

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

Xiuyu He<sup>1</sup>, Student Member, IEEE, Zhijia Zhao<sup>1</sup>, Member, IEEE, Jinya Su<sup>1</sup>, Member, IEEE, Qinmin Yang<sup>1</sup>, Senior Member, IEEE, and Dachang Zhu

**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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X. He is with the School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China, and also with the Institute of Artificial Intelligence, University of Science and Technology Beijing, Beijing 100083, China (e-mail: bhilly@163.com).

Z. Zhao and D. Zhu are with the School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou 510006, China (e-mail: zhjzhaoscut@163.com; zdc98998@gzhu.edu.cn).

J. Su is with the School of Computer Science and Electronic Engineering, University of Essex, Colchester CO4 3SQ, U.K. (e-mail: j.su@essex.ac.uk).

Q. Yang is with the State Key Laboratory of Industrial Control Technology, Zhejiang University, Hangzhou 310027, China, and also with the College of Control Science and Engineering, Zhejiang University, Hangzhou 310027, China (e-mail: qmyang@zju.edu.cn).

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71 for flexible riser systems with nonsmooth input nonlinear  
72 constraints.

73 In recent years, significant attention has focused on control  
74 of nonlinear systems subject to input nonlinearities, such  
75 as backlash, deadzone, saturation, and hysteresis [47]–[53],  
76 which are common and tough issues in mechanical  
77 connections, piezoelectric translators, and hydraulic servo  
78 valves [54]–[56]. Recently, boundary control has achieved  
79 rapid development on handling the input constraints in flex-  
80 ible riser systems [57]–[59]. In [60], an input-restricted riser  
81 system was significantly stabilized by using anti-saturation  
82 vibration control strategies. In [57], backstepping technique  
83 was employed to construct an adaptive control for riser  
84 systems to resolve the oscillation elimination, input saturation,  
85 and output constraint. Further, anti-saturation control strate-  
86 gies were presented to restrain the oscillation of flexible risers  
87 with input constraint by introducing the Nussbaum function  
88 in [58]. Note that the chattering phenomenon caused by the  
89 discontinuous sign function in [57] was removed. In [59],  
90 hybrid input deadzone and saturation constraint issue in the  
91 riser system was addressed by exploiting the auxiliary function  
92 to propose a boundary control law. However, in the aforemen-  
93 tioned research, the design was confined to eliminate vibration,  
94 tackle input saturation, or eliminate mixed input deadzone and  
95 saturation in the riser system.

96 However, the effect of the input backlash nonlinearity char-  
97 acteristic was not considered in these mentioned literatures.  
98 Backlash, which describes a dynamical input–output relation-  
99 ship, exists in various physical systems and devices, such  
100 as electronic relay circuits, mechanical actuators, electro-  
101 magnetism, biology optics, and other areas [50]. The effects  
102 of input backlash nonlinearity can seriously deteriorate system  
103 performance, give rise to undesirable inaccuracy or oscillations,  
104 and even result in closed-loop instability [50]. In [61],  
105 an adaptive control with an adjustable update law were  
106 established by decomposing and treating the backlash as  
107 “disturbance-like” items. To the best of our knowledge, despite  
108 great advances in boundary control design for flexible riser  
109 systems subjected to input nonlinearities have been made, the  
110 framework on how to develop an adaptive inverse control for  
111 tackling the simultaneous effects of the input backlash non-  
112 linearity and uncertainties in the riser system has not been  
113 reported thus far in the literature. It is what to motivate this  
114 research and, in this article, we consider and investigate a  
115 vessel-riser system depicted in Fig. 1, simultaneously affected  
116 by input backlash and system uncertainties.

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

126 This article is laid out as follows: a dynamical model  
127 of the system and preliminaries are arranged in Section II.  
128 Section III presents the stability analysis and the controller

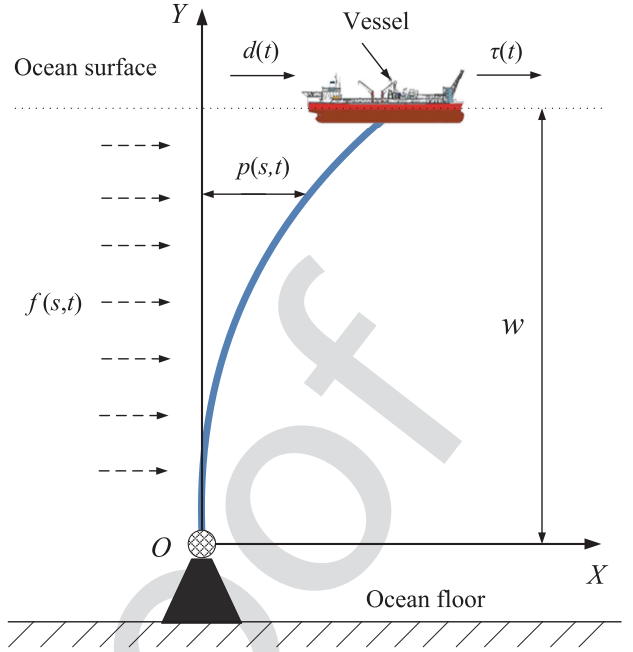


Fig. 1. Vessel-riser system.

design. Section IV makes and analyzes numerical simulations. 129  
Finally, Section V draws a conclusion. 130

