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Nonparametric identification of nonlinear ship roll motion by using the motion response in irregular waves

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ABSTRACT

In order to precisely predict the nonlinear roll motion of ships at sea, it is important to determine the nonlinear damping and restoring moment as accurately as possible. In this paper, a nonlinear mathematical model is used to describe the nonlinear roll motion of ships at sea. A novel nonparametric identification method based on a combination of random decrement technique (RDT) and support vector regression (SVR) is used to identify the nonlinear damping and restoring moments in the mathematical model simultaneously by using only the random rolling responses of ships in irregular waves. In the identification method, RDT is first used to derive the random decrement equation as well as the auto- and cross-correlation equations based on the established mathematical models, and the random decrement signatures are also obtained from the random roll responses. Then SVR is applied to identify the damping and restoring moments in the roll motion equation. For the purpose of verifying the applicability, accuracy and generalization ability of the identification method, it is applied to analyzing the simulated data with different wave excitations. The identification results show that the identification method can be applied to identify the damping and restoring moments of the nonlinear roll motion using the random responses of ships in irregular waves.

1. Introduction

When a ship is navigating at sea, the roll motion has a significant influence on its safety and operability; therefore, it is crucial to predict the roll motion as accurately as possible. In order to predict the roll motion, a universal mathematical model for describing the nonlinear roll motion of ships in waves is usually established according to the rigid body dynamics. The key issue to predict the roll motion of ships precisely is to determine the damping and restoring moments in the mathematical model correctly.

Although the roll damping has been investigated by many researchers for a long time since William Froude in the 19th century, a universal method to predict the damping moment which is mainly dependent on the fluid viscosity is still absent. To predict the roll damping, several methods are available, i.e., model test method [1–3], semi-empirical method [4–6], numerical method based on CFD [7–9] and system identification method.

System identification technique, which aims to find the best mathematical model that relates the output to the input of a system, has been used to identify the roll damping of ships. Ueno et al. [10] applied the improved energy method and the genetic algorithm respectively to estimate the roll damping coefficients and the restoring moment coefficients for fishing boats. Considering the good performance of the nonlinear fitting, artificial neural networks have been used to identify the roll motion of ships by many researchers. Mahfouz [11] applied artificial neural network to identify the roll damping and restoring moment coefficients of ships. Besides, Haddara [12], Xing and McCue [13], Ueno and Fan [14] also used artificial neural networks to identify the roll motion of ships. Kim and Park [15], Kim et al. [16] used Hilbert transform method to identify the nonlinear roll damping and restoring moments of a FPSO by analyzing the free decay test. Somayajula and Falzarano [17] applied R-MISO method to identify the roll parameters of an S-175 container ship. Recently, with the development of the inverse problem theory, it has been used to study the roll motion of ships. Jang et al. [18] applied the deterministic inverse method to identify the functional form of the nonlinear roll damping of ships. Jang [19] improved this method to simultaneously identify the nonlinear damping and the restoring moments of nonlinear sys-

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tems. Han and Kinoshita [20] presented an application of stochastic inverse method for the nonlinear damping identification and used the method to identify the nonlinear roll damping of a ship.

During the past twenty years, with the rapid development of statistic learning theory and data mining technology, support vector regression (SVR) as a new generation of machine study method has been widely used to solve problems in engineering. SVR is first proposed by Vapnik [21,22] in the 1990s. Compared to the conventional parameter estimation methods such as the least square method, maximum likelihood estimation and artificial neural network which adopt the empirical risk minimum principle and are suitable for large scale samples learning, SVR adopts the structural risk minimum principle and is suitable for small scale samples learning. Luo and Zou [23] first applied the least square SVR to identify the mathematical model of ship maneuvering motion, and the validity of SVR in the parametric identification is validated by the numerical experiment. Zhang and Zou [24], Wang et al. [25] also used SVR to identify the hydrodynamic derivatives in the equations of ship maneuvering motion. Xu et al. [26] used the least square SVR to identify the nonlinear coefficients in the dynamic model of underwater vehicles. In order to predict the roll motion accurately, Hou and Zou [27,28] used SVR to identify the nonlinear damping and restoring moment coefficients by using only the measured roll responses in regular waves and in irregular waves, respectively. From these studies, the robustness and convergence property of SVR are demonstrated and validated.

In the present study, in order to predict the nonlinear roll motion of ships in irregular waves by using the mathematical model, a robust nonparametric identification method based on a combination of random decrement technique (RDT) and SVR is proposed to identify the damping and restoring moments for the nonlinear roll motion of ships in irregular waves by using only the random roll responses. To begin with, a nonparametric mathematical model is established to describe the nonlinear roll motion of ships at sea. Then the random decrement equation as well as the auto- and cross-correlation equations is derived based on the established mathematical model by using RDT, and SVR is used to identify the nonlinear damping and restoring moments in the roll motion equation. In order to validate the applicability, accuracy and the ability of generalization, the proposed method is used to analyzing the simulated responses of a vessel model in irregular waves. Finally, some conclusions are drawn.

