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Stochastic inverse modeling of nonlinear roll damping moment of a ship

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ABSTRACT

This work presents an application of stochastic inverse method for the determination of nonlinear roll damping moment of a ship at zero forward speed. Nonlinear roll damping moment was estimated from the measured dynamic responses through stochastic inverse model. It is shown that this method enables nonlinear characteristic of the roll damping to be estimated without any assumption on its form of nonlinearity, including its confidence intervals given noisy data. The accuracy and practicability were assessed with laboratory tests related to both free-decay and forced rolling motions. The estimation results of the nonlinear damping moment show good agreement in all cases.

1. Introduction

The motion of a floating vessel has the six degrees of freedom of a rigid body, among which the roll motion plays the most significant role to produce the significant responses. The safety of a ship might be seriously threatened by a failure connected with ship stability. This failure may cause excessive amount of loads on cargo fastenings, cargo shifting, water shipping on deck and so on. In worst case, ship capsizing or structure failure may occur as a result of these factors. The modeling of roll motion of a ship is thus one of great practical importance [1–5].

Generally, wave-induced ship motions can be calculated on the basis of well-developed theory such as strip theory [1–3]. All coefficients which characterize ship motions can be successfully determined except roll damping coefficient. This is mainly because roll damping mechanism is closely related with the viscosity of surrounding fluids and is nonlinear in nature. It is very difficult to estimate the nonlinear characteristic of roll damping by theoretical methods based on hydrodynamic theory. Thus damping model is normally determined in a separate manner.

Determination of roll damping moment conventionally begins with assuming its form of nonlinearity [4–10], which is represented by some of parameters. Then the parameters are obtained from the logarithmic decrement of a free-decay roll test. These kinds of methods are referred as to parametric identification method in which a specific parametric representation of the nonlinear damping is required to begin with. Basically, the key idea behind these methods is that the loss in energy over each cycle of the decay test can be equated to the dissipated energy by damping. However, a question may be raised as to the validity of the assumed damping models. Because roll damping models can not only be used to make estimation for unknown quantities such as the damping moment, but can also be used to predict the motion of a ship. If an inappropriate damping model is selected, results of such procedures may yield discrepancies when reproducing the motions because different types of nonlinear model produce different motion responses [11,12].

Some progress toward solving this question has recently been made [13–15]. These studies are non-parametric in the sense that parametric models of the terms are not necessary. Conceptually, these methods are based on inverse formalism based on the transformation of an original motion equation in either a deterministic [13,15] or stochastic manner [15]. The result of the identification procedure will simply be functions of the desired physical quantity represented by a number of points. These points can be used to get an analytical expression for the roll damping moment.

This paper presents applications of a new stochastic inverse method, developed by Han and Kinoshita [15], to the stochastic estimation of nonlinear roll damping moment of a ship at zero forward speed in cases of both free-decay rolling and forced rolling tests. This method is believed to offer a straightforward procedure for the stochastic estimation of nonlinear damping moment from knowledge of relevant physical values. This method has also some unique features to represent an improvement on current parametric identification methods, because the concept of an assumption of nonlinearity is avoided. Furthermore, this method provides a way to quantify the related system uncertainties by rigorously considering the stochastic nature driven by data noises such as measurement error.

For the purpose of estimation, we first formulate a stochastic inverse model by defining nonlinear damping moment as a non-deterministic quantity, which is a multivariate random variable. The

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problem is then represented by a stochastic estimation problem given measurement of roll responses. A probabilistic expression, called posterior probability distribution function, is deduced for the estimation problem. To extract necessary information from the probabilistic expression, Markov chain Monte Carlo method is adopted for the determination of the desired nonlinear roll damping moment. Outline of this paper is as follows. Section 2 briefly describes the stochastic inverse modeling of the nonlinear damping for a ship in roll motion. Experimental set-ups are explained in Section 3. Sections 4 and 5 present an analysis of experimental data from the free-decay rolling and forced rolling tests, respectively. Finally, conclusions are made in Section 6.

2. Mathematical model

In this study, we assume that the roll motion is described as forced nonlinear single-degree-of-freedom system:

$$I'\ddot{\phi} + B\left(\dot{\phi}\right) + C\phi = M, \qquad \phi(0) = \alpha, \quad \dot{\phi}(0) = \beta, \tag{1}$$

where ϕ is the roll angle, I' is the roll inertia which includes added moment of inertia, $B(\dot{\phi})$ is the nonlinear damping moment, $C\phi$ is the restoring moment and M is the roll-excitation moment.

The main objective of this study is to estimate $B(\dot{\phi})$ given a measured response data ϕ based on stochastic inverse modeling. For estimation purpose, $B(\dot{\phi})$ will here be modeled as a sequence of random variable $U(t;\xi)$, U: $\Omega \to R^n$. Here, ξ is every possible outcome of an arbitrary non-empty sample space Ω.

