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Method for rudder roll stabilization control by maintaining ship speed

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Abstract: A ship navigating on the surface of the water may experience greater resistance, adversely affecting its speed and leading to energy loss. The added resistance of surface ships in both still water and waves are investigated, and the computation method of total speed loss is presented. An autopilot system is introduced to constrain the speed loss, and course keeping and rudder roll stabilization sliding mode control laws are proposed according to a compact control strategy. The two working conditions of "heading" and "heading plus anti-roll" are discussed, including roll stabilization, heading error, speed keeping and rudder abrasion. The results show that the speed can be effectively maintained using this method, and from a commercial point of view, the fin-rudder roll stabilization control is not recommended for vessels equipped with both fins and rudders.

Key words: ship; ship motion control; rudder roll stabilization; autopilot; added resistance; speed loss; sliding mode control

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0 Introduction

In order to follow the prescribed ship course, the autopilot and its control system must be available for each ship. The autopilot can not only control the heading and yaw motion of ship, but also be used to the rudder roll stabilization [1-2]. Considering the economic cost and installation space, roll stabilization fins are usually not installed in small ship. The rudder roll stabilization technology provides new development for heading and roll stabilization technology of small ships, and various series of commercial rudder roll stabilization control systems have been proposed [3]. The studies in China on rudder stabilization started in the 1980s. With the development of economic and scientific technology, researches are also gradually improved, which can verify the practicability of rudder roll stabilization and conduct control law design for such defects as nonlinear saturation of steering engine, rudder speed insufficiency and nonlinear model coupling by combining modern control theory[4-8].

For addressing the problem of energy saving in ship course control, relevant researches have been carried out since the last century. Akinsal [9] proposed a PID controller for optimal course keeping to minimize propulsion losses, which could save maximally 5% of fuel consumption; Grimble et al.[10] extended the course keeping loss function according to ship surge motion equation, and presented the LQG control of ship course with the minimum energy loss; based on the control method of Ref. [10], a method of enhancing the heading control with the minimum resistance for the polynomial ship heading control system applicable to opertion conditions in various climates was proposed by Katebi et al. [11]; Miloh et al. [12] proposed a speed variation model for ship collision avoidance to solve the speed loss of ship steering.

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Therefore, appropriate autopilot control strategy can reduce the speed loss of ship.

The main purpose of using the autopilot is to keep ship heading and trace tracking. However, the rudder roll stabilization control will reduce the precision of course keeping, meanwhile increasing the steering machine rotation frequency. From the viewpoint of energy saving, when the ship sailing in waves, how the rudder roll stabilization affects the speed cannot be determined. This study aims to use sliding mode control to design ship autopilot control system with low speed loss by considering both the added resistances in waves and still water, and meanwhile to analyze the influence of heading control system on speed when rudder roll stabilization control is added.

1 Mathematic model

1.1 Ship motion model

For the ship navigating with constant speed, its center of gravity will shift under marine disturbance. As a rigid body, there will be six degree-of-freedom (DOF) oscillating movement, including three DOF in translational movement along the axial direction and three DOF in rotational movement around the axial rotation. According to Newton's law, three DOF nonlinear dynamic equations of sway, roll and yaw are shown as follows:

$$m(\dot{v}+ur)-mz_{\mathrm{G}}\dot{p}+mx_{\mathrm{G}}\dot{r}=Y_{\mathrm{hyd}}+Y_{\delta}\delta \tag{1}$$

$$-mz_{\mathrm{G}}(\dot{v}+ur)+I_{xx}\dot{p}=K_{\mathrm{hyd}}+K_{\delta}\delta \tag{2}$$

$$mx_{\mathrm{G}}(\dot{v}+ur)+I_{zz}\dot{r}=N_{\mathrm{hyd}}+N_{\delta}\delta \tag{3}$$

$$\dot{\phi}=p \tag{4}$$

$$\dot{\psi}=r\cos(\phi) \tag{5}$$

where m is the mass of hull; I_{xx} and I_{zz} are the moments of inertia for roll and yaw respectively; u, v, r, p, ϕ and ψ are surge speed, sway speed, angular velocity in roll, angular velocity in yaw, roll angle and yaw angle; x_{G}, y_{G} and z_{G} are the center of gravity in ship body-fixed coordinate system; δ is the rudder angle; Y_{hyd}, K_{hyd} and N_{hyd} are the hydrodynamic equations of sway, roll and yaw of ship, which can be expressed as:

