

Time-domain calculation of moored ship motions in nonlinear waves

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Abstract

Numerical modelling of moored ship behaviour in a harbour requires an accurate description of the harbour geometry and bathymetry for a correspondingly accurate determination of the associated wave phenomena diffraction, refraction and reflection. On a smaller scale an accurate description of the 3D shape of the ship is required to determine the wave forces on the ship. These requirements are difficult to combine in a single model, so that a combination of a Boussinesq-type wave model with a time-domain panel model is developed and described in this paper. With this approach it is possible to determine the wave forces on a moored ship including the contributions of second-order waves and harbour oscillations and second-order drift forces. The model is validated against model tests for the wave forces due to a passing ship and further results are presented for a ship in irregular short-crested waves.

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1. Introduction

In the design stage of new ports or terminals, physical model tests and calculations need to be carried out to check the wet area for the safety of the shipping channels and for the downtime of the ships moored at the berths. Classical wave models solve the amplification factors of long waves in the port (Hwang and Tuck, 1970; Lee, 1971; Ünlüata and Mei, 1973). A common aspect of these methods is that they are all based on frequency-domain diffraction theory. The advantage of this approach is that each wave component can be treated separately. In order to determine the motions of a ship moored in the port, nonlinearities in the characteristics of the mooring system can be incorporated, provided that the equation of motion is solved in time-domain with the wave forces on the ship obtained from the linear wave model, see e.g. Kubo and Sakakibara (1997), Shiraishi et al. (1999) and Weiler and Dekker (2003). Time series of wave forces are generated by transformation of the frequency-domain results assuming the waves can be considered linear.

This assumption is violated if the low-frequency forcing is induced by subharmonics related to wave groups. These bound long waves travel with the group velocity of the short waves (Longuet-Higgins and Stewart, 1962) and also the shoaling properties differ from free waves (Battjes et al., 2004): the shoaling of bound waves is much stronger than the shoaling of the short carrier waves. However, this strong enhancement is reduced if the bed slope is relatively steep. The shoaling of long waves on a slope and the reflections from the shore are complex processes. Therefore, for a correct analysis of wave forces on a ship moored inside a port, on a sloping sea bed or close to the shore, one needs to consider the nonlinearities in the enhancement of bound harmonics on a sloping sea bed and to take the reflections from the shore or boundaries in a port into account.

Van der Molen et al. (2006) use an infragravity wave model to calculate the propagation of the incident waves. The short-wave energies are phase-resolved and act as the driving force for the generation and propagation of the associated bound waves. The short wave energies and bound and free long wave elevations are calculated in the time-domain using shallow water equations. Long wave assumptions can be used to provide simple formulations for the wave forces on the ship. This is a valid approach as long as the wave forcing on the ship is

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dominated by the infragravity waves. In situations where sub-harmonic forces and first-order forces are equally important at the berth, the situation can be represented using a wave model which treats the propagation of nonlinear waves over an uneven bathymetry. Bingham (2000) used a Boussinesq-type wave model to compute the incident waves. The scattering of the incident waves around the hull and subsequently the first-order wave forces are determined using the Haskind relations in a frequency-domain panel method. The ship motions are again calculated in the time-domain to include the nonlinear restoring forces of the mooring system. A similar approach has been described by Pinkster and Naaijen (2003) and Wenneker et al. (2006), hereafter referred to as PW (Pinkster–Wenneker). They also obtain wave forces using a combination of a Boussinesq-type model and a linear frequency-domain panel model. However, they do not use the Haskind relations to obtain the diffraction forces, but the forces are determined by solving the diffraction problem for all frequencies separately. Besides the first-order scattering of the incident waves, which leads to the first-order wave forces, the second-order wave forces are determined as well. The formulations for the second-order wave force comprise the four terms of products of first-order contributions derived by Pinkster (1980). The validity of applying a Boussinesq-type wave model to determine low-frequency harbour oscillations due to wave group forcing has been shown by Woo and Liu (2004).

