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Brief paper

Adaptive tracking of nonlinear systems with non-symmetric dead-zone input☆

Salim Ibrir*, Wen Fang Xie, Chun-Yi Su

Department of Mechanical and Industrial Engineering, Concordia University, 1455 de Maisonneuve Boulvard West, Montreal, Que., Canada H3G 1M8

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Abstract

Quite successfully adaptive control strategies have been applied to uncertain dynamical systems subject to dead-zone nonlinearities. However, adaptive tracking of systems with non-symmetric dead-zone characteristics has not been fully discussed with minimal knowledge of the dead-zone parameters. It is shown that the controlled system preceded by a non-symmetric dead-zone input can be represented as an uncertain nonlinear system subject to a linear input with time-varying input coefficient. To cope with this problem, a new adaptive compensation algorithm is employed without constructing the dead-zone inverse. The proposed adaptive scheme requires only the information of bounds of the dead-zone slopes and treats the time-varying input coefficient as a system uncertainty. The new control scheme ensures bounded-error trajectory tracking and assures the boundedness of all the signals in the adaptive closed loop. By appropriate selections of the controller parameters, we show that the smoothness of the controller does not affect the accuracy of trajectory tracking control. A numerical example is included to show the effectiveness of the theoretical results.

Keywords: Nonlinear non-smooth systems; Dead-zone nonlinearities; Adaptive control; Stabilization; Linear matrix inequalities (LMIs); Mechatronics

1. Introduction

As it is reported in many research papers, the dead-zone input nonlinearity is a non-differentiable function that characterizes certain non-sensitivity for small control inputs. This input characteristic is ubiquitous in a wide range of mechanical and electrical components such as valves, DC servo motors, and other devices. The presence of such a nonlinearity in feedback control systems may cause severe deterioration of the system performances. For example, in most practical motion systems, the dead-zone parameters are poorly known and imperfect knowledge of the non-sensitivity zone causes a serious problem in high precision control and, therefore, poses a fundamental issue on how to cross this zone by adaptation. To cope with this inherent problem, adaptive control techniques may be applied to design controllers. The study of adaptive control for systems subject to dead-zone actuators was initiated in Recker, Kokotović, Rhode, and Winkelman (1991), Tao and Kokotović (1993), Tao and Kokotović (1994) and Tao and Kokotović (1995), and the extensions may referred to Cho and Bai (1998) and Bai (2001). Fuzzy-logic and neural network approaches were further explored to give different looks (Jo, 2001; Kim, Park, Lee, & Chong, 1994; Selmic & Lewis, 2000). Robust stabilization of unknown sandwich systems with known uncertainties bounds was discussed in the references (Corradini & Orlando, 2002, 2003).

Many of existing adaptive approaches use an inverse dead-zone nonlinearity to minimize the effects of dead-zone (Tao & Kokotović, 1994; Zhou, Wen, & Zhang, 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

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* Corresponding author.
E-mail addresses: sibrir@encs.concordia.ca (S. Ibrir), wfxie@encs.concordia.ca (W.F. Xie), cysu@encs.concordia.ca (C.-Y. Su).

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be subjected to non-symmetric dead-zone control inputs. To overcome the limitation in Wang et al. (2004), a new adaptive control strategy is proposed to deal with non-symmetric dead-zones inputs case without constructing the dead-zone inverse. 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. Based on this representation, we shall then build an adaptive controller so as the system states track some bounded prescribed trajectories. The proposed adaptive scheme has two main characteristics: the first one is its capability of handling the uncertain time-varying input coefficient term as a system uncertainty and the second is related to the size of the tracking error that can be made as small as possible in the presence of bounded external perturbation term. By appropriate choice of a free design parameter, the chattering phenomena will be considerably attenuated. It is shown that the proposed adaptive control law ensures not only bounded-error tracking but also guarantees the boundedness of all the signals in the adaptation loop. By appropriate choice of the controller parameters, satisfactory trajectory tracking error is obtained with a nice trade off between smoothness and precision. A numerical example is given to demonstrate the efficacy of the control designs. The rest of the paper is as follows. In Section 2, the adaptive tracking of a class of nonlinear systems subject to a non-symmetric dead-zone input is discussed. Simulation results of a case study are presented in Section 3. Comparison results are then shown in Section 4. Finally, concluding remarks are given in Section 5. Throughout this paper the notation A^{T} stands for the matrix transpose of A. We note by $\|\cdot\|$, the usual Euclidean norm. $\lambda_{\min}(A)$ represents the smallest eigenvalue of A. $\mathbb{R}_{\geqslant 0}$ stands for the set of positive real numbers. The notation $\|x\|_P$ stands for $\sqrt{x^{\mathrm{T}}Px}$. $\triangleq$ stands for equality by definition. The notation $A>0$ (respectively $(A<0)$ with A being a matrix), means that the matrix A is positive definite (respectively, negative definite). $\lambda_{\min}(A)$ is the lowest eigenvalue of the matrix A. $y^{(i)}(t)$ is the ith derivative of $y(t)$ with respect to time.

2. Systems with non-symmetric dead-zones

2.1. System description and preliminaries

Consider the uncertain nonlinear system subject to a non-symmetric dead-zone input nonlinearity:

$$\dot{x}_i = x_{i+1}; \quad 1 \leqslant i \leqslant n-1,$$
$$\dot{x}_n = \sum_{i=1}^{v} f_i(x)\theta_i + \Gamma(u), \tag{1}$$

where $u = u(t) : \mathbb{R}_{\geqslant 0} \longmapsto \mathbb{R}$ is the applied control input, $(x_i)_{1\leqslant i\leqslant n} = (x_i(t))_{1\leqslant i\leqslant n} : \mathbb{R}_{\geqslant 0} \longmapsto \mathbb{R}$ are the system states, $(f_i(x))_{1\leqslant i\leqslant v} = (f_i(x(t)))_{1\leqslant i\leqslant v} : \mathbb{R}^n \longmapsto \mathbb{R}$ are real-valued nonlinear functions, and $(\theta_i)_{1\leqslant i\leqslant v}$ are constant unknown parameters. $\Gamma(u)$ is a single dead-zone input nonlinearity defined

