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Effect of surge motion on the vertical responses of ships in waves

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ABSTRACT

The paper investigates the effects of the surge hydrodynamic forces and surge mode of motion on the vertical responses of a container ship and a chemical tanker in waves. A partially body nonlinear time domain code based on strip theory is modified to include the surge mode. The Froude–Krylov and hydrostatic forces are calculated for the exact wetted surface area of the hull for each time instant. Certain practical engineering techniques are used to overcome the 2D limitations imposed by strip theory in order to include the surge. Surge hydrodynamic coefficients are calculated using conformal mapping technique and surge Froude–Krylov forces are calculated for instantaneous wetted surface. Surge radiation forces are calculated based on Cummins formulation. The analysis is done for the S175 container ship and a chemical tanker in head seas for a range of wave steepness and Froude numbers. The effect of surge on the transfer functions and the peaks values of the vertical motions and vertical bending moment are analyzed. The numerical results are compared with the experimental results. It is observed that longitudinal forces reduce the vertical bending moment about the transverse axis at deck level for the wave frequencies of interest.

1. Introduction

For the design of any sea going vessel, vertical bending moment is a key parameter. Several methods, varying from frequency domain code to complex CFD codes, are available for the estimation of motion and loads acting on a ship, each one with its own merits and demerits. The 2D methods based on strip theory are fast and robust while their application is limited due to their 2D assumption and applicability in a limited range of frequencies and Froude number. In this paper, a practical engineering technique is implemented to overcome the 2D assumption of strip theory by including the surge mode for the calculation of the vertical ship response. Here the method is restricted to head sea condition in which the bending moment is expected to be largest.

Due to the large bow flare above the deck and finer form, the S175 container ship model has been extensively used by many authors in the past to study the nonlinear effects on vertical response. Watanabe et al. (1989) conducted a systematic study of the response of the S175 ship in order to understand the effect of bow flare on the deck wetness and asymmetry of the vertical bending moment. They conducted tests in both regular and irregular waves. A detailed study was conducted on the first, second harmonics and peak values of the vertical bending moment. They found that the first harmonics are little influenced by the flare of the ship, however the peak of the vertical bending moment are very much influenced. O'Dea et al. (1992) conducted tests on the S175 container ship and analyzed the first, second and third harmonics of the vertical motion and acceleration. He concluded that the first harmonic value of the responses decreased as the wave steepness increased. Fonseca and Guedes Soares (2004a) conducted extensive study of the response of the S175 containership for a range of wave frequencies of interest with different incoming wave steepness (small to large amplitude incoming waves). They analyzed the absolute and relative motions, vertical accelerations and cross sectional loads at midship and at the quarter length of the ship from the forward perpendicular. They clearly identified the strong nonlinear effects on the responses in steep waves, particularly on the load, and presented by means of transfer function, higher harmonics and time series signals.

Watanabe and Guedes Soares (1999) compared the experimental results for the S175 containership with the numerical results from six different partially nonlinear numerical methods. The vertical motion, accelerations and the vertical bending moment were compared and presented in tabular form. The numerical results were in good agreement with each other for the ship responses in low wave amplitudes, however, discrepancy was found in steeper waves. Fonseca and Guedes Soares (2002) compared the numerical results from their partially nonlinear time domain method with the experimental results. The study was conducted on the S175 containership for a range of wave steepness and higher Froude number. The numerical and experimental mean

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values, transfer functions, 2nd harmonics and the peak values of the vertical bending moment were compared. The agreement between the numerical and the experimental results were good for lower Froude numbers, however, some discrepancy was found for higher Froude numbers. A further study on the effect of forward speed was conducted by Datta et al. (2013) now for a fast ferry using the same strip theory and a 3D time domain Green function method. They concluded that forward speed has a large effect on the radiation forces, especially on the coupling terms, and thus it is important to consider the full linear interactions between the steady and unsteady flows in the numerical calculations as the speed of the ship increases, which the time domain panel code is able to do but not the strip theory code, which has limitation for those very high speeds.

Clauss et al. (2007) discussed the influence of longitudinal forces on vertical bending moment. They conducted experiments on a FPSO and measured the vertical bending moment about the lateral axis at mean waterlevel and deck. Interestingly, they found that the bending moment calculated at deck level was significantly reduced by the presence of the longitudinal force. However such reduction was negligible when measured at mean water level. This observation was further confirmed by comparing the experimental results with a numerical method based on frequency domain linear strip theory which included surge mode.

