Adaptive Inverse Control of a Vibrating Coupled Vessel-Riser System With Input Backlash

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***Abstract*—This article involves the adaptive inverse control of a coupled vessel-riser system with input backlash and system uncertainties. By introducing an adaptive inverse dynamics of backlash, the backlash control input is divided into a mismatch error and an expected control command, and then a novel adaptive inverse control strategy is established to eliminate vibration, tackle backlash, and compensate for system uncertainties. The bounded stability of the controlled system is analyzed and demonstrated by exploiting the Lyapunov's criterion. The simulation comparison experiments are finally presented to verify the feasibility and effectiveness of the control algorithm.**

***Index Terms*—Adaptive inverse control, boundary control, flexible risers, input backlash, vibration control.**

I. Introduction

ADAPTIVE control as a common method for handling parametric uncertainty, provides techniques and algorithms for parameter estimation and is introduced in many literatures [1]–[6]. In recent decades, significant advancements in adaptive control for the nonlinear systems have been documented. To list some, in [7] and [8], switched nonlinear systems were stabilized by developing an adaptive neural tracking control and the semiglobal boundedness was ensured. In [9]–[11], an adaptive finite-time convergence control for uncertain nonlinear systems was investigated via parameter estimation. Liu *et al.* [12], Zhang *et al.* [13], and Liu *et al.* [14] ~~explored~~ an adaptive neural control methodologies for uncertain nonlinear systems subject to constraints. In [15] and [16], an adaptive fuzzy sliding-mode control was designed for nonlinear systems to compensate for unknown upper bounds. However, the aforesaid results ~~were~~ just concerned on the adaptive control analysis of ordinary differential equation systems and it cannot be applied in partial differential equation systems.

The flexible marine riser is crucial in the exploitation of ocean petroleum and natural gas resources, and receives more and more attention in recent years [17]. Generally, vibration and deformation appear in flexible risers due to the face of harsh conditions, however, the undesired vibration may shorten service life, lead to fatigue failure, and even cause serious environmental pollution [18]. Hence, how to develop the effective active control strategies [19], [20] for eliminating the riser's vibration has attracted many scholars, and they have presented many control approaches including model reduction method [21]–[23] and boundary control [24]–[27]. Boundary control, the implementation of which is generally considered to be nonintrusive actuation and sensing [28]–[38], is more realistic and effective for stabilizing flexible riser systems due to the circumvention of control spillover resulting from the reduced-order model method [39]–[41], and the recent developments have been documented. To mention a few examples, in [18], a boundary adaptive control framework was ~~raised~~ for the stabilization of an uncertain flexible riser system. In [42], an anti-disturbance control was ~~put forward~~ to damp the riser's oscillation and realize the extrinsic disturbance elimination. In [43], the riser vibration decrease was achieved using the presented boundary robust output feedback control, which simultaneously ensured the controlled system state's ~~convergence~~. In [44], three-dimensional (3-D) extensible risers were exponentially stabilized under the designed boundary control scheme. Meanwhile, the well-posedness and stability analysis were also presented. In [45], boundary controllers were proposed to address the large in-plane deflection reduction and the global and exponential stabilization of unshearable and extensible flexible risers subject to sea loads. In [46], 3-D longitudinal and transverse vibrations of flexible risers with bending couplings were suppressed via boundary simultaneous controllers. However, note that the above-mentioned approaches were confined to suppress vibrations, which are invalid

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for flexible riser systems with nonsmooth input nonlinear constraints.

In recent years, significant attention has ~~focused~~ on control of nonlinear systems subject to input nonlinearities, such as backlash, deadzone, saturation, and hysteresis [47]–[53], which are common and tough issues in mechanical connections, piezoelectric translators, and hydraulic servo valves [54]–[56]. Recently, boundary control has achieved rapid development on handling the input constraints in flexible riser systems [57]–[59]. In [60], an input-restricted riser system was significantly stabilized by using anti-saturation vibration control strategies. In [57], backstepping technique was employed to construct an adaptive control for riser systems to resolve the oscillation elimination, input saturation, and output constraint. Further, anti-saturation control strategies were presented to restrain the oscillation of flexible risers with input constraint by introducing the Nussbaum function in [58]. Note that the chattering phenomenon caused by the discontinuous sign function in [57] was removed. In [59], hybrid input deadzone and saturation constraint issue in the riser system was addressed by exploiting the auxiliary function to propose a boundary control law. However, in the aforementioned research, the design was confined to eliminate vibration, tackle input saturation, or eliminate mixed input deadzone and saturation in the riser system.

However, the effect of the input backlash nonlinearity characteristic was not considered in these mentioned literatures. Backlash, which describes a dynamical input–output relationship, exists in various physical systems and devices, such as electronic relay circuits, mechanical actuators, electromagnetism, biology optics, and other areas [50]. The effects of input backlash nonlinearity can seriously deteriorate system performance, give rise to undesirable inaccuracy or oscillations, and even result in closed-loop instability [50]. In [61], an adaptive control with an adjustable update law ~~were established~~ by discomposing and treating the backlash as "disturbance-like" items. To the best of our knowledge, despite great advances in boundary control design for flexible riser systems subjected to input nonlinearities have been made, the framework on how to develop an adaptive inverse control for tackling the simultaneous effects of the input backlash nonlinearity and uncertainties in the riser system has not been reported thus far in the literature. It is what to motivate this research and, in this article, we consider and investigate a vessel-riser system depicted in Fig. 1 simultaneously affected by input backlash and system uncertainties.

The main contributions of this article are summarized as follows: 1) the input backlash is reformulated in a sum of a desired control signal and a mismatch error by introducing an adaptive inverse backlash dynamics, rather than resolving and visualizing the backlash as disturbance-like items and 2) a new adaptive inverse control strategy with online update laws is developed to achieve the vibration attenuation, backlash elimination, and uncertainties compensation for the coupled vessel-riser system.

This article is laid out as follows: a dynamical model of the system and preliminaries are arranged in Section II. Section III presents the stability analysis and the controller design. Section IV makes and analyzes numerical simulations. Finally, Section V draws a conclusion.

