \left| x_i(t) - y_{ref}^{(i-1)}(t) \right| \le \delta, \qquad 1 \le \delta \le n, \tag{6}$$

Where δ is some sufficiently small positive constant and $y_{ref} = y_{ref}(t)$ is a known n -differentiable bounded trajectory. The task is to make δ sufficiently small for any bounded perturbations terms $m(t)$ and $d(t)$ while insuring a smooth control law. We summarize the design in the following statement.

3. ADAPTIVE CONTROLLER DESIGN

Define the tracking error

$$\begin{aligned} e(t) &= x(t) - y_{ref}(t) \\ &= \left[x_1(t) - y_{ref}(t), x_2(t) - y_{ref}^{(1)}(t), \cdots, x_n(t) - y_{ref}^{(n-1)}(t) \right]^T \end{aligned} \tag{7}$$

The control objective is to design an adaptive feedback such that for any bounded initial conditions $x_0 \in \mathbb{R}^n$ of system (1), one has

$$\lim_{x\to\infty} \left| e(t) \right| \le \delta \tag{8}$$

Where δ is some sufficiently small positive constant.

Theorem 1 Consider system (1) subject to the non-symmetric dead-zone input nonlinearity (2). For given strictly positive constants ε_1 : $0 < \varepsilon_1 < 0.5$ and ε_2 : $\varepsilon_2 > 0$,let P be $n \times n$ symmetric and positive define matrix that verifies the following linear matrix inequalities for $\lambda > 0$:

$$\lambda P + A^T P + PA - 2(1 - 2\varepsilon_1) PBB^T P < 0 \tag{9}$$

Where

$$A \triangleq \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \cdots & 1 \\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix} \in \mathbb{R}^{n\times n}, \qquad B \triangleq \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} \in \mathbb{R}^n,$$

$$Y_{ref} \triangleq \begin{bmatrix} y_{ref} \\ \dot{y}_{ref} \\ \vdots \\ y_{ref}^{(n-1)} \end{bmatrix} \in \mathbb{R}^n, \qquad f(x) \triangleq \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_v(x) \end{bmatrix} \in \mathbb{R}^v, \tag{10}$$

$$\theta \triangleq \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_v \end{bmatrix} \in \mathbb{R}^v,$$

Where $y_{ref} = y_{ref}(t)$ is well-defined time-dependent trajectory and globally bounded over -the-time interval $[0, \quad \infty)$.

And let:

$$\begin{aligned} &\varepsilon_3 \triangleq 5\frac{\varepsilon_2}{\lambda}, \qquad e \triangleq x - y_{ref}, \qquad \tilde{\beta} \triangleq \beta - \hat{\beta}, \qquad \tilde{\theta} \triangleq \theta - \hat{\theta}, \\ &\beta \triangleq \sup_{t\ge 0} |d(t)|, \qquad \varphi(x,\theta) \triangleq \left| f^T \hat{\theta} \right| - \sup_{t\ge 0} \left| y_{ref}^{(n)} \right| \end{aligned} \tag{11}$$

$$\dot{\hat{\alpha}} \triangleq \begin{cases} e^T PBB^T Pe + \dfrac{\varphi^2(x,\hat{\theta}) e^T PBB^T Pe}{\varphi(x,\hat{\theta}) \left| B^T Pe \right| + (\varepsilon_1/2) e^T PBB^T Pe + \varepsilon_2} \\ \quad + \dfrac{\hat{\beta}^2 e^T PBB^T Pe}{\hat{\beta} \left| B^T Pe \right| + (\varepsilon_1/2) e^T PBB^T Pe + \varepsilon_2}, & e^T Pe > \varepsilon_3, \hat{\alpha}(0) > 0 \\ 0, \quad e^T Pe \le \varepsilon_3 \end{cases} \tag{12}$$

$$\dot{\hat{\beta}} \triangleq \begin{cases} \gamma \left| B^T Pe \right|, & e^T Pe > \varepsilon_3, \hat{\beta}(0) > 0 \\ 0, \quad e^T Pe \le \varepsilon_3 \end{cases} \tag{13}$$

$$\dot{\hat{\theta}} \triangleq \begin{cases} \gamma f(x) \left| B^T Pe \right|, & e^T Pe > \varepsilon_3 \\ 0, \quad e^T Pe \le \varepsilon_3 \end{cases} \tag{14}$$