## II. PROBLEM STATEMENT 131

### A. System Model 132

As displayed in Fig. 1,  $p(s,t)$  describes the vibrational 133  
deflection of the riser whose length is  $w$ .  $d(t)$  denotes the 134  
extraneous disturbance acting on the vessel whose mass and 135  
damping coefficient are  $m > 0$  and  $d_a > 0$ .  $f(s,t)$  denotes the 136  
distributed disturbance which is acted on the riser, and  $\tau(t)$  137  
represents control input which is put on the vessel. In addition, 138  
some notations for simplification are presented:  $(*) = \partial(*)/\partial t$ , 139  
 $(*)' = \partial(*)/\partial s$ ,  $(*)'' = \partial^2(*)/\partial s \partial t$ ,  $(*)''' = \partial^2(*)/\partial s^2$ , 140  
 $(*)'''' = \partial^2(*)/\partial s^3$ ,  $(*)'''' = \partial^2(*)/\partial s^4$ , and  $(\ddot{*}) = \partial^2(*)/\partial t^2$ . 141

In this article, the goal is to propose an adaptive inverse control 142  
for damping the vibration deflection and simultaneously 143  
handling the backlash nonlinearity and system uncertainties. 144  
To realize this objective, we model the dynamics of the 145  
considered vessel-riser system as [18] 146

$$\rho \ddot{p} + EI p'''' - T p'' + c \dot{p} - f = 0, \quad 0 < s < w \quad (1) \quad 147$$

$$p(0, t) = p'(0, t) = p''(w, t) = 0 \quad (2) \quad 148$$

$$m \ddot{p}(w, t) + T p'(w, t) - EI p''''(w, t) + d_a \dot{p}(w, t) = \tau(t) + d(t) \quad (3) \quad 149 \quad 150$$

where  $EI > 0$ ,  $c > 0$ ,  $\rho > 0$ , and  $T > 0$  express the bending 151  
stiffness, damping coefficient, mass per unit length, and 152  
tension of the riser, respectively. 153

### B. Input Backlash Analysis 154

For the convenience of adaptive inverse control design, we 155  
present the expression of the backlash nonlinearity [62] shown 156

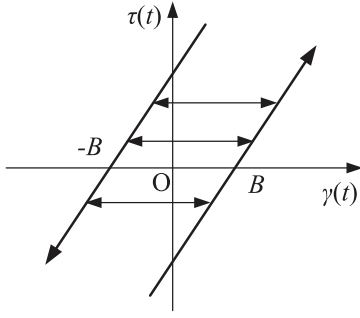


Fig. 2. Backlash nonlinearity.

157 in Fig. 2 as follows:

$$158 \quad \tau(t) = \mathcal{B}(\gamma) \\ 159 \quad = \begin{cases} \rho(\gamma(t) - B), & \text{if } \dot{\gamma} > 0 \text{ and } \tau(t) = \rho(\gamma(t) - B) \\ \rho(\gamma(t) + B), & \text{if } \dot{\gamma} < 0 \text{ and } \tau(t) = \rho(\gamma(t) + B) \\ \tau(t_-), & \text{otherwise} \end{cases} \\ 160 \quad (4)$$

161 where  $\tau(t)$  denotes the control input,  $\gamma(t)$  expresses the  
162 expected control to be developed,  $\rho$  represents the slope,  
163  $B$  denotes the ‘‘crossing,’’ and  $\tau(t_-)$  shows no change in  $\tau(t)$ .

### 164 C. Preliminaries

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

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

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

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

$$176 \quad \delta_1 \delta_2 \leq \frac{1}{\phi} \delta_1^2 + \phi \delta_2^2. \quad (5)$$

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

$$179 \quad \delta^2 \leq w \int_0^w \delta'^2 ds. \quad (6)$$

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

$$182 \quad 0 \leq |\varpi(t) - \varpi(t) \tanh(\varpi(t))| \leq 0.2785. \quad (7)$$

### 183 III. CONTROL DESIGN

184 System parameters  $T, EI, d_a$ , and  $m$ , and upper bounds of  
185 the disturbance  $D$  are utilized in the control design. However,  
186 these parameters may be unavailable in real system, thus it  
187 will bring a challenge for the control design and even make  
188 control approaches unusable. In this section, we present a  
189 new adaptive inverse controller to handle system uncertainties.  
190 Moreover, this control scheme can stabilize the vessel-riser

system and eliminate the backlash nonlinearity. Subsequently, 191  
we analyze the closed-loop system’s stability in theory. 192

### A. Boundary Adaptive Inverse Control With Input Backlash 193

Invoking [62], the inverse backlash is presented as follows: 194

$$\gamma^*(t) = \mathcal{BI}(\tau_d(t)) = \begin{cases} \frac{1}{\rho} \tau_d(t) + B, & \text{if } \dot{\tau}_d(t) > 0 \\ \frac{1}{\rho} \tau_d(t) - B, & \text{if } \dot{\tau}_d(t) < 0 \\ \gamma^*(t_-), & \text{otherwise} \end{cases} \quad (8) \quad 195$$

where  $\mathcal{BI}(\cdot)$  represents a backlash inverse function and  $\tau_d(t)$  196  
denotes the expected control command. 197

Then, according to the above analysis and [62], we propose 198  
an adaptive inverse of backlash as 199

$$\dot{\alpha}(t) = \dot{\tau}_d(t) - \frac{\beta}{B_m} |\dot{\tau}_d(t)| \alpha(t) \quad (9) \quad 200$$

$$\gamma(t) = \widehat{\mathcal{BI}}(\tau_d(t)) = \frac{1}{\rho} \tau_d(t) + \widehat{\lambda} \beta \alpha(t) \quad (10) \quad 201$$

where  $\beta$  denotes a positive gain parameter,  $B_m$  denotes a nomi- 202  
nal backlash value,  $\widehat{\mathcal{BI}}(\cdot)$  denotes an adaptive backlash inverse 203  
compensator, and  $\widehat{\lambda}$  represents an adaption to adjust  $B_m$  so 204  
as to match the actual backlash spacing  $B$  with  $B = \lambda B_m$ , 205  
 $\lambda \leq \varepsilon$ ,  $\varepsilon \in \mathbb{R}^+$ , and  $\widetilde{\lambda} = \widehat{\lambda} - \lambda$ . 206