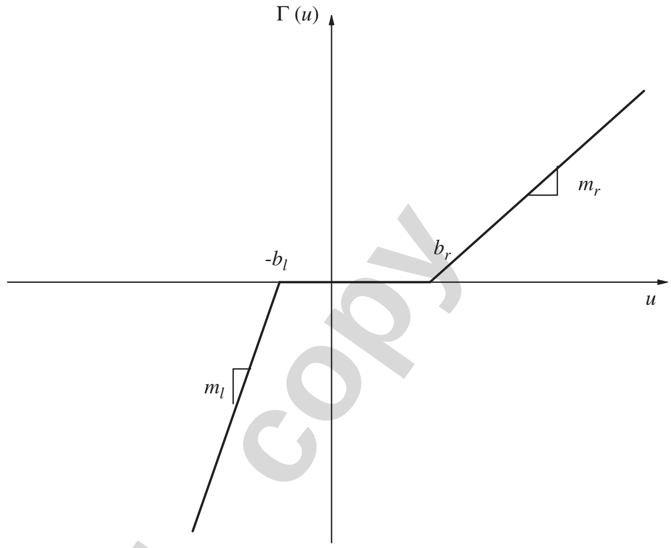

Fig. 1. Non-symmetric dead-zone nonlinearity.

as follows:

$$\Gamma(u) \triangleq \begin{cases} m_{\mathrm{r}}(u-b_{\mathrm{r}}) & \text{if } u \geqslant b_{\mathrm{r}}, \\ 0 & \text{if } -b_{\mathrm{l}} < u < b_{\mathrm{r}}, \\ m_{\mathrm{l}}(u+b_{\mathrm{l}}) & \text{if } , u \leqslant -b_{\mathrm{l}}. \end{cases} \tag{2}$$

The non-symmetric dead-zone input is shown in Fig. 1. The parameters m_{r} and m_{l} stand for the right and the left slope of the dead-zone characteristic. b_{r} and b_{l} represent the break-points of the input nonlinearity. In this section, the following assumptions are considered.

Assumption 1. The coefficients m_{r}, m_{l}, b_{l} and b_{r} are strictly positive and unknown.

Assumption 2. The maximum and the minimum values of the characteristic slopes are known; $\max\{m_{\mathrm{l}}, m_{\mathrm{r}}\} = \bar{\alpha}$, $\min\{m_{\mathrm{l}}, m_{\mathrm{r}}\} = \underline{\alpha}$, and the state vector of (1) is accessible for measurements.

Assumptions 1 and 2 are not restrictive conditions, since the a priori knowledge of the upper and the lower bounds of the slopes seems to be a natural assumption in engineering practice. According to the above notation, the dead-zone (2) can be re-defined as a slowly time-varying input-dependent function of the following form:

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

where

$$m(t) \triangleq \begin{cases} m_{\mathrm{l}} & \text{if } u \leqslant 0, \\ m_{\mathrm{r}} & \text{if } u > 0 \end{cases} \tag{4}$$

and

$$d(t) \triangleq \begin{cases} -m_{\mathrm{r}}b_{\mathrm{r}} & \text{if } u \geqslant b_{\mathrm{r}}, \\ -m(t)u & \text{if } -b_{\mathrm{l}} < u < b_{\mathrm{r}}, \\ m_{\mathrm{l}}b_{\mathrm{l}} & \text{if } u \leqslant -b_{\mathrm{l}}. \end{cases} \tag{5}$$

Remark 1. In Wang et al. (2004), the dead-zone was also expressed as a linear function of input signal $v(t)$ plus a bounded term, which, however, is obtained under the condition of symmetric dead-zone inputs. Thus the proposed control method also strongly relies on this condition. To remove such an assumption, a new method has to be re-investigated, which constitutes a main motivation for the development of this paper.

2.2. Adaptive compensation of dead-zone

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

$$\lim_{t\to\infty} |x_i(t) - y_{\text{ref}}^{(i-1)}(t)| \leqslant \delta, \quad 1 \leqslant i \leqslant n, \tag{6}$$

where δ is some sufficiently small positive constant and $y_{\text{ref}} = y_{\text{ref}}(t)$ 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.

Theorem 1. *Consider system* (1) *subject to the non-symmetric dead-zone input nonlinearity* (2). *Let us denote*

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

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

$$\theta \triangleq \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_v \end{bmatrix} \in \mathbb{R}^v, \tag{7}$$

where $y_{\text{ref}} \triangleq y_{\text{ref}}(t)$ is a $\mathscr{C}^{(n)}$ well-defined time-dependent trajectory and Y_{ref} is globally bounded over-the-time interval $[0, \infty)$. *For given strictly positive constants ε_1; $0 < \varepsilon_1 < \underline{\alpha}$ and ε_2, let P be $n \times n$ symmetric and positive definite matrix that verifies the following linear matrix inequalities for* $\lambda > 0$:

$$\begin{aligned} &\lambda P^{-1} + P^{-1}A^{\mathrm{T}} + AP^{-1} - 2(\underline{\alpha} - \varepsilon_1)BB^{\mathrm{T}} < 0, \\ &\lambda P^{-1} + P^{-1}A^{\mathrm{T}} + AP^{-1} - 2(\bar{\alpha} - \varepsilon_1)BB^{\mathrm{T}} < 0, \end{aligned} \tag{8}$$

and let $\varepsilon_3 \triangleq 5\varepsilon_2/\lambda$, $e \triangleq x - Y_{\text{ref}}$, $\tilde{\theta} \triangleq \theta - \hat{\theta}$, $\tilde{\mu} \triangleq \mu - \hat{\mu}$, $\tilde{\beta} \triangleq \beta - \hat{\beta}$, where $\mu \triangleq \sup_{t\geqslant 0}\{m(t)/\underline{\alpha} - 1\}$, $\beta \triangleq \sup_{t\geqslant 0}|d(t)|$, $\varphi(x, \hat{\theta}) \triangleq |f^{\mathrm{T}}(x)\hat{\theta}| + \sup_{t\geqslant 0}|y_{\text{ref}}^{(n)}|$ with

$$\dot{\hat{\theta}} \triangleq \begin{cases} \gamma f(x)B^{\mathrm{T}}Pe & \text{if } \|e\|_P \geqslant \sqrt{\varepsilon_3}, \quad \gamma > 0, \\ 0 & \text{if } \|e\|_P < \sqrt{\varepsilon_3}, \end{cases}$$

$$\dot{\hat{\beta}} \triangleq \begin{cases} \gamma|B^{\mathrm{T}}Pe| & \text{if } \|e\|_P \geqslant \sqrt{\varepsilon_3}, \gamma > 0, \quad \hat{\beta}(0) > 0, \\ 0 & \text{if } \|e\|_P < \sqrt{\varepsilon_3}, \end{cases}$$

$$\dot{\hat{\mu}} \triangleq \begin{cases} \gamma|B^{\mathrm{T}}Pe|\varphi(x, \hat{\theta}) & \text{if } \|e\|_P \geqslant \sqrt{\varepsilon_3}, \quad \hat{\mu}(0) > 0, \\ 0 & \text{if } \|e\|_P < \sqrt{\varepsilon_3}, \quad \gamma > 0. \end{cases} \tag{9}$$

