This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Robust Adaptive Control of a Riser-Vessel System in Three-Dimensional Space

Zhijia Zhao, *Member, IEEE*, Yiming Liu, Tao Zou, and Keum-Shik Hong, *Fellow, IEEE*

***Abstract*—In this study, an adaptive robust control technique for an uncertain riser-vessel system in a three-dimensional space is developed. A projection mapping technique and a hyperbolic tangent function are exploited to construct novel adaptive robust controllers based on adaptive laws dynamically updated online to restrain the vibration, tackle parametric uncertainties, compensate for the unknown upper bound of disturbances, and ensure robustness of the coupled system. Lyapunov's method is adopted to analyze and demonstrate the bounded stability of the closed-loop system. Simulation results are provided to validate the feasibility and effectiveness of the proposed approach.**

***Index Terms*—Adaptive control, riser-vessel system, robust control, vibration control.**

I. INTRODUCTION

As OFFSHORE oil exploration and exploitation approaches to deep-sea areas in recent years, flexible marine risers have played a critical role as transmission components connecting surface vessels and wells [1]. A harsh marine environment causes flexible risers to inevitably and frequently produce deformation and vibration [2], [3]; thus, shortening service life. This causes fatigue damage as well as irreversible environmental pollution [4]. Therefore, an effective solution should be developed for both marine and control engineers to dampen vibrations in flexible risers.

Manuscript received March 28, 2021; accepted June 30, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61803109, Grant 61803110, Grant 61803111, and Grant 61773366; in part by the Natural Science Foundation of Guangdong Province of China under Grant 2018A030310065; in part by the Science and Technology Planning Project of Guangzhou City under Grant 202102010398 and Grant 202102010411; in part by the Scientific Research Projects of Guangzhou Education Bureau under Grant 202032793; in part by the Science and Technology Planning Project of Guangdong Province under Grant 2020B0101050001; in part by the Science and Technology Planning Key Project of Guangdong Province under Grant 2020B1010010014; and in part by the National Research Foundation (NRF) of Korea under the auspices of the Ministry of Science and ICT, South Korea, under Grant NRF-2020R1A2B5B03096000. This article was recommended by Associate Editor Q. Yang. *(Corresponding author: Tao Zou.)*

Zhijia Zhao, Yiming Liu, and Tao Zou are with School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou 510006, China, and also with Pazhou Lab, Guangzhou 510330, China (e-mail: zhjzhaoscut@163.com; 1032385189@qq.com; tzou@gzhu.edu.cn).

Keum-Shik Hong is with the School of Mechanical Engineering, Pusan National University, Busan 46241, South Korea (e-mail: kshong@pusan.ac.kr).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2021.3094668.

Digital Object Identifier 10.1109/TSMC.2021.3094668

To stabilize the vibrating flexible structure systems, many scholars have specialized in exploring diverse control techniques, such as the mode-order reduction method (MORM) [5] and boundary control [6]–[8]. By employing the MORM, an infinite-dimensional system is discretized into a finite-dimensional system [9], which may weaken the system characteristics and cause spillover effects. Boundary control can remove control-spillover rooting from the MORM. Furthermore, its actuation and sensing are nonintrusive; thus, it is regarded as an effective and practical solution [10]–[12]. In [13], a novel boundary control was constructed to restrain the bending and twisting deflections in a rigid-flexible wing system and position the wing at a desired angle. In [14], a boundary controller was presented to weaken the vibration and eliminate the rate and magnitude constraints in flexible hoses. In [15] and [16], an adaptive fault-tolerant control was designed to stabilize a flexible system in the presence of external disturbances, parameter uncertainties, and actuator failures. In [17], a flexible string subject to actuator faults, dead zones, and unknown disturbances was uniformly and ultimately stabilized by developing an adaptive fault-tolerant control strategy.

In recent years, new advances in designing boundary controller for stabilizing the oscillation in flexible riser systems have been significantly achieved. In [18], a riser-vessel system with coupled (flexible and rigid) dynamics was stabilized by raising a one-dimensional (1-D) boundary adaptive controller. In [19], boundary transverse and longitudinal controllers were proposed to suppress the vibrations of riser-vessel systems in two-dimensional (2-D) space. In [20] and [21], disturbance rejection control schemes were constructed to achieve elastic vibration control and ensure the external disturbance attenuation in the riser-vessel system. In [22], the transverse vibration in flexible riser systems was suppressed by constructing a new boundary controller. In [23], exponential and global stabilizations of 2-D riser-vessel systems subject to large in-plane deflections were achieved by constructing boundary controllers. He *et al.* [24] and Zhao *et al.* [25], [26] presented an anti-saturation design for the vibration attenuation of a constrained riser-vessel system. In [27] and [28], the barrier Lyapunov function (BLF) was introduced to solve the output-restricted problem in a riser-vessel system. In [29] and [30], the issues of the backlash/deadzone nonlinear constraint in the riser-vessel system were resolved by constructing an auxiliary variable-based adaptive control. Adaptive inverse strategies have been proposed to stabilize the vibrating riser-vessel system with system uncertainties and input backlash [31].

In [32], adaptive control methodologies were developed for a coupled riser-vessel system with hybrid nonlinear constraints. The aforementioned research focused on the vibration dampening of the riser-vessel system in a 1-D or 2-D space. Nonlinear vibrational coupling in a three-dimensional (3-D) space may present increased challenges in designing and analysis. A novel development of boundary control schemes for exponential and global stabilizing 3-D flexible riser systems was presented in [33] and [34]. In [35], a boundary control technique was designed for 3-D riser systems with hydraulic actuator dynamics, and the well-posedness of the controlled system was proven using the Galerkin approximation method. In [36], the joint angle constraint and vibration suppression of a 3-D flexible riser system were achieved by presenting BLF-based boundary controllers. However, the control designs presented in [33]–[36] were confined to eliminating the oscillation or tackling the constraint in flexible riser systems, and the approaches are invalid for uncertain flexible riser systems in the 3-D space. Moreover, Zhang *et al.* [36] adopted a piecewise sign function to address extraneous disturbances, which can cause undesirable chattering in the control actuators. To the best of our knowledge, although significant improvements have been made in boundary control for 3-D flexible risers, no research has been made on simultaneously exploiting the projection mapping technique (PMT) and hyperbolic tangent function (HTF) to develop novel adaptive robust controllers for the global stabilization of flexible risers in the 3-D space; thus, the motivation of this research.

In this study, we develop an adaptive robust control of an uncertain riser-vessel system. Compared with the existing research, the main contributions are as follows.

1) In contrast to literatures [33]–[35], [37], a PMF is employed to construct novel adaptive robust controllers along with adaptive laws dynamically updated online to suppress vibrations, eliminate parametric uncertainties, and ensure robustness in the coupled system.
2) In comparison to articles [36], a smooth HTF is exploited to generate adaptive robust controllers with online updates to compensate for the unknown upper bound of disturbances, which circumvents the chattering derived from the piecewise sign function.

II. Problem Statement

A. System Model

Fig. 1 shows the riser-vessel system in the 3-D space, where *OPQR* denotes the reference frame. t and s denote the independent time and space variables, respectively. $p(s,t)$, $q(s,t)$, and $r(s,t)$ denote the transverse, longitudinal, and vertical vibrations of the riser, respectively, deflecting at length l. $f_p(s,t)$, $f_q(s,t)$, and $f_r(s,t)$ denote the distributed disturbances on the riser system in the three directions. $d_p(t)$, $d_q(t)$, and $d_r(t)$ denote the extraneous disturbances on the vessel in the three directions. u, v, and w represent the control inputs acting on the vessel with a mass M. For simplification, the following notations are used: $(\star) = (\star)(s,t)$, $(\dot{\star}) = \partial(\star)/\partial t$, $(\star)' = \partial(\star)/\partial s$, $(\dot{\star})' = \partial^2(\star)/\partial s \partial t$. $(\star)'' = \partial^2(\star)/\partial s^2$, $(\star)''' = \partial^3(\star)/\partial s^3$, $(\star)'''' = \partial^4(\star)/\partial s^4$, $(\ddot{\star}) = \partial^2(\star)/\partial t^2$, $(\star)_0 = (\star)(0,t)$, and $(\star)_l = (\star)(l,t)$.

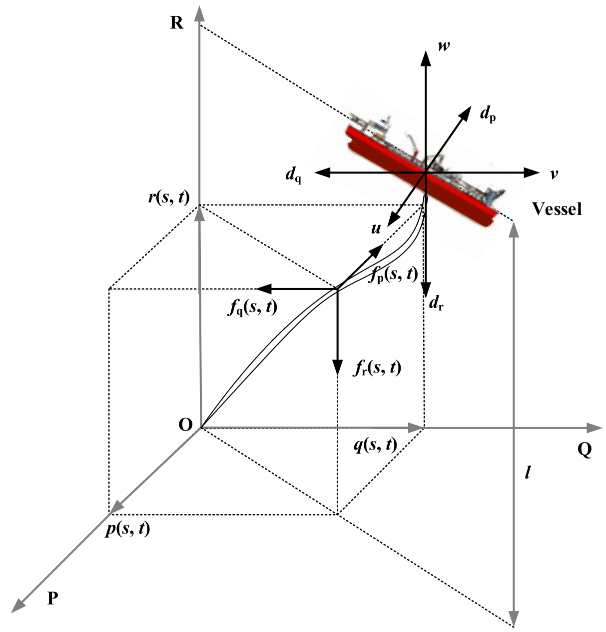


Fig. 1. Riser-vessel system.

