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Observer-based backstepping boundary control for a flexible riser system

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ABSTRACT

In order to achieve the disturbance rejection and vibration abatement of a flexible marine riser system, this article discusses the design of disturbance observers and controller. The riser system subjected to external disturbances is a distributed parameter system in essence and represented by infinite-dimensional equation coupled with finite-dimensional equations. In addition to designing a basic boundary disturbance observer to deal with the time-varying boundary disturbance in this paper, an innovative infinite dimensional disturbance observer is also designed to compensate for the spatially distributed disturbance. Applying these two observers as feedforward compensators, an observer-based boundary controller is formulated by means of combining backstepping technique with boundary control method. Moreover, the well-posedness of the closed-loop riser system is discussed, and simulations are presented to display the effectiveness of formulated control approach.

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1. Introduction

The flexible structure is a crucial module in a wide variety of mechanical engineering systems, including manipulators [1,2], marine risers [3–5], spacecrafts [6] and gantry cranes [7], where the external disturbances are unavoidable. To take one example, there are a variety of environmental loads in the oceans, including wave, wind, ocean current and so on [4]. Under the action of these environmental loads, the unwanted vibration would occur, which will inevitably degrade the performance of the system and produce the premature fatigue problem. For this reason, rejecting disturbance and restraining vibration of the flexible structure systems have already arouse extensive attentions and become a research hotspot in the area of engineering [8–12]. In view of the given example, specifically, this article will focus on the study about disturbance rejection and vibration abatement of the flexible riser system.

In the mathematical sense, the riser system is a distributed parameter system (DPS) in essence and represented by infinite-dimensional equation (PDE) coupled with finite-dimensional equations (ODEs) [4], thus the core of this article is to handle the control issue of the DPS. Up to now, there have been many rich research results of this issue, and they can be mainly separated into two categories, those which work based on truncated ODE model and those which work based on the original PDE model. The methods of the first category, including the Galerkin's method, finite-element method and assumed modes method [13–16], usually need to discretize or simplify the DPS, which will result in control spillover or even

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Nomenclature

L	the length of the riser
ρ	the uniform mass per unit length of the riser
M_s	the mass of the surface vessel
T	the tension of the riser
EI	the bending stiffness of the riser
c	the damping coefficient of the riser
d_s	the damping coefficient of the vessel
$d(t)$	the environmental disturbance on the vessel
$f(s,t)$	the distributed disturbance on the riser
$z(s,t)$	the displacement of the riser at the position s for time t
$u(t)$	the control input from the actuator in the vessel

unstable problems owing to the neglect of high frequency modes. The typical representative of another category is the boundary control method, which can describe system states and infinite dimensional dynamics quite precisely and avoid the defects mentioned above effectively. Due to the significant advantages of boundary control, it integrated with additional advanced approaches, including neural network [17–19], robust and adaptive control [20–22], sliding mode control [23,24] and so on, has been employed extensively in the control research of DPS [25–31]. In [25], the uniform boundedness of the thruster assisted position mooring system is achieved via constructing an appropriate robust adaptive boundary control. In [26,27], for reducing vibration and handling input saturation, boundary controls with auxiliary system are designed for the axially moving system and riser system, respectively. In [28], two boundary controllers are studied for decreasing riser's vibration as well as guaranteeing the top tension constraint satisfaction. For handling the boundary control issue of the flexible manipulator with input disturbances and output constraints, the boundary control with prescribed performance design is established in [29]. In [30], active vibration control of the axially moving accelerated/decelerated belt system is discussed by employing a boundary controller with disturbance observer. In [31], the vibration control scheme is investigated for an axially moving string, where the asymptotic stability of closed-loop system is realized.

In the existing literatures on control issue of the DPS, almost all the attention are focused on the boundary disturbance cancelling and great progress has been made, including signum function [25,27,28] and disturbance observer [26,29–31]. Compared with the signum function, disturbance observer has more advantages since it can not only handle the effects of boundary disturbance but also avoid chattering problem brought by the signum function. However, it must be noted that the spatially distributed disturbance, as an inevitable factor affecting the system performance, is not effectively handled. Due to its infinite dimensional feature, the above methods are invalid. Based on this, an innovative infinite dimensional disturbance observer is designed to accurately estimate the distributed disturbance with unknown model. Therefore, the first innovation of this article is that in addition to designing a basic boundary disturbance observer to handle boundary disturbance, an infinite dimensional disturbance observer is also designed to compensate for the spatially distributed disturbance.

Meanwhile, backstepping control initially for stabilizing ODE has been extended to the PDE, which is called infinite dimensional backstepping method for distinguishing [32–34]. Although this method can provide an iterative choice of Lyapunov functions and finally obtain a control law for stabilizing the state variables step by step, it is not very easy to solve the riser system discussed in this article because the issue of gain kernel selection can be so difficult. For this reason, the finite dimensional backstepping technique bind with boundary control method will be utilized to formulate an appropriate controller based on the infinite dimensional riser model, which is also an innovation of this article.

Compared with the existing results, the main contributions of this article are highlighted as follows.

i. On the basis of Lyapunov's direct method, finite dimensional backstepping technique integrated with boundary control method is employed to put forward a control approach aiming at compensating for external disturbances and suppressing the vibration of the riser system.
ii. The boundary disturbance observer is proposed to handle the time-varying boundary disturbance, and the infinite dimensional disturbance observer is designed to compensate for the spatially distributed disturbance. Applying them as feedforward compensators, the observer-based boundary controller is formulated.
iii. With the formulated control approach, the well-posedness of considered closed-loop riser system is mathematically demonstrated.

The remainder of this article is outlined as follows. The PDE dynamics of the riser system and some readiness knowledge are provided in Section 2. The control approach, including a boundary disturbance observer and an infinite dimensional disturbance observer as well as an observer-based boundary controller is formulated in Section 3. In Section 4, the well-posedness of the closed-loop riser system is discussed. In Section 5, simulations are displayed for verifying the usefulness of formulated control approach and the conclusion is presented in Section 6.

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