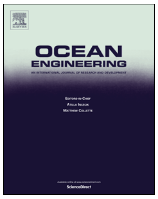
Ocean Engineering 124 (2016) 404–418

Contents lists available at ScienceDirect

Ocean Engineering

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



Experimental and numerical vertical bending moments of a bulk carrier and a roll-on/roll-off ship in extreme waves

Guillermo Vásquez, Nuno Fonseca, Carlos Guedes Soares*

Centre for Marine Engineering and Ocean Technology (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco País, Lisbon, 1049-001 Portugal

ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form
28 May 2016
Accepted 15 July 2016
Available online 6 August 2016

Keywords:
Ship motions
Extreme waves
Nonlinear motions
Bulk carrier
Roll-on/roll-off
Model tests

ABSTRACT

This paper investigates the experimental and numerical vertical bending moments induced by abnormal waves on two ships, namely, a bulk carrier and a Roll-on/Roll-off. The experimental data was obtained by seakeeping tests with scaled models in head waves at two Froude numbers. The wave traces were predefined and corresponding to wave records measured during storms in the North Sea. These wave records are particularly interesting because each of them includes one abnormal wave. The ship models, which are similar in length but different in their geometry, were tested in the same predefined wave conditions. The objective is to investigate the hull geometry influence on vertical bending moment under extreme sea conditions. Some conclusions are made by comparing directly the measured responses from the two models. The experimental data is also used as benchmark to validate the predictions by a partially nonlinear time domain seakeeping numerical model. The numerical model is then used to generalize the comparative analysis between the two ships.

1. Introduction

Reported experience shows it is dangerous to navigate in severe sea conditions (Guedes Soares et al., 2001; Guedes Soares and Teixeira, 2001). Ships encountering abnormal waves, such as Norwegian Dawn in April 2005 (Didenkulova et al., 2006) and MS Louis Majesty in March 2010 (Cavaleri et al., 2012) have ended with big damages. Ship losses, such as the sinking of the single-hull tankers Erika in the coast of France in 1999, the Prestige in the coast of Galicia in 2002, as well as the double-hull tanker Ievoli Sun in the English Channel in 2000, confirm the need for a better knowledge of ship behaviour in harsh seas.

One important parameter that requires further investigation is the wave vertical bending moment, which, after correction by appropriate safety factors, provides a basis for designing the mid ship´s section. This important parameter is of nonlinear nature since it results from the ship encountering extremely large amplitude waves. The problem can be divided in two parts: identification of the most severe expected wave conditions, and the hydrodynamic calculation of ship responses to these wave conditions. The present study is concerned with the second problem.

Several methods were proposed to estimate the ship loads induced by waves taking into account the nonlinearities especially ship sailing in extreme sea conditions. “One may distinguish between methods based on potential theory and those solving the Reynolds-Averaged-Navier-Stokes (RANS) equations. The majority of methods for ships at forward speed still belong to the first group. Within this group there is a large variety of methods ranging from linear theories to fully nonlinear methods. Between these two extremes there are many partially nonlinear, or blended, methods, in which one aims at including the most important nonlinear effect (ISSC, 2012).

The basis of the numerical method to calculate the vertical motions and global structural loads induced by large amplitude waves used here was developed by Fonseca and Guedes Soares (1998a,b). This method is based on a partial nonlinear time domain strip theory, where the linear radiation forces are represented by convolution of memory functions, infinite frequency added masses and radiation restoring coefficients. Froude–Krylov and hydrostatic forces are computed over the wetted hull surface at each time step and green water loads are computed by the momentum method. Extensive comparisons with experimental data are presented in Fonseca and Guedes Soares (2002, 2004a,b, c). The general conclusion is that the method is able to represent all nonlinear effects identified in the experiments, it represents an improvement compared to the linear predictions, although it tends to overestimate the sagging bending moment.

Fonseca et al. (2001) proposed a generalisation of the method to calculate the structural loads induced by deterministic wave traces of abnormal waves, and applied it to investigate a

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* Corresponding author.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

http://dx.doi.org/10.1016/j.oceaneng.2016.07.032

Please cite this article as: Vásquez, G., et al., Experimental and numerical vertical bending moments of a bulk carrier and a roll-on/roll-off ship in extreme waves. Ocean Eng. (2016), http://dx.doi.org/10.1016/j.oceaneng.2016.07.032

containership (Fonseca et al., 2006; Guedes Soares et al., 2008) and a FPSO platform (Fonseca et al., 2009). More recently, Rajendran et al. (2011) investigated the green water on deck model sensitivity on the maximum bending moments induced by abnormal waves on a containership.

There is also some reported experimental work with focus on the nonlinear vertical ship responses in large amplitude waves. Watanabe et al. (1989) analysed the effects of bow flare shape to the motions and bending moments on a container ship. The hull model known as S-175 was prepared to accommodate an additional bow flare so that one can easily realize another model with increased flare but with the same underwater profile and dynamic characteristics. It was concluded that increased bow flare form reduces relative bow motion and serious deck wetness, however, it increases the vertical bending moment and may deform incoming wave profile considerably.

Adegeest (1995) recognizing the lack of published experimental data regarding the wave induced vertical bending moment, leads the experiments with a standard Wigley hull form as well as with a Wigley hull form with additional bow flare, both tested in regular waves. The goal of this set of experiments was to obtain a systematic series of data on amplitude dependency of vertical ship response in head waves. The attention was focused on the first three harmonic on the bending moment and compare this experimental data with numerical approaches. The author concluded that nonlinearities in the bending moment responses cannot be considered as weak, and the nonlinearities are strongly related to amplitude of relative motion at the bow. Additional bow flare appears to increase the higher order component in the bending moments.