In this study, the dynamics of the riser-vessel system under consideration are formulated as [37]

$$\rho\ddot{p} = Tp'' + EA\left(r''p' + p''r'\right) + \frac{3}{2}EAp'^2p'' + \frac{1}{2}EA\left(p''q'^2 + 2p'q'q''\right) - EIp'''' + f_p \tag{1}$$

$$\rho\ddot{q} = Tq'' + EA\left(r''q' + q''r'\right) + \frac{3}{2}EAq'^2q'' + \frac{1}{2}EA\left(q''p'^2 + 2q'p'p''\right) - EIq'''' + f_q \tag{2}$$

$$\rho\ddot{r} = EAr'' + EAp'p'' + EAq'q'' + f_r \tag{3}$$

$$p_0 = q_0 = r_0 = 0 \tag{4}$$

$$p_0'' = q_0'' = r_0'' = 0 \tag{5}$$

$$p_l'' = q_l'' = r_l'' = 0 \tag{6}$$

$$u + d_p = M\ddot{p}_l + Tp_l' + \frac{1}{2}EAp_l'^3 + EAp_l'r_l' + \frac{1}{2}EAp_l'\left(q_l'\right)^2 - EIp_l''' \tag{7}$$

$$v + d_q = M\ddot{q}_l + Tq_l' + \frac{1}{2}EAq_l'^3 + EAq_l'r_l' + \frac{1}{2}EAq_l'\left(p_l'\right)^2 - EIq_l''' \tag{8}$$

$$w + d_r = M\ddot{r}_l + EAr_l' + \frac{1}{2}EAp_l'^2 + \frac{1}{2}EAq_l'^2 \tag{9}$$

where ρ, T, EA, and EI represent the riser's uniform mass per unit length, tension, axial stiffness, and bending stiffness, respectively.

B. Preliminaries

The following lemmas and assumptions are provided for convenience of subsequent design and analysis.

Assumption 1: Suppose that there exist positive constants F_p, F_q, F_r, D_p, D_q, D_r satisfying $|f_p(s,t)| \le F_p$, $|f_q(s,t)| \le F_q$, $|f_r(s,t)| \le F_r$ $\forall(s,t) \in [0,l]\times[0,+\infty)$, and $|d_p(t)| \le D_p$, $|d_q(t)| \le D_q$, $|d_r(t)| \le D_r$ $\forall t \in [0,+\infty)$ [38]–[40]. It is a reasonable assumption because disturbances possess finite energy, that is, $d_p(t), d_q(t), d_r(t), f_p(s,t), f_q(s,t), f_r(s,t) \in \mathcal{L}_\infty$.

Lemma 1 ([41], [42]): Let $\chi_1(s,t), \chi_2(s,t) \in \mathbb{R}$ with $(s,t) \in [0,l]\times[0,+\infty)$; for $\forall\theta > 0$

$$\chi_1\chi_2 \le \theta\chi_1^2 + \frac{1}{\theta}\chi_2^2. \tag{10}$$

Lemma 2 [43]: Let $\chi(s,t) \in \mathbb{R}$ with $(s,t) \in [0,l]\times[0,+\infty)$ satisfy the condition $\chi(0,t) = 0$. Then, we derive

$$\chi^2 \le l\int_0^l \chi'^2 ds \tag{11}$$

$$\int_0^l \chi^2 ds \le l^2\int_0^l \chi'^2 ds. \tag{12}$$

Lemma 3: For any $\nu(t) \in \mathbb{R}$, we have the following inequality [44]:

$$0 \le |\nu(t)| - \nu(t)\tanh(\nu(t)) \le b \tag{13}$$

where $b = 0.2785$.

III. Control Design

When the vessel mass M and upper bounds of disturbances D_p, D_q, and D_r are unknown, the PMT is adopted to develop a novel robust adaptive control for guaranteeing the stabilization of the riser-vessel system and tackling system uncertainties.

A. Robust Adaptive Control

To achieve the control objectives, the following robust adaptive control laws are proposed:

$$u = -\hat{M}kl\dot{p}_l' - \tanh\big(\dot{p}_l + klp_l'\big)\hat{D}_p - 2\kappa_p\dot{p}_l \tag{14}$$

$$v = -\hat{M}kl\dot{q}_l' - \tanh\big(\dot{q}_l + klq_l'\big)\hat{D}_q - 2\kappa_q\dot{q}_l \tag{15}$$

$$w = -\hat{M}kl\dot{r}_l' - \tanh\big(\dot{r}_l + klr_l'\big)\hat{D}_r - 2\kappa_r\dot{r}_l \tag{16}$$

where $k, \kappa_p, \kappa_q, \kappa_r > 0$, $\hat{M}$, $\hat{D}_p$, $\hat{D}_q$, and $\hat{D}_r$ are the estimated values of M, D_p, D_q, and D_r, respectively.

The dynamically adaptive-updating laws are designed as follows:

$$\begin{aligned}\dot{\hat{M}} = \text{Proj}_M\big\{\big(kl\big[\dot{p}_l'\big(\dot{p}_l + klp_l'\big) + \dot{q}_l'\big(\dot{q}_l + klq_l'\big)\\ +\dot{r}_l'\big(\dot{r}_l + klr_l'\big)\big]\big)\big\} - \mu_1\hat{M}\end{aligned} \tag{17}$$

$$\dot{\hat{D}}_p = \big(\dot{p}_l + klp_l'\big)\tanh\big(\dot{p}_l + klp_l'\big) - \mu_2\hat{D}_p \tag{18}$$

$$\dot{\hat{D}}_q = \big(\dot{q}_l + klq_l'\big)\tanh\big(\dot{q}_l + klq_l'\big) - \mu_3\hat{D}_q \tag{19}$$

$$\dot{\hat{D}}_r = \big(\dot{r}_l + klr_l'\big)\tanh\big(\dot{r}_l + klr_l'\big) - \mu_4\hat{D}_r \tag{20}$$

where $\mu_i > 0, i = 1, \ldots, 4$, and $\text{Proj}(\star)$ denotes the projection mapping, which is defined as follows:

$$\text{Proj}_\varpi(\star) = \begin{cases} 0, & \text{if } \hat{\varpi} \ge \varpi_{\max} \text{ and } (\star) > 0\\ 0, & \text{if } \hat{\varpi} \le \varpi_{\min} \text{ and } (\star) < 0\\ (\star), & \text{otherwise}\end{cases} \tag{21}$$

where ϖ denotes a symbol replaced by the scalar M.

Thereafter, we define the estimation errors as

$$\begin{aligned}\tilde{M} = M - \hat{M}, \tilde{D}_p = D_p - \hat{D}_p\\ \tilde{D}_q = D_q - \hat{D}_q, \tilde{D}_r = D_r - \hat{D}_r.\end{aligned} \tag{22}$$

Remark 1: The signals $r(s,t)$, $q(s,t)$, $p(s,t)$, $\dot{r}(s,t)$, $\dot{q}(s,t)$, $\dot{p}(s,t)$, $r'(s,t)$, $q'(s,t)$, $p'(s,t)$, $\dot{r}'(s,t)$, $\dot{q}'(s,t)$, and $\dot{p}'(s,t)$ in the derived control laws (14)–(16) are obtainable during execution. $r(s,t)$, $q(s,t)$, and $p(s,t)$ can be measured using laser displacement sensors, while $r'(s,t)$, $q'(s,t)$, and $p'(s,t)$ can be measured using inclinometers. Moreover, we can exploit backward difference algorithms to acquire the signals $\dot{r}(s,t)$, $\dot{q}(s,t)$, $\dot{p}(s,t)$, $\dot{r}'(s,t)$, $\dot{q}'(s,t)$, and $\dot{p}'(s,t)$ with the aid of the measured values.

Remark 2: The Lyapunov function candidate in the control design of the system is provided as follows. First, a positive definite Lyapunov function candidate $X(t)$, including the system energy term $X_1(t)$, auxiliary term $X_2(t)$, crossing term $X_3(t)$, and estimation error term $X_4(t)$, is selected and proven to be bounded, as presented in Lemma 4. Subsequently, the time derivative of the Lyapunov function candidate $\dot{X}(t)$ is proven to be upper bounded by redesigning adaptive robust controllers and updating laws, as shown in Lemma 5. Finally, we prove the uniform ultimate boundedness of the system using Theorem 1.

Remark 3: Contrary to the existing results on adaptive control [45], [46] or adaptive fault-tolerant control [47]–[50] for the finite-dimensional system, in this study, the robust adaptive control design is based on the infinite-dimensional riser-vessel system; thus, the spillover instability does not appear.

Meanwhile, we provide some lemmas for the stability analysis.