Define the adaptive controller

$$\begin{aligned} u \triangleq & -\hat{\alpha} B^T Pe - \hat{\alpha} \frac{\varphi^2(x,\hat{\theta}) B^T Pe}{\varphi(x,\hat{\theta}) \left| B^T Pe \right| + (\varepsilon_1/2) e^T PBB^T Pe + \varepsilon_2} \\ & - \hat{\alpha} \frac{\hat{\beta}^2 B^T Pe}{\hat{\beta} \left| B^T Pe \right| + (\varepsilon_1/2) e^T PBB^T Pe + \varepsilon_2}, \end{aligned} \tag{15}$$

Proof . Lyapunov function as the following:

$$V=\begin{cases}\varepsilon_3+\frac{1}{\gamma}\tilde{\theta}^T\tilde{\theta}+\frac{1}{\gamma}\tilde{\beta}^2+\frac{1}{\eta}(1-\eta\hat{\alpha})^2, & e^TPe\le\varepsilon_3\\ e^TPe+\frac{1}{\gamma}\tilde{\theta}^T\tilde{\theta}+\frac{1}{\gamma}\tilde{\beta}^2+\frac{1}{\eta}(1-\eta\hat{\alpha})^2, & e^TPe>\varepsilon_3\end{cases}\quad(16)$$

For all $t\ge 0$, $V\ge\varepsilon_3>0$ and V is piecewise continuous . Then according to (3), the dynamics of the error $e(t)$ is shown as follows:

$$\dot{e}=Ae+B\left(f^T(x)\theta+m(t)u+d(t)-y_{ref}^{(n)}\right)\quad(17)$$

For $e^TPe>\varepsilon_3$, there has

$$\begin{aligned}\dot{V}&=e^T\left[A^TP+PA-2PBB^TP\right]e+2e^TPBB^TPe\\&+2e^TPB(f^T(x)\theta+d(t)-y_{ref}^{(n)})+2e^TPBm(t)u\\&-\frac{2}{\gamma}\tilde{\beta}\dot{\hat{\beta}}-\frac{2}{\gamma}\tilde{\theta}^T\dot{\hat{\theta}}-2(1-\eta\hat{\alpha})\dot{\hat{\alpha}}\end{aligned}\quad(18)$$

Form (15):

$$\begin{aligned}2e^TPBm(t)u&=-2\hat{\alpha}e^TPBB^TPem(t)\\&-2\hat{\alpha}e^TPBm(t)\frac{\varphi^2\left(x,\hat{\theta}\right)B^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\\&-2\hat{\alpha}e^TPBm(t)\frac{\hat{\beta}^2B^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2},\end{aligned}\quad(19)$$

Since $\hat{\alpha}>0,\hat{\beta}>0,$ and $\eta\le m_r,\eta\le m_l$,then $0<\eta\le m(t)$,it can deduce that:

$$-2\hat{\alpha}e^TPBB^TPem(t)\le-2\eta\hat{\alpha}e^TPBB^TPe\quad(20)$$

$$\begin{aligned}&-2\hat{\alpha}e^TPBm(t)\frac{\varphi^2\left(x,\hat{\theta}\right)B^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}<\\&-2\eta\hat{\alpha}\frac{\varphi^2\left(x,\hat{\theta}\right)e^TPBB^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\end{aligned}\quad(21)$$

$$\begin{aligned}&-2\hat{\alpha}e^TPBm(t)\frac{\hat{\beta}^2B^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}<\\&-2\eta\hat{\alpha}\frac{\hat{\beta}^2e^TPBB^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\end{aligned}\quad(22)$$

Form (18)-(22), it can then deduce that

$$\begin{aligned}\dot{V}&\le e^T\left[A^TP+PA-2PBB^TP\right]e+2e^TPB(f^T(x)\theta+d(t)-y_{ref}^{(n)})\\&+2(1-\eta\hat{\alpha})e^TPBB^TPe-\frac{2}{\gamma}\tilde{\beta}\dot{\hat{\beta}}-\frac{2}{\gamma}\tilde{\theta}^T\dot{\hat{\theta}}-2(1-\eta\hat{\alpha})\dot{\hat{\alpha}}\\&+2(1-\eta\hat{\alpha})\frac{\varphi^2\left(x,\hat{\theta}\right)e^TPBB^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\\&-2\frac{\varphi^2\left(x,\hat{\theta}\right)e^TPBB^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\\&+2(1-\eta\hat{\alpha})\frac{\hat{\beta}^2e^TPBB^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\\&-2\frac{\hat{\beta}^2e^TPBB^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\end{aligned}\quad(23)$$

