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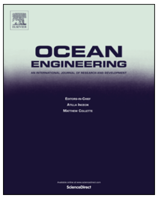

Prediction of parametric rolling of ships in single frequency regular and triple frequency group waves

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ABSTRACT

A 3D nonlinear time domain simulation method based on the impulse response function concept is applied to the investigation of parametric rolling of the ITTC-A1 containership. In the numerical simulation, the hydrodynamic coefficients are determined beforehand by a 3D frequency domain panel code on the basis of linear potential theory, whereas the most nonlinear terms in the equations of motion are taken into account, such as the excitation by large amplitude waves (exact Froude–Krylov forces/moments), exact restoring forces/moments resulting from integration of the hydrostatic pressures over the actually wetted surface of the ship and the semi-empirical nonlinear viscous damping correction. In addition, all nonlinear inertia terms are retained when considering solution of large amplitude motions. The parametric rolling is predicted by solving the 6 degrees of freedom (DoF) nonlinear equations of ship motion in the time domain in response to single frequency regular waves and triple frequency group waves. The obtained numerical results are compared with corresponding experimental measurements and numerical predictions of an earlier conducted international benchmark study proving the good performance of the developed method in terms of the predictability of parametric roll phenomena and to a lesser degree to the accuracy of predicted roll amplitude values.

1. Introduction

Parametric rolling is the induced roll motion of a ship triggered by the periodic change of the restoring characteristics (oscillator's stiffness) of the ship as she advances in waves, while strongly moving in the heave/pitch mode. The phenomenon is often observed on ships with excessive bow flares and very flat sterns, such as modern containerships, car carriers etc. Typically it takes place in regular seas when the wave frequency of encounter is close to twice of the natural roll frequency of the ship and near the heave/pitch resonance frequency. Under such condition, the occurrence and severeness of the parametric roll phenomenon, which is a strongly nonlinear oscillatory motion phenomenon, is dependent on the incident wave amplitude, ship's loading condition, ship's speed and roll damping characteristics.

The prediction of parametric rolling is of significance both from the scientific and practical point of view. The phenomenon can lead to not only the loss or shift of cargo (typically: of deck-containers), but also to the loss of the ship; thus, it is an important safety issue which is considered already in the most recent IMO intact stability regulations (Peters et al., 2011). It is, also, a favoured research subject of scientists, because of the complexity of the associated nonlinear ship dynamics and hydrodynamic phenomena; thus the correct prediction of parametric rolling, in terms of the likelihood of *occurrence and resulting roll amplitude*, in regular waves and irregular seas remains a challenge to state-of-the-art numerical simulation methods and software tools.

The investigation of parametric rolling by experimental and numerical methods has a long history, dating back to the 30ties (see Paulling (2006) for historical review). The phenomenon attracted increased interest only in the last few decades with some serious accidents of large containerships, for instance, the containership APL CHINA casualty in 1998[1] (France et al., 2003). Several approaches were employed over the years to analyze and understand the parametric roll phenomenon, ranging from analytical solutions of the uncoupled, one degree of freedom nonlinear roll equation, adjusted with appropriate parameters (Mathieu oscillator), for instance, Paulling (1961), Francescutto and Bulian (2002), Umeda et al. (2003), to more comprehensive models of multi-degrees of freedom numerical solutions, where the roll motion and ship hydrodynamics are appropriately coupled

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[1] The ship lost more than 400 containers in heavy seas, whereas double as many containers were damaged; the accident became a multi-million insurance case in USA courts.

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with the other degrees of freedom, e.g. de Kat (1990), Belenky et al., (2003), Ribeiro e Silva et al. (2005), Neves and Rodriguez (2005), Krueger and Kluwe (2006), Spanos and Papanikolaou (2006). Parametric rolling has been investigated for both regular and irregular seaway conditions, while considering both head and following seas. The predictability of parametric rolling in irregular seas, specified by a sea spectrum, is still an open issue in view of the non-ergodicity of the phenomenon. However, it was observed that the occurrence of dominating group waves within an irregular wave field may be related to excitation of parametric roll phenomena (see, e.g. Kim and Troesch, 2015). A thorough review of the related literature has been carried out earlier by ITTC (2005).

In this paper, a nonlinear time domain method based on the impulse response function concept (Liu et al., 2014) has been applied to the simulation of parametric rolling. This method has been developed (independently of earlier work by Spanos and Papanikolaou (2006)) at the Ship Design Laboratory of National Technical University of Athens in the frame of NTUA-SDL's new HYBRID software system, enabling the analysis of the seakeeping performance and safety of ships in complex environmental and/or adverse sea conditions. In the framework of potential theory, the hydrodynamic forces are decomposed into Froude–Krylov (incident wave), radiation and diffraction wave forces. Incident wave forces (both hydrodynamic and hydrostatic parts) are calculated through direct integration of the corresponding pressures over the instantaneous wetted surface, which is defined by the undisturbed incident wave and the instant position of the ship. The radiation forces are calculated using the added mass and damping coefficients calculated by a 3D frequency domain code NEWDRIFT (Papanikolaou 1985; Papanikolaou and Schellin, 1992; Papanikolaou and Zaraphonitis, 2001) and transformed into the time domain by application of the impulse response function concept of Cummins (1962). Diffraction forces are obtained in a similar manner, using corresponding diffraction force results obtained by NEWDRIFT for various wave frequencies. Solving the six coupled nonlinear integro-differential equations of motion by a time integration method, the six DOF motions of the ship are obtained in the time domain. For validation purpose, the developed code has been applied to the simulation of the parametric rolling of the ITTC-A1 containership (Umeda et al., 2000), for which the tank tests are available from the SAFEDOR project (SAFEDOR, 2008). A series of simulation cases in regular single frequency waves and triple-frequency group waves at various speeds and various headings were benchmarked, showing satisfactory agreement with experimental results, which proves that the employed methodology in combination with the software tool is capable of simulating this complicated nonlinear physical phenomenon.