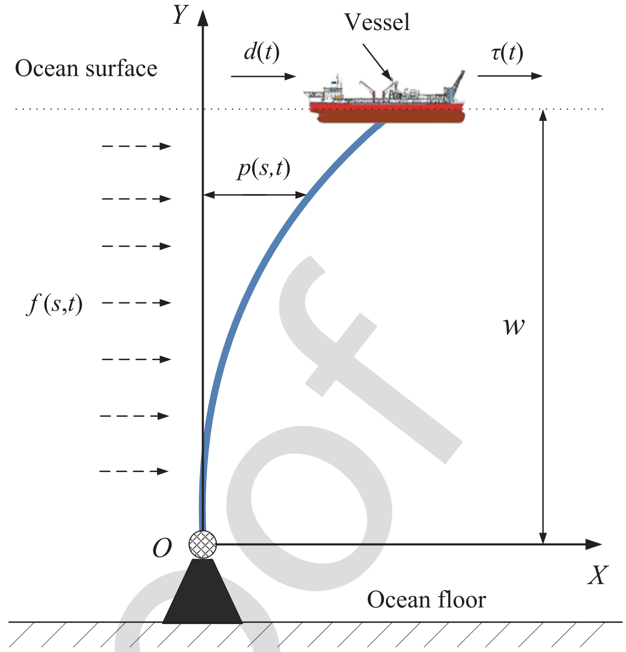

Fig. 1. Vessel-riser system.

II. Problem Statement

A. System Model

As displayed in Fig. 1, $p(s,t)$ describes the vibrational deflection of the riser whose length is w. $d(t)$ denotes the extraneous disturbance acting on the vessel whose mass and damping coefficient are $m > 0$ and $d_a > 0$. $f(s,t)$ denotes the distributed disturbance which is acted on the riser, and $\tau(t)$ represents control input which is ~~put~~ on the vessel. In addition, some notations for simplification are presented: $\dot{(*)} = \partial(*)/\partial t$, $(*)' = \partial(*)/\partial s$, $\dot{(*)}' = \partial^2(*)/\partial s \partial t$, $(*)'' = \partial^2(*)/\partial s^2$, $(*)''' = \partial^2(*)/\partial s^3$, $(*)'''' = \partial^2(*)/\partial s^4$, and $\ddot{(*)} = \partial^2(*)/\partial t^2$.

In this article, the goal is to propose an adaptive inverse control for damping the vibration deflection and simultaneously handling the backlash nonlinearity and system uncertainties. To realize this objective, we model the dynamics of the considered vessel-riser system as [18]

$$\rho\ddot{p} + EIp'''' - Tp'' + c\dot{p} - f = 0, \quad 0 < s < w \tag{1}$$

$$p(0,t) = p'(0,t) = p''(w,t) = 0 \tag{2}$$

$$\begin{aligned} &m\ddot{p}(w,t) + Tp'(w,t) - EIp'''(w,t) \\ &+ d_a\dot{p}(w,t) = \tau(t) + d(t) \end{aligned} \tag{3}$$

where $EI > 0$, $c > 0$, $\rho > 0$, and $T > 0$ express the bending stiffness, damping coefficient, mass per unit length, and tension of the riser, respectively.

B. Input Backlash Analysis

For the convenience of adaptive inverse control design, we present the expression of the backlash nonlinearity [62] shown

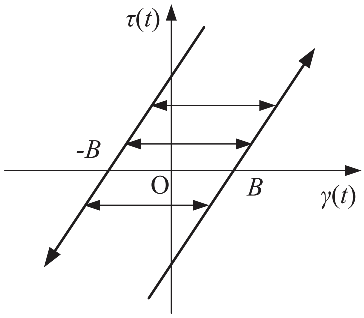

Fig. 2. Backlash nonlinearity.

in Fig. 2 as follows:

$$\tau(t) = \mathcal{B}(\gamma) = \begin{cases} \varrho(\gamma(t) - B), & \text{if } \dot{\gamma} > 0 \text{ and } \tau(t) = \varrho(\gamma(t) - B) \\ \varrho(\gamma(t) + B), & \text{if } \dot{\gamma} < 0 \text{ and } \tau(t) = \varrho(\gamma(t) + B) \\ \tau(t\_), & \text{otherwise} \end{cases} \tag{4}$$

where $\tau(t)$ denotes the control input, $\gamma(t)$ expresses the expected control to be developed, ϱ represents the slope, B denotes the "crossing," and $\tau(t\_)$ shows no change in $\tau(t)$.

C. Preliminaries

We provide the related assumptions, lemmas, and remarks for facilitating the subsequent analysis and design.

For disturbances $d(t)$ and $f(s,t)$ that possess finite energy, that is, $d(t), f(s,t) \in \mathcal{L}_\infty$ [63]–[65], we make an assumption for these disturbances in the following.

Assumption 1: We assume that extraneous disturbances $d(t)$ and $f(s,t)$ acting on the vessel and riser are bounded and there exist $D, F \in \mathbb{R}^+$ satisfying $| d(t) | \leq D$, and $| f(s,t) | \leq F$, $\forall (s,t) \in [0,w] \times [0,+\infty)$.

Lemma 1 [66]: Let $\delta_1(s,t), \delta_2(s,t) \in \mathbb{R}$, $\phi > 0$ with $(s,t) \in [0,w] \times [0,+\infty)$, then

$$\delta_1\delta_2 \leq \frac{1}{\phi}\delta_1^2 + \phi\delta_2^2. \tag{5}$$

Lemma 2 [67]: Let $\delta(s,t) \in \mathbb{R}$ be under the condition $\delta(0,t) = 0$, where $(s,t) \in [0,w] \times [0,+\infty)$, then

$$\delta^2 \leq w\int_0^w \delta'^2 ds. \tag{6}$$

Lemma 3 [68]: The following inequality is provided to derive our main results:

$$0 \leq |\varpi(t)| - \varpi(t)\tanh(\varpi(t)) \leq 0.2785. \tag{7}$$

III. Control Design

System parameters T, EI, d_a, and m, and upper bounds of the disturbance D are utilized in the control design. However, these parameters may be unavailable in real system, thus it will bring a challenge for the control design and even make control approaches ~~unusable~~. In this section, we present a new adaptive inverse controller to handle system uncertainties. Moreover, this control scheme can stabilize the vessel-riser system and eliminate the backlash nonlinearity. Subsequently, we analyze the closed-loop system's stability in theory.

A. Boundary Adaptive Inverse Control With Input Backlash

Invoking [62], the inverse backlash is presented as follows:

$$\gamma^*(t) = \mathcal{BI}(\tau_d(t)) = \begin{cases} \frac{1}{\varrho}\tau_d(t) + B, & \text{if } \dot{\tau_d}(t) > 0 \\ \frac{1}{\varrho}\tau_d(t) - B, & \text{if } \dot{\tau_d}(t) < 0 \\ \gamma^*(t\_), & \text{otherwise} \end{cases} \tag{8}$$

where $\mathcal{BI}(\cdot)$ represents a backlash inverse function and $\tau_d(t)$ denotes the expected control command.

