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Robust adaptive first–second-order sliding mode control to stabilize the uncertain fin-roll dynamic

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ABSTRACT

Controlling the roll motion involves several problems including incomplete measurements, external disturbances, and the model uncertainties. In this paper, the perturbed model for the roll-fin dynamics is extracted by considering the problems influencing the fin stabilizer system during ship sailing. The sliding mode control provides robust performance for the mentioned factors. Therefore, a sliding mode controller is designed based on the information about the upper bound of perturbations and wave excitation force. Inasmuch as the uncertainty bound is not usually known, a robust adaptive sliding mode controller is proposed. Although it has been proven that the proposed method is robust, the chattering phenomenon is accounted as a drawback of the sliding mode control. In order to overcome the chattering phenomenon, a second-order sliding mode is replaced by the first-order one to create an adaptive second-order sliding mode control. The simulation results show that the control strategy is effective to decrease the roll motion and robust to overcome the uncertainties and random waves.

1. Introduction

Large roll motion induced by ocean waves can severely affect the capacity of ships to perform their missions. In addition, its influences on human performance may produce cargo damages, and may prevent the operation of specific equipments on board. To diminish undesirable issues in this regard, roll stabilization systems have been studied for years (Perez and Goodwin, 2008) and various types of anti-rolling devices have been introduced in order to reduce undesirable roll motion (Lloyd, 1989).

Bilge keels are the earliest anti-rolling devices in use, which provide extra roll damping to the ship to attenuate the roll motion (Lewis, 1989). The anti-rolling water tank is another roll stabilizer. Water in the tanks is shifted in response to the wave motion to counteract the waves and decrease the roll momentum (Gawad et al., 2001). Among different techniques, the active stabilizer, fin, seems to be the most effective one and has been widely adopted. However, in order to utilize the active stabilizer to reduce the ship roll motion, the ship speed must reach an adequate value to make the controller act effectively (Fang et al., 2010).

Generally, PID controller based on anti-momentum principle has been commonly used in the ship fin stabilizer systems. Due to complexity, nonlinearity, and the time-varying dynamic of the roll motion and uncertainties regarding sea conditions, the satisfied control effect is very difficult to be obtained by employing conventional PID controller. Thus, different researches have been proposed on the subject of applying various control techniques to the ship roll motion control including model-based modern control (Jia and Yang, 1999), predictive control (Perez, 2005), neural network, fuzzy control (Alarcin, 2007; Cao and Lee, 2003), adaptive control (Tzeng and Lin, 2000), sliding mode control (Fang and Luo, 2007), etc.

Control under uncertainty conditions is one of the main issues in the design of a robust control system, especially in a ship control system due to random waves and the variations in parameters. The sliding mode control probably stays as the main choice when one needs to deal with uncertainties and the perturbed dynamics (Levant, 1993, 2003; Levant et al., 2000). The main advantages of the sliding mode are provided. It is insensitive to external and internal disturbances, and has ultimate accuracy and finite-time transient. Therefore, in this paper, the sliding mode has been employed to stabilize uncertain roll-fin dynamics. First, conventional sliding mode control based on the perturbed model is designed. In order to design this controller, the upper bounds of the uncertainties and disturbances are known. This controller is robust and simple to be implemented.

The information about the bounds of uncertainties is usually unavailable. In order to have a robust controller with no need for the upper bounds of the uncertainties, an adaptive sliding mode control is proposed. In the sliding mode controllers, high-frequency switching leads to the so-called chattering effect. In place of using the *signum* function, the *tanh* function is applied to

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diminish high-frequency chattering effect. Although, using *tanh* decreases the chattering motion in foils, it reduces the robustness of the closed loop system. To benefit from the advantages of the *signum* function and diminish chattering, an adaptive second-order sliding mode is proposed. By using this method, two important issues, the chattering phenomenon and having information about the bounds of the uncertainties, are obviated. The controllers' performance is evaluated via execution of some simulations. The rest of the paper is as follows. In Section 2, the dynamic of a warship is studied and the perturbed model of the fin-roll dynamics is extracted. Fixed gain and adaptive sliding mode control are designed in Section 3. In Section 4, simulation results are demonstrated and finally a conclusion is made in Section 5.