In this paper the incident waves are also calculated with a 2DH (2D horizontal) Boussinesq-type wave model to provide the pressures and particle velocities at the positions of the panels at the hull. Contrary to Bingham (2000) and PW, a time-domain panel method is applied to determine the scattering of the incident waves. By fully calculating the fluid flow around the ship it is possible to directly obtain the first-order wave forces as well as slowly varying drift forces with direct pressure integration without Fourier transformations. Therefore, a method carried out fully in the time-domain is less ambiguous than a method carried out partly in the frequency-domain. Because only the response due to disturbances in the past are treated, it is not possible that oscillations are determined ahead of the wave front due to inaccuracies in the Fourier transformations. These inaccuracies can occur if the wave record is not a repetitive event. Nonlinearities in the incident waves are treated in the wave model. The motions of the ship are considered to be small with respect to the wave length.

Thus, a 2D nonlinear wave model for the incident waves is combined with a 3D linear model for the scattered and radiated waves. A nonlinear method for the incident waves is chosen because it is important to accurately obtain the bound harmonics in the incident waves. Because the scattered and radiated waves are a relatively small perturbation of the incident wave, the nonlinearities in these wave components are considered to be small. This justifies the use of the linear free surface condition for the scattered and radiated waves. A 3D method is required to accurately include the shape of the ship and the flow around the hull for the scattered and radiated waves, whereas only gentle variations of the bottom topography need to be considered for the incident waves.

In Sections 2 through 4 of this paper the computational method is described with the focus on the time-domain panel model and the coupling between the Boussinesq model and the panel model. The validation of the method is presented in Section 5 by comparing simulation results with model tests for the wave forces on a container ship due to the waves generated by a passing ship. Further verification for the forces on an LNG carrier in irregular short-crested waves is given in Section 6. Apart from comparison with measured data, the numerical results for both cases are also compared with results obtained with the method from PW. The latter method is provided with exactly the same wave data from the Boussinesq-type wave model but treats the scattering of the incident waves around the hull of the floating body with the frequency-domain panel model DELFRAC. A discussion on the conceptual differences between the frequency-domain approach (PW) and a time-domain approach (this paper) is given in Section 7 together with the conclusions.

2. Computational approach

The computational process is as follows. The waves in the harbour or in the coastal area are determined using the Boussinesq-type wave model TRITON (Borsboom et al., 2000), developed at WL/Delft Hydraulics. This is a 2DH (2D horizontal) model for the computation of waves in time-domain. The model takes into account the geometry (bathymetry and — if present — harbour walls) and wave physics (e.g. dispersion, diffraction, refraction, shoaling and nonlinear wave interactions). The presence of the 3D shape of the ship is not incorporated in the wave model. Instead, time series of pressures and flow velocities at the hull of the ship are obtained from TRITON in the absence of the ship. A reverse transformation in TRITON is used to obtain the vertical variation of the orbital velocities and the nonhydrostatic pressure from the computed depth-averaged velocities and surface elevations. The time series are written to a file which serves as input for the 3D diffraction model. Time series of surface elevation at the waterline of the ship are also written to file to serve as input for the calculation of the second-order forces.

The pressures and velocities are obtained at the centroids of the quadrilateral panels according to the mesh of the boundary-integral model. This model computes the scattering of the incident wave field by the presence of the ship and the subsequent wave forces. It is based on time-domain boundary-integral equations, so that direct computations can be carried out in the time-domain without transformations to the frequency-domain. Because a linear approach is adopted, the forces due to the radiated waves from the moving ship are considered to be linearly related to the history of the ship movements. Therefore, coefficients can be derived beforehand that enable the force due to the radiated waves to be easily computed from the motions. Reflections of scattered waves against other structures such as nearby quay walls can be incorporated as well by adding more bodies in the boundary-integral model. For these structures it is not necessary to prescribe the incident wave conditions, because the boundary

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