Define

$$V(e, \tilde{\theta}, \tilde{\mu}, \tilde{\beta}) \triangleq \begin{cases} \varepsilon_3 + \frac{1}{\gamma}\tilde{\theta}^{\mathrm{T}}\tilde{\theta} \\ \quad + \frac{1}{\gamma}\tilde{\mu}^2 + \frac{1}{\gamma}\tilde{\beta}^2 & \text{if } \|e\|_P \leqslant \sqrt{\varepsilon_3} \\ e^{\mathrm{T}}Pe + \frac{1}{\gamma}\tilde{\theta}^{\mathrm{T}}\tilde{\theta} \\ \quad + \frac{1}{\gamma}\tilde{\mu}^2 + \frac{1}{\gamma}\tilde{\beta}^2 & \text{if } \|e\|_P > \sqrt{\varepsilon_3}. \end{cases} \tag{10}$$

Under the action of the adaptive feedback

$$\begin{aligned} u \triangleq & -\frac{1}{\underline{\alpha}} f^{\mathrm{T}}(x)\hat{\theta} - B^{\mathrm{T}}Pe + \frac{1}{\underline{\alpha}} y_{\text{ref}}^{(n)} \\ & - \frac{1}{\underline{\alpha}} \frac{\varphi^2(x, \hat{\theta})\hat{\mu}^2 B^{\mathrm{T}}Pe}{\hat{\mu}\varphi(x, \hat{\theta})|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2} \\ & - \frac{1}{\underline{\alpha}} \frac{\hat{\beta}^2 B^{\mathrm{T}}Pe}{\hat{\beta}|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2}, \end{aligned} \tag{11}$$

the first derivative of $V(e, \tilde{\theta}, \tilde{\mu}, \tilde{\beta})$ along the trajectories of system (1) *is bounded as follows*:

$$\begin{cases} \dot{V}(e, \tilde{\theta}, \tilde{\mu}, \tilde{\beta}) = 0 & \text{if } \|e\|_P \leqslant \sqrt{\varepsilon_3}, \\ \dot{V}(e, \tilde{\theta}, \tilde{\mu}, \tilde{\beta}) \leqslant -\varepsilon_2 < 0 & \text{if } \|e\|_P > \sqrt{\varepsilon_3}. \end{cases} \tag{12}$$

Proof. For all $t \geqslant 0$, $V(e, \tilde{\theta}, \tilde{\mu}, \tilde{\beta}) \geqslant \varepsilon_3 > 0$ and $V(e, \tilde{\theta}, \tilde{\mu}, \tilde{\beta})$ is piecewise continuous. Then according to (3), the dynamics of the error e is shown as follows:

$$\dot{e} = Ae + B(f^{\mathrm{T}}(x)\theta + m(t)u + d(t) - y_{\text{ref}}^{(n)}). \tag{13}$$

Using the fact that

$$\frac{m(t)}{\underline{\alpha}} = 1 + k(t), \tag{14}$$

where $k(t)$ is a some piecewise positive function, we have

$$\begin{aligned} \dot{e} = & (A - m(t)BB^{\mathrm{T}}P)e + Bf^{\mathrm{T}}(x)\tilde{\theta} - k(t)Bf^{\mathrm{T}}(x)\hat{\theta} \\ & + k(t)By_{\text{ref}}^{(n)} \\ & - (1 + k(t))\frac{\varphi^2(x, \hat{\theta})\hat{\mu}^2 BB^{\mathrm{T}}Pe}{\hat{\mu}\varphi(x, \hat{\theta})|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2} \\ & - (1 + k(t))\frac{\hat{\beta}^2 BB^{\mathrm{T}}Pe}{\hat{\beta}|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2} \\ & + Bd(t). \end{aligned} \tag{15}$$

For $\|e\|_P > \sqrt{\varepsilon_3}$, we have

$$\begin{aligned}
&\dot V(e,\tilde\theta,\tilde\mu,\tilde\beta)\\
&\quad = e^{\mathrm T}(A^{\mathrm T}P + PA - 2m(t)PBB^{\mathrm T}P)e\\
&\qquad + 2e^{\mathrm T}PBd(t) + 2e^{\mathrm T}PBf^{\mathrm T}(x)\tilde\theta\\
&\qquad - 2k(t)e^{\mathrm T}PBf^{\mathrm T}(x)\hat\theta + 2k(t)e^{\mathrm T}PBy_{\mathrm{ref}}^{(n)}\\
&\qquad - 2(1+k(t))\frac{\varphi^2(x,\hat\theta)\hat\mu^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\mu\varphi(x,\hat\theta)|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2}\\
&\qquad - 2(1+k(t))\frac{\hat\beta^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\beta|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2}\\
&\qquad - \frac{2}{\gamma}\tilde\theta^{\mathrm T}\dot{\hat\theta} - \frac{2}{\gamma}\tilde\mu\dot{\hat\mu} - \frac{2}{\gamma}\tilde\beta\dot{\hat\beta}.
\end{aligned}\tag{16}$$

Since

$$-k(t)\frac{\varphi^2(x,\hat\theta)\hat\mu^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\mu\varphi(x,\hat\theta)|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2} < 0 \tag{17}$$

and

$$-k(t)\frac{\hat\beta^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\beta|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2} < 0 \tag{18}$$

hold, this immediately implies that

$$\begin{aligned}
&\dot V(e,\tilde\theta,\tilde\mu,\tilde\beta)\\
&\quad \leqslant e^{\mathrm T}(A^{\mathrm T}P + PA - 2m(t)PBB^{\mathrm T}P)e\\
&\qquad + 2e^{\mathrm T}PBd(t) + 2e^{\mathrm T}PBf^{\mathrm T}(x)\tilde\theta - 2k(t)e^{\mathrm T}PBf^{\mathrm T}(x)\hat\theta\\
&\qquad + 2k(t)e^{\mathrm T}PBy_{\mathrm{ref}}^{(n)}\\
&\qquad - 2\frac{\varphi^2(x,\hat\theta)\hat\mu^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\mu\varphi(x,\hat\theta)|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2}\\
&\qquad - 2\frac{\hat\beta^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\beta|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2}\\
&\qquad - \frac{2}{\gamma}\tilde\theta^{\mathrm T}\dot{\hat\theta} - \frac{2}{\gamma}\tilde\mu\dot{\hat\mu} - \frac{2}{\gamma}\tilde\beta\dot{\hat\beta}.
\end{aligned}\tag{19}$$

