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Stochastic analysis of coupled heave-roll ship motion using the domain decomposition chaotic radial basis function

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ABSTRACT

The effect of uncertainties in the roll and heave natural frequencies as well as in the wave amplitude are investigated on the stochastic parametric ship roll motion using the Domain Decomposition Chaotic Radial Basis Function, which is a novel computational scheme proposed here. These uncertain parameters are represented by random variables with arbitrary distribution which in fact constitute the random input of the stochastic model of roll motion. The random input is divided into a number of random subdomains, in which the stochastic heave and the roll motions are represented using the proposed method. By applying the stochastic heave and roll responses in a nonlinear coupled model of heave and roll motions and subsequently employing a Galerkin projection, the deterministic set of equations governing the stochastic parametric roll response in each random domain are obtained. Through presenting various numerical examples, it is shown that the uncertainty in the system and loading parameters can considerably affect the prediction of the statistics of the parametric ship roll response. Further, the numerical results of the method are compared with those of the Monte Carlo simulation method and a very good agreement is obtained while the computational cost is considerably saved.

1. Introduction

In nonlinear dynamic analysis of ship motions, the presence of unsafe responses is of particular importance. In fact, the nonlinearities in dynamic systems, lead the systems to have multiple solutions. In such cases, a small variation of certain system and loading parameters such as initial conditions, natural frequency, damping ratio, wave loading amplitude, etc., could suddenly provide large motions with unusual characteristics. Therefore, accounting the effects of uncertainties in these parameters can have an important role in predicating the complex behavior of such dynamic systems. Parametric ship roll motion, which is the indirectly excited large roll amplitudes, should be carefully investigated, in order to avoid unpredictable large roll responses that could result in various types of failures such as cargo shift, structural failure or capsize. Due to the nonlinearity in the roll motion, various unusual behaviors such as several types of bifurcation and also the chaos motion are expected. In a deterministic model of ship rolling, the bifurcation points are well defined, as the system and loading parameters are constant. However, in real ship rolling both the system and loading parameters are subject to randomness which accordingly results in the uncertainty in the bifurcation points.

Various analytical and numerical techniques have been used for analyzing the dynamic behavior of parametric ship rolling under regular or irregular wave loading with deterministic system parameters. Unstable ship motion in a calm sea, produced by nonlinear second order coupling terms in the equations of motion, has been analyzed by Paulling and Rosenberg (1959). By neglecting the damping term and the effect of the nonlinear roll motion on the heave (or pitch) mode, they derived the Mathieu equation for investigating the instabilities in the roll motion. By adopting a model equation in which the pitch mode is coupled to the roll mode, Nayfeh et al. (1973) studied the indirectly excited ship roll motion in regular head sea using the method of multiple scales considering the natural frequency of pitch is twice that of roll. Tondl and Nabergoj (1990) presented two nonlinear coupled model equations for investigating the characteristics of parametrically exited ship roll motion in longitudinal or oblique regular seas. By using the perturbation method, they obtained the Mathieu equation of roll motion and then studied the stability of the roll mode. Based on a nonlinear coupled model of heave-roll ship motions in the following waves, which considered quadratic coupling term, Liaw and Bishop (1995) studied the instability behavior of roll response using the harmonic balance method. Umeda and Hashimoto (2002) em-

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Table 1
Some functions that generate CRBF ($r = \|\xi(\theta) - \xi_i(\theta)\|$).

Name of CRBF	Expression
Multiquadric (MQ)	$(1 + (\varepsilon r)^2)^q,\ q > 0$
Inverse multiquadric(IMQ)	$(1 + (\varepsilon r)^2)^q,\ q < 0$
Gaussian (GA)	$e^{-(\varepsilon r)^2}$
Polyharmonic splines	$\begin{cases} r^k, & k \in 2\mathbb{N} - 1 \\ r^k \log r, & k \in 2\mathbb{N} \end{cases}$

Table 2
Container ship principal dimensions.

Length B.P., m	Breadth Molded, m	Depth, m	Design draft, m
319.00	42.80	24.50	13.00

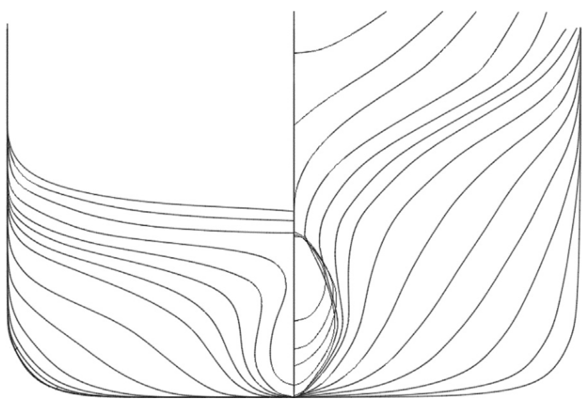

Fig. 1. Hull form of the considered container ship.

ployed a four-degrees-of-freedom numerical model with dense grids of control parameters and the sudden-change concept to intensively explore the nonlinear motions of a fishing vessel in following and quartering seas. They have shown that their presented model can successfully explain the capsizing phenomena qualitatively, but over-estimates the danger of capsizing quantitatively.

