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Research article

Reliability-based robust dynamic positioning for a turret-moored floating production storage and offloading vessel with unknown time-varying disturbances and input saturation

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ABSTRACT

In this paper, we derived a mathematical model for a floating production storage and offloading (FPSO) vessel and its buoy mooring system and developed a new robust positioning controller to keep vessels in a desired region in the presence of unknown time-varying disturbances with uncertainties and input saturation. Different materials (chain and polyester) and buoys are considered in the model of mooring system to make the developed model more realistic. We employed a disturbance observer to estimate the disturbances and designed an auxiliary dynamic system integrated with the structural reliability's derivative to quantify the input saturation's influence, and its states are used to the control design. Our proposed controller can keep the structural reliability and heading at desired values with arbitrarily small errors while guaranteeing the uniform ultimate boundedness of all signals in the closed-loop control system. It is easier for the control design because disturbances and input saturation are handled simultaneously and so is the stability analysis because only one Lyapunov function is needed. Simulations are conducted to demonstrate our proposed controller's effectiveness and a comparison with a robust controller based on hyperbolic tangent functions shows our proposed controller can avoid steady errors with desired control goals.

1. Introduction

The oil and gas exploitation is trending to the deep sea due to the increasing demand of oil and gas resource. Therefore, many kinds of floating platforms, such as drilling platforms, floating storage and offloading (FSO) vessels and floating production storage and offloading (FPSO) vessels, are being widely used. Among these platforms, the FPSO vessels have the ability to resist heavy storms and adapt to extensive water area, and the capacity for storing and offloading a large amount of oil; in addition, the FPSO vessels can be transferred and reused easily making them very popular for the oil and gas industry.

A mooring system is used to maintain the FPSO vessel's position in the desired region. However, the traditional mooring systems, suitable for shallow waters (depth below approximately 100 m) [1], are generally considered inadequate for deep water applications [2]. What's more, the catenary mooring system covers more extensive water area which seriously affects the laying of pipes and the mooring of other FPSO vessels. In order to address these issues, the mooring system with buoys is presented.

The ideas and applications of the buoys on the offshore mooring lines can be found in Ref. [3]- [6]. The dynamics of mooring lines has been studied both numerically and experimentally [3], showing that the beneficial effects of buoys in reducing the mooring line dynamic tension can be achieved through the dynamic modification of the system, using properly designed buoys attached to the mooring lines. Hong and Kim [4] carried out an experimental study for a compliant buoy mooring system keeping the location of floating oscillating water column (OWC) type wave energy device. However, this device was damaged by mooring line failure during a severe storm. This study has been made to clarify the mechanism of mooring line failure for future improvements in mooring line design. Only a few theoretical researches [5, 6] have been conducted for the mathematical modeling of mooring system with

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buoys. Smith and MacFarlane [5] proved catenary equation is computationally efficient for a three component mooring made up of two lines, connected at a buoy regarded as a mass point. However, the form of mooring line is too simple compared with the actual mooring lines. Vicente et al. [6] investigated different mooring configurations with slack chain mooring lines of a floating absorber with or without additional sinkers or floaters. The restriction is that the line weight per unit length was assumed to be same which is a simplistic assumption.

The manufacturing cost as well as the breaking probability of mooring system will be very high for FPSO vessels in deep seas. A positioning controller is often used to assist the mooring system to keep the mooring lines from failure, which is called thruster-assisted positioning mooring (PM) system [7]. Thruster-assisted PM systems differ from dynamic positioning (DP) systems, which is used to maintain the vessels' position and heading by means of active thrusters. In normal sea conditions, the thrusters and the mooring system are used for maintaining the desired heading and keeping the ship's position in an acceptable region respectively. Therefore, fuel consumption is kept to a minimum because the mooring system doesn't consume any fuel. However, when suffering harsh marine conditions, the thrusters are also needed to assist the mooring system for positioning.