2. The ship dynamic

2.1. 4-DOF equation of motion

In this section, the mathematical model for the ship dynamic is presented for a naval vessel with 4-degree of freedom. The ship model and the coordinate systems are depicted in Fig. 1. The translation motion of the ship in three directions are surge, sway, and heave; the rotation motion about three axes of x_0, y_0, z_0 are roll, pitch, and yaw, respectively. Motion in pitch and heave can generally be neglected. The dynamic equation of the motion in the body fixed frame is given by Perez (2005) in a vector form:

$$\begin{aligned} M_{RB}\dot{\upsilon} &= \tau(\dot{\upsilon},\upsilon,\eta) - C_{RB}(\upsilon)\upsilon \\ \dot{\eta} &= J(\eta)\upsilon \end{aligned} \tag{1}$$

where M_{RB} is the mass and inertia matrix due to the rigid body dynamic, $C_{RB}(\upsilon)\upsilon$ includes the coriolis and centripetal forces and moments, and $J(\eta)$ is the transformation matrix. $\eta=[x,y,\phi,\psi]^T$ is the position–orientation vector, $\upsilon=[u,v,p,r]^T$ is the linear–angular velocity vector, and $\tau(\dot{\upsilon},\upsilon,\eta)=[X,Y,K,N]^T$ is the forces–moments vector. The 4-degree of freedom equation of the motion is given as

$$\begin{aligned} \dot{\phi} &= p \\ \dot{\psi} &= r\cos(\phi) \\ m\dot{u} &= X + m(vr + x_G r^2 - z_G pr) \\ m\dot{v} - mz_G\dot{p} + mx_G\dot{r} &= Y - mur \\ -mz_G\dot{v} + I_{xx}\dot{p} &= K + mz_G ur \\ mx_G + I_{zz}\dot{r} &= N - mx_G ur \end{aligned} \tag{2}$$

where m is the ship mass, I_{xx} and I_{zz} are the inertias about $x_b$and $z_b$axes, and x_G and z_G are the coordinates of the center of gravity with respect to the body fixed frame. The hydrodynamic models $X_{hyd}, Y_{hyd}, K_{hyd}, N_{hyd}$ in the vessel are given as follows:

$$\begin{aligned} X_{hyd} &= X_{\dot{u}}\dot{u} + X_{u|u|}u|u| + X_{vr}vr + T_a \\ Y_{hyd} &= Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{\dot{p}}\dot{p} + Y_{|u|v}|u|v + Y_{ur}ur + Y_{v|v|}v|v| + Y_{v|r|}v|r| \\ &\quad + Y_{r|v|}r|v| + Y_{\phi|uv|}\phi|uv| + Y_{\phi|ur|}\phi|ur| + Y_{\phi uu}\phi u^2 \\ K_{hyd} &= K_{\dot{v}}\dot{v} + K_{\dot{p}}\dot{p} + K_{|u|v}|u|v + K_{ur}ur + K_{v|v|}v|v| \\ &\quad + K_{v|r|}v|r| + K_{r|v|}r|v| + K_{\phi|uv|}\phi|uv| + K_{\phi|ur|}\phi|ur| \\ &\quad + K_{\phi uu}\phi u^2 + K_{|u|p}|u|p + K_{p|p|}p|p| + K_p p + K_{\phi\phi\phi}\phi^3 - \rho g\nabla G_z(\phi) \\ N_{hyd} &= N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{|u|v}|u|v + N_{|u|r}|u|r + N_{r|r|}r|r| + N_{r|v|}r|v| \\ &\quad + N_{\phi|uv|}\phi|uv| + N_{\phi u|r|}\phi u|r| + N_{\phi u|u|}\phi u|u| \end{aligned} \tag{3}$$