Form (12) and (23), it can get that

$$\begin{aligned}\dot{V}&=e^T\left[A^TP+PA-2PBB^TP\right]e+2e^TPB(f^T(x)\theta+d(t)-y_{ref}^{(n)})\\&-\frac{2}{\gamma}\tilde{\beta}\dot{\hat{\beta}}-\frac{2}{\gamma}\tilde{\theta}^T\dot{\hat{\theta}}\\&-2\frac{\varphi^2\left(x,\hat{\theta}\right)e^TPBB^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\\&-2\frac{\hat{\beta}^2e^TPBB^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\end{aligned}\quad(24)$$

Since $\hat{\beta}>0$, then

$$\begin{aligned}&-\frac{\varphi^2\left(x,\hat{\theta}\right)e^TPBB^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\le\\&-\varphi\left(x,\hat{\theta}\right)\left|e^TPB\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2\end{aligned}\quad(25)$$

And

$$\begin{aligned}&-\frac{\hat{\beta}^2e^TPBB^TPe}{\hat{\beta}\left|B^TPe\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2}\le\\&-\hat{\beta}\left|e^TPB\right|+(\varepsilon_1/2)e^TPBB^TPe+\varepsilon_2\end{aligned}\quad(26)$$

Form (24), (25) and (26), it can get that:

$$\begin{aligned}\dot{V}&\le e^T\left[A^TP+PA-2PBB^TP\right]e+2e^TPB(f^T(x)\theta+d(t)-y_{ref}^{(n)})\\&-\frac{2}{\gamma}\tilde{\beta}\dot{\hat{\beta}}-\frac{2}{\gamma}\tilde{\theta}^T\dot{\hat{\theta}}\\&-2\varphi\left(x,\hat{\theta}\right)\left|e^TPB\right|-2\hat{\beta}\left|e^TPB\right|+2\varepsilon_1e^TPBB^TPe+4\varepsilon_2\end{aligned}\quad(27)$$

Then:

$$\begin{aligned}&\dot{V}\le e^T\left[A^TP+PA-2(1-2\varepsilon_1)PBB^TP\right]e+2\left|e^TPB\right|\beta-2\left|e^TPB\right|\hat{\beta}-\\&\frac{2}{\gamma}\tilde{\beta}\dot{\hat{\beta}}+2\left|e^TPB\right|\left|f^T(x)\tilde{\theta}\right|+2\left|e^TPB\right|\left|f^T(x)\hat{\theta}\right|-2\left|e^TPB\right|\left|y_{ref}^{(n)}\right|-\\&2\left|e^TPB\right|\varphi(x,\hat{\theta})-\frac{2}{\gamma}\tilde{\theta}^T\dot{\hat{\theta}}+4\varepsilon_2\end{aligned}\quad(28)$$

The external perturbation $d(t)$ is bounded whatever the applied controller u is. Then by putting $\beta \triangleq \sup_{t>0}|d(t)|$, and $\varphi(x,\theta) \triangleq \left|f^T\hat{\theta}\right| - \sup_{t\geq 0}\left|y_{ref}^{(n)}\right|$,and form (13),(14),it obtain:

$$\begin{aligned}\dot{V} &\leq e^T\left[A^TP + PA - 2(1-2\varepsilon_1)PBB^TP\right]e + 4\varepsilon_2 \\ &\leq -\lambda e^TPe + 4\varepsilon_2 < -\varepsilon_2 < 0\end{aligned} \tag{29}$$

(for $e^TPe \leq \varepsilon_3$)

For $e^TPe \leq \varepsilon_3$, there are the obvious $\dot{V} = 0$.

Then

$$\begin{cases}\dot{V} \leq -\varepsilon_2 < 0, & e^TPe > \varepsilon_3 \\ \dot{V} = 0, & e^TPe \leq \varepsilon_3\end{cases} \tag{30}$$

Conclusion, the first derivative of the system (1) is bounded. Then we known that the system error is also bounded.