B. Stability Proof

Set the Lyapunov candidate function as

$$X(t) = X_1(t) + X_2(t) + X_3(t) + X_4(t) \tag{23}$$

where

$$\begin{aligned}X_1(t) = &\frac{1}{2}\rho\int_0^l\Big(\dot{p}^2 + \dot{q}^2 + \dot{r}^2\Big)ds + \frac{1}{2}T\int_0^l\Big(p'^2 + q'^2\Big)ds\\ &+ \frac{1}{2}EA\int_0^l\Big(r' + \frac{1}{2}p'^2 + \frac{1}{2}q'^2\Big)^2 ds\\ &+ \frac{1}{2}EI\int_0^l\Big(p''^2 + q''^2\Big)ds\end{aligned} \tag{24}$$

$$\begin{aligned}X_2(t) = &\frac{1}{2}M\big(\dot{p}_l + klp_l'\big)^2 + \frac{1}{2}M\big(\dot{q}_l + klq_l'\big)^2\\ &+ \frac{1}{2}M\big(\dot{r}_l + klr_l'\big)^2\end{aligned} \tag{25}$$

$$X_3(t) = k\rho\int_0^l s\big(\dot{p}p' + \dot{q}q' + \dot{r}r'\big)ds \tag{26}$$

$$X_4(t) = \frac{1}{2}\tilde{M}^2 + \frac{1}{2}\tilde{D}_p^2 + \frac{1}{2}\tilde{D}_q^2 + \frac{1}{2}\tilde{D}_r^2. \tag{27}$$

Lemma 4: The constructed function (23) is positive

$$\begin{aligned}0 &\le \upsilon_1[W(t) + X_2(t) + X_4(t)] \le X(t)\\ &\le \upsilon_2[W(t) + X_2(t) + X_4(t)]\end{aligned} \tag{28}$$

where $\upsilon_1, \upsilon_2 > 0$, and

$$W(t) \leq \int_0^l \Big[\dot{p}^2 + \dot{q}^2 + \dot{r}^2 + p'^2 + q'^2 + r'^2 + p'^4 + q'^4 + (p'q')^2 + p''^2 + q''^2\Big] ds. \quad (29)$$

Proof: First, rewriting $X_1(t)$ yields

$$\begin{aligned} X_1(t) = {} & \frac{1}{2}\rho\int_0^l \Big(\dot{p}^2 + \dot{q}^2 + \dot{r}^2\Big) ds + \frac{1}{2}T\int_0^l \Big(p'^2 + q'^2\Big) ds \\ & + \frac{1}{2}EA\int_0^l r'^2 ds + \frac{1}{8}EA\int_0^l p'^4 ds + \frac{1}{8}EA\int_0^l q'^4 ds \\ & + \frac{1}{2}EA\int_0^l r'p'^2 ds + \frac{1}{2}EA\int_0^l r'q'^2 ds \\ & + \frac{1}{4}EA\int_0^l (p'q')^2 ds + \frac{1}{2}EI\int_0^l \Big(p''^2 + q''^2\Big) ds. \end{aligned} \quad (30)$$

Using Lemma 1, $2r_l'^2 \leq p_l'^2$, and $2r_l'^2 \leq q_l'^2$ [51], we get

$$\begin{aligned} & -\alpha\int_0^l p'^4 ds - \frac{1}{2\alpha}\int_0^l p'^2 ds \\ & \leq \int_0^l r'p'^2 ds \leq \alpha\int_0^l p'^4 ds + \frac{1}{2\alpha}\int_0^l p'^2 ds \\ & -\alpha\int_0^l q'^4 ds - \frac{1}{2\alpha}\int_0^l q'^2 ds \\ & \leq \int_0^l r'q'^2 ds \leq \alpha\int_0^l q'^4 ds + \frac{1}{2\alpha}\int_0^l q'^2 ds \end{aligned} \quad (31)$$

where $\alpha > 0$.

Selecting an appropriate α to satisfy $T - (EA/2\alpha) \geq 0$ and $(1/4) - \alpha \geq 0$, we obtain

$$0 \leq \lambda_1 W(t) \leq X_1(t) \leq \lambda_2 W(t) \quad (32)$$

where

$$\lambda_1 = \frac{1}{2}\min\left[\rho, \mathrm{T} - \frac{\mathrm{EA}}{2\alpha}, \frac{1}{2}\mathrm{EA}, \mathrm{EA}\left(\frac{1}{4} - \alpha\right), \mathrm{EI}\right] \quad (33)$$

$$\lambda_2 = \frac{1}{2}\max\left[\rho, \mathrm{T} + \frac{\mathrm{EA}}{2\alpha}, \mathrm{EA}, \mathrm{EA}\left(\frac{1}{4} + \alpha\right), \mathrm{EI}\right]. \quad (34)$$

Applying Lemma 1 on $X_3(t)$ gives

$$\begin{aligned} |X_3(t)| & \leq k\rho l\int_0^l \Big(\dot{p}^2 + \dot{q}^2 + \dot{r}^2 + p'^2 + q'^2 + r'^2\Big) ds \\ & \leq k_1 W(t) \end{aligned} \quad (35)$$

where $k_1 = k\rho l > 0$. Combining (35) yields $-k_1 W(t) \leq X_3(t) \leq k_1 W(t)$. The proper choice of k to satisfies $0 < k < \lambda_1/(\rho l)$, and we derive $0 < k_1 < \lambda_1$. Setting $k_2 = \lambda_1 - k_1$ and $k_3 = \lambda_2 + k_1$ results in

$$0 \leq k_2 W(t) \leq X_1(t) + X_3(t) \leq k_3 W(t). \quad (36)$$

Then, we invoke (23) to derive the following:

$$\begin{aligned} 0 & \leq \upsilon_1(W(t) + X_2(t) + X_4(t)) \leq X(t) \\ & \leq \upsilon_2(W(t) + X_2(t) + X_4(t)) \end{aligned} \quad (37)$$

where $\upsilon_1 = \min(\mathrm{k}_2, 1) > 0$ and $\upsilon_2 = \max(\mathrm{k}_3, 1) > 0$. ■

Lemma 5: The time derivative of (23) is upper bounded as

$$\dot{X}(t) \leq -\upsilon X(t) + \beta \quad (38)$$

where $\upsilon, \beta > 0$.

Proof: Differentiating (23), we have

$$\dot{X}(t) = \dot{X}_1(t) + \dot{X}_2(t) + \dot{X}_3(t) + \dot{X}_4(t). \quad (39)$$

Combining (1)–(9), we derive

$$\begin{aligned} \dot{X}_1(t) = {} & \int_0^l \dot{p}\Big[Tp'' + EA\big(r''p' + p''r'\big) + \frac{3}{2}EAp'^2p'' \\ & \quad + \frac{1}{2}EA\Big(p''q'^2 + 2p'q'q''\Big) - EIp'''' + f_p\Big] ds \\ & + \int_0^l \dot{q}\Big[Tq'' + EA\big(r''q' + q''r'\big) + \frac{3}{2}EAq'^2q'' \\ & \quad + \frac{1}{2}EA\Big(q''p'^2 + 2q'p'p''\Big) - EIq'''' + f_q\Big] ds \\ & + \int_0^l \dot{r}\big(EAr'' + EAp'p'' + EAq'q'' + f_r\big) ds \\ & + EAr_l'\dot{r}_l - EA\int_0^l r''\dot{r} ds + EAr_l'p_l'\dot{p}_l \\ & - EA\int_0^l (p''r' + p'r'')\dot{p} ds + EAr_l'q_l'\dot{q}_l \\ & - EA\int_0^l (r''q' + r'q'')\dot{q} ds + \frac{1}{2}EAp_l'^2\dot{r}_l \\ & - EA\int_0^l p'p''\dot{r} ds + \frac{1}{2}EAp_l'^3\dot{p}_l \\ & - EA\int_0^l q'q''\dot{r} ds - \frac{3}{2}EA\int_0^l p'^2p''\dot{p} ds \\ & + \frac{1}{2}EAp_l'^2q_l'\dot{q}_l + \frac{1}{2}EAq_l'^2p_l'\dot{p} \\ & - \frac{1}{2}EA\int_0^l \Big(2q'q''p' + q'^2p''\Big)\dot{p} ds \\ & - \frac{1}{2}EA\int_0^l \Big(2p'p''q' + p'^2q''\Big)\dot{q} ds \\ & + \frac{1}{2}EAq_l'^3\dot{q}_l - \frac{3}{2}EA\int_0^l q'^2q''\dot{q} ds - EIp_l'''\dot{p}_l \\ & + EI\int_0^l p''''\dot{p} ds - EIq_l'''\dot{q}_l + EI\int_0^l q''''\dot{q} ds \\ & + T\big(p_l'\dot{p}_l + q_l'\dot{q}_l\big) - T\int_0^l \big(p''\dot{p} + q''\dot{q}\big) ds + \frac{1}{2}EAq_l'^2\dot{r}_l \\ = {} & \int_0^l \big(\dot{p}f_p + \dot{q}f_q + \dot{r}f_r\big) ds + \big(u + d_p - M\ddot{p}_l\big)\dot{p}_l \\ & + \big(v + d_q - M\ddot{q}_l\big)\dot{q}_l + (w + d_r - M\ddot{r}_l)\dot{r}_l. \end{aligned} \quad (40)$$

Thereafter, $\dot{X}_2(t)$ is obtained as

$$\begin{aligned} \dot{X}_2(t) = {} & \big(\dot{p}_l + klp_l'\big)\big(M\ddot{p}_l + Mkl\dot{p}_l'\big) \\ & + \big(\dot{q}_l + klq_l'\big)\big(M\ddot{q}_l + Mkl\dot{q}_l'\big) \\ & + \big(\dot{r}_l + klr_l'\big)\big(M\ddot{r}_l + Mkl\dot{r}_l'\big). \end{aligned} \quad (41)$$

Invoking (1)–(9) leads to

$$\dot{X}_3(t) = -\frac{3}{8}kEA\int_0^l p'^4 ds - \frac{3}{8}kEA\int_0^l q'^4 ds$$

$$
\begin{aligned}
&- kEA\int_0^l r'p'^2ds - kEA\int_0^l r'q'^2ds \\
&- \frac{3}{4}kEA\int_0^l \big(p'q'\big)^2ds - \frac{3}{2}kEI\int_0^l p''^2ds \\
&- \frac{3}{2}kEI\int_0^l q''^2ds - \frac{1}{2}kT\int_0^l p'^2ds \\
&- \frac{1}{2}kT\int_0^l q'^2ds - \frac{1}{2}kEAl\bigg(\frac{1}{2}p_l'^2 + \frac{1}{2}q_l'^2 + r_l'^2\bigg)^2 \\
&- \frac{1}{2}kTlp_l'^2 - \frac{1}{2}kTlq_l'^2 + \frac{1}{2}k\rho l\big(\dot{p}_l^2 + \dot{q}_l^2 + \dot{r}_l^2\big) \\
&- \frac{1}{2}kEA\int_0^l r'^2ds - \frac{1}{2}k\rho\int_0^l \dot{p}^2ds - \frac{1}{2}k\rho\int_0^l \dot{q}^2ds \\
&- \frac{1}{2}k\rho\int_0^l \dot{r}^2ds + klp_l'\big(u + d_p - M\ddot{p}_l\big) \\
&+ klq_l'\big(v + d_q - M\ddot{q}_l\big) + klr_l'(w + d_r - M\ddot{r}_l) \\
&+ k\int_0^l s\big(p'f_p + q'f_q + r'f_r\big)ds. \qquad (42)
\end{aligned}
$$