Since $\hat\mu > 0$ and $\hat\beta > 0$ for all $t \in [0,\infty)$, we can write that

$$\begin{aligned}
&-\frac{\varphi^2(x,\hat\theta)\hat\mu^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\mu\varphi(x,\hat\theta)|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2}\\
&\quad \leqslant -\hat\mu|e^{\mathrm T}PB|\varphi(x,\hat\theta) + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2
\end{aligned}\tag{20}$$

and

$$\begin{aligned}
&-\frac{\hat\beta^2 e^{\mathrm T}PBB^{\mathrm T}Pe}{\hat\beta|B^{\mathrm T}Pe| + (\varepsilon_1/2)e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2}\\
&\quad \leqslant -\hat\beta|e^{\mathrm T}PB|\\
&\qquad + \frac{\varepsilon_1}{2}e^{\mathrm T}PBB^{\mathrm T}Pe + \varepsilon_2.
\end{aligned}\tag{21}$$

From (19)–(21), we can then deduce that

$$\begin{aligned}
&\dot V(e,\tilde\theta,\tilde\mu,\tilde\beta)\\
&\quad \leqslant e^{\mathrm T}(A^{\mathrm T}P + PA - 2m(t)PBB^{\mathrm T}P)e\\
&\qquad + 2|e^{\mathrm T}PB|\sup_{t\geqslant 0}|d(t)| + 2e^{\mathrm T}PBf^{\mathrm T}(x)\tilde\theta\\
&\qquad + 2\sup_{t\geqslant 0}|k(t)||e^{\mathrm T}PB||f^{\mathrm T}(x)\hat\theta|\\
&\qquad + 2\sup_{t\geqslant 0}|k(t)||e^{\mathrm T}PB|\sup_{t\geqslant 0}|y_{\mathrm{ref}}^{(n)}|\\
&\qquad - 2\hat\beta|e^{\mathrm T}PB| + 2\varepsilon_1 e^{\mathrm T}PBB^{\mathrm T}Pe - 2\hat\mu|e^{\mathrm T}PB|\varphi(x,\hat\theta)\\
&\qquad + 4\varepsilon_2 - \frac{2}{\gamma}\tilde\theta^{\mathrm T}\dot{\hat\theta} - \frac{2}{\gamma}\tilde\mu\dot{\hat\mu} - \frac{2}{\gamma}\tilde\beta\dot{\hat\beta}.
\end{aligned}\tag{22}$$

The external perturbation $d(t)$ is bounded whatever the applied controller u is. Then by putting $\sup_{t\geqslant 0}|d(t)| = \beta \leqslant \bar\alpha\max\{b_{\mathrm l}, b_{\mathrm r}\}$ and $\sup_{t\geqslant 0}|k(t)| = \mu$, we obtain

$$\begin{aligned}
&\dot V(e,\tilde\theta,\tilde\mu,\tilde\beta)\\
&\quad \leqslant e^{\mathrm T}(A^{\mathrm T}P + PA - 2(m(t)-\varepsilon_1)PBB^{\mathrm T}P)e\\
&\qquad + 2e^{\mathrm T}PBf^{\mathrm T}(x)\tilde\theta + 2|e^{\mathrm T}PB|\tilde\beta + 2\tilde\mu|e^{\mathrm T}PB|\varphi(x,\hat\theta)\\
&\qquad - \frac{2}{\gamma}\tilde\theta^{\mathrm T}\dot{\hat\theta} - \frac{2}{\gamma}\tilde\mu\dot{\hat\mu} - \frac{2}{\gamma}\tilde\beta\dot{\hat\beta} + 4\varepsilon_2.
\end{aligned}\tag{23}$$

Consequently, by plugging the dynamics of $\hat\theta$, $\hat\mu$ and $\hat\beta$ into the right hand side of the last inequality, we write

$$\begin{aligned}
&\dot V(e,\tilde\theta,\tilde\mu,\tilde\beta)\\
&\quad \leqslant e^{\mathrm T}(A^{\mathrm T}P + PA - 2(m(t)-\varepsilon_1)PBB^{\mathrm T}P)e + 4\varepsilon_2\\
&\quad \leqslant -\lambda e^{\mathrm T}Pe + 4\varepsilon_2 < -\varepsilon_2 < 0 \quad \text{for } \|e\|_P > \sqrt{\varepsilon_3}.
\end{aligned}\tag{24}$$

When $\|e\|_P \leqslant \sqrt{\varepsilon_3}$, $\dot V(e,\tilde\theta,\tilde\mu,\tilde\beta) = 0$. Define $\mathscr{T}_1$ and $\mathscr{T}_2$ as partitioning domains of $\mathbb{R}_{\geqslant 0}$ such that $\mathscr{T}_1 \triangleq \{t \in \mathbb{R}_{\geqslant 0} | \|e\|_P \leqslant \varepsilon_3\}$, $\mathscr{T}_2 \triangleq \{t \in \mathbb{R}_{\geqslant 0} | \|e\|_P > \varepsilon_3\}$. Since the Lyapunov function satisfies (12) for all $t \in \mathbb{R}_{\geqslant 0}$, this implies that the whole time during which the adaptations take place is finite. During $t \in \mathscr{T}_2$, the adaptation laws are rewritten as

$$\begin{cases}
\dot{\hat\theta} \triangleq \gamma f(e + Y_{\mathrm{ref}})B^{\mathrm T}Pe; & \gamma > 0,\\
\dot{\hat\beta} \triangleq \gamma|B^{\mathrm T}Pe|; & \gamma > 0,\ \hat\beta(0) > 0,\\
\dot{\hat\mu} \triangleq \gamma|B^{\mathrm T}Pe|(|f^{\mathrm T}(e + Y_{\mathrm{ref}})\hat\theta| & \\
\quad + \sup_{t\geqslant 0}|y_{\mathrm{ref}}^{(n)}|); & \hat\mu(0) > 0.
\end{cases}\tag{25}$$

During this finite time when $t \in \mathscr{T}_2$, the variables $\hat\theta$, $\hat\beta$ and $\hat\mu$ cannot escape to infinity since the adaptation laws in (25) are well-defined, $V(e,\tilde\theta,\tilde\mu,\tilde\beta)$ is decreasing and Y_{ref} is bounded. In addition, the following inequality $(1/\gamma)\tilde\theta'\tilde\theta + (1/\gamma)\tilde\mu^2 + (1/\gamma)\tilde\beta^2 \leqslant V(e,\tilde\theta,\tilde\mu,\tilde\beta) - \lambda_{\min}(P)\|e\|^2$ is verified. In the limit where $t \in \mathscr{T}_1$, the time-dependent adaptive variables $\hat\theta, \hat\beta, \hat\mu$ are constant and e is bounded. As a result, for any bounded conditions $e(0)$, $\hat\theta(0)$, $\hat\beta(0)$ and $\hat\mu(0)$ and by the use of (12), we conclude that e, $\hat\theta$, $\hat\beta$ and $\hat\mu$ are bounded for all $t \in \mathbb{R}_{\geqslant 0}$. This ends the proof. □

