Applied Ocean Research 78 (2018) 223–240

Contents lists available at ScienceDirect

Applied Ocean Research

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

Motion of a floating body in a harbour by domain decomposition method

Y.Y. Shi[a], Z.F. Li[b], G.X. Wu[b,*]

[a] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[b] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212003, China

ARTICLE INFO

Keywords:
Ship motion in a harbour
Domain decomposition
Three-dimensional boundary element method
Free-surface green function

ABSTRACT

A three-dimensional domain decomposition method is used to solve the problem of wave interaction with a ship floating inside a harbour with arbitrary shape. The linearized velocity potential theory is adopted. The total fluid domain is divided into two sub-ones: one for the harbour and the other for the external open sea. Boundary integral equations together with the free surface Green function are used in the both domains. Matching conditions are imposed on the interface of the two sub-domains to ensure the velocity and pressure continuity. The advantage of the domain decomposition method over the single domain method is that it removes the coastal surface from the boundary integral equation. This subsequently removes the need for elements on the coastal wall when the equation is discretized. The accuracy of the method is demonstrated through convergence study and through the comparison with the published data. Extensive results through the hydrodynamic coefficients, wave exciting forces and ship motions are provided. Highly oscillatory behaviour is observed and its mechanism is discussed. Finally, the effects of incident wave direction, ship location as well as the harbour topography are investigated in detail.

1. Introduction

The motion of a ship in a harbour is much more complex than that in the open water, due to the fact that the harbour has its natural frequencies in addition to that of the ship itself, which may lead to a large amplitude motion response of the ship floating inside the harbour. As a result, it may affect cargo handling, or even cause damage to the harbour or the ship itself. Therefore, accurate prediction of the motion behaviour of a ship inside a harbour is of great significance.

There has been a large body of work done on wave motion inside a harbour. Analytical solutions were derived by Mcnown [1] for a circular harbour and by Kravtchenko and Mcnown [2] for a rectangular one. The harbour had a small entrance where the flow into the harbour was prescribed. A particular solution was first obtained for the inhomogeneous normal velocity condition at the entrance. This was combined with the general solution satisfying the homogeneous normal velocity condition on the entire harbour boundary including the entrance. In the real problem, the harbour entrance is connected to the external water and flow into the harbour is unknown before the solution is found. Hwang and Tuck [3] studied the harbour wave diffraction problem. The incoming wave to the harbour satisfied the boundary condition on the coastal wall and therefore the wave diffraction was entirely due to the harbour itself. The problem was solved by the boundary integral equation method with sources distributed over both the harbour and coastal walls. The latter was truncated at some distance away from the entrance. Lee [4] divided the fluid domain into the inner harbour region and the external open sea region. This removed the need for the elements on the coastal wall. The solution was obtained by enforcing the flow and pressure continuities at the interface of the two regions. Isaacson and Qu [5] considered the wave field in a harbour with partially reflecting boundary. Other permeable harbour wall boundary conditions including open, partial reflection and absorbing boundary were used by Hamanaka [6]. A harbour with corner point was considered by Kumar, Zhang [7]. Besides, Martins-Rivas and Mei [8] considered the interaction of waves with a vertical circular cylinder half embedded in cliff and open on the seaside. Although the focus of that work is on the oscillations of the water column inside the cylinder for wave power extraction, the physical problem of which is similar to the wave/harbor interactions. Apart from Laplace equation in the fluid domain or Helmholtz equation in a horizontal plane with the linearized free surface boundary condition, Boussinesq wave model for shallow water was also used to analyze the motion in the harbour [9–12].