Applying (17)–(22) on $\dot{X}_4(t)$ yields

$$
\begin{aligned}
\dot{X}_4(t) = &-\tilde{M}\mathrm{Proj}_M\big\{\big(kl\big[\dot{p}_l'\big(\dot{p}_l + klp_l'\big) + \dot{q}_l'\big(\dot{q}_l + klq_l'\big) \\
&+\dot{r}_l'\big(\dot{r}_l + klr_l'\big)\big]\big)\big\} + \mu_1\tilde{M}\hat{M} \\
&- \tilde{D}_p\big(\dot{p}_l + klp_l'\big)\tanh\big(\dot{p}_l + klp_l'\big) + \mu_2\tilde{D}_p\hat{D}_p \\
&- \tilde{D}_q\big(\dot{q}_l + klq_l'\big)\tanh\big(\dot{q}_l + klq_l'\big) + \mu_3\tilde{D}_q\hat{D}_q \\
&- \tilde{D}_r\big(\dot{r}_l + klr_l'\big)\tanh\big(\dot{r}_l + klr_l'\big) + \mu_4\tilde{D}_r\hat{D}_r. \qquad (43)
\end{aligned}
$$

Considering $\tilde{M}(\star) - \tilde{M}\mathrm{Proj}_M(\star) \le 0$, $2r_l'^2 \le p_l'^2$, and $2r_l'^2 \le q_l'^2$ [51], and Lemmas 1–3, we derive

$$
\begin{aligned}
\dot{X}(t) \le &-\bigg(\frac{1}{2}k\rho - \frac{1}{\delta_1}\bigg)\int_0^l \dot{p}^2ds - \bigg(\frac{1}{2}kEA - kl\delta_6\bigg)\int_0^l r'^2ds \\
&- \bigg(\frac{1}{2}k\rho - \frac{1}{\delta_2}\bigg)\int_0^l \dot{q}^2ds - \bigg(\frac{3}{8}kEA - \frac{kEA}{2\delta_7}\bigg)\int_0^l p'^4ds \\
&- \bigg(\frac{1}{2}k\rho - \frac{1}{\delta_3}\bigg)\int_0^l \dot{r}^2ds - \bigg(\frac{3}{8}kEA - \frac{kEA}{2\delta_8}\bigg)\int_0^l q'^4ds \\
&- \bigg(\frac{1}{2}kT - kl\delta_4 - \frac{kEA\delta_7}{4}\bigg)\int_0^l p'^2ds + \frac{\mu_2}{2}D_p^2 \\
&- \bigg(\frac{1}{2}kT - kl\delta_5 - \frac{kEA\delta_8}{4}\bigg)\int_0^l q'^2ds + \frac{\mu_3}{2}D_q^2 \\
&+ \bigg(\delta_1 + \frac{kl}{\delta_4}\bigg)\int_0^l f_p^2ds + \bigg(\delta_2 + \frac{kl}{\delta_5}\bigg)\int_0^l f_q^2ds \\
&+ \bigg(\delta_3 + \frac{kl}{\delta_6}\bigg)\int_0^l f_r^2ds - \kappa_p\big(\dot{p}_l + klp_l'\big)^2 + \frac{\mu_4}{2}D_r^2 \\
&- \kappa_q\big(\dot{q}_l + klq_l'\big)^2 - \kappa_r\big(\dot{r}_l + klr_l'\big)^2 - \frac{3}{2}kEI\int_0^l p''^2ds \\
&- \frac{3}{2}kEI\int_0^l q''^2ds - \frac{3}{4}kEA\int_0^l (p'q')^2ds \\
&- \bigg(\frac{1}{4}kTl - \kappa_pk^2l^2\bigg)p_l'^2 - \bigg(\frac{1}{4}kTl - \kappa_qk^2l^2\bigg)q_l'^2 \\
&- \big(kTl - \kappa_rk^2l^2\big)r_l'^2 + b\big(D_p + D_q + D_r\big) \\
&- \frac{1}{2}kEAl\bigg[\frac{1}{2}\big(p_l'\big)^2 + \frac{1}{2}\big(q_l'\big)^2 + r_l'\bigg]^2 - \frac{\mu_1}{2}\tilde{M}^2 \\
&+ \frac{\mu_1}{2}M^2 - \frac{\mu_2}{2}\tilde{D}^2{}_p - \frac{\mu_3}{2}\tilde{D}_q^2 - \frac{\mu_4}{2}\tilde{D}_r^2 \qquad (44)
\end{aligned}
$$

where $\delta_1 \sim \delta_8 > 0$ and the parameters k, κ_p, κ_q, κ_r, δ_i, $i = 1, \ldots, 8$, and μ_j, for $j = 1, \ldots, 4$ are chosen to satisfy

$$\vartheta_1 = \frac{1}{2}k\rho - \frac{1}{\delta_1} > 0,\ \vartheta_2 = \frac{1}{2}k\rho - \frac{1}{\delta_2} > 0 \qquad (45)$$

$$\vartheta_3 = \frac{1}{2}k\rho - \frac{1}{\delta_3} > 0,\ \vartheta_4 = \frac{1}{2}kT - kl\delta_4 - \frac{kEA\delta_7}{4} > 0 \qquad (46)$$

$$\vartheta_5 = \frac{1}{2}kT - kl\delta_5 - \frac{kEA\delta_8}{4} > 0,\ \vartheta_6 = \frac{1}{2}kEA - kl\delta_6 > 0 \qquad (47)$$

$$\vartheta_7 = \frac{3}{8}kEA - \frac{kEA}{2\delta_7} > 0,\ \vartheta_8 = \frac{3}{8}kEA - \frac{kEA}{2\delta_8} > 0 \qquad (48)$$

$$\frac{1}{4}kTl - \kappa_pk^2l^2 \ge 0,\ \frac{1}{4}kTl - \kappa_qk^2l^2 \ge 0,\ kTl - \kappa_rk^2l^2 \ge 0 \qquad (49)$$

$$
\begin{aligned}
\beta = &\bigg(\delta_1 + \frac{kl}{\delta_4}\bigg)lF_p^2 + \bigg(\delta_2 + \frac{kl}{\delta_5}\bigg)lF_q^2 + \bigg(\delta_3 + \frac{kl}{\delta_6}\bigg)lF_r^2 \\
&+ \frac{\mu_1}{2}M^2 + \frac{\mu_2}{2}D_p^2 + \frac{\mu_3}{2}D_q^2 + \frac{\mu_4}{2}D_r^2 \\
&+ b\big(D_p + D_q + D_r\big) < +\infty. \qquad (50)
\end{aligned}
$$

Invoking (45)–(50), we obtain

$$
\begin{aligned}
\dot{X}(t) \le &-\vartheta_1\int_0^l \dot{p}^2ds - \vartheta_2\int_0^l \dot{q}^2ds - \vartheta_3\int_0^l \dot{r}^2ds \\
&- \vartheta_4\int_0^l p'^2ds - \vartheta_5\int_0^l q'^2ds - \vartheta_6\int_0^l r'^2ds \\
&- \vartheta_7\int_0^l p'^4ds - \vartheta_8\int_0^l q'^4ds - \frac{3}{2}kEI\int_0^l p''^2ds \\
&- \frac{3}{2}kEI\int_0^l q''^2ds - \frac{3}{4}kEA\int_0^l \big(p'q'\big)^2ds + \beta \\
&- \kappa_p\big(\dot{p}_l + klp_l'\big)^2 - \frac{\mu_1}{2}\tilde{M}^2 - \frac{\mu_2}{2}\tilde{D}^2{}_p - \frac{\mu_3}{2}\tilde{D}_q^2 \\
&- \kappa_q\big(\dot{q}_l + klq_l'\big)^2 - \kappa_r\big(\dot{r}_l + klr_l'\big)^2 - \frac{\mu_4}{2}\tilde{D}_r^2 \\
\le &\ \upsilon_3(W(t) + X_2(t) + X_4(t)) + \beta \qquad (51)
\end{aligned}
$$

where $\upsilon_3 = \min(\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5, \vartheta_6, \vartheta_7, \vartheta_8, (3/2)kEI, (3/4)kEA, (2\kappa_p/M), (2\kappa_q/M), (2\kappa_r/M), \mu_1, \mu_2, \mu_3, \mu_4)$.

Following Lemma 4 and (51), we obtain

$$\dot{X}(t) \le -\upsilon X(t) + \beta \qquad (52)$$

where $\upsilon = (\upsilon_3/\upsilon_2)$. ■

Theorem 1: For the riser-vessel system described by (1)–(9) under the action of the developed adaptive controllers (14)–(16) and dynamically updating laws (17)–(20), provided that the initial conditions are bounded and the designed parameters k, κ_i, $i = p, q, r$, and μ_j, for $j = 1, \ldots, 4$ satisfy the constraint conditions (45)–(50), then the closed-loop system is uniformly bounded.