$$\begin{aligned}Y_{\mathrm{hyd}}&=Y_{\dot{v}}\dot{v}+Y_{\dot{r}}\dot{r}+Y_{\dot{p}}\dot{p}+Y_{|u|v}|u|v+Y_{ur}ur+\\&Y_{v|v|}v|v|+Y_{v|r|}v|r|+Y_{r|v|}r|v|+Y_{\phi|uv|}\phi|uv|+\\&Y_{\phi|ur|}\phi|ur|+Y_{\phi uu}\phi u^{2}\end{aligned} \tag{6}$$

$$\begin{aligned}K_{\mathrm{hyd}}&=K_{\dot{v}}\dot{v}+K_{\dot{p}}\dot{p}+K_{|u|v}|u|v+K_{ur}ur+K_{v|v|}v|v|+\\&K_{v|r|}v|r|+K_{r|v|}r|v|+K_{\phi|uv|}\phi|uv|+K_{\phi|ur|}\phi|ur|+\\&K_{\phi uu}\phi u^{2}+K_{|u|p}|u|p+K_{p|p|}p|p|+K_{p}p+\\&K_{\phi\phi\phi}\phi^{3}-\rho g\ \overline{GM}\,\phi\end{aligned} \tag{7}$$

$$\begin{aligned}N_{\mathrm{hyd}}&=N_{\dot{v}}\dot{v}+N_{\dot{r}}\dot{r}+N_{|u|v}|u|v+N_{|u|r}|u|r+N_{r|r|}r|r|+\\&N_{r|v|}r|v|+N_{\phi|uv|}\phi|uv|+N_{\phi u|r|}\phi u|r|+N_{p}p+\\&N_{|p|p}|p|p+N_{|u|p}|u|p+N_{\phi u|u|}\phi u|u|\end{aligned} \tag{8}$$

where $Y_{(\cdot)}$, $K_{(\cdot)}$ and $N_{(\cdot)}$ are the hydrodynamic derivatives; ρ is the density of seawater; g is the gravitational acceleration constant; $\overline{GM}$ is the metacentric height of ship roll; $\varDelta$ is the displacement of ship.

The righting force/moment coefficient of sway, roll and yaw caused by rudder turning are as follows:

$$Y_{\delta}=\frac{1}{2}\rho A_{\mathrm{R}}C_{\mathrm{L}}U^{2} \tag{9}$$

$$K_{\delta}=\frac{1}{2}\rho A_{\mathrm{R}}C_{\mathrm{L}}U^{2}l_{z} \tag{10}$$

$$N_{\delta}=-\frac{1}{2}\rho A_{\mathrm{R}}C_{\mathrm{L}}U^{2}LCG \tag{11}$$

where A_{R} is the surface area of rudder; C_{L} is the lift coefficient of rudder surface; LCG is the distance from the center of gravity to the rudder; U is the designed speed; l_{z} is the roll arm.

1.2 Wave model

The wave interference acted on ship is mainly the first-order force, and the long-crested wave model used in this study is described by ITTC dual-parameter spectrum:

$$S_{\zeta}(\omega)=\frac{173H_{1/3}^{2}}{T^{4}\omega^{5}}\exp\left(-\frac{691}{T^{4}\omega^{4}}\right) \tag{12}$$

where $H_{1/3}$ is the significant wave height; T is the natural period of the waves; ω is the natural frequency of the waves.

In the main frequency range, the wave spectrum is divided into a number of superposed frequencies. In this study, it is divided into 60 frequencies and the torque of each frequency wave is accumulated. The total disturbance force/moment of the hull is calculated by slice principle.

2 Speed calculation

2.1 Added resistance in waves

During the navigation, the ship will be affected by fluid resistance. In order to maintain the forward speed, enough thrust should be provided to overcome this resistance that estimated under still water resistance. Under the action of wave, resistance is increased compared that in still water, which is called second-order wave force. At this time, main engine will inevitably consume more energy, thereby lead to the decreasing of speed. Loukakis et al.[13] described the calculation principle of wave resistance increase under oblique waves based on energy conservation.

The ship is assumed to move forward at a constant speed of U and the surge motion is neglected. As shown in Fig. 1, in the β direction of encounter angle, the ship is subjected to the second-order wave force R_T in the horizontal direction, whose component along the x axis R_x is the added resistance caused by wave and the component R_y along the y axis is called drift force.

