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Robust output feedback stabilization for a flexible marine riser system

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ABSTRACT

The aim of this paper is to develop a boundary control for the vibration reduction of a flexible marine riser system in the presence of parametric uncertainties and system states obtained inaccurately. To this end, an adaptive output feedback boundary control is proposed to suppress the riser's vibration fusing with observer-based backstepping, high-gain observers and robust adaptive control theory. In addition, the parameter adaptive laws are designed to compensate for the system parametric uncertainties, and the disturbance observer is introduced to mitigate the effects of external environmental disturbance. The uniformly bounded stability of the closed-loop system is achieved through rigorous Lyapunov analysis without any discretisation or simplification of the dynamics in the time and space, and the state observer error is ensured to exponentially converge to zero as time grows to infinity. In the end, the simulation and comparison studies are carried out to illustrate the performance of the proposed control under the proper choice of the design parameters.

1. Introduction

The flexible marine riser is a key component as the link between the production platform and the well head, and plays a significant role in offshore engineering development [1–5]. As oil drilling and gas exploration go to deep water, the current environment the riser confronts with becomes more and more harsher, and vibration and deformation due to the wind, waves, ocean currents and so on become more and more stronger [6,7]. However, the excessive vibration of the riser reduces the system performance, limits the production efficiency, gives rise to premature fatigue failure and even leads serious environment pollution [8,9]. Therefore, the vibration suppression of the riser has received considerable research interests in academic and engineering fields.

In the mathematical sense, the riser system can be perceived as a distributed parameter system (DPS), the dynamics of which is modelled as a hybrid model expressed in the form of a partial differential equation (PDE) and a variety of ordinary differential equations (ODEs). Due to the infinite-dimensional nature of the DPS, it is difficult to directly conduct the control design. The traditional truncated model-based methods are employed in different ways to extract a finite-dimensional subsystem to be controlled while showing robustness to neglecting the remaining infinite-dimensional dynamics in the design [10–16], which will result in control spillover instability. To circumvent the issue mentioned above, researchers have devoted significant efforts to boundary control for infinite-dimensional systems, where the control designs are based on the infinite-dimensional PDE dynamics [17–24].

In recent decades, motivated by practical needs and theoretical challenges, there have been some results on boundary control synthesis for flexible riser systems [1–4,6,8,9,25–29]. To mention a few, the angle control and vibration reduction for a flexible marine riser were investigated by exerting a torque actuator at the riser's top boundary [1]. Based on the Lyapunov's direct method, boundary controllers were proposed to reduce the riser's vibrations and compensate rotational effects [2–4]. The robust and adaptive boundary control was constructed to control the riser's transverse vibration and compensate the system parametric uncertainties [6]. The Lyapunov's direct method and ODE backstepping method were merged to develop boundary controllers for globally stabilizing the riser system and the well-posed problem was discussed based on Galerkin approximation method [8,9]. Top tension control and input saturation constraint were addressed by introducing an integral-barrier Lyapunov function and an auxiliary system [25,26]. In [27], the author studied the boundary controller design for 3D extensible marine risers in the presence of stochastic and deterministic sea loads. In [28], the boundary control laws were designed to exponentially stabilize extensible marine risers in three dimensional space and the system stability was

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demonstrated based on Hilbert space. In [29], the boundary control was presented to damp the vibration of a nonlinear drilling riser and the exponential stability of the closed-loop system was guaranteed.

Backstepping control (i.e., ODE backstepping method) has been the most popular nonlinear control method for stabilizing the nonlinear ODE systems since the early 1990s, because backstepping has the ability to handle a wide variety of nonlinearities in the controller design process [30]. Backstepping controller design can provide an iterative choice of control Lyapunov functions and finally generate a control law for stabilizing the state variables step by step. Around 2000, a method was proposed by Krstic to extend backstepping to PDEs in the context of boundary control [31], which is also called PDE backstepping method, but it is difficult to apply to the riser system considered in this paper due to difficulties in finding proper gain kernels. In [8], the ODE backstepping technique is exploited to develop a boundary control scheme for globally stabilizing the riser system without resort to model discretization. However, for the case that some of the system states cannot be measured and there exist the system parametric uncertainties, the ODE backstepping method [30] may not guarantee the stability of the closed-loop system. Thus, to circumvent the above-mentioned issue, the observer-based backstepping [30], high-gain observers [32,33] and robust adaptive control theory [34], will be adopted to design an adaptive output feedback boundary control, which is currently lacking in the literature of boundary control for flexible riser systems.