Proof: Invoking (38), we obtain

$$X(t) \le X(0)e^{-\upsilon t} + \frac{\beta}{\upsilon}\big(1 - e^{-\upsilon t}\big) \le X(0)e^{-\upsilon t} + \frac{\beta}{\upsilon}. \qquad (53)$$

Using $X_1(t)$, (29), and Lemma 2, we obtain

$$\frac{1}{l}p^2(s,t) \le \int_0^l p'^2(s,t)ds \le W(t) \le \frac{1}{\upsilon_1}X(t) \qquad (54)$$

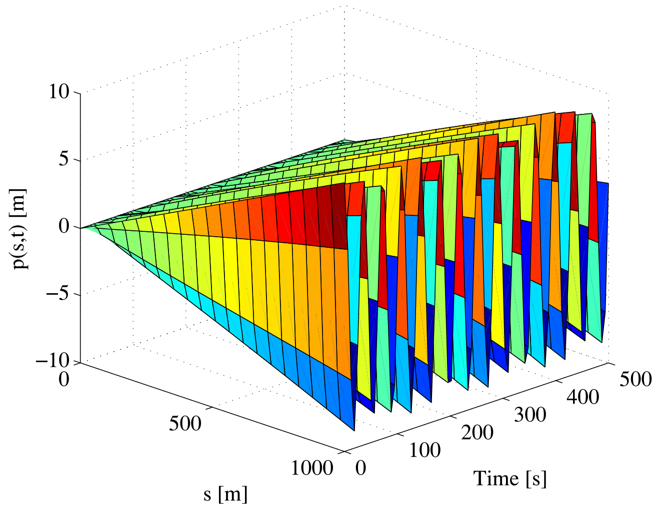


Fig. 2. 3-D offset of the riser under no control: $p(s, t)$.

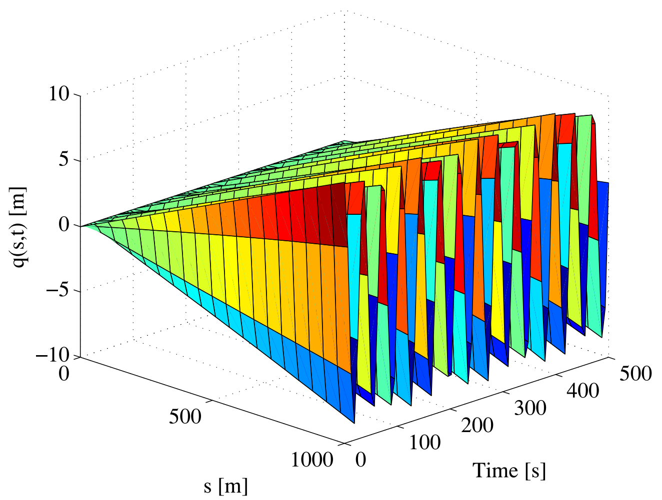


Fig. 3. 3-D offset of the riser under no control: $q(s, t)$.

$$\frac{1}{l}q^2(s,t) \leq \int_0^l q'^2(s,t)ds \leq W(t) \leq \frac{1}{\upsilon_1}X(t) \quad (55)$$

$$\frac{1}{l}r^2(s,t) \leq \int_0^l r'^2(s,t)ds \leq W(t) \leq \frac{1}{\upsilon_1}X(t). \quad (56)$$

Substituting (54)–(56) into (53) gives

$$| p(s,t) | \leq \varrho, | q(s,t) | \leq \varrho, | r(s,t) | \leq \varrho \quad (57)$$

with $\forall(s,t) \in [0,l] \times [0,+\infty)$ and $\varrho = \sqrt{(l/\upsilon_1)[X(0) + (\beta/\upsilon)]}$. ■

IV. Numerical Simulation

To illustrate the effectiveness of the proposed scheme, the finite difference method [52], [53] is used to approximate the system solution in this section. The system parameters and initial conditions are set to $l = 1000$ m, $EI = 1.5 \times 10^7$ Nm^2, $\rho = 500$ kg/m, $T = 3.0 \times 10^8$ N, $EA = 2.0 \times 10^7$ Nm^2, $c = 1.0$ Ns/m^2, $d_a = 1.5 \times 10^5$ Ns/m, $m = 9.6 \times 10^6$ kg, $p(s,0) = q(s,0) = r(s,0) = (10s/l)$, and $\dot{p}(s,0) = \dot{q}(s,0) = \dot{r}(s,0)=0$. The disturbances are formulated as $d_p(t) = d_q(t) = [1+0.2\sin(0.7t)+0.1\sin(0.5t)+0.1\sin(0.9t)]\times 10^5$ and $d_r(t) = [3 + 0.2\sin(0.5t)] \times 10^4$. The chosen distributed disturbances were the same as those in the literature [36].

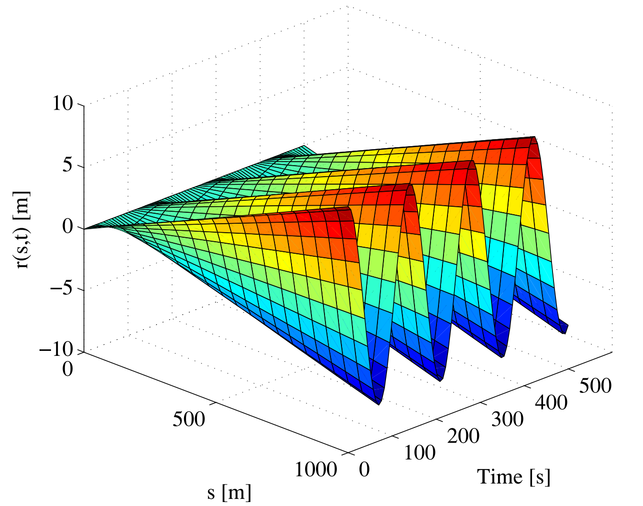


Fig. 4. 3-D offset of the riser under no control: $r(s, t)$.

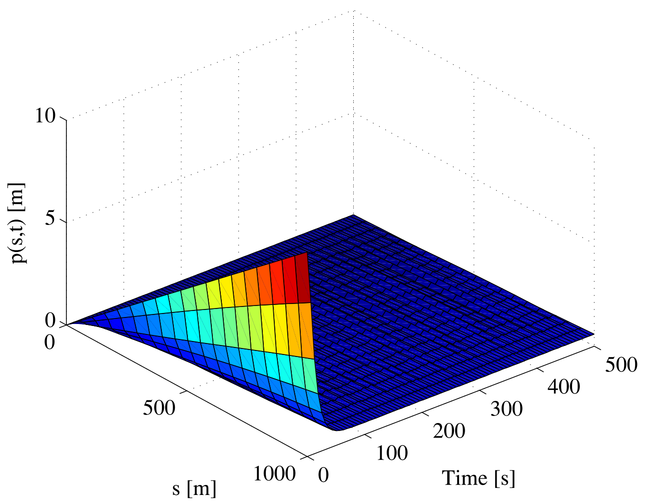


Fig. 5. 3-D offset of the riser under proposed control: $p(s, t)$.

When the riser-vessel system is in a free state, that is, there are no control input forces ($u = v = w = 0$), and the riser's dynamic performance in response to external ocean disturbances is shown in Figs. 2–4. From Figs. 2–4, we can observe that the 3-D riser vibrates freely with a larger amplitude. The sustained large deformation in risers causes fatigue damage. Consequently, effective control strategies should be developed to suppress vibrations in risers.

When the designed controllers (14)–(16) act on the coupled system by selecting the control parameters $\kappa_p = \kappa_q = 2 \times 10^6$, $\kappa_r = 5 \times 10^5$, $k = 0.0001$, and $\mu_1 = \mu_2 = \mu_3 = \mu_4 = 0.0001$, Figs. 5–7 show the spatiotemporal responses. From Figs. 5–7, we perceive that the designed control strategies (14)–(16) overcome the external disturbances' effects on the system and ensures that the displacement of the riser system converge to a small neighborhood near equilibrium position. The time responses of the proposed control inputs are shown in Figs. 11–13.

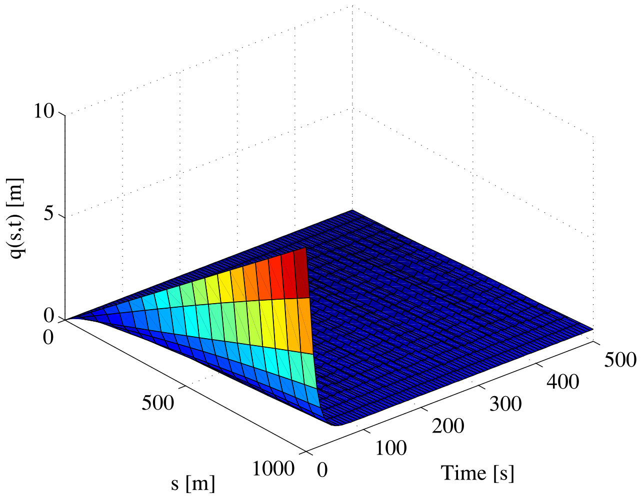


Fig. 6. 3-D offset of the riser under proposed control: $q(s, t)$.

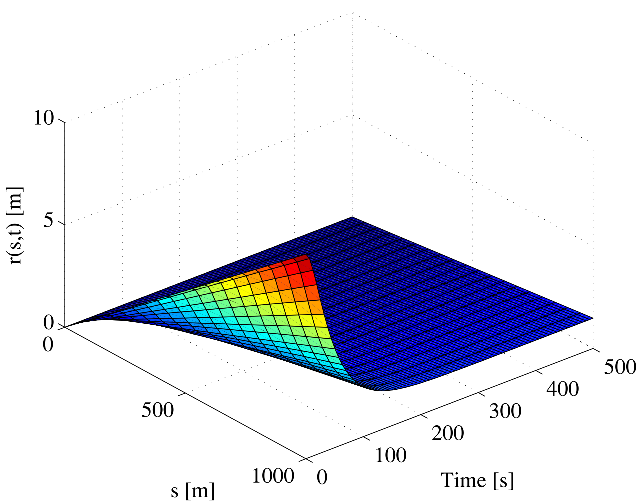


Fig. 7. 3-D offset of the riser under proposed control: $r(s, t)$.

