Robust fixed-time control for a DP semi-submersible platform based on fixed-time disturbance observer

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ABSTRACT

This paper proposes a novel robust fixed-time control scheme based on a fixed-time disturbance observer for the dynamically positioned semi-submersible platform subject to wave loadings. The control law is designed aiming at resisting the low-frequency motions with the help of the Kalman filter. In this regard, the back-stepping control technique and fixed-time control theory are integrated to guarantee the fixed-time stability of the DP system. A nonlinear first-order filter is employed to avoid the “explosion of complexity” problem inherent in conventional back-stepping method. The unknown external low-frequency environmental loadings are estimated and compensated by a fixed-time disturbance observer with predefined convergence (settling) time independently on initial conditions. Moreover, a nonlinear auxiliary dynamic system is designed to mitigate the difference between commanded forces and actual forces so that the input constraints can be guaranteed. Then, theoretical analyses are conducted via Lyapunov analysis, which demonstrates that the closed-loop system is semi-globally uniformly ultimately fixed-time bounded. Finally, the effectiveness of the proposed control law is validated based on a self-dependently developed DP time-domain simulation program. Numerical simulations and comparative studies well prove the robustness and superiority of the proposed control law.

KEY WORDS: Dynamic positioning system, fixed-time control, disturbance observer, time domain simulation

INTRODUCTION

Marine operations in harsher and deeper waters raise a higher requirement of station-keeping for offshore structures, as a result, the dynamic positioning (DP) system receives a great deal of interest owing to its characteristics of high positioning accuracy and cost independence from the increased water depth (Sørensen et al., 2001). However, the kinetics of vessels are characterized as inherent nonlinearity, strong coupling, as well as being perturbed with environmental forces from sea loads, all of which pose huge challenges to a high-performance DP controller (Qin et al., 2022). Consequently, numerous advanced control methodologies have been proposed for the dynamic positioning control of vessels or autonomous surface vehicles (ASVs), such as nonlinear proportion-integration-derivative (PID) control, adaptive control (Sun et al., 2021), H\textsuperscript{\infty} control (Donha and Tanurui, 2001), model predictive control (MPC) (Yang et al., 2020; Veksler et al., 2016; Tang et al., 2022), sliding mode control (Liu et al., 2014; Qiao and Zhang, 2020), neural network-based intelligent control (Mou et al., 2010; Zhang et al., 2020a), fuzzy logic control (Xu et al., 2020), backstepping control (Cui et al., 2010; Witkowski and Smierzchalski, 2018). The nonlinear PID control techniques were first proposed in 1990s to handle the nonlinear system. Bertin et al. (2000) proposed a nonlinear feedback linearization approach to stabilize the position and heading of a vessel. Tanurui et al. (2001) adopted a nonlinear sliding mode control method for the DP operation of a turret-moored floating production storage and offloading (FPSO). Donnarumma et al. (2017) presented a simulation methodology to design and test the DP system for a vessel with a standard propulsion configuration, and the reliability was illustrated through a comparison with trial measurements. Tang et al. (2022) designed a motion controller for DP vessels based on the nonlinear model predictive controller (NMPC). Among these methods, backstepping control stands out for handling nonlinear system owing to its applicability to high-order nonlinear systems consisting of multiple integral links (Wang et al., 2019). However, traditional backstepping control suffers from the weak robustness problem. In Ejaz and Chen (2018), an optimal backstepping controller was proposed by using the disturbance observer (DO) and firefly optimization algorithm. In Li et al. (2020), an adaptive disturbance observer was proposed to online estimate the unknown time-varying disturbances for the DP ship. Yuan et al. (2016) presented a nonlinear robust neural network approach to determine the parameters of the unknown part of ideal virtual backstepping control law, and the weight vectors of neural network are updated by adaptive technique. On the other hand, the derivation of the virtual control laws for backstepping control method is very complex, and even leads to the “complexity explosion” of the whole algorithm. In order to eliminate this limitation and reduce the computational cost, an usual approach, so-called dynamic surface control (DSC) (Li et al., 2020), was proposed by employing a first-order filter to get indirect differentiation. Li et al. (2020) designed a DP robust control scheme combining the disturbance observer with the dynamic surface DSC technique. In Zhang et al. (2017), a nonlinear adaptive backstepping control algorithm based on neural networks and DSC was proposed, which worked well as compared to other controllers but still there exists delayed convergence for state errors.

In general, the above Lyapunov stability theory-based method can guarantee the global asymptotic stability of the entire system. Nevertheless,