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Experimental and numerical study of a containership under parametric rolling conditions in waves

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ABSTRACT

A set of scaled model experiments have been conducted at HSVA towing tank to study the occurrence of parametric rolling on a containership in regular and irregular waves. Herein the performed model tests are described and the experimental results are presented. Forced rolling tests were also performed with the ship model in order to investigate its roll damping characteristics. By means of these tests the roll damping coefficients were determined for different maximum roll amplitudes and advance speeds. The experimental data of this containership is compared with results from a non-linear time domain model, where the prediction of maximum roll amplitude under parametric rolling conditions associated with different viscous roll damping models is thoroughly discussed.

1. Introduction

In this work the effect of parametric resonance on a containership sailing in following or head seas is dealt with to illustrate the capabilities and limitations of both the experimental model testing and numerical simulations. An extensive series of tests on a containership were carried at “Hamburgische Schiffbau-Versuchsanstalt” (HSVA) and some of these are used to obtain accurate estimates of the roll damping coefficients at different speeds, and to validate the numerical model developed by Ribeiro e Silva and Guedes Soares (2013) to study the phenomenon of parametric rolling in waves.

One main focus of the model tests was the investigation of conditions that lead to parametrically excited rolling in both regular waves and irregular seas. Notice that this phenomenon occurs only at certain combination of wave/seaway condition, load case, encounter angle and ship speed.

In order to carry out effective model tests, it is very helpful to perform numerical calculations prior to the model tests to identify the combination of parameters at which parametric rolling might occur. Thus, in advance of the model tests HSVA extensive non-linear time domain simulations of parametrically excited roll motions in waves were performed.

For the container vessel simulations were mainly conducted in regular bow and following waves at constant ship speed and encounter angle. The values of wavelength, ship speed, metacentric height and encounter angle were varied. The calculation results identify the parameter combinations where the vessel would properly execute parametrically excited roll motions in regular bow and following waves caused by low-cycle (1:2 ratio of wave to ship natural roll periods) resonance conditions. By means of these pre-determined parameter combinations it was also possible to generate irregular seaways which would be likely to lead to the occurrence of parametric rolling. The obtained information was used to choose the most promising test conditions and to compile a rough test program.

Specifically, based on the computations in regular waves some additional simulations were conducted in irregular head and stern seas to identify wave sequences which would lead to parametrically excited roll motion. The identified wave sequences were then isolated and delivered to the University of Berlin, which generated the corresponding control signals for the wave generator in order to reproduce these sequences in the towing tank at HSVA during the test campaign.

2. Parametric rolling prediction models

Theoretical works on parametric roll resonance can be found in the 1950s, where linear and non-linear roll damping models were taken into account by Grim (1952), Kerwin (1955) and Paulling and Rosenberg (1959). These studies enabled the discussion of

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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, non-linear dynamical system approach including geometrical and analytical studies is required to identify all potential danger 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 mechanism of the phenomena with rather simplified mathematical modeling. For example, the amplitude of 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 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. On 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 that model a quasi-static approach was adopted to study the roll motion, where only the variations on transverse stability in regular waves were considered. For that purpose, an uncoupled roll equation, which included the effects of heave and pitch responses in regular waves, and immersed hull variations due to wave passage on roll restoring term, was used to describe the parametrically excited roll motions. 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 the 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 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. Particularly, the magnitude of the roll response during parametric rolling is dictated in large part by the amount of viscous damping in the roll DOF, where damping improves the stability character of the system by reducing the instability regions in size. Moreover, from SAFEDOR results it has been commented by Spanos and Papanikoloau (2009) that accuracy of numerical simulations could be significantly improved by adopting a linear plus quadratic roll damping model. Various models are available in the literature for estimating a total roll damping coefficients of which, the most well-known and widely used model is the original method due to Ikeda et al. (1978). For example, Levadou and van't Veer (2006) used a time domain implementation of Ikeda's method with specific assessment of the fluid velocities at the bilge keel for evaluating the bilge keel damping. Neves and Rodriguez (2005) used Ikeda's method represented in a quadratic form. In this study the availability of an extensive series of free-decay and forced rolling experimental results on a scaled model of a containership, allowed the measurement of several roll time traces and maximum amplitudes of roll at different advance speeds to be utilized in the numerical simulations represented in a quadratic form.

France et al. (2003) and Shin et al. (2004) used an empirical model for their C11 containership investigation, where 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.

Ribeiro e Silva et al. (2005) have adopted Ikeda's method, while