As a first step of estimation, the roll-angle data ϕ is converted to a quantity g by a relationship:

$$\begin{aligned} g(t) &= \phi(t) - \alpha x_1(t) - \beta x_2(t) \\ &- \int_0^t \frac{x_1(\tau)x_2(t) - x_1(t)x_2(\tau)}{I' \cdot W(x_1, x_2; \tau)} M(\tau)\, d\tau, \end{aligned} \tag{2}$$

where $W(x_1, x_2; \tau) \equiv |x_1(\tau)\dot{x}_2(\tau) - x_2(\tau)\dot{x}_1(\tau)|$ and x_1, x_2 are chosen to satisfy:

$$\begin{aligned} I'\ddot{x}_1 + Cx_1 &= 0, \qquad x_1(0) = 1, \quad \dot{x}_1(0) = 0, \\ I'\ddot{x}_2 + Cx_2 &= 0, \qquad x_2(0) = 0, \quad \dot{x}_2(0) = 1. \end{aligned} \tag{3}$$

The quantity g is directly observable since it is represented as the function of the measured response data ϕ. The random variable U can then be related to the directly observable quantity g by a stochastic inverse model [15]:

$$p(U|g) \propto p(g|(U)\, p(U), \tag{4}$$

where the functions $p(g|U)$ and $p(U)$ are known as the likelihood and the prior probability density function, respectively. The part of importance of the above equation lies in a form of a probabilistic description. Using this stochastic inverse model, it is possible to treat the estimation problem as a stochastic inverse function whose output values are random variables given several deterministic arguments. As a result, the non-deterministic quantity U is expressed as a certain probability distribution, which is called the posterior probability density function [15]:

$$\begin{aligned} p(U|g) \propto \left(\sigma^2\right)^{-m/2} &\exp\left(-\frac{\| \mathcal{F}(U) - g \|_2^2}{2\sigma^2}\right) \\ \lambda^{n/2} &\exp\left(-\frac{1}{2}\lambda U^T H U\right), \end{aligned} \tag{5}$$

where $\|\cdot\|_2$ is Euclidean norm, σ is the standard deviation of the noise in the observable quantity g, m is the number of dimensions for a single realization g, the $n \times n$ matrix H is given as $H_{ij} = n_i$ (the number of neighbors) if $i = j$, $H_{ij} = -1$ if i, j are adjacent, and 0 otherwise, and the operator $\mathcal{F}$ is defined by

$$\mathcal{F}(U) \equiv \int_0^t \frac{x_1(\tau)x_2(t) - x_1(t)x_2(\tau)}{I' \cdot W(x_1, x_2; \tau)} U(\tau)\, d\tau. \tag{6}$$

The probabilistic description (5) gives a way to estimate the nonlinear damping moment. A more detailed justification for the derivation of the stochastic inverse model is shown in Appendix A. It is worth noting that in order to extract meaningful information for the nonlinear damping moment, a numerical sampling technique such as Markov chain Monte Carlo [16,17] is required. This technique numerically computes the required densities by generating a random sequence of realizations $\{U_k\}$ with each element $U_k \subset R^n$. The sampled set of realizations $\{U_k\}$ can then be used to approximate the statistics of the desired densities by

$$p(U|g) \approx \frac{1}{N_{MCMC}} \sum_{k=1}^{N_{MCMC}} \delta(U - U_k), \tag{7}$$

where N_{MCMC} is the number of Monte Carlo simulation and δ is Dirac delta function.

3. Experimental set-up

The practicability of the present method is verified by the nonlinear roll damping estimation for free-decay rolling test and forced rolling test at zero forward speed. All the experiments were conducted in the Ocean Engineering Basin of the University of Tokyo. The basin is designed to perform tests related to various kinds of floating structures. Fig. 1 shows the schematic of the experiment. The test model is shown in Fig. 2 and its particulars are summarized in Table 1. During the experiments, the experimental model was rigidly clamped in all degrees of freedom, excepting roll motion.

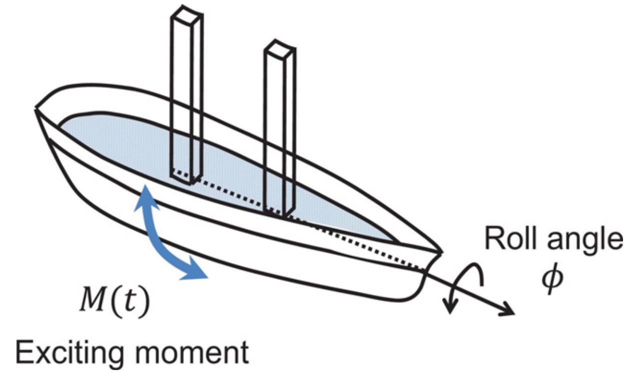

Fig. 1. Schematic of the experiments.

Table 1
Particulars of the test model.

Length, L_{pp}	2.500 m
Breadth, B	0.387 m
Draft, D	0.132 m
Displacement volume, ∇	0.110 m^3
GM	0.074 m

For the case of free-decay rolling test, initial roll angle is given by static means. The external moment is then removed and the gradual decay of the roll angle is measured with the potentiometer attached to the center of gravity of the test model. To investigate the workability of the present method, the bilge model was also considered. Bilge keels (BK) with approximately 1 m long are attached to both sides of the test model as in Fig. 3 to generate different roll characteristics from the original model.