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Prediction of parametric rolling in waves with a time domain non-linear strip theory model

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ABSTRACT

A time-domain non-linear strip theory model of ship's motions in six degrees-of-freedom is described and is validated by comparing numerical predictions with experimental results of parametric rolling of a containership. The calculation of the time variations of the restoring force is made using a pressure integration technique over the instantaneous submerged hull. Hydrodynamic effects are based on a potential flow strip theory using Frank's Close fit method. A semi-empirical formulation is adopted for the surge motion. Different models for roll damping have been introduced so far in the governing equations but in the present case roll damping is determined directly from experimental data that includes roll decay tests with different forward speed, which allows the assessment of the effect of ship speed on roll damping. Comparisons between numerical and experimental results demonstrate the usefulness and accuracy of the method proposed.

1. Introduction

The problem of occurrence of certain ship dynamic instabilities in waves, such as parametric rolling, has been already studied and discussed by several investigators: Grim (1952), Kerwin (1955), Paulling and Rosenberg (1959), Sanchez and Nayfeh (1990), Umeda et al. (1995), Hamamoto and Panjaitan (1996), and safety authorities: IMO (1995). According to Burcher (1990), this particular phenomenon in head waves had mostly been considered to be of theoretical interest and less worthy of practical concern. However, more recent evidence of parametric rolling in head seas on a post-Panamax C11 class container ship, which resulted in the loss of 400 containers and damage to as many more (France et al., 2003), received wide and renewed attention from IMO (2008), demonstrating the practical importance of this phenomenon. Around that time the American Bureau of Shipping issued the first guide for the assessment of parametric rolling in the design of container vessels (ABS, 2004).

The fundamental dynamics that create this kind of behavior is considered nowadays as reasonably clarified, namely that the frequency of encounter with waves of length on the order of the ship's length is comparable to twice the ship's roll natural frequency. Also, hull forms with pronounced flare at fore and aft extremities or a flat transom stern, together with wall-sided ship sides near the waterline amidships, are most vulnerable to parametric rolling. For instance, containerships have a box type central section to store large number of containers in the cargo holds. At the same time the underwater hull in the fore and aft extremes is streamlined to minimize the resistance and improve propeller performance. Thus container ships are usually prone to parametric rolling in longitudinal and oblique waves.

For a ship encountering a head wave, as the crest travels along the hull the righting arm and the stability of the ship varies. Two crests in one roll period represent the most critical case, usually described as a low-cycle resonant condition. In this case the bow is trimmed down due to pitching coupled with roll, and the large flare is suddenly immersed in the wave crest. The restoring buoyant forces along with the wave induced force push the ship to the other side. Such features contribute additionally to the variation of the ship's stability characteristics due to the constant change of the underwater hull geometry as waves travel along the ship. Coupling and resonance push the ship to roll in larger angles, which are only limited by the energy dissipated by roll damping or a significant change of the instantaneous wetted hull geometry. It has been shown by France et al. (2003) that parametric rolling can occur not only in long-crested head and following seas, but also at slightly oblique heading angles with and without directional wave energy spreading. In fact, provided there is sufficient encountered energy near twice the natural roll period, this behavior can be explained by an energy balance between damping and stability variations similar to a regular wave scenario, as originally suggested by Burcher (1990).

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Despite the progress, a few issues remain open, such as the development of effective susceptibility and severity criteria for the prevention of parametric rolling at the design stage; the assessment of the effects of coupling with other motions of large amplitude; and the derivation of optimal experimental or numerical procedures for safety assessment in a realistic seaway.

In this work the effect of parametric resonance on a containership sailing in following, quartering, oblique or head seas is investigated to illustrate the capabilities and limitations of the numerical modeling technique. Moreover, open issues and important parameters that are effective in auto-parametric roll resonance are indicated. An extensive series of tests on a containership were carried at "Hamburgische Schiffbau-Versuchsanstalt" (HSVA) and some of these are used in this paper to obtain accurate estimates of the roll damping coefficients at different speeds, and to validate the proposed numerical model to describe the phenomenon of parametric rolling in waves.