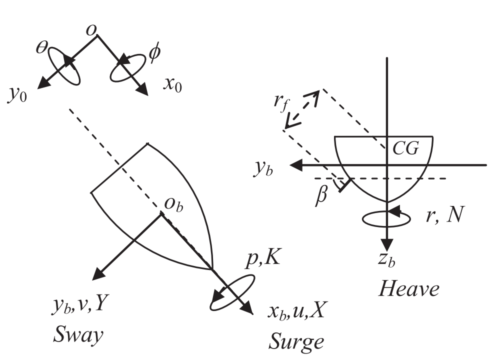

Fig. 1. Coordinate system.

where ρ is the mass density of water, g is the gravity constant, $G_z(\phi)$ is the buoyancy, and ∇ is the ship displacement. The rudder equation is added to the system when simulation is done and its dynamic is not considered in this paper. The position of the fin on the ship is shown in Fig. 1. The hydrodynamic forces acting on fins can be written as follows (Perez, 2005; Surendran et al., 2007):

$$\begin{bmatrix} X_{fin} \\ Y_{fin} \\ K_{fin} \\ N_{fin} \end{bmatrix} = \begin{bmatrix} -T \\ -N\sin(\beta) \\ 2Nr_f \\ L_G N\sin(\beta) \end{bmatrix} \tag{4}$$

where β is the fin tilt angle, L_G is the longitudinal distance from the center of pressure of the fin to the center of gravity. T and N are computed as follows:

$$\begin{aligned} N &= L\cos(\alpha_e) + D\sin(\alpha_e) \\ T &= D\cos(\alpha_e) - L\sin(\alpha_e) \end{aligned} \tag{5}$$

where L and D are lift and drag forces. α_e is the effective angle of attack computed by

$$\alpha_e = -\alpha_f - \alpha, \quad \alpha_f = \tan^{-1}\left(\frac{r_f p}{u}\right) \tag{6}$$

where α_f is the flow angle, and α is the mechanical angle of the fin. In order to prevent dynamic stall in the fin, the foil motion is restricted to move within certain angles $\alpha_{min} < \alpha < \alpha_{max}$. In the following section, the perturbed roll-fin dynamic is extracted to be used for designing a robust controller.

2.2. Uncertain fin-roll dynamic

The nonlinear dynamic equation of the fin-roll is gained from Eqs. (2)–(4):

$$\begin{aligned} \dot{\phi} &= p \\ -mz_G\dot{v} + I_{xx}\dot{p} &= K + mz_G ur, \quad K = K_{hyd} + K_{fin} + K_{rudder} \end{aligned} \tag{7}$$

A good approximation of K_{fin} can be written as below (Surendran et al., 2007):

$$K_{fin} = C_L \rho A u^2 r_f \tag{8}$$

where A is the fin area and r_f is the characteristic lever. Inasmuch as the variations of the fin are constrained, $C_L$can be approximated by

$$C_L = K_{CL}\alpha_e \tag{9}$$

where K_{CL} is the slope of the C_L equation at $\alpha_e = 0$. Eqs. (7) and (8) are rewritten as follows:

$$a\ddot{\phi} + b\dot{\phi} + c\phi = F_{wint} + F_u \tag{10}$$

where

$$\begin{aligned} a &= I_{xx} - K_p \\ b &= -K_{|u|p}|u| - K_{p|p|}|p| - K_p \\ c &= -K_{\phi|uv|}\phi|uv| - K_{\phi|ur|}|ur| - K_{\phi uu}u^2 \\ F_{wint} &= (mz_G + K_{\dot{v}})\dot{v} + K_{|u|v}|u|v + K_{ur}ur + K_{v|v|}v|v| + K_{v|r|}v|r| + \\ &\quad K_{r|v|}r|v| + K_{\phi\phi\phi}\phi^3 - \rho g\nabla G_z(\phi) + K_{rudder} \\ F_u &= K_{fin} \end{aligned}$$