Meanwhile, we bring a mismatch error as follows: 207

$$\tau(t) = \mathcal{B}(\widehat{\mathcal{BI}}(\tau_d(t))) = \tau_d(t) + \tau_e(t) \quad (11) \quad 208$$

where we formulate the mismatch error  $\tau_e(t)$  as 209

$$\tau_e(t) = \rho \widetilde{\lambda} B_m \text{sgn}(\dot{\tau}_d(t)) = \rho \widetilde{\lambda} \beta \alpha(t). \quad (12) \quad 210$$

Invoking (9)–(12), we then rewrite (3) as 211

$$m\ddot{p}(w, t) + Tp'(w, t) - EI p'''(w, t) + d_a \dot{p}(w, t) - d(t) \\ = \tau(t) = \mathcal{B}(\gamma(t)) \quad (13) \quad 212 \quad 213$$

Then, an adaptive inverse control is proposed as 214

$$\gamma(t) = \widehat{\mathcal{BI}}(\tau_d(t)) = \frac{1}{\rho} \tau_d(t) + \widehat{\lambda} \beta \alpha(t) \quad (14) \quad 215$$

where  $\tau_d(t)$  is designed as 216

$$\tau_d(t) = -\kappa_1 x(t) - \widehat{EI} p'''(w, t) + \widehat{T} p'(w, t) + \widehat{d}_a \dot{p}(w, t) \\ + \widehat{m} (\kappa_2 \dot{p}'''(w, t) - \kappa_3 \dot{p}'(w, t)) - \tanh(x(t)) \widehat{D} \quad (15) \quad 217 \quad 218$$

where  $\kappa_1, \kappa_2, \kappa_3 > 0$ ,  $\widehat{D}$ ,  $\widehat{T}$ ,  $\widehat{EI}$ ,  $\widehat{d}_a$ , and  $\widehat{m}$  are the estimated 219  
values of  $D, T, EI, d_a$ , and  $m$ , and we define the auxiliary 220  
variable  $x(t)$  as 221

$$x(t) = \dot{p}(w, t) - \kappa_2 p'''(w, t) + \kappa_3 p'(w, t). \quad (16) \quad 222$$

Now, we present the following inverse backlash dynamics: 223

$$\dot{\alpha}(t) = \dot{\tau}_d(t) - \frac{\beta}{B_m} |\dot{\tau}_d(t)| \alpha(t) \quad (17) \quad 224$$

and the estimation  $\widehat{\lambda}$  is obtained from the following: 225

$$\dot{\widehat{\lambda}} = -\frac{\rho}{\nu} \beta x(t) \alpha(t) - \widehat{\lambda}. \quad (18) \quad 226$$

At this time, the adaptive laws are presented when system 227  
parameters  $T, EI, d_a$ , and  $m$ , and upper bounds of the 228  
disturbance  $D$  are not available 229

$$\dot{\widehat{D}} = x(t) \tanh(x(t)) - \varsigma_1 \widehat{D} \quad (19) \quad 230$$

$$\hat{T} = -x(t)p'(w, t) - \varsigma_2 \hat{T} \quad (20)$$

$$\hat{E}I = x(t)p'''(w, t) - \varsigma_3 \hat{E}I \quad (21)$$

$$\hat{d}_a = -x(t)\dot{p}(w, t) - \varsigma_4 \hat{d}_a \quad (22)$$

$$\hat{m} = x(t)(\kappa_3 \dot{p}'(w, t) - \kappa_2 \dot{p}'''(w, t)) - \varsigma_5 \hat{m} \quad (23)$$

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

The estimation errors are defined as

$$\begin{aligned} \tilde{D} &= \hat{D} - D, \tilde{T} = \hat{T} - T, \\ \tilde{E}I &= \hat{E}I - EI, \tilde{d}_a = \hat{d}_a - d_a, \tilde{m} = \hat{m} - m. \end{aligned} \quad (24)$$

*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

$$\Theta(t) = \Theta_1(t) + \Theta_2(t) + \Theta_3(t) + \Theta_4(t) \quad (25)$$

where

$$\Theta_1(t) = \frac{\xi}{2} EI \int_0^w p''^2 ds + \frac{\xi}{2} \rho \int_0^w \dot{p}^2 ds + \frac{\xi}{2} T \int_0^w p^2 ds \quad (26)$$

$$\Theta_2(t) = \frac{\sigma}{2} m x^2(t) \quad (27)$$

$$\Theta_3(t) = \frac{\sigma}{2} \tilde{D}^2 + \frac{\sigma}{2} \tilde{T}^2 + \frac{\sigma}{2} \tilde{E}I^2 + \frac{\sigma}{2} \tilde{d}_a^2 + \frac{\sigma}{2} \tilde{m}^2 + \frac{\sigma \nu}{2} \tilde{\lambda}^2 \quad (28)$$

$$\Theta_4(t) = \psi \rho \int_0^w s \dot{p} p' ds \quad (29)$$

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

*Lemma 4:* The constructed function (25) is positive

$$\begin{aligned} 0 &\leq \iota_1 [\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \leq \Theta(t) \\ &\leq \iota_2 [\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \end{aligned} \quad (30)$$

where  $\iota_1, \iota_2 > 0$ .

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

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

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

We select  $\xi$  and  $\psi$  appropriately to satisfy the following:

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

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

$$0 \leq (1 - \vartheta) \Theta_1(t) \leq \Theta_1(t) + \Theta_4(t) \leq (1 + \vartheta) \Theta_1(t). \quad (33)$$

Invoking (25) and (33) yields

$$\begin{aligned} 0 &\leq \iota_1 [\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \leq \Theta(t) \\ &\leq \iota_2 [\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] \end{aligned} \quad (34)$$

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

$$\dot{\Theta}(t) \leq -\iota \Theta(t) + \chi \quad (35)$$

where  $\iota, \chi > 0$ .

