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Parameter identification of nonlinear roll motion equation for floating structures in irregular waves

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ABSTRACT

In order to predict the roll motion of a floating structure in irregular waves accurately, it is crucial to estimate the unknown damping coefficients and restoring moment coefficients in the nonlinear roll motion equation. In this paper, a parameter identification method based on a combination of random decrement technique and support vector regression (SVR) is proposed to identify the coefficients in the roll motion equation of a floating structure by using the measured roll response in irregular waves. Case studies based on the simulation data and model test data respectively are designed to validate the applicability and validity of the identification method. Firstly, the roll motion of a vessel is simulated by using the known coefficients from literature, and the simulated data are used to identify the coefficients in the roll motion equation. The identified coefficients are compared with the known values to validate the applicability of the identification method. Then the roll motion is predicted by using the identified coefficients. The prediction results are compared with the simulated data, and good agreement is achieved. Secondly, the model test data of a FPSO are used to identify the coefficients in the roll motion equation. Then the random decrement signature of the roll motion is predicted by using the identified coefficients and compared with that obtained from the model test data, and satisfactory agreement is achieved. From this study, it is shown that the identification method can be effectively applied to identify the coefficients in the nonlinear roll motion equation in irregular waves.

1. Introduction

The roll motion of a floating structure at sea has a significant influence on its safety and operability; therefore, it is crucial to predict the roll motion of a floating structure accurately. Although the roll motion of floating structures has been investigated by many researchers for a long time, because of the strong nonlinear nature of the roll damping, it is still challenging to predict the roll motion correctly, and a universal method to predict the roll damping is still absent.

Traditionally, there are three kinds of methods available for predicting the roll damping, i.e., model test [1–3], semi-empirical method [4–7] and numerical calculation [8–10]. During the last decade, system identification techniques, which aim to find the best mathematical model that relates the output to the input of a system, have been applied to estimate the roll damping by analyzing the roll motion of floating structures. Unar [11] applied artificial neural network to identify the roll damping coefficient of a ship. Muñoz-Mansilla et al. [12] applied system identification method to estimate the parametric model of heave-pitch-roll dynamics of a high-speed craft. Xing and McCue [13] applied artificial neural network to identify the nonlinear roll motion of a ship by using experimental data. Jang et al. [14,15] applied an inverse formulism to identify the functional form of the nonlinear roll damping for a ship by using a free-roll decay experiment and the measured transient response, respectively. Jang [16] improved this identification method to simultaneously identify the nonlinear damping and the restoring characteristics of nonlinear oscillation systems. Han and Kinoshita [17–19] presented an application of stochastic inverse method for the nonlinear damping identification and applied this method to identify the nonlinear roll damping of a ship at zero forward speed and non-zero forward speed. Yin et al. [20] applied sequential learning RBF neural networks to on-line predict the roll motion of a ship during maneuvering.

Compared to the conventional learning methods based on large scale samples, support vector machine (SVM), as a new generation of machine study method, is very suitable for learning based on small scale samples. It was first proposed by Vapnik [21] in the 1990s. By taking advantage of the Lagrangian dual theorem and structural risk minimum principle to solve quadratic programming

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problems, SVM can achieve the global optimal solution of the quadratic programming problems. According to its application, SVM can be divided into two categories: one is support vector classifier (SVC) which is often used to solve classification problems; and the other is support vector regression (SVR) which is used to solve regressive problems. Because SVR can not only acquire the global optimum solution, but also can avoid the curse of dimensionality and the problem of data over-fitting to some extent, SVR has been successfully applied to parameter identification in ship and ocean engineering. Luo and Zou [22], Zhang and Zou [23,24] used least square SVR and ε-SVR respectively to identify the hydrodynamic derivatives in ship maneuvering motion equations. Xu et al. [25,26] applied least square SVR to identify the nonlinear coefficients in the dynamic model of underwater vehicles. Liu and Yang [27] applied varying parameters least square SVR to on-line predict the roll motion of a ship.

In the present study, a parameter identification method based on a combination of random decrement technique and SVR is proposed to identify the unknown coefficients in the nonlinear roll motion equation of a floating structure in irregular waves. Firstly, case studies based on the simulation data are designed to validate the applicability of this method. Secondly, the parameter identification method is applied to identify the unknown coefficients in the nonlinear roll motion equation by using the model test data of a FPSO. Then the roll motion is predicted based on the identified coefficients and the prediction results are compared with the measured data to demonstrate the validity of the identification method. Finally, some conclusions are drawn.