The boundedness of the applied control input is of a major concern in adaptive compensation strategies. For this reason we shall prove that the adaptive control law is bounded when all the conditions of the main Theorem 1 are satisfied. According to the definition of the adaptive law (11), we have

$$\begin{aligned}|u| &\leqslant \frac{1}{\underline{\alpha}}|f^{\mathrm{T}}(e+Y_{\mathrm{ref}})|\|\hat{\theta}\| + |B^{\mathrm{T}}Pe| + \frac{1}{\underline{\alpha}}\sup_{t\geqslant 0}|y_{\mathrm{ref}}^{(n)}| \\ &+ \frac{1}{\underline{\alpha}}\frac{\varphi^2(e+Y_{\mathrm{ref}},\hat{\theta})\hat{\mu}^2|B^{\mathrm{T}}Pe|}{\hat{\mu}\varphi(x,\hat{\theta})|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2} \\ &+ \frac{1}{\underline{\alpha}}\frac{\hat{\beta}^2|B^{\mathrm{T}}Pe|}{\hat{\beta}|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2}. \end{aligned} \tag{26}$$

Since for all $e \in \mathbb{R}^n$ and $\varepsilon_2 \neq 0$, we have

$$\frac{\hat{\mu}^2\varphi^2(e+Y_{\mathrm{ref}},\hat{\theta})|B^{\mathrm{T}}Pe|}{\hat{\mu}\varphi(x,\hat{\theta})|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2} \leqslant \hat{\mu}\varphi(e+Y_{\mathrm{ref}},\hat{\theta}) \tag{27}$$

and

$$\frac{\hat{\beta}^2|B^{\mathrm{T}}Pe|}{\hat{\beta}|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2} \leqslant \hat{\beta}, \tag{28}$$

then from (26)–(28), we obtain

$$\begin{aligned}|u| &\leqslant \frac{1}{\underline{\alpha}}|f^{\mathrm{T}}(e+Y_{\mathrm{ref}})|\|\theta-\tilde{\theta}\| + |B^{\mathrm{T}}Pe| + \frac{1}{\underline{\alpha}}\sup_{t\geqslant 0}|y_{\mathrm{ref}}^{(n)}| \\ &+ \frac{1}{\underline{\alpha}}|\mu-\tilde{\mu}|\varphi(e+Y_{\mathrm{ref}},\hat{\theta}) + \frac{1}{\underline{\alpha}}|\beta-\tilde{\beta}|. \end{aligned} \tag{29}$$

From the proof of Theorem 1, it implies that e, $\tilde{\theta}$, $\tilde{\mu}$ and $\tilde{\beta}$ are bounded over $t \in [0, \infty)$. Since the right-hand side of (29) (which is the upper bound of u) is not singular and contains bounded terms by Theorem 1, then we conclude that u is globally bounded for all $t \in \mathbb{R}_{\geqslant 0}$.

Remark 2. In case where $\varepsilon_2 = 0$ and by the use of LaSalle theorem, we conclude that $\dot{V} \leqslant 0$. Then the dynamics of the error states e_i, $1 \leqslant i \leqslant n$, are globally asymptotically stable. However, the chattering cannot be completely removed even if the function $B^{\mathrm{T}}Pe/(|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2)$ remains differentiable for $\varepsilon_2 = 0$.

Remark 3. The chattering phenomena is often undesirable for mechanical actuators. Then, by appropriate choice of $\varepsilon_2 \neq 0$ the chattering will be significantly attenuated. However, a practical stability is guaranteed instead of asymptotic stability, see (24). The main role of ε_2 is to enhance the smoothness of the applied controller for $\varepsilon_1 \neq 0$. However, we can always act on the parameters ε_1 and ε_2 in order to make the function $B^{\mathrm{T}}Pe/(|B^{\mathrm{T}}Pe| + (\varepsilon_1/2)e^{\mathrm{T}}PBB^{\mathrm{T}}Pe + \varepsilon_2)$ relatively equivalent to $\mathrm{sign}(e^{\mathrm{T}}PB)$.

2.3. Discussion

The proposed adaptive controller gives a new idea how to handle the time-varying input coefficient terms by the knowledge of their bounds. The passage from (13) to (15) shows the implication of the adaptive controller in translating the unknown time-varying input coefficient term from the input term to the system uncertainties. Notice that the proposed design does not require the differentiability of $m(t)$ which means that the adaptive compensation can also handle the effect of different kinds of slowly time-varying $m(t)$ and $d(t)$. Since the effect of the input nonlinearity appears as a combination of a system uncertainty and an external perturbation, the stability of the tracking error is in part guaranteed by solving two LMIs while the external perturbation that results by this operation is enfeebled by the smooth two nonlinear terms in (11). In summary, the compensation of the input nonlinearity turns out to be a robust adaptive control issue. As a matter of fact, the adaptive controller (11) achieves bounded-error tracking in the presence of non-symmetric dead-zone input nonlinearity and under the minimal knowledge of the upper bounds of the slopes. The order of the tracking error when times elapses is about $\sqrt{5\varepsilon_2/\lambda\lambda_{\min}(P)}$, and hence, we can make this error sufficiently small by choosing ε_2 adequately small. Recall that the choice of ε_2 is related to neither the system parameters nor the bound of the external perturbation $d(t)$. Therefore, the proposed adaptation strategy is robust against the effects of large values of the dead-zone parameters. Notice that the solution of the LMIs (8) does not depend on the dead-zone width $[-b_{\mathrm{l}}, b_{\mathrm{r}}]$. Then if we choose $P > 0$ such that $\lambda_{\min}(P) \geqslant 1$ and $\lambda \geqslant 1$, the tracking error when time elapses shall be dependent only upon ε_2. As a result, the tracking error is not dependent, in this case, upon the norm of the perturbation $d(t)$ which may increase for large values of b_{l} and b_{r}. To make all the eigenvalues of P greater than one, it is sufficient to solve the LMIs (8)under an additional constraint $P^{-1} \leqslant I_n$, where I_n is the n by n identity matrix. More importantly, the width of the dead-zone characteristic is not required by the adaptation scheme. However, the requirement for sufficient energy is needed to make the controller able to operate outside the dead-zone region. Evidently, the proposed adaptation algorithm is applicable in case of unknown symmetric dead-zone inputs and no additional requirements are imposed.

3. Illustrative example

The compromise between the smoothness of the adaptive control law and the precision of the tracking error is the main feature of any adaptive scheme. In this section, we shall discuss all these issues through numerical simulations.