Then, according to the above analysis and [62], we propose an adaptive inverse of backlash as

$$\dot{\alpha}(t) = \dot{\tau}_d(t) - \frac{\beta}{B_m}|\dot{\tau}_d(t)|\alpha(t) \tag{9}$$

$$\gamma(t) = \widehat{\mathcal{BI}}(\tau_d(t)) = \frac{1}{\varrho}\tau_d(t) + \widehat{\lambda}\beta\alpha(t) \tag{10}$$

where β denotes a positive gain parameter, B_m denotes a nominal backlash value, $\widehat{\mathcal{BI}}(\cdot)$ denotes an adaptive backlash inverse compensator, and $\widehat{\lambda}$ represents an adaption to adjust B_m so as to match the actual backlash spacing B with $B = \lambda B_m$, $\lambda \leq \varepsilon, \varepsilon \in \mathbb{R}^+$, and $\widetilde{\lambda} = \widehat{\lambda} - \lambda$.

Meanwhile, we bring a mismatch error as follows:

$$\tau(t) = \mathcal{B}\big(\widehat{\mathcal{BI}}(\tau_d(t))\big) = \tau_d(t) + \tau_e(t) \tag{11}$$

where we formulate the mismatch error $\tau_e(t)$ as

$$\tau_e(t) = \varrho\widetilde{\lambda}B_m sgn(\dot{\tau}_d(t)) = \varrho\widetilde{\lambda}\beta\alpha(t). \tag{12}$$

Invoking (9)–(12), we then rewrite (3) as

$$\begin{aligned} &m\ddot{p}(w,t) + Tp'(w,t) - EIp'''(w,t) + d_a\dot{p}(w,t) - d(t) \\ &\quad = \tau(t) = \mathcal{B}(\gamma(t)) \end{aligned} \tag{13}$$

Then, an adaptive inverse control is proposed as

$$\gamma(t) = \widehat{\mathcal{BI}}(\tau_d(t)) = \frac{1}{\varrho}\tau_d(t) + \widehat{\lambda}\beta\alpha(t) \tag{14}$$

where $\tau_d(t)$ is designed as

$$\begin{aligned} \tau_d(t) = &-\kappa_1 x(t) - \widehat{EI}p'''(w,t) + \widehat{T}p'(w,t) + \widehat{d_a}\dot{p}(w,t) \\ &+ \widehat{m}\big(\kappa_2\dot{p}'''(w,t) - \kappa_3\dot{p}'(w,t)\big) - \tanh(x(t))\widehat{D} \end{aligned} \tag{15}$$

where $\kappa_1, \kappa_2, \kappa_3 > 0$, $\widehat{D}$, $\widehat{T}$, $\widehat{EI}$, $\widehat{d_a}$, and $\widehat{m}$ are the estimated values of D, T, EI, d_a, and m, and we define the auxiliary variable $x(t)$ as

$$x(t) = \dot{p}(w,t) - \kappa_2 p'''(w,t) + \kappa_3 p'(w,t). \tag{16}$$

Now, we present the following inverse backlash dynamics:

$$\dot{\alpha}(t) = \dot{\tau}_d(t) - \frac{\beta}{B_m}|\dot{\tau}_d(t)|\alpha(t) \tag{17}$$

and the estimation $\widehat{\lambda}$ is obtained from the following:

$$\dot{\widehat{\lambda}} = -\frac{\varrho}{\upsilon}\beta x(t)\alpha(t) - \widehat{\lambda}. \tag{18}$$

At this time, the adaptive laws are presented when system parameters T, EI, d_a, and m, and upper bounds of the disturbance D are not available

$$\dot{\widehat{D}} = x(t)\tanh(x(t)) - \varsigma_1\widehat{D} \tag{19}$$

$$\dot{\widehat{T}} = -x(t)p'(w,t) - \varsigma_2\widehat{T} \tag{20}$$
$$\dot{\widehat{EI}} = x(t)p'''(w,t) - \varsigma_3\widehat{EI} \tag{21}$$
$$\dot{\widehat{d}}_a = -x(t)\dot{p}(w,t) - \varsigma_4\widehat{d}_a \tag{22}$$
$$\dot{\widehat{m}} = x(t)\big(\kappa_3\dot{p}'(w,t) - \kappa_2\dot{p}'''(w,t)\big) - \varsigma_5\widehat{m} \tag{23}$$

where $\varsigma_i > 0, i = 1\cdots 5$.

The estimation errors are defined as

$$\widetilde{D} = \widehat{D} - D, \widetilde{T} = \widehat{T} - T,$$
$$\widetilde{EI} = \widehat{EI} - EI, \widetilde{d}_a = \widehat{d}_a - d_a, \widetilde{m} = \widehat{m} - m. \tag{24}$$

Remark 1: Note that available boundary signals $p'''(w,t)$, $p'(w,t)$, $p(w,t)$, $\dot{p}'''(w,t)$, $\dot{p}'(w,t)$, and $\dot{p}(w,t)$ consist of the proposed control law (15), where $p'''(w,t)$ is measured by shear force sensors, $p'(w,t)$ is measured by inclinometers, and $p(w,t)$ is measured by laser displacement sensors. Moreover, we can use the backward difference algorithm to achieve the one-order time derivative of some measurable signals $\dot{p}'''(w,t)$, $\dot{p}'(w,t)$, and $\dot{p}(w,t)$ in the designed controller.

Now, we will present the stability analysis for deriving our main results.

B. Stability Proof

Select the Lyapunov candidate function as

$$\Theta(t) = \Theta_1(t) + \Theta_2(t) + \Theta_3(t) + \Theta_4(t) \tag{25}$$

where

$$\Theta_1(t) = \frac{\xi}{2}EI\int_0^w p''^2 ds + \frac{\xi}{2}\rho\int_0^w \dot{p}^2 ds + \frac{\xi}{2}T\int_0^w p'^2 ds \tag{26}$$
$$\Theta_2(t) = \frac{\sigma}{2}mx^2(t) \tag{27}$$
$$\Theta_3(t) = \frac{\sigma}{2}\widetilde{D}^2 + \frac{\sigma}{2}\widetilde{T}^2 + \frac{\sigma}{2}\widetilde{EI}^2 + \frac{\sigma}{2}\widetilde{d}_a^2 + \frac{\sigma}{2}\widetilde{m}^2 + \frac{\sigma\upsilon}{2}\widetilde{\lambda}^2 \tag{28}$$
$$\Theta_4(t) = \psi\rho\int_0^w s\dot{p}p' ds \tag{29}$$

with $\xi, \sigma, \psi > 0$ being constants.