*Proof:* We differentiate (25) to derive

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

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

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

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

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

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

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

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

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

where  $\nu_2, \nu_3 > 0$ .

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

$$\begin{aligned}
306 \quad \dot{\Theta}(t) \leq & -\frac{3\psi EI}{2} \int_0^w p'^2 ds \\
307 & - \left( \frac{\xi EI \kappa_3^2}{2\kappa_2} - \frac{\xi |T - EI\kappa_3/\kappa_2|}{2\nu_4} \right. \\
308 & \quad \left. - \frac{EI|\xi\kappa_3 - w\psi|v_5}{2} - \frac{\psi Tw}{2} \right) p^2(w, t) - \frac{\sigma \zeta_1}{2} \tilde{D}^2 \\
309 & - \left( \frac{\xi EI}{2\kappa_2} - \frac{\xi |T - EI\kappa_3/\kappa_2|v_4}{2} - \frac{\psi \rho w}{2} \right) \dot{p}^2(w, t) \\
310 & - \left( \frac{\xi EI \kappa_2}{2} - \frac{|\xi \kappa_3 - w\psi|}{2\nu_5} \right) p''^2(w, t) + \frac{\sigma \zeta_1}{2} D^2 \\
311 & - \left( \xi c - \xi v_1 - \frac{w\psi c}{v_2} + \frac{\psi \rho}{2} \right) \int_0^w \dot{p}^2 ds + \frac{\sigma \zeta_5}{2} m^2 \\
312 & - \left( \frac{\psi T}{2} - \psi v_2 c w - \psi v_3 w \right) \int_0^w p^2 ds - \frac{\sigma \zeta_1}{2} \tilde{D}^2 \\
313 & - \left( \sigma \kappa_1 - \frac{\xi EI}{2\kappa_2} \right) x^2(t) - \frac{\sigma \zeta_2}{2} \tilde{T}^2 - \frac{\sigma \zeta_3}{2} \tilde{E}I^2 + 0.2785\sigma D \\
314 & - \frac{\sigma \zeta_4}{2} \tilde{d}_a^2 - \frac{\sigma \zeta_5}{2} \tilde{m}^2 + \frac{\sigma \zeta_2}{2} T^2 + \frac{\sigma \zeta_3}{2} EI^2 + \frac{\sigma \zeta_4}{2} d_a^2 \\
315 & + \left( \frac{\xi}{v_1} + \frac{w\psi}{v_3} \right) \int_0^w f^2 ds - \frac{\sigma \nu}{2} \tilde{\lambda}^2 + \frac{\sigma \nu}{2} \lambda^2 \quad (41)
\end{aligned}$$

316 where  $\nu_4, \nu_5 > 0$  and we choose  $\psi, \sigma, \xi, \kappa_i, i = 1 \dots 3, \nu_j,$   
317 for  $j = 1 \dots 5$  to satisfy

$$\begin{aligned}
318 \quad \frac{\xi EI \kappa_3^2}{2\kappa_2} - \frac{\xi |T - EI\kappa_3/\kappa_2|}{2\nu_4} - \frac{EI|\xi\kappa_3 - w\psi|v_5}{2} - \frac{\psi Tw}{2} & \geq 0 \\
319 & \quad (42)
\end{aligned}$$

$$\begin{aligned}
320 \quad \frac{\xi EI}{2\kappa_2} - \frac{\xi |T - EI\kappa_3/\kappa_2|v_4}{2} - \frac{\psi \rho w}{2} & \geq 0 \\
321 & \quad (43)
\end{aligned}$$

$$\begin{aligned}
321 \quad \frac{\xi EI \kappa_2}{2} - \frac{|\xi \kappa_3 - w\psi|}{2\nu_5} & \geq 0 \\
322 & \quad (44)
\end{aligned}$$

$$\begin{aligned}
322 \quad \omega_1 = \xi c - \xi v_1 - \frac{w\psi c}{v_2} + \frac{\psi \rho}{2} & > 0 \\
323 & \quad (45)
\end{aligned}$$

$$\begin{aligned}
323 \quad \omega_2 = \frac{\psi T}{2} - \psi v_2 c w - \psi v_3 w & > 0 \\
324 & \quad (46)
\end{aligned}$$

$$\begin{aligned}
324 \quad \omega_3 = \sigma \kappa_1 - \frac{\xi EI}{2\kappa_2} & > 0 \\
325 & \quad (47)
\end{aligned}$$

$$\begin{aligned}
325 \quad \chi = \left( \frac{\xi}{v_1} + \frac{w\psi}{v_3} \right) w F^2 + \frac{\sigma \zeta_1}{2} D^2 + \frac{\sigma \zeta_2}{2} T^2 + \frac{\sigma \zeta_3}{2} EI^2 \\
326 \quad + \frac{\sigma \zeta_4}{2} d_a^2 + \frac{\sigma \zeta_5}{2} m^2 + \frac{\sigma \nu}{2} \varepsilon^2 + 0.2785\sigma D < +\infty. \\
327 & \quad (48)
\end{aligned}$$

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

$$\begin{aligned}
329 \quad \dot{\Theta}(t) \leq & \chi - \frac{\sigma \zeta_1}{2} \tilde{D}^2 - \omega_1 \int_0^w \dot{p}^2 ds - \omega_2 \int_0^w p'^2 ds \\
330 & - \frac{3\psi EI}{2} \int_0^w p'^2 ds - \omega_3 x^2(t) - \frac{\sigma \nu}{2} \tilde{\lambda}^2 \\
331 & - \frac{\sigma \zeta_2}{2} \tilde{T}^2 - \frac{\sigma \zeta_3}{2} \tilde{E}I^2 - \frac{\sigma \zeta_4}{2} \tilde{d}_a^2 - \frac{\sigma \zeta_5}{2} \tilde{m}^2 \\
332 & \leq -\iota_3 [\Theta_1(t) + \Theta_2(t) + \Theta_3(t)] + \chi \quad (49)
\end{aligned}$$

333 where  $\iota_3 = \min(\frac{2\omega_1}{\xi\rho}, \frac{2\omega_2}{\xi T}, \frac{3\psi}{\xi}, \frac{2\omega_3}{\sigma m}, \zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, 1)$ .