Define 1

$$\Gamma_1 \triangleq \left\{t \in \mathbb{R} \geq 0 \left| e^TPe \leq \varepsilon_3 \right|\right\}$$
$$\Gamma_2 \triangleq \left\{t \in \mathbb{R} \geq 0 \left| e^TPe > \varepsilon_3 \right|\right\}$$

When $t \in \Gamma_1$:

$$\begin{aligned}\dot{\hat{\alpha}} &= e^TPBB^TPe + \frac{\varphi^2\left(x,\hat{\theta}\right)e^TPBB^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right| + (\varepsilon_1/2)e^TPBB^TPe + \varepsilon_2} \\ &\quad + \frac{\hat{\beta}^2e^TPBB^TPe}{\hat{\beta}\left|B^TPe\right| + (\varepsilon_1/2)e^TPBB^TPe + \varepsilon_2}, \qquad \dot{\hat{\alpha}}(0) > 0 \\ \dot{\hat{\beta}} &= \gamma\left|B^TPe\right|, \qquad \dot{\hat{\beta}}(0) > 0, \qquad \gamma > 0 \\ \dot{\hat{\theta}} &= \gamma f(x)\left|B^TPe\right| \\ f(x) &= f\left(e + y_{ref}\right)\end{aligned} \tag{31}$$

Due to the Lyapunov function V is the decreasing function, and y_{ref} , $f(x)$ is bounded. Then $\hat{\beta},\hat{\theta},e,\hat{u}$ is bounded. Similarly, when $t \in \Gamma_2$ the $\hat{\alpha},\hat{\beta},e,\hat{u}$ is also bounded. So it can obtain that $\hat{\beta},\hat{\theta},e,\hat{u}$ is bounded for $t \in \mathbb{R} \geq 0$.

Form (15), it can obtain that:

$$\begin{aligned}|u| &\leq \hat{\alpha}B^TPe + \hat{\alpha}\frac{\varphi^2\left(e+Y_{ref},\hat{\theta}\right)B^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right| + (\varepsilon_1/2)e^TPBB^TPe + \varepsilon_2} \\ &\quad + \hat{\alpha}\frac{\hat{\beta}^2B^TPe}{\hat{\beta}\left|B^TPe\right| + (\varepsilon_1/2)e^TPBB^TPe + \varepsilon_2},\end{aligned} \tag{32}$$

Since $\varepsilon_1 > 0, \varepsilon_2 > 0$, then

$$\frac{\varphi^2\left(e+Y_{ref},\hat{\theta}\right)B^TPe}{\varphi\left(x,\hat{\theta}\right)\left|B^TPe\right| + (\varepsilon_1/2)e^TPBB^TPe + \varepsilon_2} \leq \varphi\left(e+Y_{ref},\hat{\theta}\right) \tag{33}$$

$$\frac{\hat{\beta}^2B^TPe}{\hat{\beta}\left|B^TPe\right| + (\varepsilon_1/2)e^TPBB^TPe + \varepsilon_2} \leq \hat{\beta} \tag{34}$$

Form (32)-(34), it can obtain that:

$$|u| \leq \hat{\alpha}B^TPe + \varphi\left(e+Y_{ref},\hat{\theta}\right) + \hat{\beta} \tag{35}$$

Since $\hat{\beta},\hat{\theta},e,\hat{u}$ is bounded for $t \in \mathbb{R} \geq 0$, then the right of (35) is bounded overall situation.

4. ILLUSTRATIVE EXAMPLE

Consider the nonlinear uncertain plant subject to the non-symmetric dead-zone nonlinearity:

$$\begin{aligned}\dot{x}_1 &= x_2, \\ \dot{x}_2 &= \theta_1 \bullet (0.25x) + \theta_2 \bullet \left(x_2^2 + 2x_1 + 0.5\cos(t)\right) + \Gamma(u)\end{aligned} \tag{36}$$

Where $\Gamma(u)$ is an output of a non-symmetric dead-zone. The parameters to be simulated are: $\theta_1 = 1$, and $\theta_2 = 1$. In the simulated, parameters of the dead-zone are $m_l = 1, m_r = 0.7$, $b_l = 3, b_r = 1$. According to these parameters, we have set $\varepsilon_1 = 0.2$, and $\varepsilon_2 = 0.6$. For $\lambda = 1$, the solution of the LMIs (9) gives $P = \begin{bmatrix} 18.3476 & 16.2509 \\ 16.2509 & 16.2509 \end{bmatrix}$. Choosing the desired trajectory $y_{ref} = \sin(t)$ and $\gamma = 5$, simulation results, with initial values as $B = [0 \quad 1]^T$, $X(0) = [1 \quad 1]^T$, $\hat{\alpha}(0) = 0.1$, $\hat{\beta}(0) = 0.1$, $\hat{\theta}_1(0) = 0.1$, $\hat{\theta}_2(0) = 0.2$, are shown in Fig. 2.