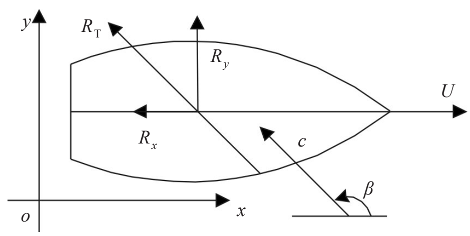


Fig.1 Definition of added resistance and drift force

The added resistance essentially induced by the wave is energy consumption of ship swaying. The energy mainly diffuses outward through the diffraction wave caused by ship motion. According to the radiation work and energy conservation principle, in each wave encounter period, work P made by the second-order wave force in the encounter wave direction can be expressed as follows:

$$P = R_T(c + U\cos\beta)T_e \tag{13}$$

where c is the wave speed; U is the designed speed of the ship; T_e is the wave encounter period; β is the encounter angle.

After integration of energy produced by ship strip along the ship length, in a wave encounter period, the radiation energy P of the damping force generated by the interaction between the fluid and five DOF harmonic motion of the ship with its coupling interaction is shown as follows:

$$P_{35} = \frac{\pi}{\omega_e}\int_0^L b_{35}\left|U_{RZ}\right|^2 dx \tag{14}$$

$$P_4 = \frac{\pi}{\omega_e}\int_0^L b_4\left|p\right|^2 dx \tag{15}$$

$$P_{24} = P_{42} = \frac{\pi}{\omega_e}\int_0^L b_{24}\left|pU_{RY}\right| dx \tag{16}$$

$$P_{26} = \frac{\pi}{\omega_e}\int_0^L b_{26}\left|U_{RY}\right|^2 dx \tag{17}$$

where P is the radiation energy and the subscript represents five DOF motion modes, namely sway, surge, roll, yaw and pitch; p stands for angular speed of roll in each section of the hull; U_{RZ} stands for the vertical relative speed of each section of the hull; U_{RY} is the transverse relative speed of each section of hull; ω_e is wave encounter frequency; b is the corresponding damping coefficient of each section of the hull, and the subscript represents the freedom mode of corresponding motion.

Total energy conservation equation is:

$$R_T(c + U\cos\beta)T_e = P_{35} + P_4 + P_{26} + 2P_{24} \tag{18}$$

Therefore, under the condition of oblique waves, the final expressions of the two-order horizontal wave force R_T, the wave added resistance R_x and the transverse drift force R_y are as follows:

$$\left|R_T\right| = \frac{k}{\omega_e}(P_{35} + P_4 + P_{26}) + \frac{2k}{\omega_e}P_{24} \tag{19}$$

$$\left|R_x\right| = \left|R_T\cos\beta\right| \tag{20}$$

$$\left|R_y\right| = \left|R_T\sin\beta\right| \tag{21}$$

where k is the wave number.

2.2 Added resistance in still water

In fact, the steering motion will cause added resistance not only in waves, but also in still water, also known as the "hydrostatic added resistance" or "inertia resistance". Yawing motion can be regarded as a constant steering movement of the ship. Extra vertical eccentric resistance will generate when the ship is turning around, which causes the loss of propulsion energy and finally reduces the speed.

According to the rudder steering principle and Newton's laws of motion, the forward motion equation of hull can be expressed as follows under the ship coordinate system framework [14]:

$$M(\dot{u} - vr) = X_{\dot{u}}\dot{u} - R_t(u) + (1-\tau)T(u, n) + X_{vv}v^2 + X_{vr}vr + X_{rr}r^2 + X_{\delta\delta}\delta^2 \tag{22}$$

where $X_{\dot{u}}$, X_{vv}, X_{vr}, X_{rr}, $X_{\delta\delta}$ are hydrodynamic derivatives of hull and rudder; M is the total mass of the hull; $R_t(u)$ is the resistance in still water; τ is the loss coefficient of propeller thrust; n is revolution speed of the propeller; $T(u, n)$ is the propeller thrust in open water conditions.