Lemma 4: The constructed function (25) is positive

$$0 \le \iota_1[\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \le \Theta(t)$$
$$\le \iota_2[\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \tag{30}$$

where $\iota_1, \iota_2 > 0$.

Proof: We invoke Lemma 1 and combine (29) to derive

$$|\ \Theta_4(t)\ | \le \frac{\psi\rho w}{2}\int_0^w \Big(\dot{p}^2 + p'^2\Big) ds \le \vartheta\Theta_1(t) \tag{31}$$

where $\vartheta = (\psi\rho w/\min(\xi\rho, \xi T, \xi EI))$.

We select ξ and ψ appropriately to satisfy the following:

$$\xi > \frac{\psi\rho w}{\min(\rho, T, EI)}. \tag{32}$$

Equation (32) indicates $0 < \vartheta < 1$. Then, rearranging (31) and adding (26) gives

$$0 \le (1-\vartheta)\Theta_1(t) \le \Theta_1(t) + \Theta_4(t) \le (1+\vartheta)\Theta_1(t). \tag{33}$$

Invoking (25) and (33) yields

$$0 \le \iota_1[\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \le \Theta(t)$$
$$\le \iota_2[\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \tag{34}$$

where $\iota_1 = \min(1-\vartheta, 1) > 0$ and $\iota_2 = \max(1+\vartheta, 1) > 1$. ■

Lemma 5: The time derivative of (25) is upper bounded as

$$\dot{\Theta}(t) \le -\iota\Theta(t) + \chi \tag{35}$$

where $\iota, \chi > 0$.

Proof: We differentiate (25) to derive

$$\dot{\Theta}(t) = \dot{\Theta}_1(t) + \dot{\Theta}_2(t) + \dot{\Theta}_3(t) + \dot{\Theta}_4(t). \tag{36}$$

Invoking (1) and applying Lemma 1, $\dot{\Theta}_1(t)$ is obtained as

$$\begin{aligned}\dot{\Theta}_1(t) \le\ & \frac{\xi EI}{2\kappa_2}x^2(t) - \frac{\xi EI\kappa_2}{2}p'''^2(w,t) - \frac{\xi EI}{2\kappa_2}\dot{p}^2(w,t)\\ & - \frac{\xi EI\kappa_3^2}{2\kappa_2}p'^2(w,t) + (\xi T - \frac{\xi EI\kappa_3}{\kappa_2})p'(w,t)\dot{p}(w,t)\\ & + \xi EI\kappa_3 p'''(w,t)p'(w,t) - (c-\nu_1)\xi\int_0^w \dot{p}^2 ds\\ & + \frac{\xi}{\nu_1}\int_0^w f^2 ds,\end{aligned} \tag{37}$$

where $\nu_1 > 0$. Combining (11)–(16), we derive $\dot{\Theta}_2(t)$ as

$$\begin{aligned}\dot{\Theta}_2(t) =\ & \sigma x(t)\tau_e(t) - \sigma x(t)\\ & \times\big[\widetilde{T}p'(w,t) - \widetilde{EI}p'''(w,t)\\ & + \widetilde{d}_a\dot{p}(w,t) + \widetilde{m}\big(\kappa_2\dot{p}'''(w,t) - \kappa_3\dot{p}'(w,t)\big)\big]\\ & - \sigma x(t)\tanh(x(t))\hat{D} + \sigma x(t)d(t) - \sigma\kappa_1 x^2(t).\end{aligned} \tag{38}$$

Invoking (17)–(24), we obtain $\dot{\Theta}_3(t)$ as

$$\begin{aligned}\dot{\Theta}_3(t) \le\ & \frac{\sigma\varsigma_5}{2}m^2 - \frac{\sigma\varsigma_1}{2}\widetilde{D}^2 + \frac{\sigma\varsigma_1}{2}D^2 + \sigma x(t)\tanh(x(t))\widetilde{D}(t)\\ & + \sigma x(t)\big[\widetilde{T}p'(w,t) - \widetilde{EI}p'''(w,t) + \widetilde{d}_a\dot{p}(w,t)\\ & + \widetilde{m}\big(\kappa_2\dot{p}'''(w,t) - \kappa_3\dot{p}'(w,t)\big)\big] - \frac{\sigma\varsigma_2}{2}\widetilde{T}^2 - \frac{\sigma\varsigma_3}{2}\widetilde{EI}^2\\ & - \frac{\sigma\varsigma_4}{2}\widetilde{d}_a^2 - \frac{\sigma\varsigma_5}{2}\widetilde{m}^2 + \frac{\sigma\varsigma_2}{2}T^2 + \frac{\sigma\varsigma_3}{2}EI^2 + \frac{\sigma\varsigma_4}{2}d_a^2\\ & -\sigma\varrho\widetilde{\lambda}\beta\alpha(t)x(t) - \frac{\sigma\upsilon}{2}\widetilde{\lambda}^2 + \frac{\sigma\upsilon}{2}\lambda^2.\end{aligned} \tag{39}$$

We invoke (1) and apply Lemma 1 to derive $\dot{\Theta}_4(t)$ as

$$\begin{aligned}\dot{\Theta}_4(t) \le\ & -w\psi EIp'''(w,t)p'(w,t) - \frac{3\psi EI}{2}\int_0^w p''^2 ds\\ & + \frac{w\psi c}{\nu_2}\int_0^w \dot{p}^2 ds + \frac{\psi\rho w}{2}\dot{p}^2(w,t) + \frac{w\psi}{\nu_3}\int_0^w f^2 ds\\ & - \left(\frac{\psi T}{2} - \psi\nu_2 cw - \psi\nu_3 w\right)\int_0^w p'^2 ds\\ & + \frac{\psi Tw}{2}p'^2(w,t) - \frac{\psi\rho}{2}\int_0^w \dot{p}^2 ds\end{aligned} \tag{40}$$

where $\nu_2, \nu_3 > 0$.