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

$$\begin{aligned}
335 \quad \dot{\Theta}(t) \leq & -\iota \Theta(t) + \chi \quad (50)
\end{aligned}$$

336 where  $\iota = (\iota_3/\iota_2)$ .

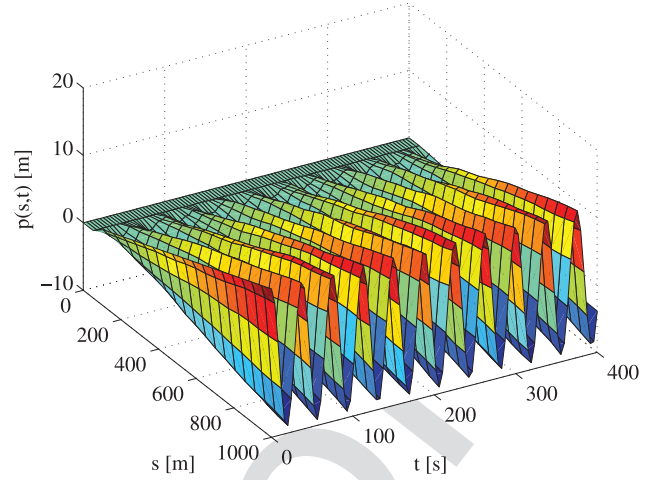


Fig. 3. 3-D offset of the riser under no control.

*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  $\psi, \sigma, \xi, \kappa_i, i = 1 \dots 3, \nu_j,$   
for  $j = 1 \dots 5$  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

$$\begin{aligned}
343 \quad \Theta(t) \leq & \Theta(0)e^{-\iota t} + \frac{\chi}{\iota}(1 - e^{-\iota t}) \leq \Theta(0)e^{-\iota t} + \frac{\chi}{\iota}. \quad (51)
\end{aligned}$$

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

$$\begin{aligned}
344 \quad \frac{\xi T}{2w} p^2(s, t) \leq & \frac{\xi T}{2} \int_0^w p^2(s, t) ds \leq \Theta_1(t) \leq \frac{1}{\iota_1} \Theta(t). \quad (52)
\end{aligned}$$

We substitute (51) into (52) to derive

$$\begin{aligned}
345 \quad |p(s, t)| \leq & \sqrt{\frac{2w}{\xi \iota_1 T} \left[ \Theta(0)e^{-\iota t} + \frac{\chi}{\iota} \right]}, \forall (s, t) \in [0, w] \times [0, +\infty). \\
346 & \quad (53)
\end{aligned}$$

Combining (53) further gives

$$\begin{aligned}
347 \quad \lim_{t \rightarrow \infty} |p(s, t)| \leq & \sqrt{\frac{2w\chi}{\xi T \iota_1}}, \forall s \in [0, w]. \quad (54)
\end{aligned}$$

*Remark 2:* This article presents a framework of adap-  
tive inverse control of uncertain vessel-riser systems subject  
to input backlash, system uncertainties, and external distur-  
bances, 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

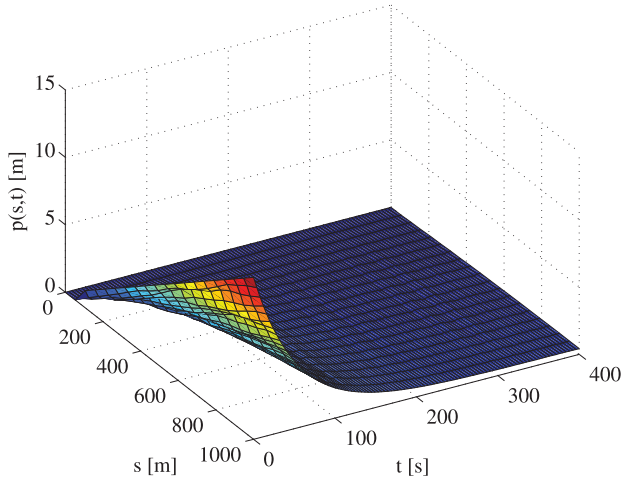


Fig. 4. 3-D offset of the riser under proposed control.

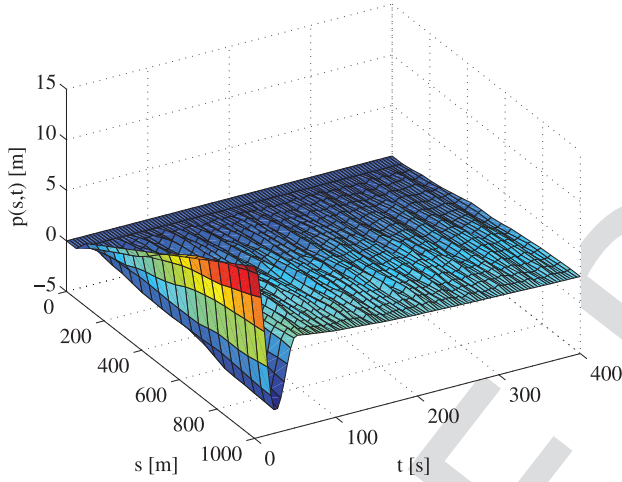


Fig. 5. 3-D offset of the riser under previous control in [18].