Through the analysis of Eq. (22), it shows that the added resistance in still water is determined by the mass item Mvr and added mass force item $X_{vr}vr$. X_{vr} is actually equal to added mass induced by transverse swaying. For other items, still water resistance $R_t(u)$ and propeller thrust $T(u, n)$ are independent of steering motion. According to the theory of potential flow, supposing that the hull is symmetrical, the hydrodynamic items X_{vv} and X_{rr} are zero. The last item at the right side of the equation $X_{\delta\delta}\delta^2$ is the added resistance generated by the rudder with turning angle δ. The magnitude of this resistance is relatively small and can be neglected. Therefore, the added resistance R_{yaw} in still water generated by yawing steering motion can be represented by:

$$R_{yaw} = (M + X_{vr})vr \tag{23}$$

2.3 Speed loss

The resistance of ship when moving forward is determined by geometrical shape and ship speed. Therefore, in order to keep constant speed, the corresponding propulsion is required for the ship. The designed effective propulsion power of the ship is determined by the estimated resistance of bare hull in still water. According to Newton's law of force balance, the designed effective propulsion power P_E can be expressed as:

$$P_E = R_t(u)U \tag{24}$$

Assuming that when the ship is driven by a constant power, the overall propulsion power under the combined effect of wave added resistance, still water added resistance and still water resistance is as follows:

$$P_E = \left[R_t(u) + R_x + R_{yaw}\right]U_0 \tag{25}$$

The actual ship speed U_0 can be calculated by:

$$U_0 = \frac{R_t(u)}{R_t(u) + R_x + R_{yaw}}U \tag{26}$$

Hence, the speed loss is the difference between the designed speed U and actual speed U_0, namely $\Delta U = U - U_0$.

3 Controller design

According to the analysis of added resistance induced by both waves and still water, it can be found that the total resistance increase of the ship is determined by the sway speed v, angular speed in roll p and angular speed in yaw r. Meanwhile, in order to keep the stability of navigation, roll angle ϕ and yaw angle ψ should be firstly controlled. Therefore, in the course control, states of v, r and ψ need to be controlled. In working condition of rudder roll stabilization, p and ϕ should be controlled as well.

Due to good robust performance of sliding mode control, this study adopts this control law. For the studied three DOF model, the autopilot control system is a single-input multi-output system. In view of this, eigenvalue decomposition method is used to design the sliding mode control law of heading and roll [15-16].

3.1 Heading control law

Heading dynamic model requires extracting Eq. (1), Eq. (2), Eq. (6) and Eq. (8). After eliminating nonlinear strong coupling item and ignoring vertical swaying motion, then $u = U$ and $\dot{u} = 0$. When the speed U is the designed speed, the dynamic model of heading can be regarded as a linear model and be transformed into $\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{b}\delta$ in the standard state space.

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix} \delta \tag{27}$$

The function of sliding mode surface s is defined by the attitude error of three DOF motion:

$$s = \boldsymbol{h}^{\mathrm{T}}(\boldsymbol{x} - \boldsymbol{x}_{\mathrm{d}}) \tag{28}$$

where $\boldsymbol{h} = [h_1, h_2, h_3]^{\mathrm{T}}$ is the weight vector; $\boldsymbol{x}_{\mathrm{d}} = [0, 0, \psi_{\mathrm{d}}]^{\mathrm{T}}$ is the set vector of altitude.

In order to stabilize swaying and yawing of ship, the state feedback vector is defined as $\boldsymbol{k} = [k_1, k_2, 0]^{\mathrm{T}}$, since there is a pure integration element in Eq. (7), and then the state matrix is obtained as:

$$\boldsymbol{A}_{\mathrm{c}} = \boldsymbol{A} - \boldsymbol{b}\boldsymbol{k}^{\mathrm{T}} = \begin{bmatrix} a_{11} - b_1k_1 & a_{12} - b_1k_2 & 0 \\ a_{21} - b_2k_1 & a_{22} - b_2k_2 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{29}$$

Let $\boldsymbol{h}$ be the right eigenvector of matrix $\boldsymbol{A}_{\mathrm{c}}^{\mathrm{T}}$ and λ be the corresponding right eigenvalue. Since there is a pure integral channel in $\boldsymbol{A}_{\mathrm{c}}$, there must be an eigenvalue $\lambda = 0$ that makes:

$$\boldsymbol{A}_{\mathrm{c}}^{\mathrm{T}}\boldsymbol{h} = 0 \tag{30}$$

The coefficient vector of sliding mode surface can be obtained by Eq. (30). The nonlinear switching law is used to offset the wave disturbance and the sliding mode control law of heading can be expressed as:

$$\delta = -\boldsymbol{k}^{\mathrm{T}}\boldsymbol{x} - \left(\boldsymbol{h}^{\mathrm{T}}\boldsymbol{b}\right)^{-1}\eta\tanh(s/\Omega) =$$
$$-(k_1v + k_2r) - (h_1b_1 + h_2b_2)^{-1}\eta\tanh(s/\Omega) \tag{31}$$

where η is the switching gain; Ω is the boundary layer thickness.