The main contributions of this paper include the following. First, for the case that the system state available for feedback cannot be accurately obtained, the observer-based backstepping is exploited to refactor the system state, and then an adaptive boundary control is developed for vibration suppression and parametric uncertainties compensation of the riser system fusing with Lyapunov's direct method and robust adaptive control theory. Second, when some of the system states in the initially proposed control cannot be measured, high-gain observers are adopted to estimate the unmeasurable system states for output feedback control. Third, the disturbance observer is introduced to deal with external environmental disturbance, and the online adaptive laws are designed to compensate the system parametric uncertainties. Fourth, under the proposed control, the uniformly bounded stability of the controlled system is assured employing rigorous analysis without any discretisation or simplification of the dynamics in the time and space, and the state observer error converges exponentially to zero as time tends to infinity.

The remainder of this paper is structured as follows. The governing equation and boundary conditions of the riser system are introduced and problem statement is completed in Section 2. An adaptive output feedback boundary control is developed to suppress the riser's vibration and Lyapunov's synthetic method is used to analyze the stability of the closed-loop system in Section 3. Numerical simulations are presented in Section 4 and the conclusion is given in Section 5.

2. Problem statement

Fig. 1 shows a typical marine riser system. Let XOY be the reference frame, O be coordinate origin, x and t be the independent spatial and time variables, respectively, $w(x,t)$ be the deflection at spatial coordinate x for time t, L, m, T, EI, and c be the length, uniform mass per unit length, tension, bending stiffness, damping coefficient of the riser, respectively, d_a and M be the damping coefficient and the mass of the vessel, $d(t)$ be the environmental disturbance on the vessel, $f(x,t)$ be the distributed disturbance arising from the hydrodynamic effects of the ocean current, and

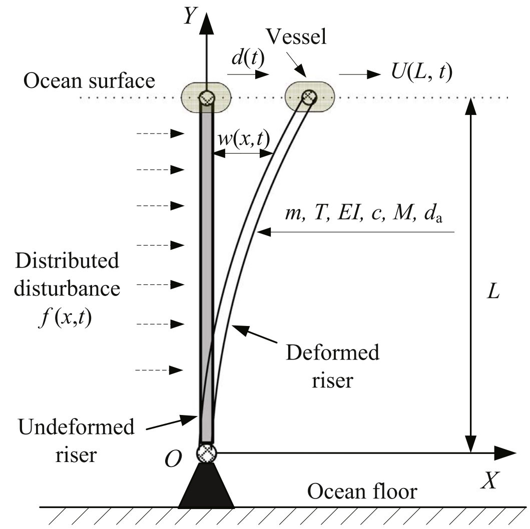

Fig. 1. A typical marine riser system.

$U(L,t)$ be the control input exerted at the riser's top boundary. In this paper, we assume that there is no deflection in the Y direction and the riser is filled with seawater.

In this paper, the governing equation and boundary conditions of the riser system shown in Fig. 1 are given as follows [6]

$$m\ddot{w}(x,t) + EIw''''(x,t) - Tw''(x,t) - f(x,t) + c\dot{w}(x,t) = 0,\ 0 < x < L. \quad (1)$$

$$\begin{cases} w(0,t) = w'(0,t) = w''(L,t) = 0, \\ -EIw'''(L,t) + Tw'(L,t) = U(L,t) + d(t) - d_a\dot{w}(L,t) - M\ddot{w}(L,t). \end{cases} \quad (2)$$

Assumption 1. For the disturbances $d(t)$ and $f(x,t)$, we assume that there exist constants ϖ_1, $\varpi_2 \in \mathbb{R}^+$, such that $|d(t)| \le \varpi_1$, $\forall\ t \in [0,+\infty)$ and $|f(x,t)| \le \varpi_2$, $\forall\ (x,t) \in [0,L] \times [0,+\infty)$.

Assumption 2. For the time derivative of external environmental disturbance $\dot{d}(t)$, we assume that it is uniformly bounded and there exists a constant $\varpi_3 \in \mathbb{R}^+$, such that $|\dot{d}(t)| \le \varpi_3$, $\forall\ t \in [0,+\infty)$.

Remark 1. For control design in Section 3, only the assertion that there exist upper bounds on the disturbances in Assumption 1, $|d(t)| \le \varpi_1$, and $|f(x,t)| \le \varpi_2$, is necessary.

Remark 2. Different from the existing results associated with the approximation of nonlinear terms via fuzzy models [35,36], in this paper, the governing Eq. (1) of the considered riser system is governed by a linear hyperbolic partial differential equation, and the following control design and stability analysis are conducted with no simplifying or approximating the original infinite dimensional system dynamics.

3. Control design

In this section, observer-based backstepping, robust adaptive control theory, high-gain observers and Lyapunov's direct method are synthesized to design an adaptive output feedback boundary control for globally stabilizing the riser system. The parameter adaptive laws are adopted to compensate the system parametric uncertainties when EI, m, d_a and T are not available, and the disturbance observer is proposed to handle external environmental disturbance. In addition, the uniformly bounded stability of the closed-loop system is detailedly demonstrated via Lyapunov's synthetic method.

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