2. Equation of roll motion

According to the rigid body dynamics, the roll motion of a ship at sea can be described by a second order nonlinear ordinary differential equation of the form

$$(I_{xx}+J_{xx})\ddot{\phi}+D(\dot{\phi})+R(\phi)=M(t) \tag{1}$$

where ϕ is the roll angle (rad); I_{xx} is the mass moment of inertia (kg m^2); J_{xx} is the added mass moment of inertia (kg m^2); D is the nonlinear damping moment (N m); R is the restoring moment (N m); M is the wave exciting moment (N m).

From Eq. (1), it can be seen that there are four variables to be determined, i.e., J_{xx}, D, R and M. Dividing Eq. (1) by the total mass moment of inertia $(I_{xx}+J_{xx})$, the normalized roll motion equation is obtained

$$\ddot{\phi}+d(\dot{\phi})+r(\phi)=K(t) \tag{2}$$

where $d(\dot{\phi})=D(\dot{\phi})/(I_{xx}+J_{xx})$; $r(\phi)=R(\phi)/(I_{xx}+J_{xx})$; $K(t)=M(t)/(I_{xx}+J_{xx})$. In order to predict the roll damping of a ship in waves accurately, various mathematical models have been proposed [29–32]. The nonlinear damping, as a function of roll rate, can be expressed as a sum of two terms: a linear term and a nonlinear term. Two forms are usually used to describe the nonlinear term, i.e., the quadratic form and the cubic form. In this study, the nonlinear damping is expressed in the form of

$$d(\dot{\phi})=d_1\dot{\phi}+f_1(\dot{\phi}) \tag{3}$$

where d_1 is the linear damping coefficient; the function f_1 denotes the nonlinear component of the damping.

The restoring moment, as an odd function of the roll angle, can be expressed by the Taylor series of the roll angle

$$r(\phi)=c_1\phi+c_3\phi^3+c_5\phi^5+\ldots \tag{4}$$

where c_i (i = 1,3,5,...) is the restoring moment coefficient.

However, the order of the Taylor expansion is usually determined empirically. In the present study, the restoring moment is expressed by

$$r(\phi)=c_1\phi+f_2(\phi) \tag{5}$$

where c_1 is the linear restoring moment coefficient; f_2 denotes the nonlinear component of the restoring moment.

Substituting Eqs. (3) and (5) into Eq. (2), the normalized roll motion equation is rewritten as

$$\ddot{\phi}+d_1\dot{\phi}+c_1\phi+f(\phi,\dot{\phi})=K(t) \tag{6}$$

where $f(\phi,\dot{\phi})=f_1(\dot{\phi})+f_2(\phi)$.

3. Identification method

The identification method consists of two parts: one is RDT which is applied to derive the random decrement equation and obtain the random decrement signatures from the roll responses of a ship in irregular waves; the other is SVR which is applied to identify the nonlinear damping and restoring moments based on the derived random decrement equation and the obtained random decrement signatures.

3.1. Random decrement technique

Random decrement technique (RDT), as an averaging technique, has been successfully applied to system identification in ship and ocean engineering by combining with conventional identification methods [33,34]. The basic concept of RDT is that the random roll response of a ship in irregular waves can be divided into two components: one is the deterministic component which is dependent on the initial state; the other is the random component which is dependent on the external excitation. By using RDT, the random component is removed and the deterministic component of the roll motion, named as the random decrement signature, is kept.

When Eq. (6) is used to describe the roll motion of a ship in irregular waves, the following variable substitutions are used

$$y_1=\phi,\qquad y_2=\dot{\phi},\qquad Y=[y_1,y_2]^{\mathrm{T}} \tag{7}$$

The wave excitation is assumed to satisfy the following conditions

$$E\left[K(t)\right]=0,\qquad E\left[K(t)K(t+\tau)\right]=\psi_0\delta(\tau) \tag{8}$$

where $E[\cdot]$ denotes the ensemble average of variables; ψ_0 is the variance of the excitation; δ is the Dirac delta function.

Then the random process Y is a Markov process, and its conditional probability density function can be described by virtue of the Fokker-Planck equation

$$\frac{\partial P}{\partial t}=-\frac{\partial}{\partial y_1}(y_2P)+\frac{\partial}{\partial y_2}\left\{\left[d_1y_2+c_1y_1+f(y_1,y_2)\right]P\right\}+\frac{\psi_0}{2}\frac{\partial^2P}{\partial y_2^2} \tag{9}$$