Substituting (37)–(40) into (36) and using Lemmas 1–3 and (13), $\dot{\Theta}(t)$ gives

$$
\begin{aligned}
\dot{\Theta}(t) \le{}& -\frac{3\psi EI}{2}\int_0^w p''^2 ds \\
&-\left(\frac{\xi EI\kappa_3^2}{2\kappa_2} - \frac{\xi|T-EI\kappa_3/\kappa_2|}{2\nu_4}\right. \\
&\qquad\left. - \frac{EI|\xi\kappa_3 - w\psi|\nu_5}{2} - \frac{\psi Tw}{2}\right)p'^2(w,t) - \frac{\sigma\varsigma_1}{2}\widetilde{D}^2 \\
&-\left(\frac{\xi EI}{2\kappa_2} - \frac{\xi|T-EI\kappa_3/\kappa_2|\nu_4}{2} - \frac{\psi\rho w}{2}\right)\dot{p}^2(w,t) \\
&-\left(\frac{\xi EI\kappa_2}{2} - \frac{|\xi\kappa_3 - w\psi|}{2\nu_5}\right)p'''^2(w,t) + \frac{\sigma\varsigma_1}{2}D^2 \\
&-\left(\xi c - \xi\nu_1 - \frac{w\psi c}{\nu_2} + \frac{\psi\rho}{2}\right)\int_0^w \dot{p}^2 ds + \frac{\sigma\varsigma_5}{2}m^2 \\
&-\left(\frac{\psi T}{2} - \psi\nu_2 cw - \psi\nu_3 w\right)\int_0^w p'^2 ds - \frac{\sigma\varsigma_1}{2}\widetilde{D}^2 \\
&-\left(\sigma\kappa_1 - \frac{\xi EI}{2\kappa_2}\right)x^2(t) - \frac{\sigma\varsigma_2}{2}\widetilde{T}^2 - \frac{\sigma\varsigma_3}{2}\widetilde{EI}^2 + 0.2785\sigma D \\
&-\frac{\sigma\varsigma_4}{2}\widetilde{d}_a^2 - \frac{\sigma\varsigma_5}{2}\widetilde{m}^2 + \frac{\sigma\varsigma_2}{2}T^2 + \frac{\sigma\varsigma_3}{2}EI^2 + \frac{\sigma\varsigma_4}{2}d_a^2 \\
&+\left(\frac{\xi}{\nu_1} + \frac{w\psi}{\nu_3}\right)\int_0^w f^2 ds - \frac{\sigma\upsilon}{2}\widetilde{\lambda}^2 + \frac{\sigma\upsilon}{2}\lambda^2
\end{aligned}
\tag{41}
$$

where $\nu_4, \nu_5 > 0$ and we choose ψ, σ, ξ, κ_i, $i = 1\cdots 3$, ν_j, for $j = 1\cdots 5$ to satisfy

$$\frac{\xi EI\kappa_3^2}{2\kappa_2} - \frac{\xi|T-EI\kappa_3/\kappa_2|}{2\nu_4} - \frac{EI|\xi\kappa_3 - w\psi|\nu_5}{2} - \frac{\psi Tw}{2} \ge 0 \tag{42}$$

$$\frac{\xi EI}{2\kappa_2} - \frac{\xi|T-EI\kappa_3/\kappa_2|\nu_4}{2} - \frac{\psi\rho w}{2} \ge 0 \tag{43}$$

$$\frac{\xi EI\kappa_2}{2} - \frac{|\xi\kappa_3 - w\psi|}{2\nu_5} \ge 0 \tag{44}$$

$$\omega_1 = \xi c - \xi\nu_1 - \frac{w\psi c}{\nu_2} + \frac{\psi\rho}{2} > 0 \tag{45}$$

$$\omega_2 = \frac{\psi T}{2} - \psi\nu_2 cw - \psi\nu_3 w > 0 \tag{46}$$

$$\omega_3 = \sigma\kappa_1 - \frac{\xi EI}{2\kappa_2} > 0 \tag{47}$$

$$
\begin{aligned}
\chi ={}& \left(\frac{\xi}{\nu_1} + \frac{w\psi}{\nu_3}\right)wF^2 + \frac{\sigma\varsigma_1}{2}D^2 + \frac{\sigma\varsigma_2}{2}T^2 + \frac{\sigma\varsigma_3}{2}EI^2 \\
&+ \frac{\sigma\varsigma_4}{2}d_a^2 + \frac{\sigma\varsigma_5}{2}m^2 + \frac{\sigma\upsilon}{2}\varepsilon^2 + 0.2785\sigma D < +\infty.
\end{aligned}
\tag{48}
$$

Combining (42)–(48), (41) is derived as

$$
\begin{aligned}
\dot{\Theta}(t) \le{}& \chi - \frac{\sigma\varsigma_1}{2}\widetilde{D}^2 - \omega_1\int_0^w \dot{p}^2 ds - \omega_2\int_0^w p'^2 ds \\
&- \frac{3\psi EI}{2}\int_0^w p''^2 ds - \omega_3 x^2(t) - \frac{\sigma\upsilon}{2}\widetilde{\lambda}^2 \\
&- \frac{\sigma\varsigma_2}{2}\widetilde{T}^2 - \frac{\sigma\varsigma_3}{2}\widetilde{EI}^2 - \frac{\sigma\varsigma_4}{2}\widetilde{d}_a^2 - \frac{\sigma\varsigma_5}{2}\widetilde{m}^2 \\
\le{}& -\iota_3[\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] + \chi
\end{aligned}
\tag{49}
$$

where $\iota_3 = \min(\frac{2\omega_1}{\xi\rho}, \frac{2\omega_2}{\xi T}, \frac{3\psi}{\xi}, \frac{2\omega_3}{\sigma m}, \varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4, \varsigma_5, 1)$.

We then invoke (30) and (49) to obtain

$$\dot{\Theta}(t) \le -\iota\Theta(t) + \chi \tag{50}$$

where $\iota = (\iota_3/\iota_2)$. ■

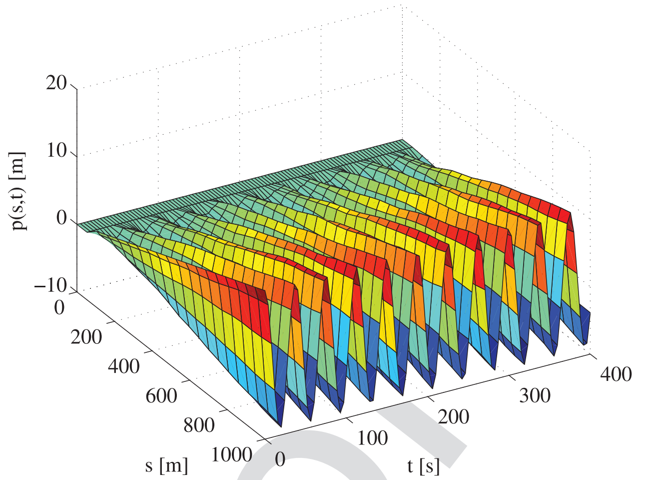

Fig. 3. 3-D offset of the riser under no control.

