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The application of the self-tuning neural network PID controller on the ship roll reduction in random waves

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ABSTRACT

In this paper, we present a mathematical model including seakeeping and maneuvering characteristics to analyze the roll reduction for a ship traveling with the stabilizer fin in random waves. The self-tuning PID controller based on the neural network theory is applied to adjust optimal stabilizer fin angles to reduce the ship roll motion in waves. Two multilayer neural networks, including the system identification neural network (NN1) and the parameter self-tuning neural network (NN2), are adopted in the study. The present control technique can save the time for searching the optimal PID gains in any sea states. The simulation results show that the present developed self-tuning PID control scheme based on the neural network theory is indeed quite practical and sufficient for the ship roll reduction in the realistic sea.

1. Introduction

As we know, the ship sailing in a seaway usually endures large motions and large accelerations due to waves, which may lead to seasickness, disturbance of the ship operation, stability loss, etc. Regarding the ship motions, rolling is one of the most undesirable phenomena for crews because it may cause some convenience and accidents at sea. Therefore several techniques, either passive or active, for avoiding large rolling motions have been employed, for example bilge keels, gyroscopic stabilizer, anti-rolling tank, rudder, stabilizer fin, etc. Among these techniques, the active stabilizer fin seems to be the most effective and widely adopted. However, in order to apply the active stabilizer fin to reduce the ship roll motion, the ship speed must reach the adequate value to make the controller act efficiently (Jerrold and Michael, 1999).Generally, the active stabilizer fin needs to incorporate the automatic controller to achieve the optimal roll reduction for the ship traveling in rough sea. Therefore how to select a suitable controller for the stabilizer fin to reduce the ship rolling motion in waves is an important technology. Several kinds of controllers were already developed in the past, e.g. PD and PID control (Dove and Wright, 1991), adaptive control (Nejim, 2000; Tzeng and Lin, 2000), fuzzy control (Cao and Lee, 2003), sliding mode control (Fang and Luo, 2007) etc. The PID controller may be the one which is the most extensively applied. However, in the past, the control gain parameters adopted in PID controller were usually determined based on the experience of the operator, trial and error or experiments. Therefore Natarajan and Gilbert (1997) developed some theoretical formulas to determine the related parameters and other optimization methods such as genetic algorithm (Fang and Luo, 2006) or neural network (Hemerly and Nascimento, 1999) were also incorporated to improve its efficiency. Because the neural network can handle the nonlinear problem very well, it is adopted here to promote the efficiency of the controller to reduce the ship roll motion. Incorporating the back-propagation algorithm, Rumelhart and McClelland (1986) applied the neural network research more extensively in many areas, for example, image process and division, system identification and system control. Li et al. (2005) applied the PID controller to the ship stabilizer fin based on the wavelet neural network identification and tuning, which shows the effectiveness and the performance were improved. Hemerly and Nascimento (1999) applied neural network adaptive control algorithm to train the controller and simulate control parameters for PID controller. This technique has been successfully applied to the position control of an ultrasonic motor (Hsu, 1998), therefore it is adopted in the present study.

In the paper, the mathematical model for a ship steering in waves was based on the 6-DOF mathematical model used by Fang and Luo (2006). This mathematical model treats the seakeeping and maneuvering characteristics separately in order to simplify the problem caused by the complicated interactions. This model has been successfully applied by Fang and Luo (2006, 2007). In order to keep the ship to sail in the desired path, the track keeping control technique used by Fang and Luo (2006) is also applied directly here for reducing the calculation time. A PID control system incorporating back-propagation neural network algorithm is then applied to the stabilizer fin for roll reduction. In the following section, the control system incorporated the mathematical

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model for the ship maneuvering in waves is described. Different wave conditions are adopted to investigate the efficiency of this control system.

2. Mathematical model

In the present mathematical model, three coordinate systems are defined in Fig. 1. The earth-fixed coordinate system $O-X_0Y_0Z_0$ is used to describe the incident wave. The body coordinate system $G-xyz$, with its origin at the ship's center of gravity, is moving with the ship motion. The horizontal body coordinate system $G-x'y'z'$ is also fixed at the ship's center of gravity, but the $Gx'y'$ plane is always parallel to the OX_0Y_0 plane. ϕ, θ and ψ are Euler angles.

