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Neural network based fin control for ship roll stabilization with guaranteed robustness

Weilin Luo[a,*], Bingbing Hu[a], Tieshan Li[b]

[a] School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou, Fujian 350116, China
[b] Navigation College, Dalian Maritime University, Dalian, Liaoning 116026, China

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ABSTRACT

To reduce the ship roll motion, an adaptive robust fin controller based on a feedforward neural network is proposed. The dynamics of the fin actuator is considered in the plant of a roll-fin cascaded system with uncertainties which refer to as the modeling errors and the environmental disturbance induced by waves. An on-line feedforward neural network is constructed to account for the uncertainties. Lyapunov design is employed to obtain the fin stabilizer with guaranteed robustness. Simulation results demonstrate the validity of the controller designed and the superior performance over a conventional PD controller.

1. Introduction

Ship motion is essentially nonlinear since a moving ship is inevitably affected by surrounding environmental forces. Representative environmental forces encompass wind, waves, and current. In some cases, the interaction between a ship and other structures (e.g., the ship-ship, ship-bank, ship-bridge, ship-platform interactions) also exerts an influence on the ship motion. One of the ship problems caused by environmental disturbances is rolling for many ships such as fishing vessels, crane vessels, passenger ships and naval vessels [1]. Adverse influences due to rolling refer to cargo damage, seasickness of crew and passengers, low efficiency of operations performed by the crew, and even the capsizing of a ship. Over past decades, the problem of ship rolling has been continually studied and some effective measures to reduce the roll motion have been presented. Representative measures are the uses of bilge keels, anti-rolling tanks, fins, rudder, and gyroscope [2]. A well-designed roll stabilizer can guarantee such ship performances as seaworthiness and operability in case the ship is subjected to adverse environmental impacts [3].

Among the ship roll stabilization devices, the gyrostabilizer and fin stabilizer present higher performance than the other stabilizers. However, the high cost for a gyrostabilizer prevents its wide application. Comparatively, the lift-based fin stabilizer provides a more practical device for roll damping. Especially in high-speed cases, the roll motion can be reduced to a large extend by using fin stabilizers [2]. Two kinds of fins are available in practice, including passive fins and active fins. To produce significant roll reduction, the size of passive fins should be large enough, which limits their practical use [4]. Despite the fairly complicated structure, active fin stabilizers are normally used in many ships owing to the high effectiveness. In some cases, an active fin stabilizer can afford up to a 90% roll reduction [5]. Such high effectiveness can be achieved if the fins are sized correctly and a control system is designed appropriately. During past decades, many efforts have been devoted to the development of control strategies for fin stabilizers, from conventional schemes to advanced schemes. A representative conventional control scheme is the PID approach. However, it was noted that the feasibility of this kind of controller for the roll stabilization is limited by the vessel types and the environmental conditions [6]. Especially for the environmental conditions like wind, waves, and current, it is actually difficult to describe these factors in accurate mathematical forms. As a result, it is challenging to obtain an adaptive accurate and robust fin controller although some approximation formulas have been proposed for the modeling of environmental forces [7]. Over the past years, design of a fin stabilizer using advanced control schemes is of interest and many applications have been presented. For example, H_∞ control was implemented to the roll stabilization of surface ships [8]. Neural networks (NN) were employed to approximate the uncertain nonlinearities to achieve robust fin roll stabilization [9]. A NN based internal model controller was used to reduce the roll motion [10]. An adaptive fuzzy logic scheme was proposed to design a robust fin stabilizer [11]. A variable structure robust controller was presented to deal with the uncertainties in the ship roll dynamics [12]. Linear quadratic regulation (LQG) scheme in combination with a disturbance observer was

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[*] Corresponding author.
E-mail address: wlluo@fzu.edu.cn (W. Luo).

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applied to design a robust fin controller [13]. A weighted LQG based fin stabilizer was proposed to reduce the roll motion in irregular waves [14]. A constrained model predictive control (MPC) was proposed for the fin stabilizers of ships affected by dynamic stall [15]. An adaptive robust sliding mode controller was presented for the roll stabilization [16]. A L2-gain based adaptive fin controller was proposed for the roll reduction of surface ships [17]. Particle swarm optimization (PSO) was incorporated into a proportional-derivative-second derivative controller to improve the performance of a fin stabilizer [18]. Generally, for the control of the ship roll motion with uncertainties like environmental disturbances, the fin stabilizers based on advanced control schemes have presented better performance than conventional control schemes.