3.1. Sensitivity to a small amplitude reference trajectory

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

$$\begin{aligned}\dot{x}_1 &= x_2, \\ \dot{x}_2 &= \theta_1\frac{1-e^{-x_1}}{1+e^{-x_1}} + \theta_2(x_2^2+2x_1)\sin x_2 + \Gamma(u), \end{aligned} \tag{30}$$

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

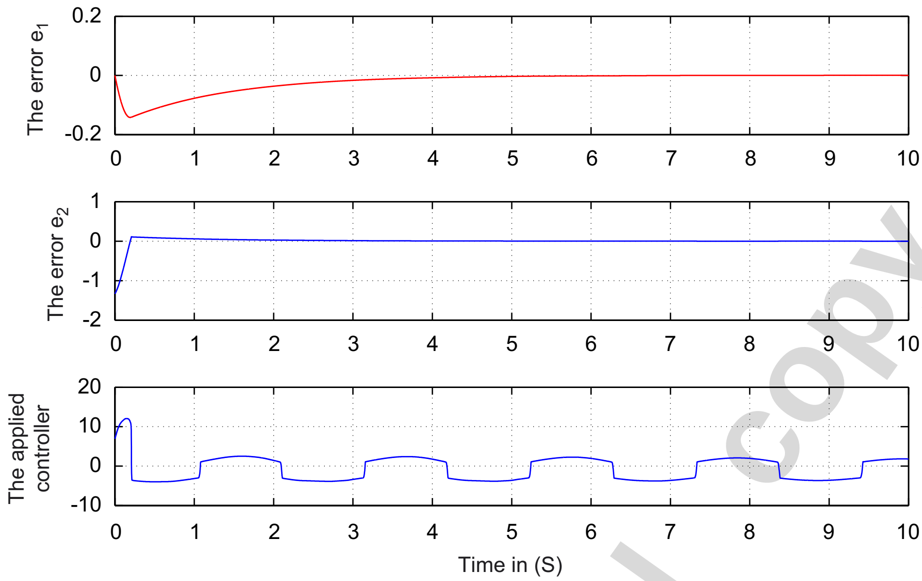

Fig. 2. The tracking performance for $y_{\mathrm{ref}} = \frac{1}{9}\sin(3t)\cos(0.1t)$.

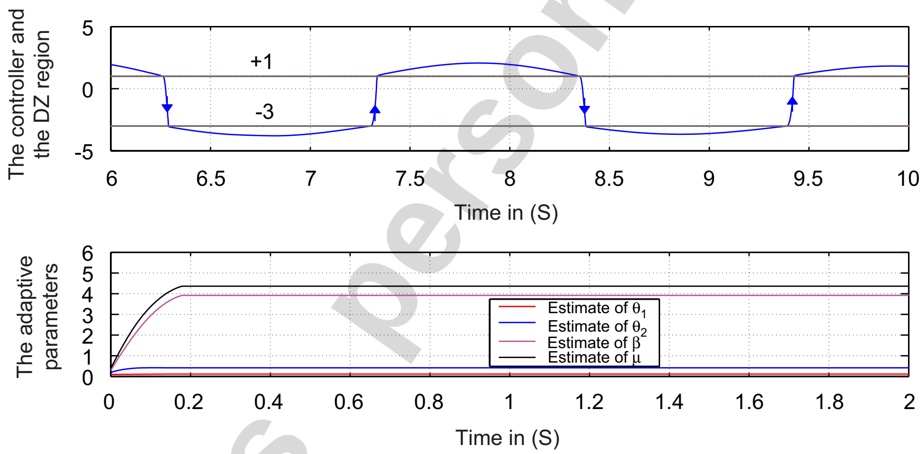

Fig. 3. The control law and the adaptive parameters for $y_{\mathrm{ref}} = \frac{1}{9}\sin(3t)\cos(0.1t)$.

simulation, parameters of the dead-zone are $m_{\mathrm{l}} = 1$, $m_{\mathrm{r}} = 0.7$, $b_{\mathrm{r}} = 1$, $b_{\mathrm{l}} = 3$. The control parameters are computed according to $\bar{\alpha} = 1$, $\underline{\alpha} = 0.7$. According to these parameters, we have set $\varepsilon_1 = 0.2$ and $\varepsilon_2 = 0.05$. For $\lambda = 1$, the solution of the LMIs (8) gives $P^{-1} = \begin{bmatrix} 0.8142 & -0.6140 \\ -0.6140 & 0.6752 \end{bmatrix}$. Choosing the desired trajectory $y_{\mathrm{ref}} = \frac{1}{9}\sin(3t)\cos(0.1t)$ and $\gamma = 5$, simulation results, with initial values as $x(0) = [0\ -1]^{\mathrm{T}}$, $\hat{\theta}_1(0) = 0.1$, $\hat{\theta}_2(0) = 0.2$, $\hat{\beta}(0) = 0.3$, $\hat{\mu}(0) = 0.4$, are shown in Fig. 2. One can easily verify that the response of the second derivative of the reference is inside $[-1, 1]$. We have particularly chosen a small amplitude reference trajectory in order to show the accuracy of the developed adaptive compensation algorithm for a non-symmetric dead-zone.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 addition, we remark that the nonlinear feedback (11) has also diminished the effect of the chattering due to its smoothness properties. In Fig. 3, we have zoomed on the adaptive control law in order to show that the adaptive controller does not stay for a long time inside the dead-zone region. This is clearly manifested by the jumps inside the dead-zone region $[-3, 1]$, see Fig. 3. The adaptive parameters $\hat{\theta}_1$, $\hat{\theta}_2$, $\hat{\beta}$ and $\hat{\mu}$ are globally bounded as shown in Fig. 3. In order to show the robustness of the adaptive controller against the variation of the width of the dead-zone, let us enlarge the width of the dead-zone by taking $b_{\mathrm{l}} = 6$, $b_{\mathrm{r}} = 1.5$ and keeping the previous adaptive scheme with the same initial conditions and the same control parameters $\varepsilon_1 = 0.2$, $\varepsilon_2 = 0.05$. In Fig. 4, we have depicted all the signals of the adaptive loop. Referring to this simulation, we see that the performance of the controller in achieving a small bounded-error tracking is comparable to that of the last simulation, but the controller requires more energy to handle the effect of the large dead-zone. As a matter of fact,