Theorem 1: For the riser system with input backlash (4), under the presented adaptive backlash inverse control (15), online updating laws (18)–(23), and bounded initial conditions, with the choice of design parameters $\psi, \sigma, \xi, \kappa_i, i = 1\cdots 3, \nu_j$, for $j = 1\cdots 5$ satisfying constraints (42)–(48), we arrive at a conclusion that the controlled system's state $p(s,t)$ is uniformly ultimately bounded.

Proof: We multiply (35) by $e^{\iota t}$ and then integrate the consequence to derive

$$\Theta(t) \le \Theta(0)e^{-\iota t} + \frac{\chi}{\iota}\left(1 - e^{-\iota t}\right) \le \Theta(0)e^{-\iota t} + \frac{\chi}{\iota}. \tag{51}$$

Invoking $\Theta_1(t)$, (30), and Lemma 2, we get

$$\frac{\xi T}{2w}p^2(s,t) \le \frac{\xi T}{2}\int_0^w p'^2(s,t)ds \le \Theta_1(t) \le \frac{1}{\iota_1}\Theta(t). \tag{52}$$

We substitute (51) into (52) to derive

$$|\, p(s,t)\,| \le \sqrt{\frac{2w}{\xi\iota_1 T}\left[\Theta(0)e^{-\iota t} + \frac{\chi}{\iota}\right]}, \forall(s,t) \in [0,w]\times[0,+\infty). \tag{53}$$

Combining (53) further gives

$$\lim_{t\to\infty}|p(s,t)| \le \sqrt{\frac{2w\chi}{\xi T\iota_1\iota}}, \forall s \in [0,w]. \tag{54}$$

■

Remark 2: This article presents a framework of adaptive inverse control of uncertain vessel-riser systems subject to input backlash, system uncertainties, and external disturbances, which is invalid for the system with input hysteresis. To address this issue, the approaches in [50] will be employed in the next step. Moreover, an issue about communication limit in actuator is ignored in this article, and we will cope with it with recourse to the technique in [69]–[71].

IV. NUMERICAL SIMULATION

On the basis of the vessel-riser system dynamical model with input backlash (1), (2), (4), and (13), we exploit the finite difference method [72] with time and space

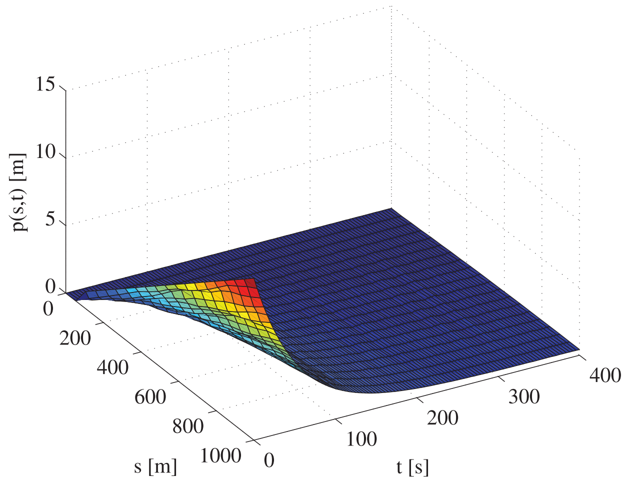

Fig. 4. 3-D offset of the riser under proposed control.

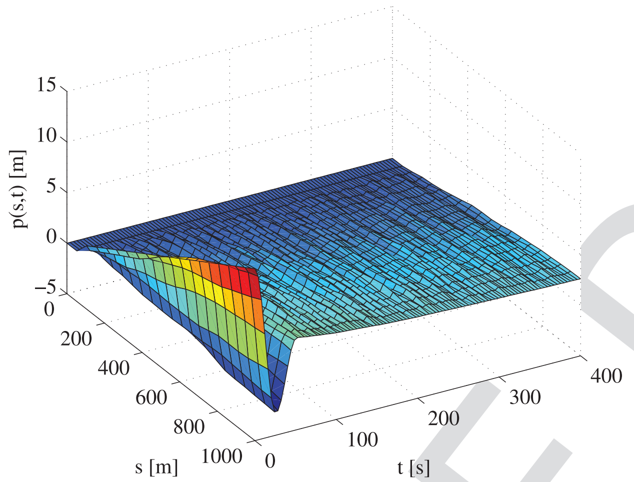

Fig. 5. 3-D offset of the riser under previous control in [18].

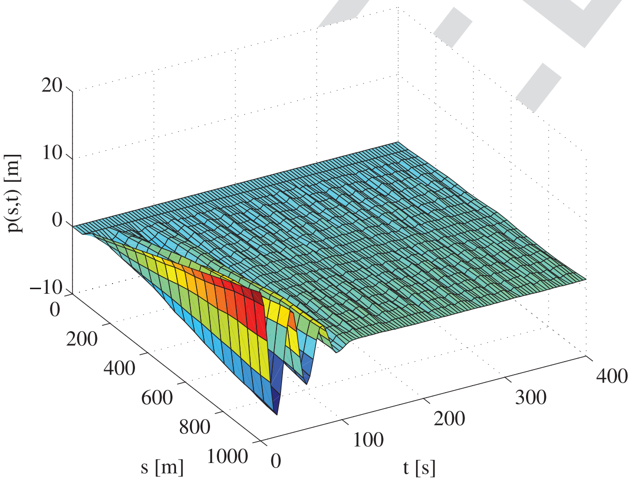

Fig. 6. 3-D offset of the riser under previous control in [60].

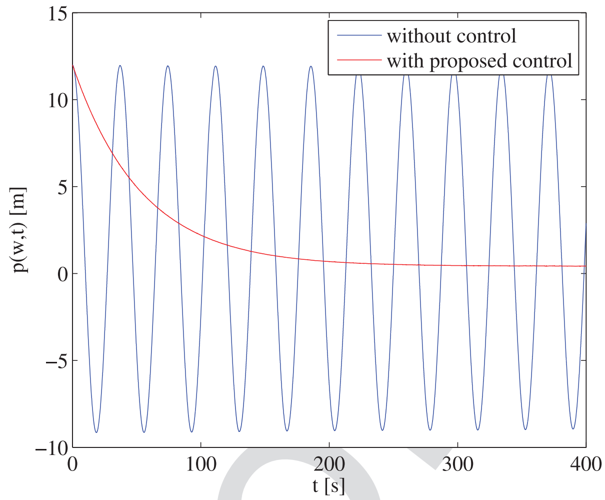

Fig. 7. 2-D offset of the vessel under proposed control.