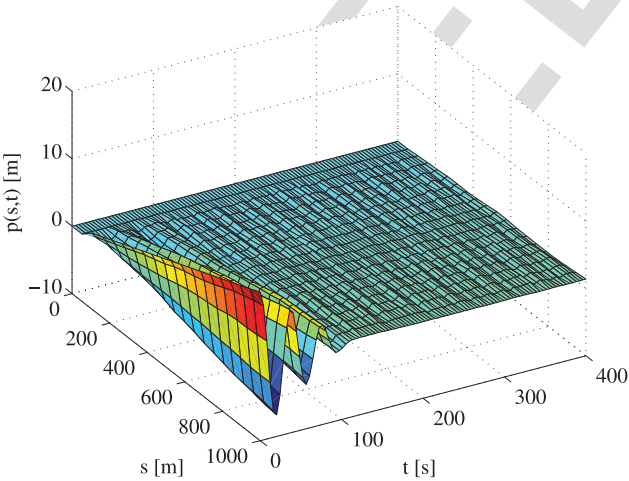


Fig. 6. 3-D offset of the riser under previous control in [60].

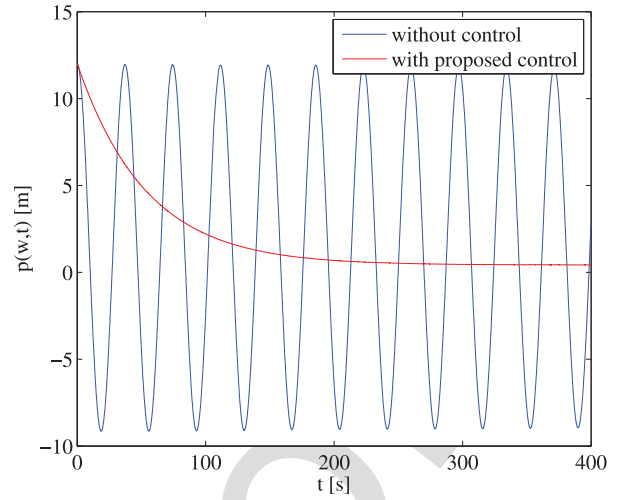


Fig. 7. 2-D offset of the vessel under proposed control.

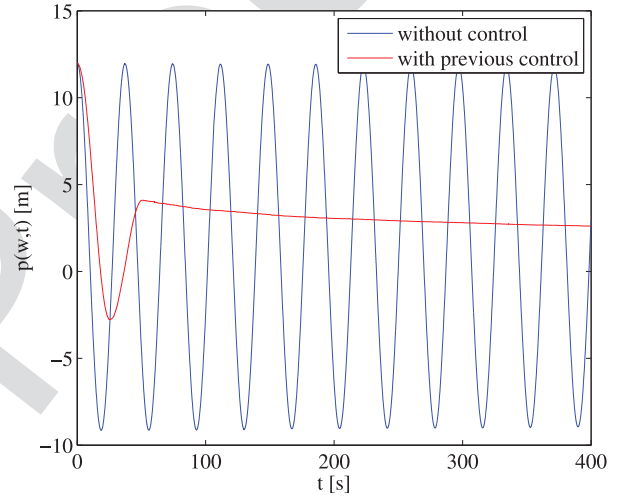


Fig. 8. 2-D offset of the vessel under previous control in [18].

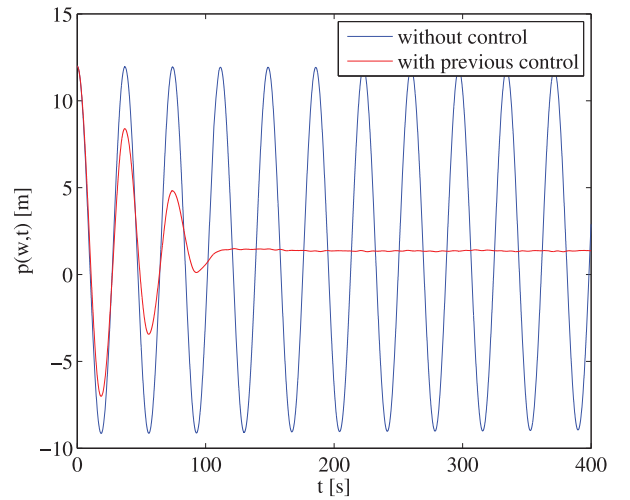


Fig. 9. 2-D offset of the vessel under previous control in [60].

steps as  $2 \times 10^{-5}$  and 0.05 to illustrate the dynam-  
ics of this nonlinear coupled system by setting system  
parameters as  $EI = 1.5 \times 10^7 \text{ Nm}^2$ ,  $\rho = 500 \text{ kg/m}$ ,

$T = 3.0 \times 10^8 \text{ N}$ ,  $c = 1.0 \text{ Ns/m}^2$ ,  $w = 1000 \text{ m}$ ,  $d_a =$   
 $1.5 \times 10^5 \text{ Ns/m}$ , and  $m = 9.6 \times 10^6 \text{ kg}$ . System initial condi-  
tions are presented as  $p(s, 0) = 12 \sin(\frac{s}{w})$  and  $\dot{p}(s, 0) = 0$ .

