Ocean Engineering 127 (2016) 368–386

Contents lists available at ScienceDirect

Ocean Engineering

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

Prediction of extreme motions and vertical bending moments on a cruise ship and comparison with experimental data

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ARTICLE INFO

Keywords:
Wave induced motions
Vertical bending moment
Body nonlinear time domain seakeeping code
Experimental program

ABSTRACT

The wave induced motions and vertical bending moments induced by extreme seas on a Cruise Ship is investigated numerically and experimentally. Six sea states and extreme wave sequences, which could trigger modulation instability and induce high nonlinear ship responses, were chosen. The ship responses are simulated in the time domain with a body nonlinear seakeeping code based on strip theory. Two levels of complexity are used and compared: (a) the first assumes that the body nonlinear effects in the vertical responses are dominated by the hydrostatic and Froude-Krylov components, therefore the related forces are nonlinear, while radiation and diffraction is kept linear (partially body nonlinear method); (b) the second considers all forces as body nonlinear and they are updated at each time instant during the simulation depending on the hull wetted surface (fully body nonlinear method). The paper presents comparisons of direct time domain simulations with experimental records, as well as probability distribution of maxima. The fully body nonlinear code compares very well with the experiments in extreme wave conditions.

1. Introduction

Prediction of ship responses in extreme sea condition has always been a challenging task. Large ship motions severely affect the operability while the extreme loads pose threat to the structural strength and safety. Classical linear methods are valid for the calculation of the extreme loads on conventional ships like bulk carriers and large tankers as shown by Guedes Soares and Schellin (1998) and Clauss et al. (2010). However, these methods are not reliable for the estimation of the responses of the ships with large bow flare angle (e.g. container ships and FPSO) in steep waves as shown by several researchers including Fonseca and Guedes Soares, (2004a, (2004b and Fonseca et al. (2010). Highly nonlinear sea conditions and the complex geometry of the ships result in large nonlinear ship response for which the nonlinear numerical method are necessary for calculation.

The last four decades witnessed a major leap in the development of the numerical methods intended for the sea keeping calculations. These methods vary from the popular strip theories, still used widely because of their simplicity and ease of practical application, to sophisticated Computational Fluid Dynamic (CFD) techniques. Reynolds-Averaged Navier-Stokes (RANS) solvers are extensively verified and validated for the ship resistance and steady wave problems, Stern et al. (2012) and the CFD techniques already have promising results in the field of sea keeping, Oberhagemann et al. (2012). However, due to heavy computational effort and the complexities involved with implementation of nonlinear free surface and large ship motions, their application in the seakeeping problem that deals with the ship response in extreme sea conditions still limited and needs validation, (Von Graefe et al., 2013).

Boundary element methods based on the potential theory are a good tool for the estimation on nonlinear ship responses in low to moderate seas. Several numerical codes (e.g. LAMP2) based on 3D panel method dealing up to 2nd level of nonlinearity, which includes body nonlinear Froude-Krylov and hydrostatic forces as defined by ISSC Committee on Loads, 2012, are extensively validated and give good results for the estimation of ship response up to moderate sea conditions. However, their capability to predict the ship responses in extreme seas still need further investigation and remains a major concern for practical applications, particularly when it comes to calculation of short term distribution of loads of certain long duration in extreme sea conditions. Apparently, calculation of the ship response in extreme seas demands a fully nonlinear panel method, the development of which is confronted with stability problems, Bandyk and Beck (2008), and heavy computation time.

One alternative practical solution is to apply methods based on time domain strip theories. Fonseca and Guedes Soares (1998a, 1998b) proposed a partially nonlinear time domain method where Froude-Krylov and hydrostatic related forces are nonlinear, while radiation and

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http://dx.doi.org/10.1016/j.oceaneng.2016.10.021
Received 23 October 2015; Received in revised form 17 September 2016; Accepted 7 October 2016

diffraction is kept linear. The method was recently generalized by Rajendran et al. (2015a) by accounting for the nonlinear effects on the radiation and diffraction forces associated to the changing hull geometry under the incident wave. The method was developed keeping in mind that the technique should be fast, robust and accurate enough for the calculation of the short term probability distribution of the nonlinear loads in order to apply for practical engineering scenario.

The specialized literature reports many ship seakeeping experimental studies in small amplitude waves, including the experimental. There exist also some published studies considering moderate to large amplitude waves and with focus on the responses nonlinearities. There are, however, very few reported experimental studies with the ship responses in realistic extreme wave conditions. Among these, Drummen et al. (2009) compared the experimental and numerical responses of a modern container ship with large bow flare in severe head seas. The numerical calculations were conducted using a nonlinear hybrid strip theory, (Wu and Moan, 2005). Short term statistics of the rigid and flexible hull responses were derived from long simulations. In general, the agreement between the experiments and numerical results were good for the rigid body vertical bending moment even though there was a tendency to overestimate the sagging peaks.

More recently, Guo et al. (2013) presented short term statistics of the vertical response of three ships (LNG tanker, chemical tanker and a cruise ship) in extreme seas using a 3D Rankine panel method in which the Froude-Krylov and hydrostatics forces are body nonlinear. The cruise vessel was tested in very high seas with a significant wave height of 11.5 m and the loads acting on the ship was highly nonlinear characterized with large asymmetry in the distribution of sagging and hogging moment peaks. The extreme sagging moment was almost twice of the extreme hogging moment. The cruise ship had large bow flare than the normal containerships which made its response highly nonlinear. The sagging peaks were in good agreement with the experimental value, however vertical motion and the hogging peaks were underestimated by the code. The same cruise vessel is used as a case study in the present paper.