A thruster-assisted PM system consists of a mooring system and a DP system. The mooring system will be fixed once the construction of FPSO vessel is completed. So the study on thruster-assisted PM systems is mainly based on the research on the DP technology. The DP technology using nonlinear control theory has attracted much attention of researchers working in this field. In 1990s, nonlinear control laws for DP systems were developed using the backstepping method in component form [8] and vector form [9] where environmental disturbances were neglected. In 1999, Fossen and Strand [10] proposed a passive observer with wave filtering for the DP system to estimate low-frequency positions and velocities of ships from noisy position measurements and environmental disturbances. Benetazzo et al. [11] presented a DP discrete variable-structure controller with Kalman filters estimating the disturbances induced by the first order waves, which exhibits better performance than the proportional–integral–derivative (PID) controller with the passive observer. Considering the variations of sea states, Hassani et al. [12] designed a series of Kalman filters for the DP system to adapt to sea state variations using the multiple model adaptive estimate techniques. However, the DP controllers in Ref. [10]- [12] required that the model dynamics of ships were exactly known which is restricted. In the presence of ship unknown dynamic parameters, unavailable velocities, and unknown time-varying disturbances, Du et al. [13] developed an adaptive robust output feedback controller for the DP system by incorporating adaptive RBF neural networks and the high-gain observer into the vectorial backstepping method. The inertia and damp matrices were regarded as time-invariant unknown in Ref. [13], but the parameters of these system matrices are time-variant actually due to the change of ship's velocity and loading condition. It can be drawn from Ref. [10]- [13] that the observer and filter design techniques are the research emphasis of the DP system. In the last two years, Zhang et al. carried out a series of researches on the observer design to deal with the system uncertainties: a gain-scheduling Luenberger observer was proposed to estimate the nitrogen oxides (NO and NO_2) concentration for a diesel-engine-aftertreatment system [14]; an adaptive sliding-mode observer was designed for a selective catalytic reduction system of ground-vehicle diesel engines [15]; a gain-scheduling sliding mode observer was proposed for polytopic linear-parameter-varying systems with uncertain measurements on scheduling variables [16]. However, almost no study on the observer design for DP system appeared in these two years.

For the DP system of moored ships, only a few backstepping-based nonlinear control algorithms based on the structural reliability index have been developed [17, 18] in which the structural reliability index is used to quantify the breakage probability of mooring lines. Smaller structural reliability index corresponds to larger tension and higher breakage probability of the mooring line. Larger tension of the mooring line means that smaller control effort from the position controller is needed. Therefore, by considering the structural reliability index, the positioning ability of the mooring system can be used as much as possible under the breaking strength of mooring lines, and hence the control force from the positioning controller will be reduced. However, the backstepping technique suffers from the problem of “explosion of terms” [19]. Fortunately, the dynamic surface control can avoid repeated differentiation by introducing first-order filtering of the virtual control. So far, several works using dynamic surface control in the DP system have been reported [19–22]. However, the dynamic models of the DP vessel in these papers are all linearly simplified; and the Coriolis term is neglected.

It should also be noted that the input saturation [23] has been ignored in all aforementioned controllers for the DP system. The forces and moment the propulsion system can provide are limited, meaning that the commanded control inputs given by the DP controller will not be always satisfied. Since actuator input saturation can severely degrade the closed-loop system performance [24], the DP control design becomes a challenging problem. The hyperbolic tangent function [25] is a very popular approach to deal with the input saturation. However, few studies for DP technology are found that have used this method. Only Qi [25] employed the hyperbolic tangent functions to design path following controller for underactuated underwater vehicles to prevent the actuators from saturation. However, there exist errors between the control inputs produced by the propulsion system and calculated by the controller. The errors will also degrade the performance of the closed-loop system. Besides the hyperbolic tangent function, Donaire and Perez proposed a DP passivity-based controller, where input saturation was handled by using anti-windup compensator [26]. Veksler et al. developed a model predictive controller (MPC) for the DP system combining DP control design with thrust allocation, where actuator saturation was handled in the optimization problem of MPC [27]. However, these two controllers in Refs. [26, 27] are restricted to some extent because of a simplified assumption that the unknown disturbances were constant. Chen et al. proposed a robust adaptive controller for the positioning of marine vessels equipped with a thruster assisted mooring system, in which the unknown time-varying disturbances and input saturation were dealt with by neural network approximation and variable structure-based techniques respectively [28]. The disturbances and the input saturation were considered and handled separately, which made the control design and stability analysis more difficult.

In our previous work [29], by making the structural reliability an intrinsic part of the adaptive dynamic surface controller, the proposed controller can not only fully use the mooring system to keep the FPSO vessel within the allowable region but also efficiently reduce the computational complexity of the actual control law. In addition, the Nussbaum gain is used to deal with the MIMO thruster-assisted PM system's uncertainties when designing the adaptive law. However, the environmental disturbances are assumed to be known and the input saturation is neglected. On the basis of the work we have done, we design a new structural reliability-based robust dynamic surface controller for a turret-moored FPSO vessel in the presence of unknown time-varying disturbances with uncertainties and input saturation. Our contributions are summarized as follows:

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