Neves and Rodriguez (2006) presented a nonlinear model equations of the ship motion in which the heave, pitch and roll modes are coupled with coupling terms up to the third order. They used a time integration method for solving the coupled motion equation in time domain and showed that for low metacentric height, the results of the third order model equation provide good agreement with the experimental results in comparison to those of the second order model.

Yu et al. (2006) employed the wavelet transforms theory to investigate the nonlinear dynamical characteristics of ship roll and coupled heave-roll motion under regular wave loading. Based on the linear potential theory, a nonlinear 6 DOF time domain numerical simulation method, which considers a variety of important non-linear terms of ship's equations of motions, was employed by Spanos and Papanikolaou (2007) to investigate the parametric ship roll motion in regular head seas for two different types of vessels including a fishing vessel and a RoRo ship. Parametric ship roll motion under regular and irregular wave excitation was studied by Kreuzer and Sichermann (2007) using a nonlinear single degree of freedom roll model. For the case of regular wave loading, they used the multiple scales method to investigate the stability of the roll motion and for the case of irregular wave loading, they utilized a stochastic averaging method along with the Ito's rule to investigate the stability of stochastic roll motion. Chang (2008) proposed a numerical motion simulation method in time domain for investigating the parametric ship roll motion in longitudinal regular waves considering the effect of important nonlinear terms including the nonlinear shape of the righting arm curve, nonlinear damping and cross coupling among all 6 degrees of freedom. The method of path integral was employed by Cottone et al. (2010) for investigating ship roll oscillations subjected to simultaneous Gaussian white noise parametric excitation and external Poisson white noise which simulates the pulse of random events of floating ice impact to the ship.

A probabilistic methodology was developed by Bulian (2010) for detecting, at the early design stage, the vulnerability of a ship to a pure loss of stability in irregular longitudinal long crested following waves. The pure loss of stability failure was modelled as the persistence of the metacentric height below a critical level for a too long time. The metacentric height was modelled as a stationary Gaussian process and the time dependent failure index was achieved considering a filtered Poisson process for the occurrence of critical events. Maki et al. (2011) proposed a practical method to estimate the probabilistic index of parametric rolling in irregular seas using a combination of deterministic ship dynamics and probabilistic wave theory. They obtained the ship's response in regular seas by applying the nominal averaging method to a one degree of freedom roll model, and random waves necessary for occurrence of parametric rolling is achieved by using Longuet-Higgins's or Kimura's wave group theory. The first order reliability method was used by Vidic-Perunovic (2011) for analyzing the parametrically excited roll response of a container ship subjected to irregular head seas Silva and Soares (2013) proposed a time-domain non-linear strip theory model of ship′s motions in six degrees-of-freedom and studied the effect of parametric roll resonance on a containership sailing in following, quartering, oblique or head seas for

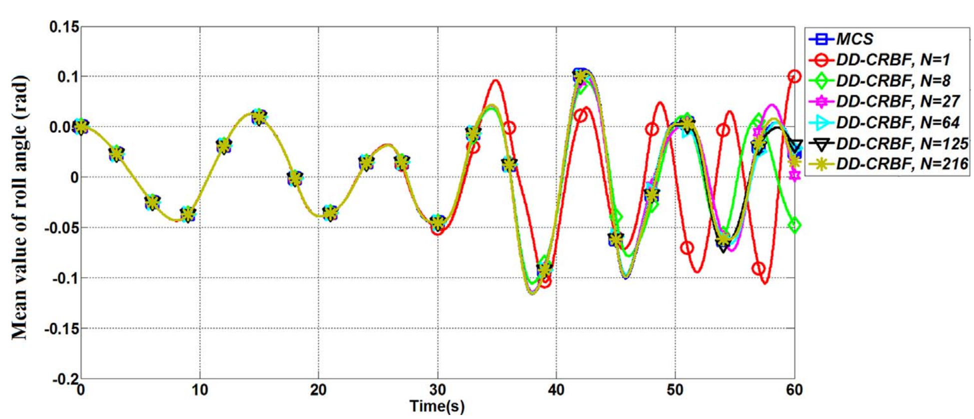

Fig. 2. Comparison of the mean value of the roll motion obtained by the DD-CRBF with that of the Monte Carlo simulation (Number of nodes in each subdomain n=2).