Following the mathematical model used by Fang and Luo (2006), the nonlinear 6-DOF equations of motions including the control forces due to the stabilizer fin are developed and shown in Eqs. (1)–(6). The engine torque equation is also shown simultaneously, i.e. Eq. (7).

$$\text{Surge}: \quad m(\dot{u}-v\dot{\psi}) = (m_y(\omega_e)-X_{v\dot{\psi}})v\dot{\psi} - m_x(\omega_e)\dot{u} - m_z(\omega_e)w\dot{\theta} + X_{FK}(\omega_e) + X_{RF} + X_{FF} + T(1-t_p) - R \tag{1}$$

$$\text{Sway}: \quad m(\dot{v}+u\dot{\psi}) = -m_x(\omega_e)u\dot{\psi} - m_y(\omega_e)\dot{v} - Y_v v - Y_{\ddot{\psi}}\ddot{\psi} + Y_{\dot{\psi}}\dot{\psi} + Y_{v|v|}v|v| + Y_{v|\dot{\psi}|}v|\dot{\psi}| + Y_{\dot{\psi}|\dot{\psi}|}\dot{\psi}|\dot{\psi}| + Y_{FK}(\omega_e) + Y_{DF}(\omega_e) + Y_{RF} + Y_{FF} \tag{2}$$

$$\text{Heave}: \quad m\dot{w} = -m_z(\omega_e)\dot{w} - Z_w(\omega_e)w - Z_{\ddot{\theta}}(\omega_e)\ddot{\theta} - Z_{\dot{\theta}}(\omega_e)\dot{\theta} - Z_{\theta}(\omega_e)\theta + Z_{FK}(\omega_e) + Z_{DF}(\omega_e) + Z_{FF} + mg \tag{3}$$

$$\text{Roll}: \quad I_{xx}(\omega_e)\ddot{\phi} - I_{xx}(\omega_e)\dot{\theta}\dot{\psi} = J_{xx}(\omega_e)\dot{\theta}\dot{\psi} - J_{xx}(\omega_e)\ddot{\phi} - K_{\dot{\phi}}\dot{\phi} + (Y_v v - Y_{\dot{\psi}}\dot{\psi})z_H + K_{FK}(\omega_e) + K_{DF}(\omega_e) + K_{RF} + K_{FF} \tag{4}$$

$$\text{Pitch}: \quad I_{yy}(\omega_e)\ddot{\theta} + I_{xx}(\omega_e)\dot{\psi}\dot{\phi} = -J_{xx}(\omega_e)\dot{\phi}\dot{\psi} - J_{yy}(\omega_e)\ddot{\theta} - M_{\dot{\theta}}(\omega_e)\dot{\theta} - M_{\theta}(\omega_e)\theta - M_{\dot{w}}(\omega_e)\dot{w} - M_w(\omega_e)w + M_{FK}(\omega_e) + M_{DF}(\omega_e) + M_{FF} \tag{5}$$

$$\text{Yaw}: \quad I_{zz}(\omega_e)\ddot{\psi} - I_{xx}(\omega_e)\dot{\theta}\dot{\phi} = J_{xx}(\omega_e)\dot{\theta}\dot{\phi} - J_{zz}(\omega_e)\ddot{\psi} - N_{\dot{v}}\dot{v} - N_v v - N_{\dot{\psi}}\dot{\psi} + N_{\dot{\psi}|\dot{\psi}|}\dot{\psi}|\dot{\psi}| + N_{vv\dot{\psi}}v^2\dot{\psi} + N_{v\dot{\psi}\dot{\psi}}v\dot{\psi}^2 + N_{\phi}\phi + N_{v|\phi|}v|\phi| + N_{\dot{\psi}|\phi|}\dot{\psi}|\phi| + (-Y_v v + Y_{\dot{\psi}}\dot{\psi} + Y_{v|v|}v|v| + Y_{v|\dot{\psi}|}v|\dot{\psi}| + Y_{\dot{\psi}|\dot{\psi}|}\dot{\psi}|\dot{\psi}|)x_H + N_{FK}(\omega_e) + N_{DF}(\omega_e) + N_{RF} + N_{FF} \tag{6}$$