This paper presents an analysis of the vertical motions and bending moments on a cruise ship induced by realistic extreme seas. The seastates are derived from the IACS scatter diagram and correspond to a return period of 20 years. The calculations are carried out with the "fully body-nonlinear code" proposed by Rajendran et al. (2015a) and the results are compared with experimental data obtained in a seakeeping tank. The analysis includes direct time domain comparisons in selected extreme wave sequences and short term probability distributions comparisons. Throughout the paper, the body exact numerical method is called 'fully body nonlinear' for the sake of convenience, even though the fundamental solution for the radiation and diffraction forces is of the first order. An approximate method is applied to make these forces dependent of the underwater hull geometry. The results from the fully body nonlinear code are denoted with the acronym 'TDNL' and the experimental results are denoted by 'Exp' in the following figures. For comparative proposes, results from the partially nonlinear version of the code are also included and denoted by 'TD'.

2. Theory

2.1. Wave induced ship motions

The formulation of the partial and the fully body nonlinear numerical model was presented in Fonseca and Guedes Soares (1998a, 1998b) and Rajendran et al. (2015a) respectively, in detail and the surge mode is included in the equation of motion through a semi-empirical method, (Rajendran et al., 2015b). However, the method is briefly explained here for the sake of completion.

Assuming inviscid flow the hydrodynamic problem is formulated in terms of potential flow theory. Further assuming small enough amplitudes of unsteady motions and incident waves, the potential can be linearized. Substitution of the velocity potential into linearized Bernoulli´s equation results in the hydrodynamic pressure. Integration of the oscillatory pressure terms over the wetted surface of the hull results in the hydrodynamic forces associated with the oscillatory ship motions in waves. As a result from the former assumptions, the hydrodynamic forces can be separated in several independent components, namely: radiation forces, wave exciting forces (composed by the Froude-Krylov part and the diffraction part) and hydrostatic forces. Afterwards, the forces are combined to obtain the equations of wave induced ship motions and global structural loads. Equating the external hydrodynamic forces with the mass and gravitation force, one could write the equation of motion for the ship. For surge, heave and pitch, the equation of motion could be written as

$$(M + A_{11}^{\infty})\ddot{\xi}_1(t) + \int_0^t K_{11}(t-\tau)\dot{\xi}_1(\tau)d\tau + C_{11}\xi_1(t) + (M.\,Z_{cg} + A_{15})\ddot{\xi}_5 + \int_0^t K_{15}(t-\tau)\dot{\xi}_5(\tau)d\tau + C_{15}\xi_5(t) = F_1{}^E(t) \quad (1)$$

$$(M + A_{33}^{\infty})\ddot{\xi}_3(t) + \int_0^t K_{33}(t-\tau)\dot{\xi}_3(\tau)d\tau + C_{33}\xi_3(t) + A_{35}^{\infty}\ddot{\xi}_5 + \int_{.0}^t K_{35}(t-\tau)\dot{\xi}_5(\tau)d\tau + C_{35}\xi_5(t) + F_3{}^H(t) - Mg = F_3{}^E(t) + F_3^{gw}(t) \quad (2)$$

$$(I_{55} + A_{55}^{\infty})\ddot{\xi}_5(t) + \int_0^t K_{55}(t-\tau)\dot{\xi}_5(\tau)d\tau + C_{55}\xi_5(t) + A_{53}^{\infty}\ddot{\xi}_3 + \int_0^t K_{53}(t-\tau)\dot{\xi}_3(\tau)d\tau + C_{53}\xi_3(t) + (M.\,Z_{cg} + A_{51}^{\infty})\ddot{\xi}_1 + \int_0^t K_{51}(t-\tau)\dot{\xi}_1(\tau)d\tau + C_{51}\xi_1(t) + F_5^H(t) = F_5{}^E(t) + F_5^{gw}(t) \quad (3)$$

where ξ_1, ξ_3 and ξ_5 represent respectively surge, heave and pitch motions and dots over the symbols represent differentiation with respect to time. M is the ship mass, g is acceleration of gravity, Z_{cg} is the vertical distance from the ship centre of gravity and the height where the vertical bending moment is to be calculated and I_{55} represent the ship inertia about the y-axis. The hydrostatic force and moment, F_3^H andF_5^H, are calculated at each time step by integration of the hydrostatic pressure over the wetted hull under the undisturbed wave profile. The exciting forces due to the incident waves,F_1^E, F_3^E and F_5^E, are decomposed into a diffraction part, F_1^D, F_3^D *and* F_5^D, and the well-known Froude-Krylov part, F_1^K, F_3^K *and* F_5^K. A_{jk}^{∞} (j, k=1, 3, 5) are the infinite frequency added masses, K_{jk} represent the memory functions and C_{kj}^m is the radiation restoration coefficients. F_3^{gw} *and*F_5^{gw} are green water force and moment. The description of the coefficients and the force components are given in the following sections.

It is not possible to calculate surge coefficients using a 2D strip theory based computation. Therefore an approximate method proposed by Journée (1999) and implemented successfully in the commercial FD code SEAWAY/Octopus, (Journée and Adegeest, 2003), is used. Even though the method calculates surge coefficients, the method is purely empirical and is not based on any strip theory assumptions and calculations. The method is used in the paper, since it gives reasonably accurate results for practical applications, as shown in Rajendran et al. (2015a, 2015b). The basic idea was to calculate the sway hydrodynamic coefficient of an equivalent cross section with breadth and draft equal to length and draft of the ship, and sectional area coefficient equal to block coefficient of ship. Sway coefficients were calculated using multi parameter conformal mapping. However, these coefficients obtained through aforementioned method did not reflect any 3D hull effects. Final global surge coefficients were calculated by including 3D effects of surge motion through an empirical method. The linearized surge viscous damping was calculated from the derivative of frictional part of the hull resistance curve defined by ITTC 1957.