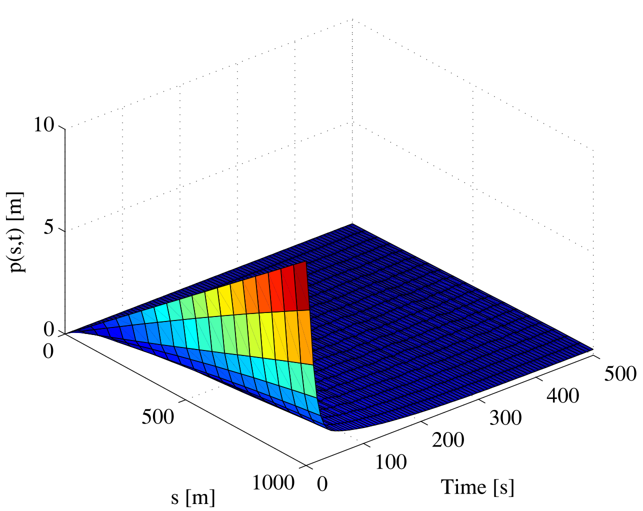


Fig. 8. 3-D offset of the riser with control in (58)–(60): $p(s, t)$.

To further verify the effectiveness of the derived control, we also provide a simulation with the following adaptive controllers proposed in [37], which employs the symbolic function

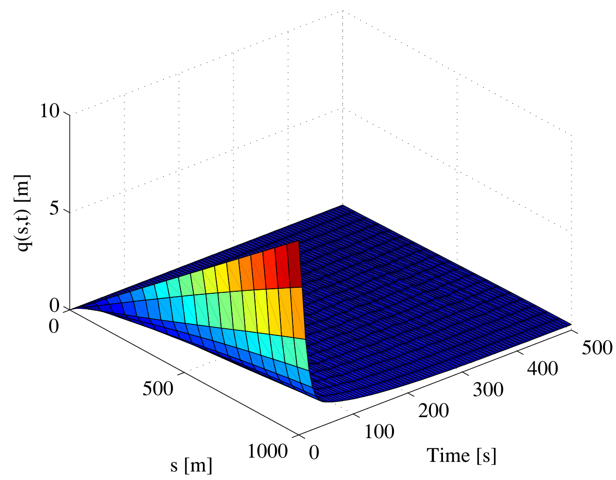


Fig. 9. 3-D offset of the riser with control in (58)–(60): $q(s, t)$.

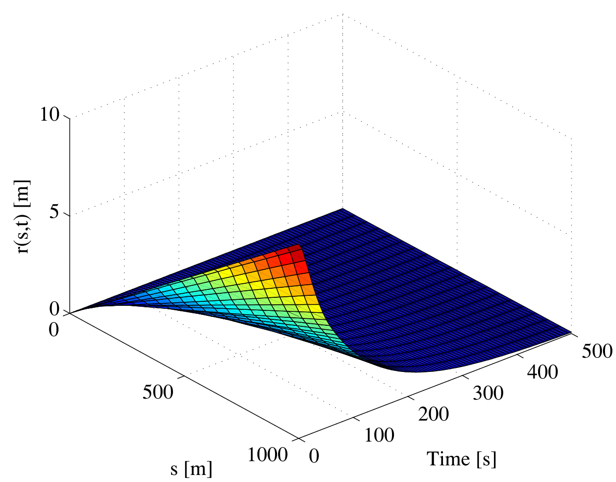


Fig. 10. 3-D offset of the riser with control in (58)–(60): $r(s, t)$.

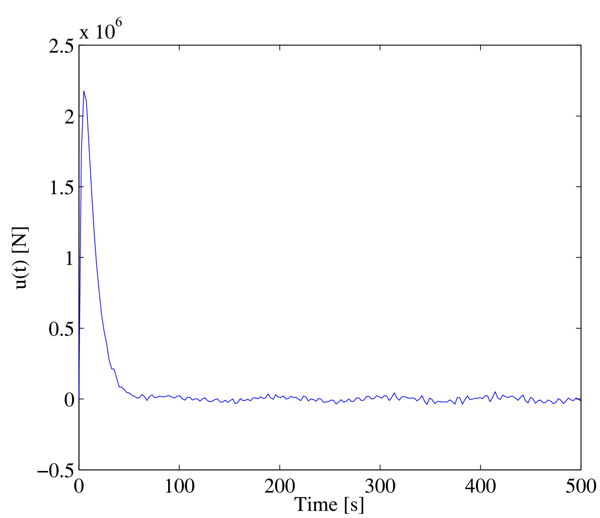


Fig. 11. Proposed control input u.

to address disturbances:

$$u = -\hat{M}kl\dot{p}_l' - \operatorname{sgn}(\dot{p}_l + klp_l')D_p - 2\kappa_p\dot{p}_l \quad (58)$$

$$v = -\hat{M}kl\dot{q}_l' - \operatorname{sgn}(\dot{q}_l + klq_l')D_q - 2\kappa_q\dot{q}_l \quad (59)$$

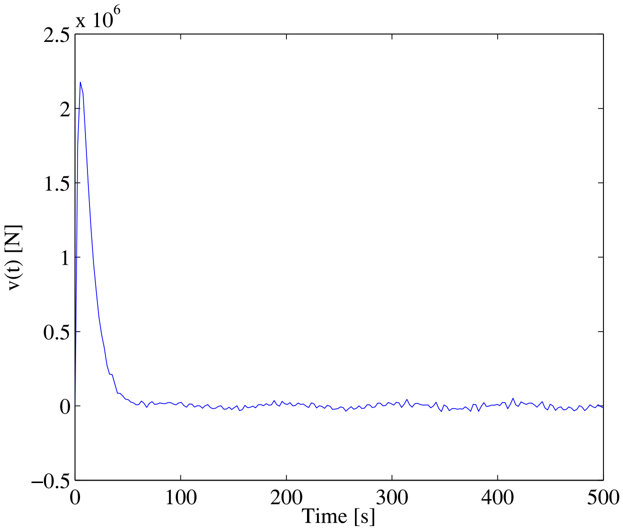


Fig. 12. Proposed control input v.

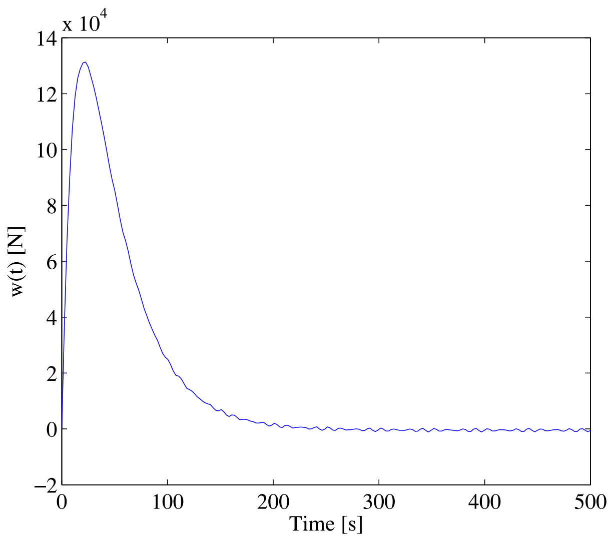


Fig. 13. Proposed control input w.

$$w = -\hat{M}kl\dot{r}_l' - \mathrm{sgn}\big(\dot{r}_l + klr_l'\big)D_r - 2\kappa_r\dot{r}_l \tag{60}$$

$$\dot{\hat{M}} = \mathrm{Proj}_M\big\{\big(kl\big[\dot{p}_l'\big(\dot{p}_l + klp_l'\big) + \dot{q}_l'\big(\dot{q}_l + klq_l'\big) + \dot{r}_l'\big(\dot{r}_l + klr_l'\big)\big]\big)\big\} - \mu_1\hat{M} \tag{61}$$

where $k, \kappa_p, \kappa_q, \kappa_r, \mu_1 > 0$. When selecting the same design parameters as the proposed control (14)–(16), the responses of the coupled system are as shown in Figs. 8–10 and 14–16. From Figs. 8–10, we observe that the control strategies (58)–(60) can also counteract external disturbances and achieve the vibration elimination in risers. However, the control effects are not as effective as those of the proposed control strategies (14)–(16). In addition, the symbol function in (58)–(60) causes chattering in the control inputs, as depicted in Figs. 14–16. This phenomenon is harmful to the system and should not be practiced.

Therefore, the proposed controllers can dramatically weaken the vibration in the coupled system with excellent performance, and the proposed control inputs are relatively smooth and have no chattering in comparison with the adaptive controllers in (58)–(60), revealing a satisfactory performance in stabilizing the coupled system and handling system uncertainties as well as ensuring the system robustness.

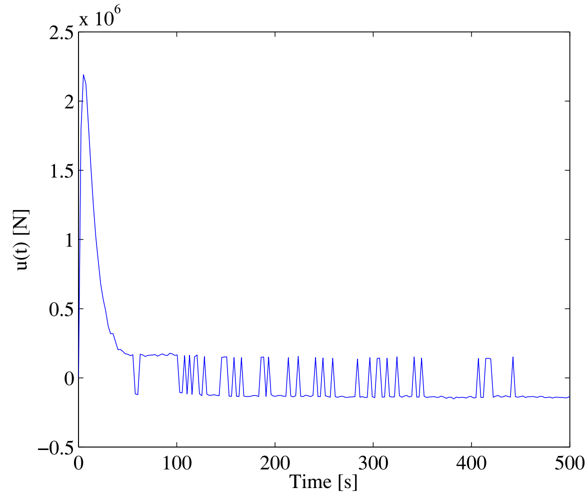


Fig. 14. Control input u in (58).