2. Parametric rolling prediction models

Theoretical works on parametric roll resonance can be found dating from the 1950′s, where linear and non-linear roll damping models were taken into account by Grim (1952) and Kerwin (1955). These studies enabled the discussion of parametric roll resonance with the Mathieu equation. Then, to investigate capsizing, non-linearity of restoring moment in still water was taken into account. At this stage a non-linear dynamical system approach, including geometrical and analytical studies, is required to identify all potential dangers among co-existing states. Such examples can be found in Sanchez and Nayfeh (1990), Soliman and Thompson (1992) for uncoupled roll models and Oh et al. (2000) for a coupled pitch-roll model. These theoretical studies focused on understanding fundamental mechanisms of the phenomenon with rather simplified mathematical modeling. For example, the amplitude of the restoring arm is often provided a priori without any relationship with wave steepness or exciting moment.

On the other hand, several six degree-of-freedom (DOF) models such as Munif and Umeda (2000) and Matusiak (2003) have been developed for quantitative numerical prediction in the time domain. Here the relationship between wave steepness and restoring moment is fully taken into account. However, the works using these detailed models only show simulated results with limited number of initial condition sets. Because of the non-linearity of the system, there is a possibility to either overestimate or underestimate the roll responses and, therefore, to overlook some potential danger, as has been raised by some authors.

Longitudinal waves (i.e. head or following waves) cause the largest variations in stability and, therefore, create maximum parametric excitation. Whilst the physical basis for parametric rolling is the same in head and following waves, parametric rolling in head waves 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 waves (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 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) DOF. 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) used a system with 3 DOF, with the coupled heave and pitch motions providing input to the parametric excitation simulated using a one DOF 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). More recently, Ahmed et al. (2010) used coupled non-linear equations of motion in the time domain with 4 (sway, heave, roll and pitch) DOF, where 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.

Numerical simulations and experimental measurements in regular waves are an effective procedure to observe and understand the physics of the parametric rolling phenomenon as well as to validate numerical methods. Parametric rolling in realistic irregular seas, however, is of greater practical interest to shipmasters. The numerical work conducted by Bulian and Francescutto (2006) is an example of investigations in this field. This investigation is conducted in long-crested head seas and makes use of the concept of Grim′s effective wave amplitude within a one DOF equation of motion in roll.

Ribeiro e Silva and Guedes Soares (2000) demonstrated that both linearized and non-linear theories could be used to predict parametric rolling in regular head waves. Using the linear model (in the form of Mathieu′s equation) stability variations were evaluated from the linearized righting arm curves with the wave crest varying longitudinally along the ship hull. However, this model was not adequate to predict ship′s roll response magnitude under wave-induced parametric resonance conditions, since deck submergence effect on restoring characteristics of the vessel and non-linear damping terms could not be included and therefore the limit cycle behavior could not be obtained.

A non-linear numerical model of parametric resonance taking into consideration deck submergence and other non-linearities on restoring moment of ships in regular waves was also proposed by Ribeiro e Silva and Guedes Soares (2000). In this model a quasi-static approach was adopted to study the roll motion, where only the variations on transverse stability in regular waves were considered. An uncoupled roll equation was used to describe the parametrically excited roll motions, which included the effects of heave and pitch responses in regular waves and immersed hull variations due to wave passage on roll restoring term. While good agreement in terms of limited response behavior was found between the time domain simulation of roll motion in longitudinal regular waves and the existing experimental data, simulations of parametric rolling in irregular waves as presented in literature by Francescutto and Bulian (2002), Belenky et al. (2003), and Pereira (2003), could not be performed using that single DOF model.

To overcome these shortcomings a non-linear model, coupled in the five (sway, heave, roll, pitch and yaw) DOF was then developed and proposed Ribeiro e Silva et al. (2005) to simulate the time domain responses of a ship in uni-directional long-crested irregular waves. The model is now extended to six DOF making use of a semi-empirical formulation for surge motion.

Notice should be given to the fact that accounting for non-potential roll damping is of utmost importance for an accurate simulation of parametric rolling. Various models are available in the literature for estimating a total roll damping coefficients of