$$\text{Engine}: \quad 2\pi(I_{pp}+J_{pp})\dot{n} = Q_E - Q_P \tag{7}$$

where m and I are ship mass and mass moment of inertia, respectively. X, Y and Z are external forces with respect to surge, sway and heave, whereas K, M and N are external moment with respect to roll, pitch and yaw. Surge, sway and heave velocities are represented by u, v and w, respectively, whereas roll, pitch and yaw displacements are represented by ϕ, θ and ψ, respectively. T is propeller thrust, R is ship resistance and t_p is the thrust deduction factor. In Eqs. (3) and (5), the corresponding hydrodynamic coefficients with respect to heave and pitch can be found in the reference, Kim et al. (1980), and they are calculated by Frank close-fit method. The $(m_y - X_{v\dot{\psi}})$ term can be written as $C_m m_y$, and C_m is about 0.5–0.75 (Yoshimura & Nomoto, 1978). m_x, m_y and m_z represent the added masses with respect to the x, y and z axes, respectively, whereas J_{xx}, J_{yy} and J_{zz} represent the added moments of inertia with respect to the x, y and z axes, respectively. The maneuvering derivatives of sway and yaw motions, i.e. Y_v, $Y_{v|v|}$, $N_{\dot{\psi}}$, $N_{v|\phi|}$, etc., are estimated by empirical formulas (Inoue et al. 1981) based on the model experiment in calm water. The roll damping coefficient $K_{\dot{\phi}}$ can be computed from the empirical formula derived by Takahashi (1969). The related nonlinear terms for maneuvering derivatives can be found from Hirano and Takashina (1980) and Inoue et al. (1981). The terms I_{PP}, J_{pp}, Q_E, Q_P, n in Eq. (7) represent the moment of inertia of propeller-

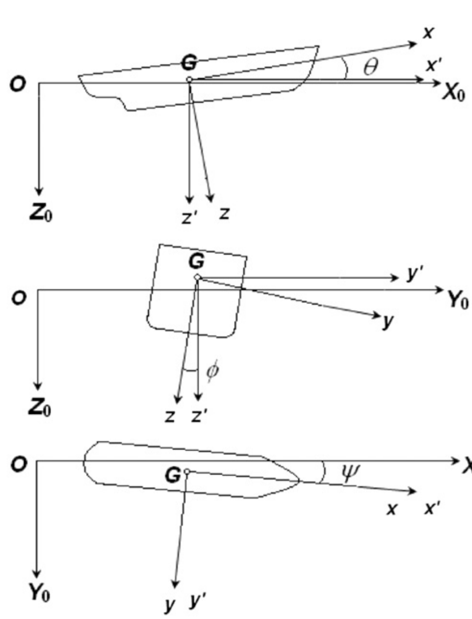

Fig. 1. Coordinate systems

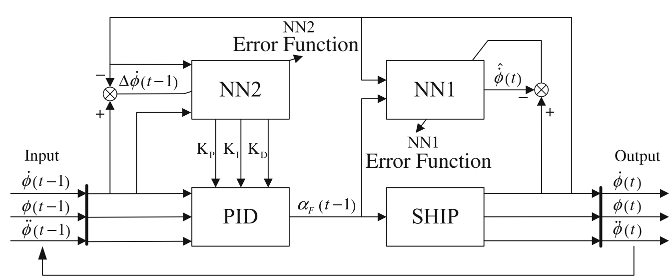

Fig. 2. The control system scheme for self-tuning neural network PID controller

Table 1
Principal dimensions of the container ship.

Length (m)	185.5
Breadth (m)	30.5
Draft (m)	11.0
Metacentric height (m)	2
Block coefficient	0.67
Propeller diameter (m)	7.45
Propeller Pitch ratio	1.0
Rudder area (m^2)	40.42
Aspect ratio of rudder	1.55