Amongst the commonly used advanced control schemes, fuzzy logic and NN have some things in common. Both of them are suitable for the control of a system with a mathematical model that is difficult to derive. By using fuzzy logic, the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans [19]. Due to the high adaptivity, NN presents a distinctive approach to obtain an adaptive robust controller [20]. For ship roll stabilization, a non-adaptive controller might result in more severe rolling instead of damping [21]. Therefore the adaptivity of the controller becomes vital to the roll stabilization. Another important advantage of NN is its powerful learning ability, which makes it applicable for a complicated nonlinear system with uncertainties [22]. For the ship roll dynamics in which uncertain environmental forces might involve, NN can be used to identify such uncertainties in a fin controller design. Many studies have demonstrated the validity of the fin controller based on NN, e.g. [9,10,23,24]. In this paper, a NN based adaptive robust fin controller is proposed for roll stabilization. Not only the ship roll dynamics but also the dynamics of fin actuator are considered in the plant. In many studies, the influence of the fin actuator on the roll dynamics was disregarded (e.g. [10,23–25]). From an operational point of view, this effect should have been taken into account especially when the time constant of the fin actuator cannot be ignored in comparison with the time constant of the ship. Two kinds of uncertainties are also considered in the plant. One is referred to as the generalized modeling errors possibly due to parametric perturbation, neglected high-order modes of the system, or unmodelled dynamics [26]. In literatures, usually only the parameter uncertainty is considered, e.g. [12,16]. The moment induced by waves is viewed as another uncertainty in the plant. Both the generalized modeling errors and the wave-induced moment are identified by an on-line feedforward neural network and feedback compensated in the close-loop system. The design process of the fin control system can be briefly described as follows. First, a linear system with respect to tracking error is derived from the original cascaded roll-fin dynamic system using feedback linearization. Second, two auxiliary controllers are respectively introduced into the two subsystems related to roll dynamics and the fin actuator. With the help of Lyapunov design and NN, the structures of auxiliary controllers are obtained. Finally, the terminal control input to the cascaded system is determined based on the obtained auxiliary controllers. The rest of the paper is organized as follows. In Section 2, mathematical descriptions of the ship roll dynamics and the dynamics of the fin actuator are given. In Section 3, the process of controller design and the analysis of stability are stated. Section 4 presents an example of numerical simulation and the final section gives concluding remarks.

2. Mathematical models of ship roll-fin dynamics

2.1. Ship roll dynamics

A six-degree-of-freedom (6DOF) model can be used to describe the ship motion [27]

$$\left.\begin{aligned} \dot{\eta} &= J(\eta)v \\ M_{\boldsymbol{RB}}\dot{v} + C_{\boldsymbol{RB}}(v)v &= \tau \end{aligned}\right\}, \tag{1}$$

where $\eta = [x, y, z, \phi, \theta, \psi]^{\mathrm{T}}$ is the position vector associated with the North-East-Down (NED) reference frame; $v = [u, v, w, p, q, r]^{\mathrm{T}}$ is the velocity vector associated with the body-fixed reference frame; $J(\eta)$ is the kinematic transformation matrix between these two reference frames; $M_{\boldsymbol{RB}}$ is the rigid-body mass matrix; $C_{\boldsymbol{RB}}(v)$ is the Coriolis-centripetal matrix; τ is the generalized force vector.

System (1) provides a general model to describe the ship motion in the horizontal plane (referring to as surge, sway, and yaw) and in the vertical plane (i.e., heave, pitch, and roll), as shown in Fig. 1. In the specific applications of this model to ship control, 6DOF is often reduced to 1DOF, 3DOF, or 4DOF because of the fact that most vessels are underactuated [27]. Such a reduced-DOF model for the purpose of control can be called as a control-design model [2]. It is feasible because the essential characteristic of the ship roll dynamics is captured in the reduced-DOF model. How to select the model with an appropriate DOF depends on the types of control objective and the conditions of controller implementation [21]. For ship roll stabilization, the 1DOF and 4DOF models are available in the fin controller design. A 4DOF model is formed by considering the ship motion in the horizontal plane along with roll motion, which makes it suitable to describe both ship manoeuvrability and seakeeping characteristics. In a 1DOF model, the ship roll dynamics is only concerned about. Despite simpler structure than a 4DOF model, the 1DOF model is usually preferred to design roll damping system since this kind of model captures the important response characteristics of the roll dynamics. In this paper, the 1DOF model is studied. A simple form of this model can be described as

$$\left.\begin{aligned} \dot{\phi} &= p \\ I_x\dot{p} &= K \end{aligned}\right\}, \tag{2}$$

where ϕ is the roll angle; p is the roll rate; I_x is the moment of inertia; K is the roll moment which is determined by [21]:

$$K = K_{\boldsymbol{h}} + K_{\boldsymbol{c}} + K_{\boldsymbol{d}} \tag{3}$$

where K_h represents the hydrodynamic moment; K_c the control moment; K_d the disturbance moment. For the first term, i.e, K_h, it can be obtained by

$$K_h = K_{\dot{p}}\dot{p} + f_1(\phi, \dot{\phi}) + f_2(\phi), \tag{4}$$

where the first term $K_{\dot{p}}\dot{p}$ represents the inertia added to the ship due to

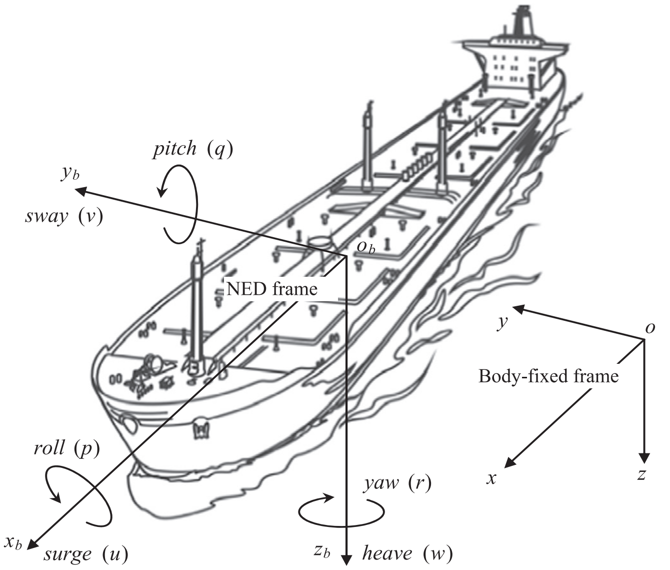

Fig. 1. 6DOF Ship motion.