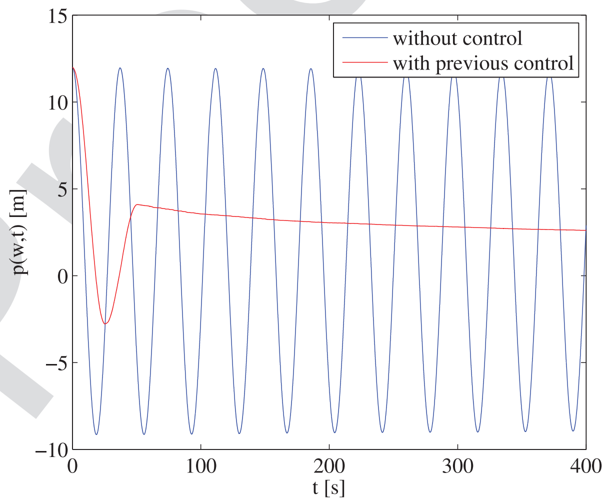

Fig. 8. 2-D offset of the vessel under previous control in [18].

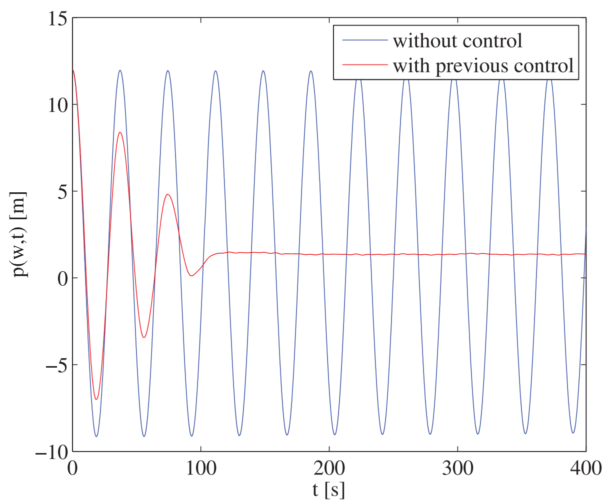

Fig. 9. 2-D offset of the vessel under previous control in [60].

steps as 2×10^{-5} and 0.05 to illustrate the dynamics of this nonlinear coupled system by setting system parameters as $EI = 1.5 \times 10^7$ Nm^2, $\rho = 500$ kg/m, $T = 3.0 \times 10^8$ N, $c = 1.0$ $\mathrm{Ns/m}^2$, $w = 1000$ m, $d_a = 1.5 \times 10^5$ Ns/m, and $m = 9.6 \times 10^6$ kg. System initial conditions are presented as $p(s, 0) = 12\sin(\frac{s}{w})$ and $\dot{p}(s, 0) = 0$.

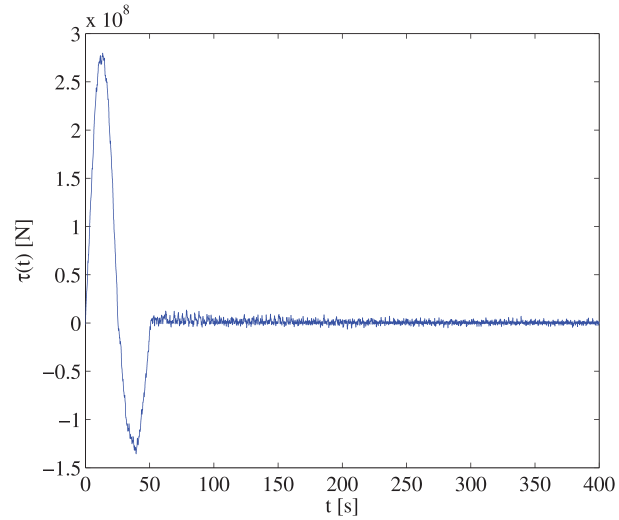

Fig. 10. Previous control input in [18].

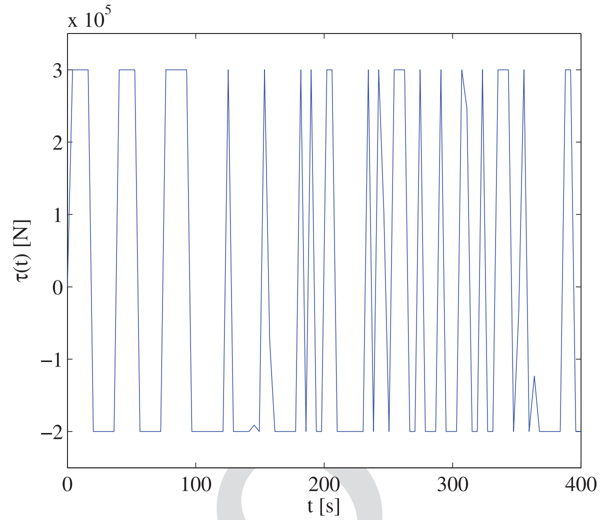

Fig. 12. Saturation control input in [60].

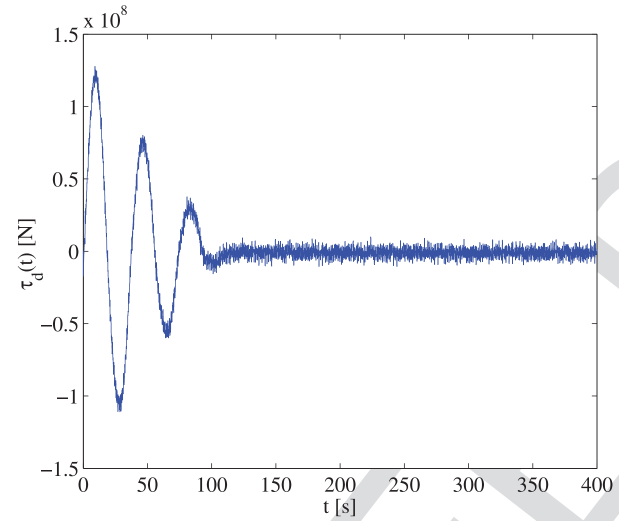

Fig. 11. Designed control command in [60].

