Ocean Engineering 37 (2010) 1307–1320

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

An investigation into parametric roll resonance in regular waves using a partly non-linear numerical model

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A R T I C L E I N F O

Article history:
Received 27 March 2010
Accepted 17 June 2010

Editor-in-Chief: R.C. Ertekin

Keywords:
Parametric roll resonance
Non-linear
Regular waves
Time-domain
Transom stern Trawler
Modern containerships

A B S T R A C T

A partly non-linear time-domain numerical model is used for the prediction of parametric roll resonance in regular waves. The ship is assumed to be a system with four degrees of freedom, namely, sway, heave, roll and pitch. The non-linear incident wave and hydrostatic restoring forces/moments are evaluated considering the instantaneous wetted surface whereas the hydrodynamic forces and moments, including diffraction, are expressed in terms of convolution integrals based on the mean wetted surface. The model also accounts for non-potential roll damping expressed in an equivalent linearised form. Finally, the coupled equations of motion are solved in the time-domain referenced to a body fixed axis system.

This method is applied to a range of hull forms, a post-Panamax C11 class containership, a transom stern Trawler and the ITTC-A1 containership, all travelling in regular waves. Obtained results are validated by comparison with numerical/experimental data available in the literature. A thorough investigation into the influence of the inclusion of sway motion is conducted. In addition, for the ITTC-A1 containership, an investigation is carried out into the influence of tuning the numerical model by modifying the numerical roll added inertia to match that obtained from roll decay curves.

1. Introduction

Parametrically excited roll motion has been known to naval architects for almost half a century now (Paulling, 1961, 2007). In this phenomenon, transversely symmetrical ships may experience extreme roll motions in longitudinal waves i.e. head or following waves. This is explained by reasoning that in longitudinal waves, ships experience variations in their transverse stability due to time-varying changes in the underwater hull geometry. In the past the concern with parametric roll was mostly for smaller ships in following seas e.g. the work by De Kat and Paulling (1989) and Umeda and Hamamoto (1995). Nowadays the concern is for the vulnerability of large ships in head seas, exemplified by significant cargo loss and damage sustained by a C11 post-Panamax container carrier on a voyage from Taiwan to Seattle in 1998. The ensuing detailed investigation by France et al. (2003) showed that the ship had experienced large roll motions resulting from the periodic change of the transverse stability in head seas. The large change of stability was attributed to the hull form which is typical of large container carriers, namely, a substantial bow flare and stern overhang, causing a large variation in the underwater hull form with time and hence, the transverse stability of the ship.

Based on past research one notes that, for parametric roll to occur, certain conditions need to be satisfied, namely, an encounter frequency equal or close to twice the natural frequency of roll, a wavelength of the same order as the ship length, a wave height exceeding a critical level, or threshold value and finally, roll damping to be below a threshold value (France et al., 2003). Roll damping plays an important role in the development of parametric roll. If the "loss" of energy per cycle caused by damping is more than the energy "gain" caused by the change in stability, the roll angles will not increase and parametric roll will not develop. On the other hand, if the energy "gain" per cycle is more than the energy "loss" due to damping, the amplitude of parametric roll will start to grow (Shin et al., 2004). This defines the concept of a "damping threshold". It is worth noting, however, that non-linear damping tends to increase with roll velocity, thus, it will eventually exceed the damping threshold leading to stabilization of the roll motion and reaching a steady roll amplitude.

Longitudinal waves i.e. head or following waves, cause the largest change in stability and, therefore, create maximum parametric excitation. Whilst the physical basis for parametric roll is the same in head and following seas, parametric roll in head seas is more likely to be influenced by and coupled with heave and pitch motions of the ship, since these motions are typically more pronounced in head seas (Shin et al., 2004). Treatment of the coupling between the vertical motions of heave, pitch and roll varies in the numerical methods used. For example, Neves and

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doi:10.1016/j.oceaneng.2010.06.009

Nomenclature

a_w	wave amplitude (m)
A_n	area of nth panel
$A_{44}(\omega_e)$	roll added inertia—equilibrium axis system
$A_{44}(\infty)$	roll added inertia at infinite frequency
$B_{44}(\omega_e)$	roll damping—equilibrium axis system
$B_{44}(\infty)$	roll damping at infinite frequency
$Cxyz$	body fixed axis system
Fn	Froude number
GM_T	transverse metacentric height (m)
H_w	wave height (m)
h_{44}	roll-roll impulse response function—equilibrium axis system
h_α	wave diffraction impulse response function—equilibrium axis system
I_{44}	roll moment of inertia (kg m^2)
K_{xx}	roll radius of gyration (m)
K_{yy}	pitch radius of gyration (m)
k_p^*	roll-roll impulse response function—body fixed axis system
$\tilde{K}_p(\infty)$	infinite frequency value of roll velocity derivative—body fixed axis system
$\tilde{K}_{\dot{p}}(\infty)$	infinite frequency value of roll acceleration derivative—body fixed axis system
$K_{\alpha I}$	total (incident+restoring) roll moment
$n_n(n_{xn}, n_{yn}, n_{zn})$	unit normal vector to nth panel
$p,\dot{p}$	roll velocity and acceleration—body fixed axis system
$P(x_n^*,y_n^*,z_n^*)$	pressure on nth panel
$r_n=(x_n, y_n, z_n)$	centroid co-ordinates of nth panel in body fixed axis system
$r_n^*=(x_n^*,y_n^*,z_n^*)$	centroid co-ordinates of nth panel in spatial axis system
t	time (s)
T_w	wave period (s)
V	ship forward speed (knots)
∇	ship displacement volume (m^3)
$\Xi(i\omega_e)$	frequency domain complex wave diffraction component—equilibrium axis system
$\eta_4,\dot{\eta}_4,\ddot{\eta}_4$	roll displacement, velocity and acceleration—equilibrium axis system
ω	wave frequency (rad/s)
ω_e	encounter frequency (rad/s)
ω_n	roll natural frequency (rad/s)