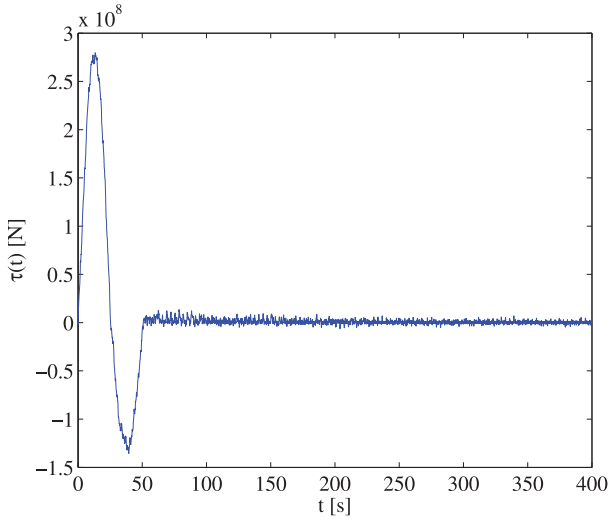


Fig. 10. Previous control input in [18].

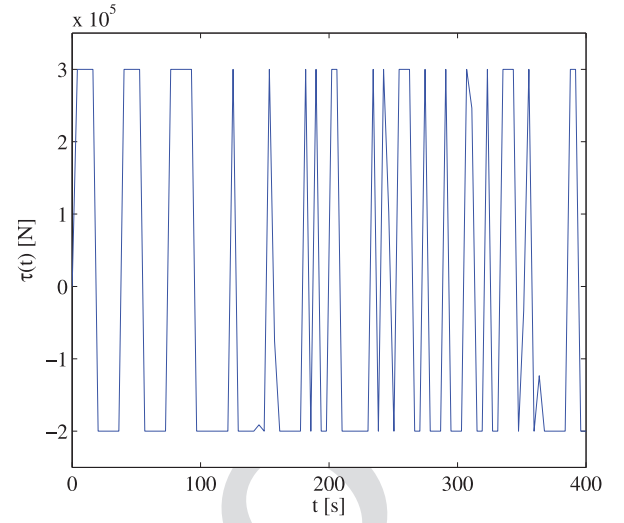


Fig. 12. Saturation control input in [60].

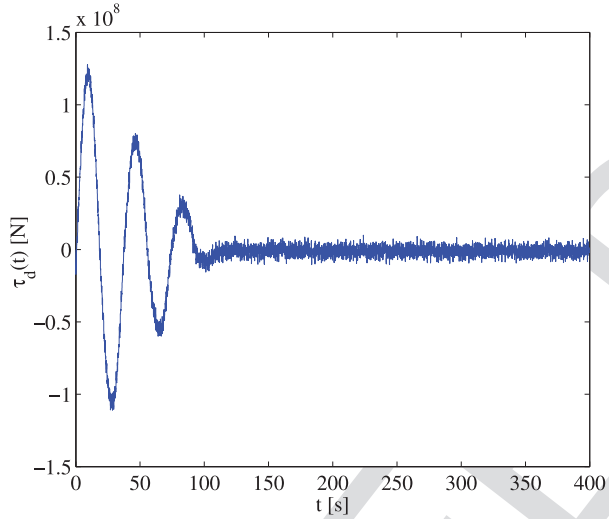


Fig. 11. Designed control command in [60].

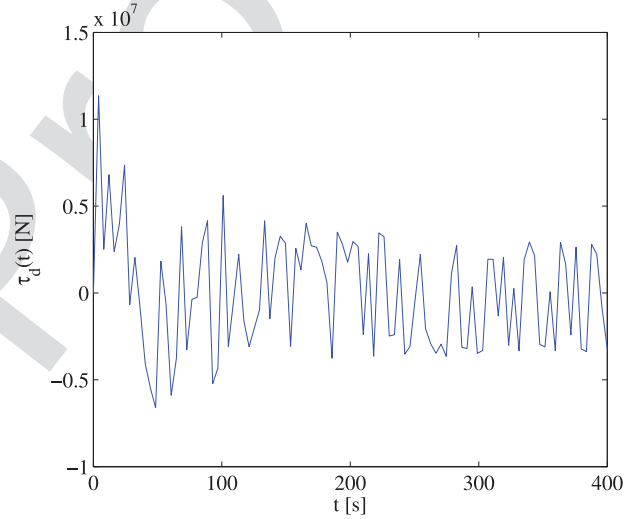


Fig. 13. Designed control input.

373 Meanwhile,  $d(t)$  is given as  $d(t) = [3 + 0.8\sin(0.7t) +$   
 374  $0.2\sin(0.5t) + 0.2\sin(0.9t)] \times 10^5$ .

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

385 With presented control law (15) by choosing control gains  
 386  $\kappa_1 = 3 \times 10^8$ ,  $\kappa_2 = 1$ ,  $\kappa_3 = 20$ , and control parameters  
 387  $\varsigma_1 = \varsigma_2 = \varsigma_3 = \varsigma_4 = \varsigma_5 = 0.001$ ,  $\varrho = 1$ ,  $\beta = 1.2$ ,  
 388  $\nu = 3$ ,  $B = 3 \times 10^6$ , and  $B_m = 1 \times 10^7$ , the spatio-temporal  
 389 response and end point offset are depicted in Figs. 4 and 7.  
 390 From Figs. 4 and 7, it is seen that the effects of the considered

external ocean disturbance and the input backlash nonlinearity 391  
 are eliminated under the proposed control (15). Moreover, it 392  
 has a positive effect on the vibration attenuation of the marine 393  
 flexible riser, and the displacement of the vessel reduces to a 394  
 small neighborhood around the original position. Meanwhile, 395  
 Figs. 13 and 14 display 2-D responses of presented control 396  
 input and backlash input. 397

398 For the comparison with the proposed control law, we con- 398  
 sider two control strategies presented in previous works [18] 399  
 and [60]. When exerting the previous control proposed in [18] 400  
 on the riser system with the given control parameters  $k =$  401  
 $3 \times 10^8$ ,  $k_1 = 1$ , and  $k_2 = 10$ , Figs. 5, 8, and 10 dis- 402  
 play the responses of the marine flexible riser, vessel, and 403  
 the control law, respectively. Note that this previous research 404  
 does not consider the effect of the input constraint and 405  
 the control law presented in [18] requires longer convergent 406  
 time and larger convergent neighborhood than the proposed 407  
 control (15) for the marine vessel-riser system with input 408