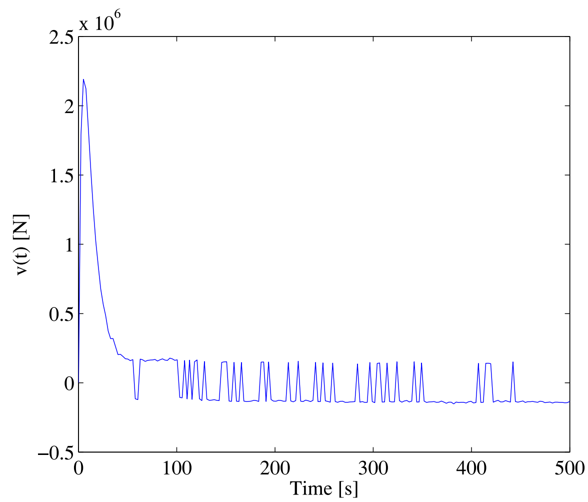


Fig. 15. Control input v in (59).

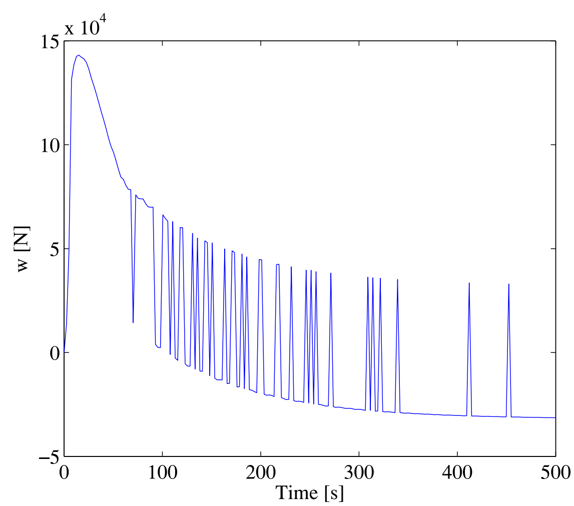


Fig. 16. Control input w in (60).

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

V. CONCLUSION

In this study, adaptive robust control schemes were proposed for a 3-D riser-vessel system subject to uncertainties in the system parameters and the upper bound of external disturbances. An adaptive robust control methodology and dynamically updating laws were designed to dampen vibrations and eliminate system uncertainties. By introducing the PMT and HTF in the design process, system robustness was ensured and the chattering phenomenon was prevented. The rigorous Lyapunov analysis guaranteed uniformly bounded stability in the controlled system. The control performance was verified by comparing the simulation results. Future interesting topics lie in the intelligent techniques [54]–[56] for controlled riser-vessel systems.

REFERENCES

[1] K.-S. Hong and U. H. Shah, "Vortex-induced vibrations and control of marine risers: A review," *Ocean Eng.*, vol. 152, pp. 300–315, Mar. 2018.

[2] Z. J. Zhao, Z. J. Liu, W. He, K.-S. Hong, and H.-X. Li, "Boundary adaptive fault-tolerant control for a flexible timoshenko arm with backlash-like hysteresis," *Automatica*, vol. 13, Aug. 2021, Art. no. 109690.

[3] P.-T. Pham and K.-S. Hong, "Dynamic models of axially moving systems: A review," *Int. J. Control Autom. Syst.*, vol. 100, no. 1, pp. 315–349, 2020.

[4] X. Y. He, W. He, Y. R. Liu, Y. H. Wang, G. Li, and Y. Wang, "Robust adaptive control of an offshore ocean thermal energy conversion system," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 12, pp. 5285–5295, Dec. 2020.

[5] M.-L. Wang, H.-X. Li, X. Chen, and Y. Chen, "Deep learning-based model reduction for distributed parameter systems," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 12, pp. 1664–1674, Dec. 2016.

[6] U. H. Shah and K.-S. Hong, "Active vibration control of a flexible rod moving in water: Application to nuclear refueling machines," *Automatica*, vol. 93, pp. 231–243, Jul. 2018.

[7] J. M. Wang, J. J. Liu, B. B. Ren, and J. H. Chen, "Sliding mode control to stabilization of cascaded heat pde-ode systems subject to boundary control matched disturbance," *Automatica*, vol. 52, pp. 23–34, Feb. 2015.

[8] T. Endo, F. Matsuno, and Y. Jia, "Boundary cooperative control by flexible timoshenko arms," *Automatica*, vol. 81, pp. 377–389, Jul. 2017.

[9] W. He, H. Gao, C. Zhou, C. Yang, and Z. Li, "Reinforcement learning control of a flexible manipulator: An experimental investigation," *IEEE Trans. Syst., Man, Cybern., Syst.*, early access, Mar. 5, 2020, doi: 10.1109/TSMC.2020.2975232.

[10] Z. J. Liu, J. K. Liu, and W. He, "Modeling and vibration control of a flexible aerial refueling hose with variable lengths and input constraint," *Automatica*, vol. 77, pp. 302–310, Mar. 2017.

[11] Z.-J. Liu, Z.-J. Zhao, and C.-K. Ahn, "Boundary constrained control of flexible string systems subject to disturbances," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 1, pp. 112–116, Jan. 2020.

[12] Z. J. Zhao and C. K. Ahn, "Boundary output constrained control for a flexible beam system with prescribed performance," *IEEE Trans. Syst., Man, Cybern., Syst.*, early access, Oct. 18, 2019, doi: 10.1109/TSMC.2019.2944900

[13] W. He, T. Wang, X. He, L. Yang, and O. Kaynak, "Dynamical modeling and boundary vibration control of a rigid-flexible wing system," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 6, pp. 2711–2721, Dec. 2020.

[14] Z. Liu, X. He, Z. Zhao, C. Ahn, and H. Li, "Vibration control for spatial aerial refueling hoses with bounded actuators," *IEEE Trans. Ind. Electron.*, vol. 68, no. 5, pp. 4209–4217, May 2021.

[15] Z. J. Liu, J. K. Liu, and W. He, "Robust adaptive fault tolerant control for a linear cascaded ode-beam systems," *Automatica*, vol. 98, pp. 42–50, Dec. 2018.

[16] Z. J. Liu, Z. J. Han, Z. J. Zhao, and W. He, "Modeling and adaptive control for a spatial flexible spacecraft with unknown actuator failures," *Sci. China Inf. Sci.*, vol. 68, Apr. 2021, Art. no. 152208, doi: 10.1007/s11432-020-3109-x.

[17] Y. Ren, P. Zhu, Z. Zhao, J. Yang, and T. Zou, "Adaptive fault-tolerant boundary control for a flexible string with unknown dead zone and actuator fault," *IEEE Trans. Cybern.*, early access, Jan. 21, 2021, doi: 10.1109/TCYB.2020.3044144.

[18] W. He, S. S. Ge, B. V. E. How, Y. S. Choo, and K.-S. Hong, "Robust adaptive boundary control of a flexible marine riser with vessel dynamics," *Automatica*, vol. 47, no. 4, pp. 722–732, 2011.

[19] T. L. Nguyen, K. D. Do, and J. Pan, "Boundary control of two-dimensional marine risers with bending couplings," *J. Sound Vib.*, vol. 332, no. 16, pp. 3605–3622, 2013.

[20] F. Guo, Y. Liu, Y. L. Wu, and F. Luo, "Observer-based backstepping boundary control for a flexible riser system," *Mech. Syst. Signal Process.*, vol. 111, pp. 314–330, Oct. 2018.

[21] Z. J. Zhao, C. K. Ahn, and G. L. Wen, "Cooperative disturbance rejection control of vibrating flexible riser systems," *Nonlinear Dyn.*, vol. 98, pp. 1603–1613, Jul. 2019.

[22] K. D. Do, "Boundary control of transverse motion of flexible marine risers under stochastic loads," *Ocean Eng.*, vol. 155, pp. 156–172, May 2018.

[23] K. D. Do and A. D. Lucey, "Boundary stabilization of extensible and unshearable marine risers with large in-plane deflection," *Automatica*, vol. 77, pp. 279–292, Mar. 2017.

[24] W. He, X. Y. He, and S. S. Ge, "Vibration control of flexible marine riser systems with input saturation," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 254–265, Feb. 2016.

[25] Z. J. Zhao, X. Y. He, and G. L. Wen, "Boundary robust adaptive anti-saturation control of vibrating flexible riser systems," *Ocean Eng.*, vol. 179, pp. 298–306, May 2019.

[26] Z. J. Zhao, Z. J. Liu, Z. F. Li, N. Wang, and J. F. Yang, "Control design for a vibrating flexible marine riser system," *J. Franklin Inst.*, vol. 354, no. 18, pp. 8117–8133, 2017.

[27] F. Guo, Y. Liu, and F. Luo, "Adaptive stabilisation of a flexible riser by using the Lyapunov-based barrier backstepping technique," *IET Control Theory Appl.*, vol. 11, no. 14, pp. 2252–2260, 2017.

[28] W. He, C. Sun, and S.-S. Ge, "Top tension control of a flexible marine riser by using integral-barrier Lyapunov function," *IEEE Trans. Mechatronics*, vol. 20, no. 2, pp. 497–505, Apr. 2015.

[29] Z. J. Zhao, S. M. Lin, D. C. Zhu, and G. L. Wen, "Vibration control of a riser-vessel system subject to input backlash and extraneous disturbances," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 3, pp. 516–520, Mar. 2020.

[30] Z. J. Zhao, C. K. Ahn, and H.-X. Li, "Dead zone compensation and adaptive vibration control of uncertain spatial flexible riser systems," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 3, pp. 1398–1408, 2020.