Clauss et al. (2010) presented a study of influence of the bow shape on load in high and steep waves for two different ships, a Roll-on/Roll-off (Ro–Ro) vessel with its V-shaped frame design and the bulk carrier with its full bow. The wave height and steepness have been selected to obtain wave profiles with different crest/trough asymmetries according to the various gravity water wave theories. Waves were chosen and classified into three groups: linear, Stokes II and Stokes III waves. The results from this analyses shows that vertical bending moment of Ro–Ro is affected strongly for higher steeper waves, whilst bulk carrier did not show large differences.

The review of previous investigations seems to indicate that the nonlinear behaviour of the wave induced vertical ship responses is very much related to the ship's hull geometry – nonlinear effects are relatively small for large block coefficient ships and they are significant for small block coefficient ships. The objective of the present study is to present experimental evidence of the hull geometry influence on the wave vertical bending moment induced by extreme waves and systematically compare the linear and nonlinear response effects for two ships with different block coefficients. The two ships are a bulk carrier (Cb=0.82) and a Ro–Ro (Cb=0.71). Scaled models were tested in a seakeeping basin under the same irregular waves (same wave traces), under head sea condition and several Froude numbers. The experimental wave traces were predefined and correspond to wave records measured during storms in the North Sea. They include abnormal waves, which are individual waves with height larger than two times the sea state significant wave height.

The motions of these models have been studied in Vásquez et al. (2015), while in the present paper the wave induced loads will be studied. Partial conclusions are made by comparing directly the measured responses from the two models. But the experimental data is also used to validate the load predictions by a partially nonlinear time domain seakeeping numerical model. The seakeeping numerical model is then used to generalize the comparative analysis between the two ships for a wide range of regular wave conditions.

2. Calculation method

The seakeeping calculations of the following section are carried out with a time domain seakeeping numerical model based on the formulation proposed by Fonseca and Guedes Soares (1998a, b). The method assumes that the nonlinear contribution for the vertical responses is dominated by hydrostatic and Froude–Krylov forces, thus these components depend of the instantaneous hull wetted surface. The exciting forces due to the incident waves are decomposed into diffraction part and Froude–Krylov part. The diffraction part, which is related to the scattering of the incident wave field due to the presence of the non-moving ship, is kept linear. Since this is a linear problem and the exciting waves are known a priori, it can be solved in the frequency domain and the resulting transfer functions can be used to generate a time history of the diffraction heave force and pitch moment. The Froude–Krylov part is related to the incident wave potential and results from the integration at each time step of the associated pressure over the wetted surface of the hull under the undisturbed wave profile.

The radiation forces are represented in the time domain by infinite frequency added masses, radiation restoring coefficients and convolution integrals of memory functions. The convolution integrals represent the effects of the whole past history of the motion accounting for the memory effects due to the radiated waves. Both the radiation and diffraction coefficients in the frequency domain are calculated by a strip method. The vertical forces associated with the green water on deck, which occurs when the relative motion is larger than the freeboard, are calculated using the momentum method (Buchner, 1995). This seakeeping numerical model is based on a "partially nonlinear method". This means that the equations of motions and loads combine linear and nonlinear terms.

The heave and pitch equations of motion in the time domain are given bellow:

$$\begin{aligned}(M + A_{33}^{\infty})\ddot{\xi}_3(t) + \int_{-\infty}^{t}\left[K_{33}^{m}(t-\tau)\dot{\xi}_3(\tau)\right]d\tau + C_{33}^{m}\xi_3(t) + A_{35}^{\infty}\ddot{\xi}_5(t)\\ + \int_{-\infty}^{t}\left[K_{35}^{m}(t-\tau)\dot{\xi}_5(\tau)\right]d\tau + C_{35}^{m}\xi_5(t) + F_3^{H}(t) \qquad - Mg\\ + F_3^{gw}(t) = F_3^{D}(t) + F_3^{K}(t)\end{aligned} \tag{1}$$

$$\begin{aligned}(I_{55} + A_{55}^{\infty})\ddot{\xi}_5(t) + \int_{-\infty}^{t}\left[K_{55}^{m}(t-\tau)\dot{\xi}_5(\tau)\right]d\tau + C_{55}^{m}\xi_5(t) + A_{53}^{\infty}\ddot{\xi}_3(t)\\ + \int_{-\infty}^{t}\left[K_{53}^{m}(t-\tau)\dot{\xi}_3(\tau)\right]d\tau + C_{53}^{m}\xi_3(t) + F_5^{H}(t) + F_5^{gw}(t)\\ = F_5^{D}(t) + F_5^{K}(t)\end{aligned} \tag{2}$$

where ξ_3 and ξ_5 represent, respectively, the heave and pitch motions and the dots over the symbols represent differentiation with respect to time. M is the ship mass; g is the acceleration of gravity and I_{55} represents the ship inertia about the y-axis.

The hydrostatic force and moment, F_3^H and F_5^H, are calculated at each time step by integration of the hydrostatic pressure over the wetted hull under the undisturbed wave profile, as well as the Froude–Krylov contribution of the exciting forces F_k^K. The diffraction forces are represented by F_k^D.

The radiation forces, which are represented in the time domain by infinite frequency added masses A_{kj}^{∞}, radiation restoring coefficients C_{kj}^{m}, and convolution integrals of memory functions $K_{kj}^{m}(t)$. The radiation restoring forces, associated with the restoring coefficients, represent a correction to the hydrodynamic steady forces acting on the ship due to the steady flow. The memory functions and the radiation restoring coefficients are obtained by relating

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