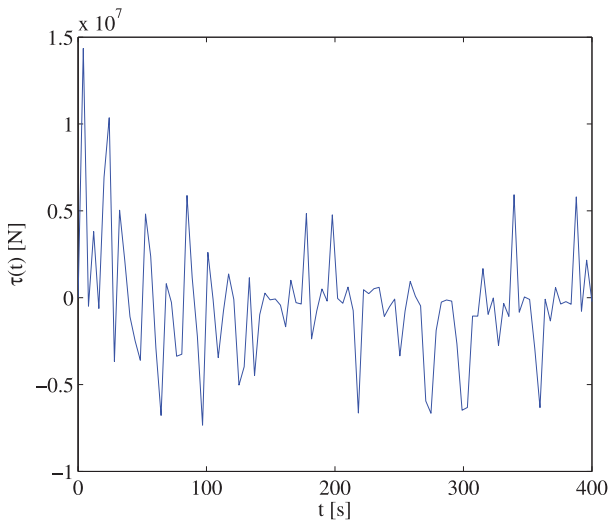


Fig. 14. Backlash control input.

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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**Jinya Su** (S'13–M'16) received the B.Sc. degree  
in mathematics from Shandong University,  
Jinan, China, in 2011, and the Ph.D. degree  
from the Department of Aeronautical and  
Automotive Engineering, Loughborough University,  
Loughborough, U.K., in 2016.

Since 2015, he has been a Research Associate  
with Loughborough University. In 2019, he joined  
the School of Computer Science and Electronic  
Engineering, University of Essex, Colchester,  
U.K., as a Lecturer of Computer Science and AI.

His current research interests include applied machine learning, control  
engineering, and their applications to intelligent autonomous systems, such  
as intelligent vehicle and smart farming.

Dr. Su was a recipient of the Chinese Government Award for Outstanding  
Self-Financed Students Abroad in 2015.



**Qinmin Yang** (S'05–M'10–SM'18) received the  
bachelor's degree in electrical engineering from the  
Civil Aviation University of China, Tianjin, China,  
in 2001, the Master of Science degree in control  
science and engineering from the Institute of  
Automation, Chinese Academy of Sciences, Beijing,  
China, in 2004, and the Ph.D. degree in electrical  
engineering from the University of Missouri at  
Rolla, Rolla, MO, USA, in 2007.

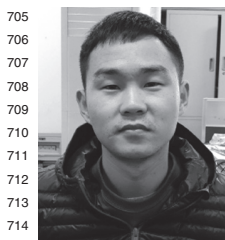
From 2007 to 2008, he was a Post-Doctoral  
Research Associate with the University of Missouri  
at Rolla. From 2008 to 2009, he was a System Engineer with Caterpillar Inc.,  
Deerfield, IL, USA. From 2009 to 2010, he was a Post-Doctoral Research  
Associate with the University of Connecticut, Mansfield, CT, USA. Since  
2010, he has been with the State Key Laboratory of Industrial Control  
Technology, College of Control Science and Engineering, Zhejiang University,  
Hangzhou, China, where he is currently a Professor. He has also held visit-  
ing positions in the University of Toronto, Toronto, ON, Canada, and Lehigh  
University, Bethlehem, PA, USA. His current research interests include intel-  
ligent control, renewable energy systems, smart grid, and industrial big data.

Prof. Yang has been serving as an Associate Editor for the IEEE  
TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART A:  
SYSTEMS AND HUMANS, *Transactions of the Institute of Measurement and  
Control*, and *IEEE/CAA Journal of Automatica Sinica*.



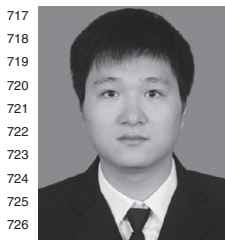
**Dachang Zhu** received the B.S degree in mechanics  
design and the M.S degree in theoretical mechan-  
ics from the Jiangxi University of Technology and  
Science, Ganzhou, China, in 1996 and 1999, respec-  
tively, and the Ph.D degree in mechanical engineer-  
ing from Beijing Jiaotong University, Beijing, China,  
in 2008.

He was a Post-Doctoral Research Fellow with the  
South China University of Technology, Guangzhou,  
China, in 2012. He is currently a Full Professor  
with the School of Mechanical and Electrical  
Engineering, Guangzhou University, Guangzhou. His current research interests  
include topology optimization theory and applications in compliant mecha-  
nisms, robotics, and feedback control of dynamic systems.



**Xiuyu He** (S'15) received the B.Eng. degree  
in automation from the Hubei University of  
Technology, Wuhan, China, in 2012, and the M.E.  
degree from the School of Automation Engineering  
and Center for Robotics, University of Electronic  
Science and Technology of China, Chengdu, China,  
in 2016. He is currently pursuing the Ph.D. degree  
with the School of Automation and Electrical  
Engineering, University of Science and Technology  
Beijing, Beijing, China.

His current research interests include distributed  
parameter system, marine cybernetics, and robotics.



**Zhijia Zhao** (S'14–M'19) received the B.Eng.  
degree in automatic control from the North China  
University of Water Resources and Electric Power,  
Zhengzhou, China, in 2010, and the M.Eng. and  
Ph.D. degrees in automatic control from the South  
China University of Technology, Guangzhou, China,  
in 2013 and 2017, respectively.

He is currently an Associate Professor with the  
School of Mechanical and Electrical Engineering,  
Guangzhou University, Guangzhou. His current  
research interests include flexible systems, marine  
cybernetics, and robotics.