[31] X. Y. He, Z. J. Zhao, J. Y. Su, Q. M. Yang, and D. C. Zhu, "Adaptive inverse control of a vibrating coupled vessel-riser system with input backlash," *IEEE Trans. Syst., Man, Cybern., Syst.*, early access, Oct. 17, 2019 doi: 10.1109/TSMC.2019.2944999.

[32] Z. J. Zhao, X. Y. He, Z. G. Ren, and G. L. Wen, "Boundary adaptive robust control of a flexible riser system with input nonlinearities," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 10, pp. 1971–1980, Oct. 2019.

[33] K. D. Do, "Stochastic boundary control design for extensible marine risers in three dimensional space," *Automatica*, vol. 77, pp. 184–197, Mar. 2017.

[34] K. D. Do, "Boundary control design for extensible marine risers in three dimensional space," *J. Sound Vib.*, vol. 388, no. 3, pp. 1–19, 2017.

[35] K. D. Do and J. Pan, "Boundary control of three-dimensional inextensible marine risers," *J. Sound Vib.*, vol. 327, nos. 3–5, pp. 299–321, 2009.

[36] S. Zhang, X. Y. He, and C. Yang, "Vibration control of a flexible marine riser with joint angle constraint," *Nonlinear Dyn.*, vol. 87, pp. 617–632, Jan. 2017.

[37] W. He, C. Yang, J. X. Zhu, J. K. Liu, and X. Y. He, "Active vibration control of a nonlinear three-dimensional Euler–Bernoulli beam," *J. Vib. Control*, vol. 23, no. 19, pp. 3196–3215, 2017.

[38] Z. J. Zhao, X. Y. He, and C. K. Ahn, "Boundary disturbance observer-based control of a vibrating single-link flexible manipulator," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 4, pp. 2382–2390, Apr. 2021.

[39] W. He, T. T. Meng, D. Q. Huang, and X. F. Li, "Adaptive boundary iterative learning control for an Euler–Bernoulli beam system with input constraint," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 29, no. 5, pp. 1524–1535, May 2018.

[40] Z. J. Zhao, C. K. Ahn, and H.-X. Li, "Boundary antidisturbance control of a spatially nonlinear flexible string system," *IEEE Trans. Ind. Electron.*, vol. 67, no. 6, pp. 4846–4856, Jun. 2020.

[41] Y. Liu, W. Zhan, M. Xing, Y. Wu, R. Xu, and X. Wu, "Boundary control of a rotating and length-varying flexible robotic manipulator," *IEEE Trans. Syst., Man, Cybern., Syst.*, early access, Jun. 24, 2020, doi: 10.1109/TSMC.2020.2999485.

[42] Z. J. Zhao and Z. J. Liu, "Finite-time convergence disturbance rejection control for a flexible timoshenko manipulator," *IEEE/CAA J. Automatica Sinica*, vol. 8, no. 1, pp. 157–168, Jan. 2021.

[43] Y. Liu, F. Guo, X. He, and Q. Hui, "Boundary control for an axially moving system with input restriction based on disturbance observers," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 11, pp. 2242–2253, Nov. 2019.

[44] M. M. Polycarpou and P. A. Ioannou, "A robust adaptive nonlinear control design," *Automatica*, vol. 32, no. 3, pp. 423–427, 1996.

[45] W. Meng, Q. Yang, J. Si, and Y. Sun, "Adaptive neural control of a class of output-constrained nonaffine systems," *IEEE Trans. Cybern.*, vol. 46, no. 1, pp. 85–95, Jan. 2016.

[46] J. Li, Q. Yang, B. Fan, and Y. Sun, "Robust state/output-feedback control of coaxial-rotor MAVs based on adaptive nn approach," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 30, no. 12, pp. 3547–3557, Dec. 2019.

[47] X. Li, C. Ahn, D. Lu, and S. Guo, "Robust simultaneous fault estimation and nonfragile output feedback fault-tolerant control for Markovian jump systems," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 9, pp. 1769–1776, Sep. 2019.

[48] X.-G. Guo, D.-C. Tan, C. K. Ahn, and J.-L. Wang, "Fully distributed adaptive fault-tolerant sliding-mode control for nonlinear leader-following multiagent systems with ANASS and IQCs," *IEEE Trans. Cybern.*, early access, Oct. 12, 2020, doi: 10.1109/TCYB.2020.3023747.

[49] Z. Ruan, Q. Yang, S. Ge, and Y. Sun, "Performance-guaranteed fault-tolerant control for uncertain nonlinear systems via learning-based switching scheme," *IEEE Trans. Neural Netw. Learn. Syst.*, early access, Sep. 1, 2020, doi: 10.1109/TNNLS.2020.3016954.

[50] Z. Ruan, Q. Yang, S. Ge, and Y. Sun, "Adaptive fuzzy fault tolerant control of uncertain MIMO nonlinear systems with output constraints and unknown control directions," *IEEE Trans. Fuzzy Syst.*, early access, Jan. 29, 2021, doi: 10.1109/TFUZZ.2021.3055336.

[51] Q. C. Nguyen and K.-S. Hong, "Simultaneous control of longitudinal and transverse vibrations of an axially moving string with velocity tracking," *J. Sound Vib.*, vol. 331, no. 13, pp. 3006–3019, 2012.

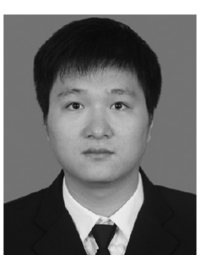
[52] Z. Liu, J. Liang, Z. Zhao, M. O. Efe, and K.-S. Hong, "Adaptive fault-tolerant control of a probe-and-drogue refueling hose under varying length and constrained output," *IEEE Trans. Control Syst. Technol.*, early access, May 25, 2021, doi: 10.1109/TCST.2021.3079275.

[53] Z. Zhao, Y. Ren, C. Mu, T. Zou, and K.-S. Hong, "Adaptive neural-network-based fault-tolerant control for a flexible string with composite disturbance observer and input constraints," *IEEE Trans. Cybern.*, early access, doi: 10.1109/TCYB.2021.3090417.

[54] T. Zhang, X. Wang, X. Xu, and C. L. P. Chen, "GCB-Net: Graph convolutional broad network and its application in emotion recognition," *IEEE Trans. Affect. Comput.*, early access, Aug. 27, 2019, doi: 10.1109/TAFFC.2019.2937768.

[55] T. Zhang, X. Gong, and C. L. P. Chen, "BMT-Net: Broad multitask transformer network for sentiment analysis," *IEEE Trans. Cybern.*, early access, Mar. 4, 2021, doi: 10.1109/TCYB.2021.3050508.

[56] T. Zhang, C. Lei, Z. Zhang, X. Meng, and C. L. P. Chen, "AS-NAS: Adaptive scalable neural architecture search with reinforced evolutionary algorithm for deep learning," *IEEE Trans. Evol. Comput.*, early access, Feb. 23, 2021, doi: 10.1109/TEVC.2021.3061466.



Zhijia Zhao (Member, IEEE) 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 research interests include adaptive and learning control, flexible mechanical systems, and robotics.

Yiming Liu received the B.Eng. degree in robotics engineering from Guangzhou University, Guangzhou, China, in 2021, where he is currently pursuing the master's degree.

His research interests include flexible systems, distributed parameter system control, and robotics.

Tao Zou was born in Liaoning, China, in 1975. He received the Ph.D. degree in control theory and control engineering from Shanghai Jiao Tong University, Shanghai, China, in 2005.

Since 2019, he has been a Professor with the School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou, China. His research interests include industrial process modeling and simulation, model predictive control, advanced process control, decision making, and real-time optimization technology research and application.

Keum-Shik Hong (Fellow, IEEE) received the B.S. degree in mechanical design and production engineering from Seoul National University, Seoul, South Korea, in 1979, the M.S. degree in mechanical engineering from Columbia University, New York, NY, USA, in 1987, and both an M.S. degree in applied mathematics and the Ph.D. degree in mechanical engineering from the University of Illinois at Urbana–Champaign, Champaign, IL, USA, in 1991.

He joined the School of Mechanical Engineering, Pusan National University (PNU), Busan, South Korea, in 1993. His Integrated Dynamics and Control Engineering Laboratory was designated a National Research Laboratory by the Ministry of Science and Technology of Korea in 2003. In 2009, under the auspices of the World Class University Program of the Ministry of Education, Science and Technology of Korea, he established with the Department of Cogno-Mechatronics Engineering, PNU. His current research interests include brain–computer interface, nonlinear systems theory, adaptive control, distributed parameter systems, autonomous vehicles, and innovative control applications in brain engineering.

Dr. Hong has received many awards, including the Best Paper Award from the KFSTS of Korea in 1999, the F. Harashima Mechatronics Award in 2003, the IJCAS Scientific Activity Award in 2004, the Automatica Certificate of Outstanding Service in 2006, the Presidential Award of Korea in 2007, the Institute of Control, Robotics and Systems (ICROS) Achievement Award in 2009, the IJCAS Contribution Award in 2010, the Premier Professor Award in 2011, the JMST Contribution Award in 2011, the IJCAS Contribution Award in 2011, and the IEEE Academic Award of ICROS in 2016. He served as an Associate Editor of *Automatica* from 2000 to 2006, the Editor-in-Chief of the *Journal of Mechanical Science and Technology* from 2008 to 2011, and the Editor-in-Chief of the *International Journal of Control, Automation, and Systems*. He was a Past President of the ICROS, Korea, and the President-Elect of Asian Control Association. He was the Organizing Chair of the ICROS-SICE International Joint Conference 2009, Fukuoka, Japan. He is a Fellow of the Korean Academy of Science and Technology, an ICROS Fellow, a Member of the National Academy of Engineering of Korea, and many other societies.