Automatica 50 (2014) 1843–1851

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Brief paper

Robust adaptive control of a thruster assisted position mooring system[☆]

Wei He [a], Shuang Zhang [b], Shuzhi Sam Ge [c,d,1]

[a] Robotics Institute and School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

[b] School of Aeronautics and Astronautic, University of Electronic Science and Technology of China, Chengdu 611731, China

[c] Robotics Institute and School of Computer Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

[d] Department of Electrical & Computer Engineering, National University of Singapore, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 9 July 2012
Received in revised form
25 January 2014
Accepted 22 March 2014
Available online 16 May 2014

Keywords:
Distributed parameter system
Flexible structure
Boundary control
Vibration control
Marine mooring system

ABSTRACT

In this paper, robust adaptive control is developed for a thruster assisted position mooring system in the transverse direction. To provide an accurate and concise representation for the dynamic behavior of the mooring system, the flexible mooring lines are modeled as a distributed parameter system of partial differential equations (PDEs). The proposed control is applied at the top boundary of the mooring lines for station keeping via Lyapunov's direct method. Adaptive control is designed to handle the system parametric uncertainties. With the proposed robust adaptive control, uniform boundedness of the system under the ocean current disturbance is achieved. The proposed control is implementable with actual instrumentations since all the signals in the control can be measured by sensors or calculated by using a backward difference algorithm. The effectiveness of the proposed control is verified by numerical simulations.

1. Introduction

In recent years, with the increasing trend towards oil and gas exploitation in deep water (>500 m), fixed platforms based on the seabed have become impractical (He, Ge, & Zhang, 2012; He, Zhang, & Ge, 2013b). Instead, floating platforms such as anchored Floating Production Storage and Offloading (FPSO) vessels with positioning systems have been used widely. Station keeping means maintaining the vessel within a desired position in the horizontal-plane, which has been identified as one of the most typical problems in offshore engineering. The thruster assisted position mooring system is an economical solution for station keeping in deep water due to the long operational period in harsh environmental conditions. The thruster assistance is required in harsh environmental conditions to avoid the failure of mooring lines. A typical thruster assisted position mooring system consisting of an ocean surface vessel and a number of flexible mooring lines is shown in Fig. 1. The surface vessel, to which the top boundary of the mooring lines is connected, is equipped with a dynamic positioning system with active thrusters. The bottom boundary of the mooring lines is fixed in the ocean floor by the anchors. The total mooring system is subjected to environmental disturbances including ocean current, wave, and wind. The mooring lines that span a long distance can produce large vibrations under relatively small disturbances, which will degrade the performance of the system and result in a larger offset from the target position of the vessel. Taking into account the unknown time-varying ocean disturbances of the mooring lines lead to the appearance of oscillations, which make the control problem of the mooring system relatively difficult.

Many results have been obtained for control of dynamic positioning systems (Chen, Ge, How, & Choo, 2012; Do & Pan, 2004; Tee & Ge, 2006). An elegant neural learning control design technique is developed for marine positioning systems in Dai, Wang, and Luo (2012) and Dai, Wang, Wang, and Li (2014). Earlier research on the control of the thruster assisted position mooring systems mainly focus on the dynamics of the vessel,

☆ This work was supported by the National Natural Science Foundation of China under Grant 61203057, the Fundamental Research Funds for the China Central Universities of UESTC under Grant ZYGX2012J087, ZYGX2013Z003, and the National Basic Research Program of China (973 Program) under Grant 2014CB744206. The material in this paper was partially presented at the 31st Chinese Control Conference (CCC 2012), July 25–27, 2012, Hefei, China. This paper was recommended for publication in revised form by Associate Editor Yoshihiko Miyasato under the direction of Editor Toshiharu Sugie.

E-mail addresses: hewei.ac@gmail.com (W. He), zhangshuang.ac@gmail.com (S. Zhang), samge@nus.edu.sg (S.S. Ge).

1 Tel.: +65 65166821; fax: +65 65166821.

http://dx.doi.org/10.1016/j.automatica.2014.04.023
0005-1098/

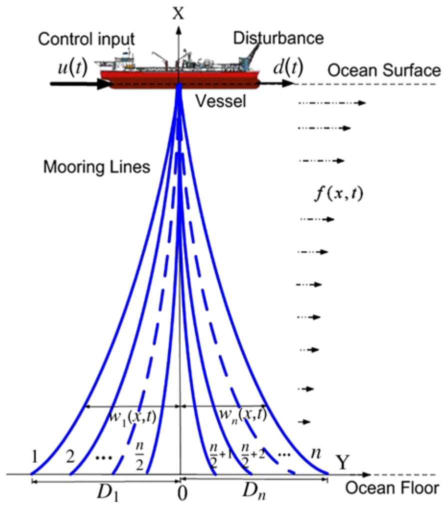

Fig. 1. A FPSO vessel with the thruster assisted position mooring system.