Rodriguez (2005) used a two-dimensional analysis for a set of coupled heave, pitch and roll equations of motion with 2nd and 3rd order non-linearities describing the restoring actions. Levadou and van't Veer (2006) used coupled non-linear equations of motion in the time domain with 3 (heave, roll and pitch) and 5 (sway, heave, roll, pitch and yaw) degrees of freedom. Non-linear excitations are incorporated by pressure integration over the actual wetted surface while diffraction forces are considered linear. Hydrodynamics are calculated in the frequency domain by a 3D panel code and are incorporated in the time domain by adopting the impulse response functions method. France et al. (2003) and Shin et al. (2004) adopted a similar approach but with a hybrid singularity based on the Rankine source in the near field and transient Green's function in the far field. On the other hand, Neves et al. (1999) and Ahmed et al. (2006, 2008) used a system with 3 degrees of freedom, with the coupled heave and pitch motions providing input to the parametric excitation simulated using a one degree of freedom non-linear roll equation of motion. The heave and pitch motions are solved simultaneously and independently of the roll motion, an assumption that has been shown to be adequate in simulating parametric roll and has been justified experimentally (Oh et al., 2000).

Accounting for non-potential roll damping is of utmost importance for an accurate simulation of parametric roll. Various models are available in the literature for estimating a total roll damping coefficient/s of which, the most prominent and commonly used model is the method due to Ikeda and described by Himeno (1981). France et al. (2003) and Shin et al. (2004) used an empirical model derived from the Kato (1966) method. For their C11 containership investigation, the numerical roll decay response was tuned to match the experimental roll decay tests by specifying an equation with up to cubic order terms of roll angle and roll velocity. Levadou and van't Veer (2006) used a time domain implementation of Ikeda's method with the fluid velocities at the bilge keel assessed with a Keulegan–Carpenter number for evaluating the bilge keel damping. Neves and Rodriguez (2005) used Ikeda's method represented in a quadratic form.

In a recent paper, Ikeda (2004) reviews continuous developments to his original method, introducing modifications to extend its applicability to special hull forms (e.g. barges with sharp corners, small craft with hard-chine hull and skeg), together with an application to determine the optimum size and location of bilge keels. In addition, Ikeda (2004) mentions and references other special cases of the roll damping problem, for instance, reduction of the bilge keel effect of a shallow draft ship and interaction effects between fin stabilizers and bilge keels.

Numerical simulations and experimental measurements in regular waves are a useful way of observing and understanding the physics of the parametric roll phenomenon as well as validating numerical methods. Parametric roll in realistic irregular seas, however, is of greater practical interest to masters and operators. The numerical work by Bulian and Francescutto (2006) is an example of investigations in this area. This investigation is conducted in long-crested head seas and makes use of the concept of effective wave amplitude within a one degree of freedom equation of motion in roll.

In this paper, a three-dimensional partly non-linear time domain numerical model by Bailey et al. (2002) and Ballard et al. (2003) is applied, for the first time, to investigate the occurrence of parametric roll resonance for a range of vessels, namely a post-Panamax C11 class containership (France et al., 2003; Levadou and van't Veer, 2006; Ahmed et al., 2006, 2008), a transom stern Trawler (Neves et al., 1999, 2002; Neves and Rodriguez, 2005; Ahmed et al., 2008) and the ITTC-A1 containership (HYDRALAB III, 2007; SAFEDOR, 2008), travelling in regular waves encountered at different headings. In this model, the incident wave and hydrostatic restoring forces/moments are assumed non-linear and are evaluated at every time step considering the instantaneous wetted surface. On the other hand, the hydrodynamic forces and moments, including diffraction, are assumed linear and are expressed in terms of convolution integrals. The requisite impulse response functions are obtained from Fourier transforms performed on frequency domain data evaluated from a three-dimensional potential flow analysis based on the mean wetted surface, using pulsating source distribution (Inglis and Price, 1981). Even though the presented model is capable of coupling all six degrees of freedom, results in this paper were predicted by coupling four degrees of freedom only, namely, sway-heave-roll-pitch. This is due to the fact that; in the absence of reliable estimates of the added