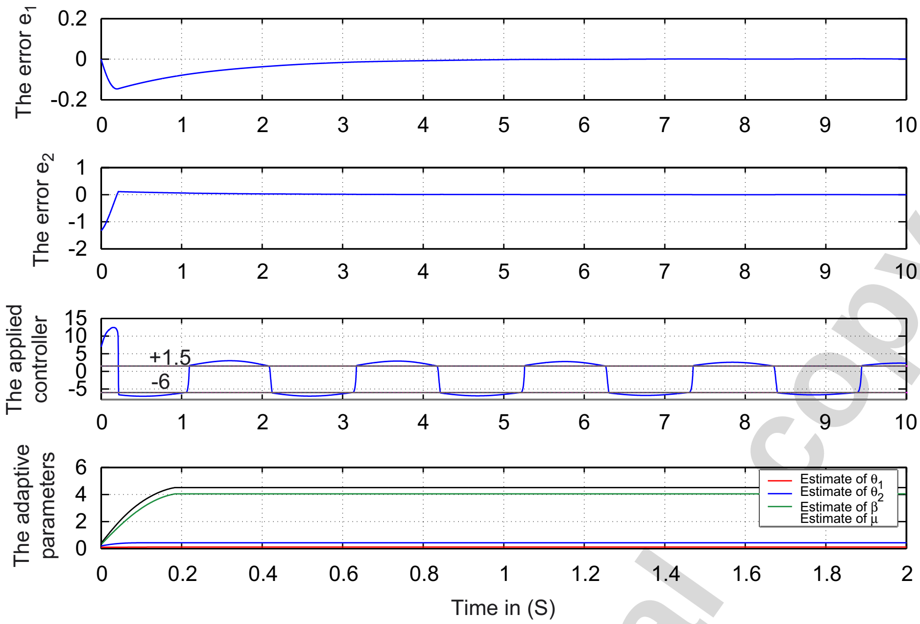

Fig. 4. The tracking performance for $y_{\text{ref}} = \frac{1}{9}\sin(3t)\cos(0.1t)$ and $b_l = 6$, $b_r = 1.5$.

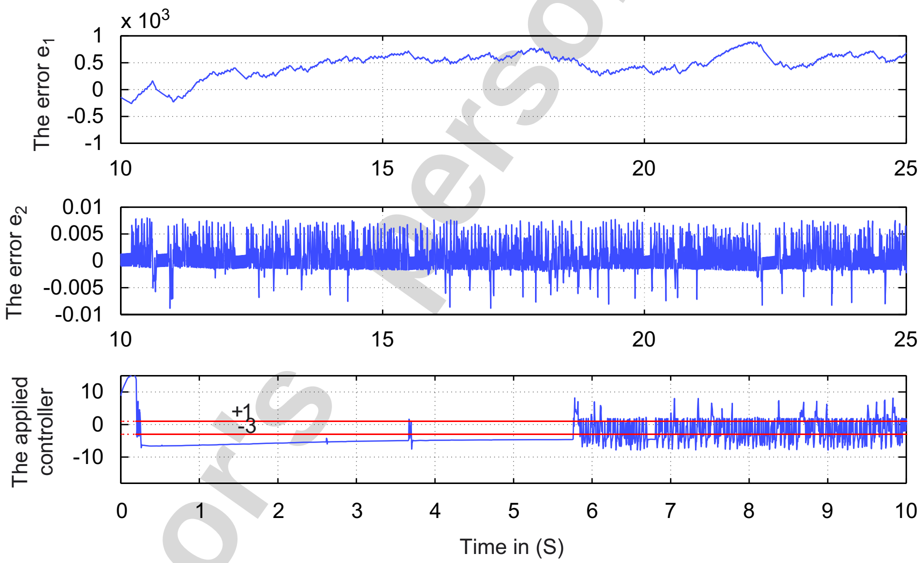

Fig. 5. $y_{\text{ref}} = 1$, $\varepsilon_2 = 0.2$.

if the upper bound of the controller is limited to b_l, the adaptive controller cannot achieve satisfactory tracking which means that the robustness of the adaptive controller is dependent on the limitation level of the applied input.

3.2. *Case of constant reference trajectory*

In this subsection, we show the performance of the adaptive algorithm in case of a constant reference. In Figs. 5 and 6, we show the effect of the coefficient ε_2 on both the smoothness and the precision of the solutions. In Fig. 5, the tracking performance is shown for $10 \leqslant t \leqslant 25$, $y_{\text{ref}} \triangleq 1$, $\varepsilon_2 = 0.2$, $b_l = 3$, $b_r = 1$ and $\gamma = 5$. In Fig. 6 the smoothness of the controller is improved after augmenting ε_2 to 0.85.

4. Discussion and comparisons

In this section we present some comparisons between the proposed approach and the already published algorithms that have been devoted to dead-zone compensation. In Cho and Bai (1998), an adaptive dead-zone inverse technique is proposed for control of systems containing an unknown dead-zone. It is shown that the effect of the unknown dead-zone on the closed-loop control system can be eliminated asymptotically if both

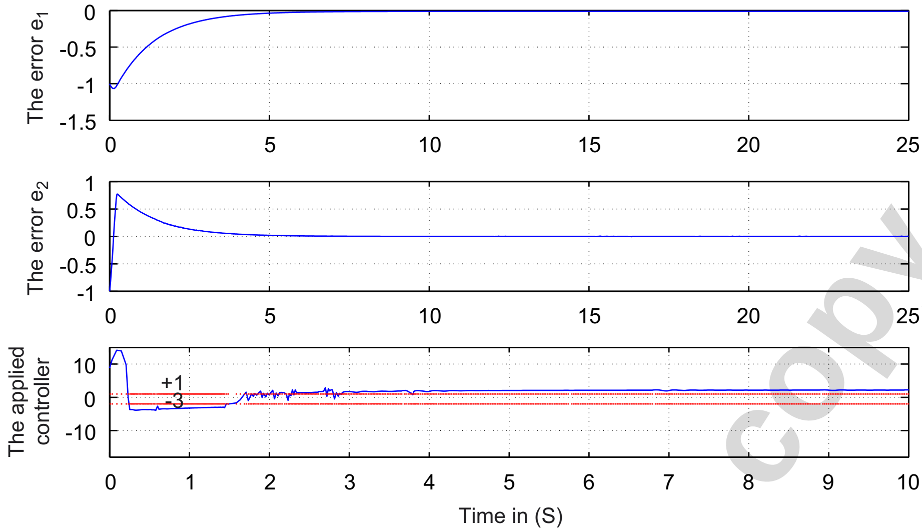

Fig. 6. The tracking performance for $y_{\text{ref}} = 1$, $\varepsilon_2 = 0.85$.