2. Mathematical model

In order to study the nonlinear ship motion problem, three coordinate systems are defined: the earth-fixed *OXYZ* system, a system O′*X′Y′Z′* travelling with the mean ship speed, always parallel to *OXYZ* and a body-fixed *Gxyz* system, with its origin *G* at the centre of gravity. It is assumed that at $t=0$ both *O* and *O*″coincide with *G*. The two coordinate systems, *O′X′Y′Z′* and *Gxyz* are connected by the three Euler angles: θ (roll), ψ (pitch), and ϕ (yaw). If *O′X′Y′Z′* is rotated by the three Euler angles, it becomes parallel with *Gxyz*. The order of rotation is θ, ψ, and ϕ. A vector $\vec{x}$ in the *Gxyz* system may be expressed as $\vec{X}'$ in *O′X′Y′Z′* system as follows:

$$\vec{X}' = \mathbf{T}\vec{x} \tag{1}$$

where **T** is the transformation matrix:

$$\mathbf{T} = \begin{bmatrix} \cos\psi\cos\phi & \begin{matrix}\sin\theta\sin\psi\cos\phi - \\ -\cos\theta\sin\phi\end{matrix} & \begin{matrix}\cos\theta\sin\psi\cos\phi + \\ +\sin\theta\sin\phi\end{matrix} \\ \cos\psi\sin\phi & \begin{matrix}\sin\theta\sin\psi\sin\phi + \\ +\cos\theta\cos\phi\end{matrix} & \begin{matrix}\cos\theta\sin\psi\sin\phi - \\ -\sin\theta\sin\phi\end{matrix} \\ -\sin\psi & \sin\theta\cos\psi & \cos\theta\cos\psi \end{bmatrix} \tag{2}$$

The ship is assumed travelling on the free-surface with a mean speed $\vec{V}_{O'} = [U, 0, 0]^{\mathrm{T}}$ parallel to the *OX* axis, subject to incident regular waves. The location of the ship in the *OXYZ* system is expressed by the location of the centre of gravity (*G*) and the three Euler angles. The location of the centre of gravity is defined by $\vec{X}_G(t) = [X_G(t), \Upsilon_G(t), Z_G(t)]^{\mathrm{T}}$ and its velocity $\vec{V}_G(t)$ by the time derivative of $\vec{X}_G(t)$. The relationship between the absolute velocity of the ship and the relative velocity (both expressed in the earth-fixed coordinate system) is:

$$\vec{V}_G^R = \vec{V}_G - \vec{V}_{O'} = \vec{V}_G - [U, 0, 0]^{\mathrm{T}} \tag{3}$$

The angular velocities about the ship-fixed coordinate axes given by $\vec{\omega}$ are related to the time derivatives of the Euler angles as follows:

$$\vec{\omega} = \begin{bmatrix}\omega_1 \\ \omega_2 \\ \omega_3\end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\psi \\ 0 & \cos\theta & \sin\theta\cos\psi \\ 0 & -\sin\theta & \cos\theta\cos\psi \end{bmatrix} \begin{bmatrix}\dot{\theta} \\ \dot{\psi} \\ \dot{\varphi}\end{bmatrix} = \mathbf{B}\begin{bmatrix}\dot{\theta} \\ \dot{\psi} \\ \dot{\varphi}\end{bmatrix} \tag{4}$$

where:

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & -\sin\psi \\ 0 & \cos\theta & \sin\theta\cos\psi \\ 0 & -\sin\theta & \cos\theta\cos\psi \end{bmatrix} \tag{5}$$

Let $\vec{a}_G$ be the (total) acceleration vector of the centre of gravity *G*, expressed in the body-fixed system; $\vec{a}_G$ may be expressed as follows:

$$\vec{a}_G = \dot{\vec{v}}_G + \vec{\omega} \times \vec{v}_G \tag{6}$$

The first term in the above equation corresponds to the rate of change of the translational velocity of the ship, while the second one takes into account the effect of rotation of the body-fixed coordinate system.

The equations of motion are given by application of Newton's second law:

$$m(\dot{\vec{v}}_G + \vec{\omega} \times \vec{v}_G) = \vec{F} \tag{7}$$

$$\mathbf{I}\dot{\vec{\omega}} + \vec{\omega} \times \mathbf{I}\vec{\omega} = \vec{M} \tag{8}$$

In the above equations, the external forces and moments are expressed in the body-fixed system of coordinates and they consist of the gravitational, radiation, diffraction, incident wave force, restoring forces and possible viscous terms, while **I** is the inertial moment matrix of the ship.

a. **Diffraction forces**

For weakly nonlinear motions, assuming the ship in the upright/mean position when calculating the diffraction forces due to the incoming waves is a reasonable and efficient approach. However, as the motions increase and particularly when the dimensions of the ship are small compared to the wave length, the effect of the ship motions on the diffraction forces will be more significant, and their calculation assuming the ship at her instantaneous position may be considered. On the other hand, in this latter case, diffraction effects will tend to zero due to the small disturbance of the incoming waves by