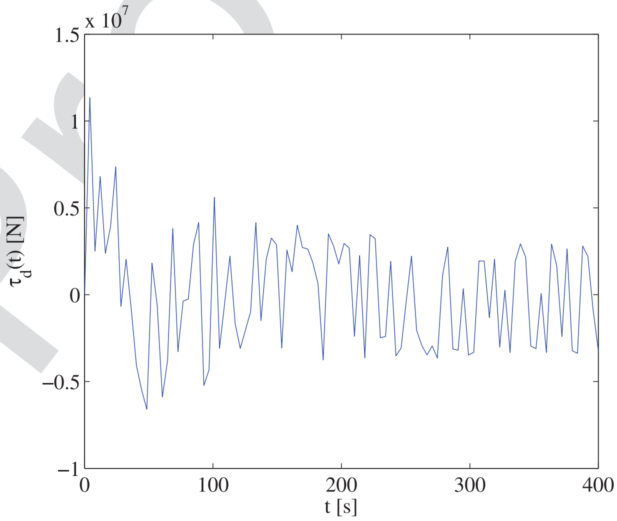

Fig. 13. Designed control input.

Meanwhile, $d(t)$ is given as $d(t) = [3 + 0.8\sin(0.7t) + 0.2\sin(0.5t) + 0.2\sin(0.9t)] \times 10^5$.

Without any control, namely, $\tau(t) = 0$, 3-D and two-dimensional (2-D) responses of this coupled system are portrayed in Figs. 3 and 7. From Fig. 3, it is seen that the marine flexible riser is vibrating with an equal amplitude under the external ocean disturbance. Fig. 7 illustrates the displacement of the vessel in the ocean surface. The persistent large deformation of this marine riser will lead to the produce fatigue problems, and it is crucial to reduce the vibration by implementing the effective control strategy.

With presented control law (15) by choosing control gains $\kappa_1 = 3 \times 10^8$, $\kappa_2 = 1$, $\kappa_3 = 20$, and control parameters $\varsigma_1 = \varsigma_2 = \varsigma_3 = \varsigma_4 = \varsigma_5 = 0.001$, $\varrho = 1$, $\beta = 1.2$, $\upsilon = 3$, $B = 3 \times 10^6$, and $B_m = 1 \times 10^7$, the spatio-temporal response and end point offset are depicted in Figs. 4 and 7. From Figs. 4 and 7, it is seen that the effects of the considered external ocean disturbance and the input backlash nonlinearity are eliminated under the proposed control (15). Moreover, it has a positive effect on the vibration attenuation of the marine flexible riser, and the displacement of the vessel reduces to a small neighborhood around the original position. Meanwhile, Figs. 13 and 14 display 2-D responses of presented control input and backlash input.

For the comparison with the proposed control law, we consider two control strategies presented in previous works [18] and [60]. When exerting the previous control proposed in [18] on the riser system with the given control parameters $k = 3 \times 10^8$, $k_1 = 1$, and $k_2 = 10$, Figs. 5, 8, and 10 display the responses of the marine flexible riser, vessel, and the control law, respectively. Note that this previous research does not consider the effect of the input constraint and the control law presented in [18] requires longer convergent time and larger convergent neighborhood than the proposed control (15) for the marine vessel-riser system with input

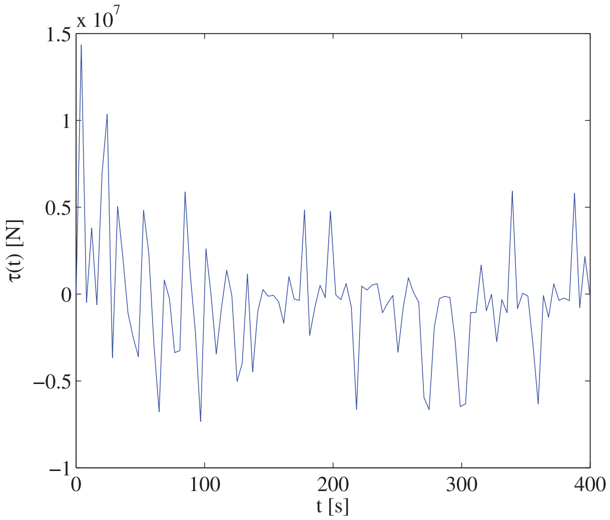

Fig. 14. Backlash control input.

backlash nonlinearity. Under the action of previous anti-saturation control developed in [60] on the riser system, when the control design parameters are selected as $k_1 = k_3 = \beta_1 = \beta_2 = \beta_3 = \beta_4 = 1$, $k_2 = 20$, $k_4 = 0.01$, $k_5 = 8 \times 10^7$, $\sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = 1 \times 10^{-4}$, $\sigma = 1 \times 10^{-5}$, $\tau_{\max} = 3 \times 10^5$, and $\tau_{\min} = -2 \times 10^5$, the time and spatial responses are described in Figs. 6, 9, 11, and 12. Note that the control law presented in [60] also has the positive effect on reducing the deformation of the coupled system, however it has the large overshoot and convergent neighborhood than the proposed control (15).

We observe from Figs. 3–14 that the vibration in the coupled vessel-riser system is observably suppressed under the proposed adaptive inverse control, which achieves a better control performance than the previous control; the end point offset $p(w, t)$ is stabilized at a small region around zero, and the backlash nonlinearity in the control input is fairly obvious. In other words, this approach leads to a good performance on the vibration decrease, uncertainties compensation, and input backlash elimination.

V. Conclusion

The framework of the adaptive inverse control of uncertain vessel-riser systems possessing input backlash has been presented in this article. The adaptive inverse of backlash was used to formulate the nonlinear input backlash as a desired control signal with a mismatch error. An adaptive inverse control and relevant adaptive laws were presented for stabilizing the riser's offset, eliminating the backlash, and compensating for system uncertainties. Exploiting the rigorous analysis without recourse to model reducing technique, the derived control ensured and realized the uniform stability of the controlled system. In conclusion, the simulation comparison studies validated the control performance. Future interesting topics include exploiting the intelligent control techniques [73]–[79] to regulate the transient performance of the controlled vessel-riser systems.

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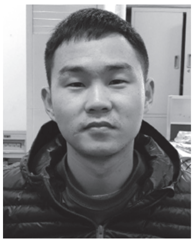

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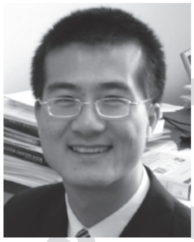

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