3.2 Control law of rudder roll stabilization

The state space of linear model of three DOF coupling motion can be obtained according to Eq. (1)–Eq. (8).

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ 0 \\ 0 \end{bmatrix} \delta \tag{32}$$

The sliding mode surface function s can be defined as follows:

$$s = h_1 v + h_2 p + h_3 r + h_4 \phi + h_5 (\psi - \psi_d) \quad (33)$$

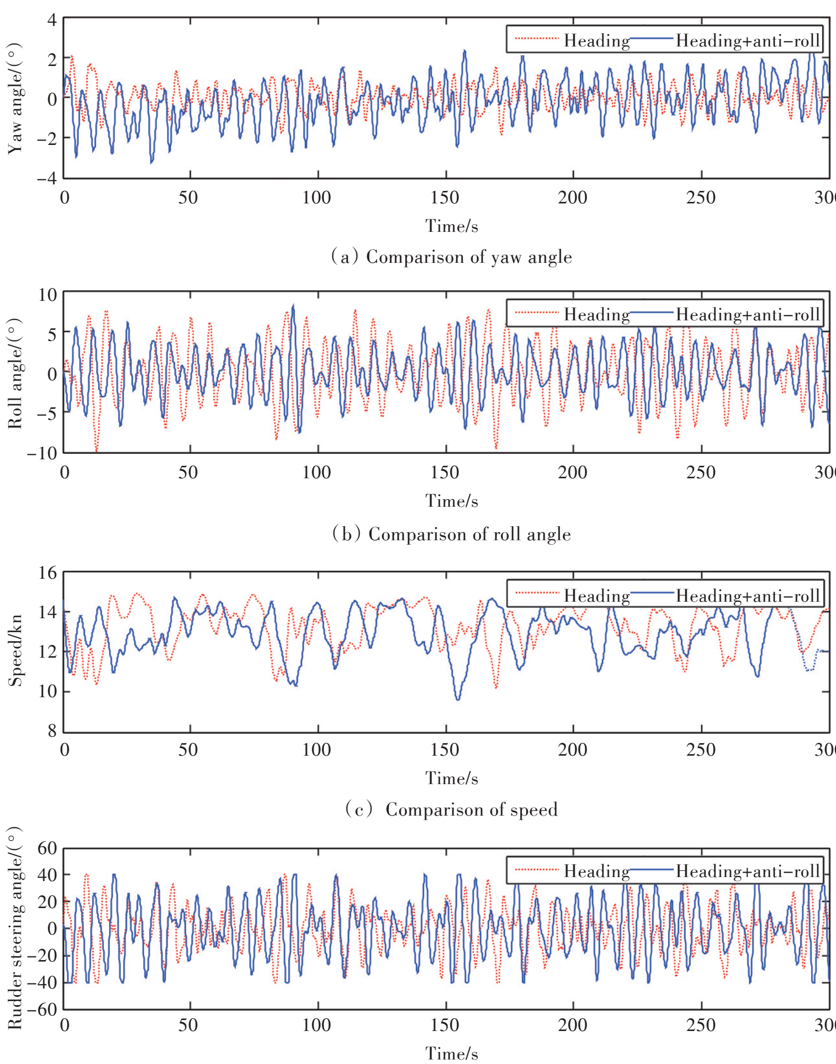
Since there is a restoring force item in rolling motion, state matrix $\boldsymbol{A}_c$ still has only one pure integral channel. According to the derivation of previous section, the sliding mode control law of heading roll can be expressed as:

$$\delta = -(k_1 v + k_2 p + k_3 r + k_4 \phi) - (h_1 b_1 + h_2 b_2 + h_3 b_3 + h_4 b_4)^{-1} \eta \tanh(s/\Omega) \quad (34)$$

