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Nonparametric Identification of Roll Damping and Nonlinear Restoring Forces for a Ship from a Free Roll Decay Simulation

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Roll damping and nonlinear restoring forces have an important influence on ship roll motion. To identify them from free roll decay behaviors, the models are generally assumed to be known a priori. Here, the stochastic inverse method is introduced, and a new nonparametric approach is adopted to identify roll damping and nonlinear restoring forces from a free roll decay simulation, which is carried out by the Reynolds-averaged Navier–Stokes method and overset mesh technology. In the nonparametric identification of roll damping and nonlinear restoring forces, the nonlinear Volterra integral equation of the first kind is solved by the Markov chain Monte Carlo (MCMC) method. The conditional expectation and covariance of the conditional component distribution used in the Gibbs sampler are derived directly in the matrix-vector form by using an analytic inversion formula. Reconstructed roll histories are compared with ones from both the earlier work of the authors and the computational fluid dynamics method. Results show that the MCMC method is an effective way to identify roll damping and nonlinear restoring forces from free roll decay.

INTRODUCTION

Safety against the capsizing of a ship is very important. A ship can experience three types of displacement motions (surge, sway, and heave) and three types of angular motions (roll, pitch, and yaw). The roll motion has more influence on capsizing and is significantly influenced by fluid viscosity compared with the other motions.

Roll damping is too complex to be solved analytically because of viscous effects. Various models of roll motion containing nonlinear terms in the damping force and restoring force have been studied by many researchers, such as Taylan (2000), De Kat and Paulling (1989), and Ahmed et al. (2010). The forms of the roll damping force and restoring force need to be known a priori; the corresponding coefficients in the roll damping force are determined by the free roll decay model test. The restoring force, including the nonlinear part, can be computed according to the ship's geometry.

The model test (Aloisio & Felice, 2006; de Oliveira and Fernandes, 2014; Irvine, 2004; Roddier et al., 2000) is reliable for obtaining the time history of free roll decay, but the cost is high. Numerical simulations based on computational fluid dynamics (CFD) by using the Reynolds-averaged Navier–Stokes (RANS) model considering the fluid viscosity are more popular with the development of computational science and technology (Irkal et al., 2016; Ommani et al., 2016). Chen et al. (2002) simulated large-amplitude ship roll motions by using the RANS model in conjunction with a chimera domain decomposition. Wilson et al. (2006) proposed an unsteady RANS method considering the viscous phenomenon of roll decay motion for a surface combatant. The numerical uncertainties of roll motion were less than 1%. The validation was performed by comparing available experimental data with the predictions validated at 1.7% and 1.5% for the uncorrected and corrected solutions, respectively. Yang et al. (2013) carried out numerical simulations of free roll decay at various forward speeds for a three-dimensional ship hull by using the RANS model, and the error of nature roll period between the numerical data and experimental data was less than 3%. Jiang et al. (2016) performed simulations of free roll decay for the DTMB 5512 with bilge keel, and the roll time history was in good agreement with the experiments. All the numerical simulation cases above show that the RANS model considering the viscosity effect is excellent for the simulation of free roll decay.

In general, the forms of roll damping force are given in advance, such as the linear-plus-quadratic damping model and the linear-plus-cubic damping model. The roll damping coefficient is computed by the extinction curve method with the given free roll decay time history. However, Taylan (1999, 2000) pointed out that an inappropriate selection of damping and restoring terms may lead to a severe discrepancy with the peak roll amplitudes and corresponding frequency. Unlike the roll damping evaluation method above, the nonparametric identification method requires no priori assumption about the form of damping force, with only the displacement and velocity being required. Jang et al. (2009) proposed a nonparametric identification method based on the deterministic inverse approach to recover the functional form of both nonlinear damping and nonlinear restoring forces in the nonlinear oscillatory motions of an autonomous system, in which the nonlinear Volterra integral equation of the first kind appears, and its solution lacks numerical stability (Groetsch and Groetsch, 1993; Tihonov, 1963). Various regularization methods such as those of Landweber and Tikhonov can be used to overcome the instability and further be applied in the identification of roll damping coefficients of a fishing vessel through free roll decay (Jang, 2013; Jang et al., 2009). However, the regularization solution is highly influenced by the regularization parameter as the deterministic inverse approach. Therefore, Han et al. (2012; 2013) proposed an original method based on a stochastic inverse approach to identify the nonlinear damping force of the nonlinear oscillatory system. First, the differential equation of roll motion is transformed into a non-

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