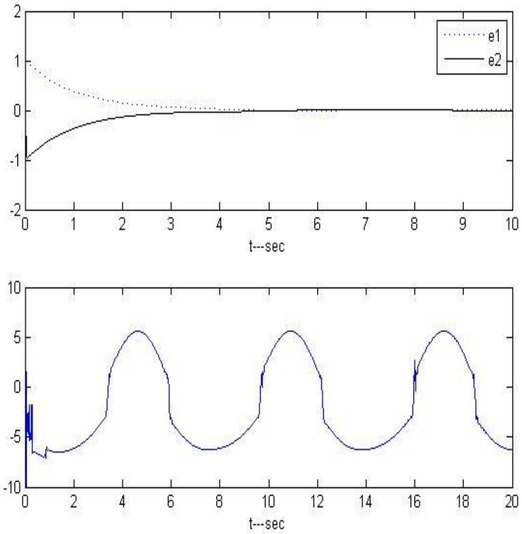

Fig. 2. The tracking error e and control signal u for $\varepsilon_1 = 0.2$, $\varepsilon_2 = 0.6$

Form Fig. 2, it can easily verify that the response of the second derivative of the reference is inside [-1, 1]. According to these simulations, we see that the adaptive law is capable of handling the effect of non-symmetric dead-zone control input with a minimal information on the dead-zone nonlinearity. In Fig. 3, then change the control parameters by taking $\varepsilon_2 = 0.3$ and keeping the previous adaptive scheme with the same initial conditions and the same control parameters $\varepsilon_1 = 0.2$. In Fig. 4, we take $\varepsilon_2 = 0.8$ and other parameters keep constant.

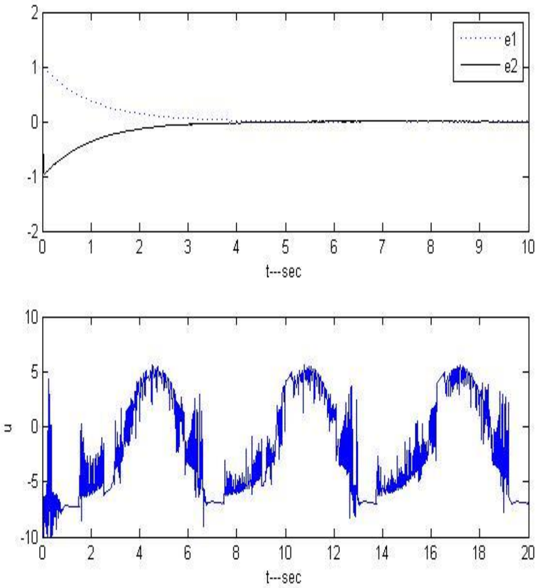

Fig. 3. The tracking error e and control signal u for $\varepsilon_1 = 0.2$, $\varepsilon_2 = 0.3$

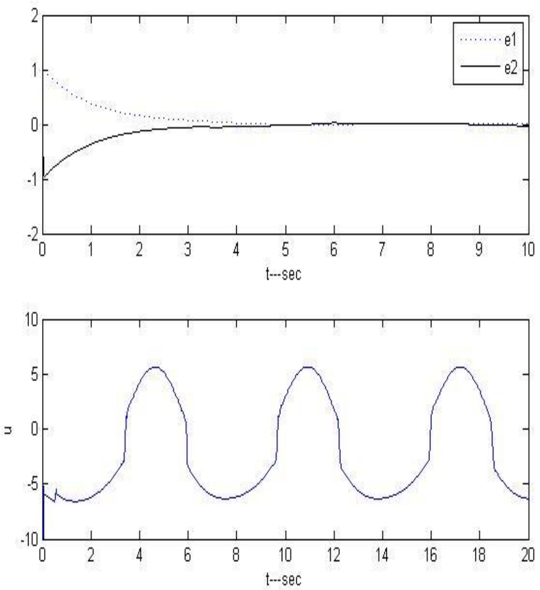

Fig. 4. The tracking error e and control signal u for $\varepsilon_1 = 0.2$, $\varepsilon_2 = 0.8$

Analyzing the Fig. 2 and Fig. 3, it can obtain that the chattering phenomena of controller aggravated while the tracking error of system weakened when ε_2 take a smaller value.

Analyzing the Fig. 2 and Fig. 4, it can obtain that the chattering phenomena of controller weakened while the tracking error of system aggravated when ε_2 take a bigger value.

5. CONCLUSION

This thesis design a new adaptive controller for a nonlinear system with non-symmetric actuator dead-zone fault basing on adaptive compensation algorithm. And the dead-zone parameters are unknown and non-symmetric. What is more, the limitation that the upper and lower limits of dead-zone is also unknown. By simulation, the proposed control law ensures bounded-error trajectory tracking with a smooth controller.

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