4 Simulation analysis

The ship type and its parameters are taken from Ref. [17]. The main parameters are as follows: ship length of 51.5 m, beam of 8.6 m, draft of 2.3 m, speed of 15 kn; the ship is installed with double rudders, with chord length of 1.5 m, span length of 1 m, and the maximum rudder steering angle of 40°. In simulation, the significant wave height is 4 m, the average period of long-crested wave disturbance is 7 s, and navigation encounter angle is 135°; the course control parameters $\boldsymbol{k} = (-10, -100, 0)^T$, $\eta = 1.0512$, $\Omega = 1$; the course/roll control parameters $\boldsymbol{k} = (-5, -200, -100, -10, 0)^T$, $\eta = 0.0751$, $\Omega = 0.5$. The simulation results are shown in Fig. 2.

As can be seen from Fig. 2, although the increase of rudder roll stabilization can reduce the roll to a certain extent, with a roll reduction rate of 21.46%, but the heading control precision is reduced. What's more, the ship speed maintenance is reduced consequently. Taking "heading" with average speed of 13.28 kn and "heading + roll stabilization" with average speed of 12.93 kn as examples, the capacity of speed maintenance decreases by 2.33% when compared with pure heading control. Therefore, speed loss is not negligible for energy loss of ocean navigation. In addition, in order to resist the roll disturbance, rudder roll stabilization increases the amplitude and frequency of steering and thus increase the rudder abrasion.



(a) Comparison of yaw angle

(b) Comparison of roll angle

(c) Comparison of speed

(d) Comparison of rudder steering angle

Fig.2 Comparison of ship performance by "heading" and "heading+anti-roll" control mode

The added resistance of ship is determined by the sway speed, angular speed in yaw and angular speed in roll. Because of limited controllability of swaying motion by rudder, the controllable factors of speed loss are merely angular speed in yaw and angular speed in roll. Therefore, the rudder roll stabilization control reduces the ability of speed maintenance, which is because when reducing the angular speed in roll, the angular speed in yaw is increased at the same time. Thus, the resistance is increased, which indirectly indicates that the resistance induced by yawing motion is higher than that induced by rolling motion.

5 Conclusions

This study analyzes the mechanism of added resistance of ships in both still water and waves. The calculation method of speed decrease is proposed, and the key control factors affecting ship speed are identified. Cooperative control method is used to design the sliding mode control law of rudder roll stabilization, and the influences of added rudder roll stabilization on ship performance is analyzed, especially its influence on maintaining ship speed. The results show that, with the anti-roll effect, rudder roll stabilization reduces the maintaining ability of ship speed and increases the wear and tear of steering machine. Therefore, the fin-rudder roll stabilization control is not recommended for large vessels equipped with fin roll stabilization. However, for small vessels without the ability and space to install fin roll stabilization, the matching problem of speed maintenance and anti-rolling effect should be balanced based on the actual navigation requirements.

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基于航速保持的舵减摇控制方法

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摘 要: 船舶航行受阻力影响引起航速和能量损耗。研究船舶在静水和波浪中的附加阻力,给出船舶航行时的总体航速损失的计算方法。设计带有航速损失约束的自动舵控制系统,依据舵角协同控制方法设计航向和舵减摇滑模控制规律。综合讨论"航向"与"航向+减摇"两种工作情况,包括横摇稳定、航向精度、航速保持、操舵能量消耗。仿真结果表明:该方法可以有效保持航速;从航行经济性的角度,对于同时安装有减摇鳍和自动舵的船舶,不推荐采用舵鳍联合减摇的控制方法。

关键词: 船舶; 运动控制; 舵减摇; 自动舵; 附加阻力; 航速损失; 滑模控制

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纵振动对声传输测量带来的干扰及其避免方法

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摘 要: 弹性充液管道在一端固定,另一端受到谐和力作用时自身会产生稳态纵振动。相比于管道自身模态的谐振,弹性管道稳态纵振动的幅度更大,对于声场的影响也更大。对于管道稳态纵振动的研究可以更好地说明充液管道对管口辐射声场的影响。通过等效梁模型的解析计算及与实验结果的对比,验证了等效梁模型用于计算管道稳态纵振动的正确性,同时,提出一种用于隔离管道纵振动的方法,并通过实验验证了其有效性。

关键词: 弹性充液管道; 声传输特性; 稳态纵振动