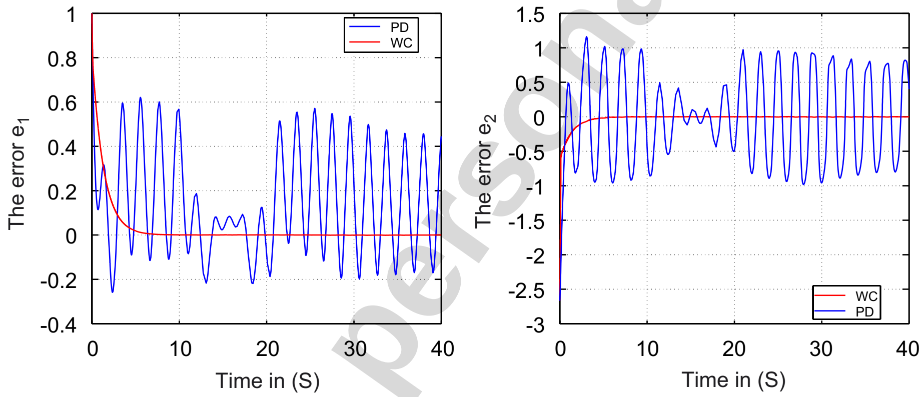

Fig. 7. WC: with compensation of the dead-zone, PD: prop. and derivative controller.

input and output measurements of the dead-zone are available. However, the condition is strong if compared with those in the literature since the measurements of the dead-zone output is required. The algorithm presented in Corradini and Orlando (2003) achieves practical stability under the assumption that the bounds of the dead-zone nonlinearity are known. The proposed design in the present paper is simple and straightforward in the sense that the non-smooth nonlinearity is treated in the same way as the system uncertainties. Therefore, the presented results can be easily extended to multiple-input systems. Actually, the present work can be seen as an alternative to adaptive design proposed in Selmic and Lewis (2000) and Tao and Kokotović (1994). The importance of the main Theorems of this paper lies in that only the information of the slopes are required. It has been shown that the controller is self-tuning without the information of the width of the dead-zone, namely, the break-points of the dead-zone. This certainly avoids a preliminary identification of the unknown dead-zone and makes the controller robust against small variation of the dead-zone.

Now, we shall compare the performance of the proposed adaptive controller with a simple proportional and derivative (PD) controller. A simple PD controller with adaptation of $\hat{\theta}$ is given by

$$u \triangleq -f^{\mathrm{T}}(x)\hat{\theta} - k_{\mathrm{p}}(x_1 - y_{\text{ref}}) - k_{\mathrm{d}}\frac{\mathrm{d}}{\mathrm{d}t}(x_1 - y_{\text{ref}}) + y_{\text{ref}}^{(2)},$$

$$\dot{\hat{\theta}} \triangleq \gamma f(x) B^{\mathrm{T}} P e, \tag{31}$$

where k_{p} and k_{d} stand for the proportional gain and the derivative gain, respectively. When the amplitude of the reference trajectory is five times higher than the previous one and the system parameters are changed to $\theta_1 = -2$ and $\theta_2 = 1$, $b_{\mathrm{r}} = 1.5$, $b_{\mathrm{l}} = 6$, $m_{\mathrm{r}} = 0.7$, $m_{\mathrm{l}} = 1$, we remark that the performance of the tracking error deteriorates under the effect of controller (31), see Fig. 7 (maximum absolute value of the error e_1 for $t \geqslant 5$ (s) is about 0.6 while maximum absolute value of the error e_2 for $t \geqslant 5$ (s) is about 1). In Fig. 7, we have plotted the tracking errors e_1 and e_2 when (31) is applied for $k_{\mathrm{p}} = 3.554$, $k_{\mathrm{d}} = 4.713$. We see that the maximum error exceeds in certain instants the maximum value of the trajectory reference which is absolutely not acceptable. In the same figure, we see that the adaptive controller given by the main theorem of this paper assures an acceptable bounded error (maximum error made on e_1 and e_2 for $t \geqslant 5$ is about 10^{-3}). The parameters of the simulations of Fig. 7 are $\gamma = 5$, $\varepsilon_1 = 0.2$, $\varepsilon_2 = 0.08$. When the adaptation is switched off in (31) (i.e., $\hat{\theta} = 0$), the performance of tracking error deteriorates more and more which indicates that the specific treatment for the dead-zone is needed.

5. Conclusion

In this paper, we discussed adaptive trajectory tracking of nonlinear linearizable uncertain systems subject to non-symmetric dead-zone control inputs. A robust adaptive compensation algorithm is therefore developed without constructing a dead-zone inverse. The proposed control law ensures bounded-error trajectory tracking with a smooth controller. Simulation results have shown satisfactory results of the developed compensation algorithm.

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Salim Ibrir received his B. Eng. degree from Blida Institute of Aeronautics, Algeria, in 1991, his Master's degree from Institut des Sciences Appliquées, Lyon, France, in 1994 and his Ph.D. degree from Paris-11 University, in 2000. From 1999 to 2000, he was a research associate (ATER) in the department of Physics of Paris-11 University. In 2003, Dr. Ibrir was a lecturer in the department of Automated Production of École de Technologie Supérieure, Montreal, Canada. He spent more than two years as postdoctoral fellow and visiting assistant professor in diverse north American universities. His current research interests are in the areas of adaptive control of non-smooth systems, nonlinear observers, robust system theory and applications, time delay systems, hybrid systems, signal processing, ill-posed problems in estimation, singular hybrid systems and aero-servo-elasticity. Dr. Ibrir is the author of more than 50 technical research papers and one text book.

Wen-Fang Xie is an assistant professor with the Department of Mechanical and Industrial Engineering at Concordia University, Montreal, Canada. She was an Industrial Research Fellowship holder from Natural Sciences and Engineering Research Council of Canada (NSERC) and served as a senior research engineer in InCoreTec, Inc. Canada before she joined Concordia University. She received her Ph.D. from The Hong Kong Polytechnic University in 1999 and her Master's degree from Beijing University of Aeronautics and Astronautics in 1991. Her research interests include nonlinear control in mechatronics, artificial intelligent control, advanced process control and system identification.

Chun-Yi Su received his B.E. degree in control engineering from Xian University of Technology in 1982, his M.E. and Ph.D. degrees in control engineering from South China University of Technology, China, in 1987 and 1990, respectively. His Ph.D. study was jointly directed at Hong Kong Polytechnic (now Hong Kong Polytechnic University), Hong Kong. After a long stint at the University of Victoria (1991–1998, Canada), he joined the Concordia University (Canada) in 1998, where he is currently Associate Professor of Mechanical Engineering. Dr. Su's research covers control theory and its applications to various mechanical systems. Dr. Su is serving as Associate Editors for IEEE Transactions on Automatic Control, IEEE Transactions on Control Systems Technology, and Journal of Control Theory & Applications. He is on the Editorial Board of Mechatronics and International Journal of Intelligent Systems Technologies and Applications. He is a Senior Member of IEEE.