2. Equation of roll motion

The roll motion of a floating structure at sea can be described by a second-order nonlinear ordinary differential equation of the form

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

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); $D(\dot{\phi})$ is the damping moment (N m); $C(\phi)$ is the restoring moment (N m); M is the wave exciting moment (N m).

Various expressions of the damping and restoring moments are proposed [28,29]. In this paper, the most commonly used expression of a linear term plus a quadratic term is used to represent the nonlinear damping moment

$$D(\dot{\phi})=D_1\dot{\phi}+D_2\dot{\phi}|\dot{\phi}| \tag{2}$$

where D_1 and D_2 are the linear and nonlinear damping coefficients, respectively. The restoring moment is represented as an odd function of the roll angle by a linear term plus a cubic term in the form

$$C(\phi)=C_1\phi+C_3\phi^3 \tag{3}$$

where C_1 and C_3 are the linear and third-order restoring moment coefficients, respectively.

In irregular waves, the wave exciting moment M can be expressed by

$$M=\sum_{i=1}^{\infty}F_i\cos(\omega_i t+\theta_i) \tag{4}$$

where F_i and ω_i are the amplitude and frequency of the wave exciting moment component, respectively, and θ_i is the phase shift which is taken as a random variable uniformly distributed between 0 and 2π.

Substituting Eqs. (2), (3) and (4) into Eq. (1), the second-order nonlinear ordinary differential equation of roll motion for a floating structure in irregular waves is derived:

$$(I_{xx}+J_{xx})\ddot{\phi}+D_1\dot{\phi}+D_2\dot{\phi}|\dot{\phi}|+C_1\phi+C_3\phi^3=\sum_{i=1}^{\infty}F_i\cos(\omega_i t+\theta_i) \tag{5}$$

Dividing Eq. (5) by the total moment of inertia ($I_{xx}+J_{xx}$), the normalized roll motion equation is obtained:

$$\ddot{\phi}+p_1\dot{\phi}+p_2\dot{\phi}|\dot{\phi}|+r_1\phi+r_3\phi^3=\sum_{i=1}^{\infty}A_i\cos(\omega_i t+\theta_i) \tag{6}$$

where $p_1=D_1/(I_{xx}+J_{xx})$, $p_2=D_2/(I_{xx}+J_{xx})$; $r_1=C_1/(I_{xx}+J_{xx})$, $r_3=C_3/(I_{xx}+J_{xx})$ and $A_i=F_i/(I_{xx}+J_{xx})$.

3. Identification method

The identification method consists of two parts: one is the random decrement technique which is applied to obtain the random decrement signature from the steady roll response of a floating structure in irregular waves; the other is SVR which is applied to identify the unknown coefficients in the nonlinear roll motion equation based on the obtained random decrement signature.

3.1. Random decrement technique

Random decrement technique, as an averaging technique, has been successfully applied in parameter or nonparametric identification in ship and ocean engineering in combination of conventional identification methods [30,31]. The basic concept of the random decrement technique is that the random response of a floating structure 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 applying the random decrement technique, the random component is removed and the deterministic component, named as random decrement signature, is kept.

To derive the random decrement equation of the nonlinear roll motion in irregular waves, the following two variable substitutions are used:

$$y_1=\phi,\quad y_2=\dot{\phi} \tag{7}$$

Substituting Eq. (7) into Eq. (6), the following equation is obtained:

$$\begin{cases}\dot{y}_1=y_2\\ \dot{y}_2=-p_1y_2-p_2y_2|y_2|-r_1y_1-r_3y_1^3+\sum_{i=1}^{\infty}A_i\cos(\omega_i t+\theta_i)\end{cases} \tag{8}$$

When the random decrement technique is used to analyze the roll motion, the wave excitation is assumed to be a white noise random process which satisfies the following conditions

$$E[M(t)]=0,\quad E[M(t_1)M(t_2)]=\psi_0\delta(t_1-t_2) \tag{9}$$

where $E[\cdot]$ denotes the ensemble average of variables; ψ_0 is the zero-order spectral moment of the excitation; δ is the Dirac delta function [32,30].

Then the random process $Y(t)=[y_1, y_2]^T$ is a Markov process, and its conditional probability density function can be described by virtue of the Fokker–Planck equation

$$\frac{\partial P}{\partial t}=-\frac{\partial}{\partial y_1}(y_2P)+\frac{\partial}{\partial y_2}[(p_1y_2+p_2y_2|y_2|+r_1y_1+r_3y_1^3)P]+\frac{\psi_0}{2}\frac{\partial^2P}{\partial y_2^2} \tag{10}$$