Fonseca and Guedes Soares (1998) calculated the ship responses using a nonlinear time domain method based on strip theory. Radiation forces were calculated based on Cummins' formulation and Froude Krylov and hydrostatic forces were integrated over the instantaneous wetted surface. The method's ability to calculate the vertical motions and global structural loads in large amplitude waves has been assessed by comparisons with experimental data for different types of ships (Fonseca and Guedes Soares, 2002, 2004a, 2004b; Guedes Soares et al., 2008; Fonseca et al., 2010). The agreement was in general good, however it was concluded that one of the needed improvements is related to the inclusion of surge mode effects, as strip theory regards surge hydrodynamic forces as negligible and does not account for them. This aspect continues relevant nowadays, since the strip theory is still regarded as a useful tool to calculate the ship responses in waves and in particular when nonlinear effects need to be taken into account. The same techniques as in Fonseca and Guedes Soares (1998) are used in this paper, extending the formulation to include the longitudinal forces.

Journée (1999) provided a semi-empirical method to calculate the surge coefficients. This paper makes use of a similar technique to calculate the surge hydrodynamic coefficients and viscous damping coefficients and later on, applies it in the frequency and time domain formulation. Here surge Froude–Krylov forces are calculated for the instantaneous wetted surface area and surge infinite frequency added mass and memory function, calculated from damping coefficients, are used for the calculation of surge radiation force. Later on, three coupled equation of motion are solved in the time domain.

2. Theory

A coordinate system fixed with respect to the mean position of the ship is defined, $X=(x,y,z)$ with z in the vertical upward direction and passing through the centre of gravity of the ship, x along the longitudinal direction of the ship and pointing to the bow and y perpendicular to the latter and in the port direction. The coordinate system and the displacements are presented in Fig. 1. The origin is in the plane of the undisturbed free-surface. The present work is restricted to head seas, in which the maximum response in vertical bending moment is expected.

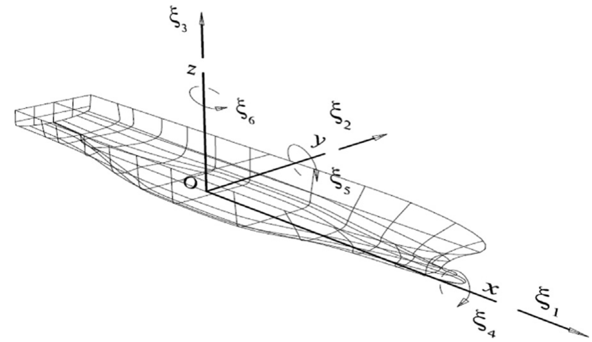

Fig. 1. Co-ordinate system and conventions for oscillatory motion.

2.1. Ship motions

2.1.1. Surge hydrodynamic coefficients

In order to include the surge motion and its effect on the vertical loads, the method proposed by Journee (1999) is used. The basic idea is to calculate the sway hydrodynamic coefficient of an equivalent section with breadth and draft equal to length and draft of the ship, respectively, and midship area coefficient equal to block coefficient of the ship. However the usage of Frank's method to calculate the sway coefficient for such an unrealistic cross section with a beam to depth ratio in the order of 30 seemed to be unacceptable because of the presence of large number of irregular frequencies.

Therefore, multi parameter conformal mapping is used to calculate the sway coefficient. Ursell (1949) calculated sway coefficients of cylinders on the free surface and Tasai (1959) extended Ursell's theory to Lewis forms. Von Kerczek and Tuck (1969) proposed an iterative method based on the least square method for N parameter conformal mapping of the complex shapes. De Jong (1973) gave added mass and damping coefficients for a N parameter conformal mapped shape. Ramos and Guedes Soares (1997) have revisited this problem and studied the effect of the number of parameters in the N parameter conformal mapping and the error in the predictions of the added mass and damping coefficients for different types of shapes of ship sections, making practical recommendations.

Based on these works, conformal mapping technique is used in this work to calculate the sway hydrodynamic coefficient of the equivalent longitudinal ship section. In this study, 9 parameter conformal mapping is used. They are found to be optimum for representing the shape of the section. Once the surge coefficients of the equivalent longitudinal section are calculated, they are multiplied with breadth of the ship to get global coefficients.

$$A_{11}=B.A^*_{11}$$

$$B_{11}=B.B^*_{11} \quad (1)$$

However, these coefficients obtained through the aforementioned method do not reflect any 3D effect. The 3D effects of surge motion are incorporated through an empirical method given by Journee (1999). Tasai (1961) gave the zero frequency sway added mass of a Lewis section:

$$A_{22}(\omega\to 0)=\rho\frac{\pi}{2}\left(\frac{D_s}{1-a_1+a_3}\right)^2\left\{(1-a_1)^2+3.a_3^2\right\} \quad (2)$$

where D_s is the draft of the section, B is the breadth of the ship, ρ is the density, A^*_{11} is the surge added mass of the equivalent section, B^*_{11} is the surge damping coefficient of the equivalent section, a_1 and a_3 are mapping parameters, A_{11} and A_{22} are global surge and sway added mass and B_{11} is global surge damping coefficient.

A frequency independent total hydrodynamic mass coefficient is estimated empirically by Sargent and Kaplan (1974) as a proportion