where the dynamics of the mooring lines is usually ignored for the convenience of the control design (Chen et al., 2012). In these works, the dynamics of the mooring lines is usually considered as an external force term to the vessel dynamics. One drawback of the model is that it can influence the dynamic response of the whole mooring system due to the neglect of the coupling between the vessel and the mooring lines. To overcome this shortcoming, in this paper, the mooring system is represented by PDEs describing the dynamics of the mooring lines coupled with ODEs representing the lumped vessel dynamics. However, the dynamics of the flexible mechanical system modeled by PDE is difficult to control due to the infinite dimensionality of the system. Approaches to control infinite dimensional PDE systems such as the finite element method, Galerkin's method, the Laplace transform and the assumed modes method (Barczyk & Lynch, 2008) are based on the truncated finite-dimensional models of the system. The truncated models are obtained via the model analysis or spatial discretization, in which the system is represented by a finite number of modes by neglecting the higher frequency modes (Luo & Wu, 2012; Wu & Li, 2007). The problems arising from the truncation procedure in the modeling need to be carefully treated in practical applications. In the last decades, there has been a growing interest in the use of the control techniques for the flexible systems to overcome the shortcomings of the truncated model based control. Boundary control combining with other control methodologies such as the energy-based control (He & Ge, 2012), the averaging method (Hong & Bentsman, 1994), the backstepping method (Krstic & Smyshlyaev, 2008a,b), and the robust adaptive control (Ge, He, How, & Choo, 2010; Ge, Zhang, & He, 2011; Yang, Hong, & Matsuno, 2004) have been developed. In these approaches, system dynamics analysis and control design are carried out directly based on the PDEs of the system. In contrast, boundary control where the actuation and sensing are applied only through the boundary of the system utilizes the original distributed parameter model with PDEs to avoid control spillover instabilities.

Boundary control is considered to be more practical in a number of research fields including vibration control of flexible structures (He, Ge, How, & Choo, 2013; He, Ge, How, Choo, & Hong, 2011; He, Zhang, & Ge, 2013c), fluid dynamics (Xu, Schuster, Vazquez, & Krstic, 2008) and heat transfer (Huang, Xu, Li, Xu, & Yu, 2013; Wang, Ren, & Krstic, 2012), which requires less sensors and actuators. The relevant applications for this approach in mechanical flexible structures consist of second order structures (strings, and cables) and fourth order structures (beams and plates) (Rahn, 2001). Based on Lyapunov's direct method, the authors in Guo and Guo (2013), He, Ge, and Zhang (2011), He, Zhang, and Ge (2013a), Nguyen and Hong (2010, 2012) and Yang, Hong, and Matsuno (2005) have presented the results for the boundary control of the flexible string systems. In all these works, boundary control is designed for vibration suppression only for one flexible beam or string. Considering a multi-cable mooring system, the system is governed by arbitrary nonhomogeneous hyperbolic PDEs, which make the system model quite different compared with the previous work due to the coupling between the mooring lines and the vessel. In this paper, we are going to further study the robust adaptive boundary control problem for the mooring system with parametric uncertainties and under unknown time-varying disturbance. Both the dynamics of the vessel and the mooring lines are considered explicitly in the control design.

The rest of the paper is organized as follows. The governing equations (PDEs) and boundary conditions (ODEs) of the mooring system are derived by use of Hamilton's principle in Section 2. The control design via Lyapunov's direct method is discussed in Section 3, where it is shown that the uniform boundedness of the closed-loop system can be achieved by the proposed control. Simulations are carried out to illustrate the performance of the proposed control in Section 4. The conclusion of this paper is presented in Section 5.

2. Problem formulation and preliminaries

In this paper, we assume that (i) the vessel is at the top boundary of the mooring lines and all the mooring lines are filled with seawater; (ii) the mooring lines deform in one vertical plane, and their axial motions are ignored; and (iii) the flexible mooring lines with uniform density and flexural rigidity are modeled as the mechanical string structure. For the practical application of the thruster assisted position mooring system, there are a total of n (n is a even number) mooring lines in the system, in which $\frac{n}{2}$ mooring lines are located at the left and right hand sides of the vessel respectively. As shown in Fig. 1, the numbers of mooring lines in the left hand side of the vessel are $1, 2, \dots, \frac{n}{2}$, and the numbers of the mooring lines in the right hand side of the vessel are $\frac{n}{2}+1, \frac{n}{2}+2, \dots, n$.

2.1. Dynamic analysis

The dynamics of the surface vessel in the vertical plane can be modeled as

$$M\frac{\partial^2 w(L,t)}{\partial t^2} + d_s\frac{\partial w(L,t)}{\partial t} = u(t) - \tau(t) + d(t), \tag{1}$$

where $w(L,t)$, $\frac{\partial w(L,t)}{\partial t}$ and $\frac{\partial^2 w(L,t)}{\partial t^2}$ are the position, velocity and acceleration of the vessel respectively, M is the mass of the surface vessel, d_s is the damping, $u(t)$ is the control force from controller actuation, $\tau(t)$ is the tension force exerted on the vessel from the mooring lines, and $d(t)$ is the unknown disturbance on the vessel due to the ocean wave, wind and current. From Fig. 1, we can see that the vessel is connected to the top boundary of the mooring lines. Therefore, $w(L,t)$ is also a boundary value of the function $w(x,t)$. Note that $\frac{\partial w(L,t)}{\partial t} = \frac{\partial w(x,t)}{\partial t}|_{x=L}$ and $\frac{\partial^2 w(L,t)}{\partial t^2} = \frac{\partial^2 w(x,t)}{\partial t^2}|_{x=L}$.

The kinetic energy of the mooring system E_k can be represented as

$$\begin{aligned} E_k = {} & \frac{1}{2}M\left[\frac{\partial w(L,t)}{\partial t}\right]^2 \\ & + \frac{1}{2}\sum_{i=1}^{\frac{n}{2}}\rho\int_0^L\left[\frac{\partial[w_i(x,t)+D_i]}{\partial t}\right]^2 dx \\ & + \frac{1}{2}\sum_{i=\frac{n}{2}+1}^{n}\rho\int_0^L\left[\frac{\partial[w_i(x,t)-D_i]}{\partial t}\right]^2 dx, \end{aligned} \tag{2}$$