In the above work, no floating body is present in the harbour. Sawaragi and Kubo [13] analyzed the motion of a rectangular body floating in a rectangular harbour by domain decomposition method. The whole fluid domain was divided into three sub-domains, a domain of the outer open sea, a domain underneath the ship and the rest of the domain in the harbour. The velocity potential in each domain was

* Corresponding author. Permanent address: Department of Mechanical Engineering, University College London, Torrington Place, London, WCIE 7JE, UK.
E-mail address: g.wu@ucl.ac.uk (G.X. Wu).

https://doi.org/10.1016/j.apor.2018.06.015
Received 20 April 2018; Received in revised form 19 June 2018; Accepted 20 June 2018
Available online 30 June 2018

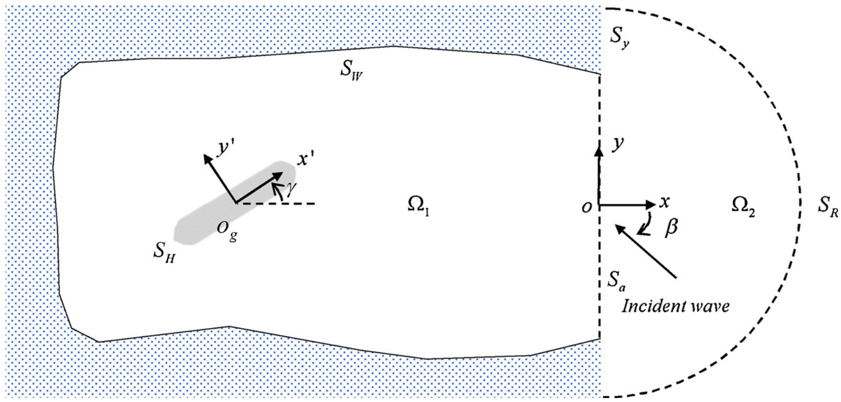

Fig. 1. Bird view of a floating ship in a harbour of an arbitrary shape.

expanded into eigenfunctions in the vertical direction. Sawaragi, Aoki [14] proposed a slightly different domain decomposition. Domain one enclosed the ship, domain two covered the rest of the harbour and domain three was the external open sea. The three-dimensional (3-D) boundary element method (BEM) was used in domain one. In domains two and three, eigenfunction expansion was adopted in the vertical direction. The number of terms used in the expansion was balanced by the rate of decay of evanescent modes in the horizontal direction. Takagi, Naito [15] proposed a different domain decomposition method to analyze hydrodynamic force on a floating body in a harbour. The total domain was also divided into three sub-domains. The floating body was enclosed by a cylindrical surface, within which the 3-D BEM was used. Outside this cylindrical surface, a finite element method was used for the mild-slope equation up to an external boundary beyond which was the third domain. Ohyama and Tsuchida [16] adopted similar domain decomposition method. The boundary element method was used in a domain surrounding the ship, a mild-slope equation in the outer domain, which was matched with the waves at the far filed. Later Ohyama and Tsuchida [17] solved the problem by including the evanescent modes. Recently, Kumar, Zhang [18] adopted a domain decomposition which was similar to that of Sawaragi, Aoki [14] mentioned previously to investigate the ship motion as well as wave field under the harbour resonance conditions. They adopted the 3-D BEM for the domain surrounding the ship. Away from the ship, the velocity potential was expanded based on eigenfunctions in the vertical dimension in the harbour and open sea. Then the 2-D Helmholtz equation was used for the term of propagating wave in the horizontal plane. For the linear theory different idealizations or approximations have been used to a certain degree, which can be broadly divided into two categories. One is the analytical solution for fluid motion in a harbour of a specific geometry. The other involves domain decomposition. The boundary element method is commonly used near the body together with the series expansion in other domains. However, it is common to ignore the evanescent modes in the expansion or keep only a few terms. In addition to the above work using the linear Stokes wave as the incoming wave, Bingham [19] used the Boussinesq theory for shallow water incoming wave and the body motion was solved in the time domain. However, the nonlinear theory is often adopted for some special wave events. It is not practical to use the fully nonlinear theory to undertake systematic investigations of the general performance of a ship in waves, partly due to the computational effort required.

In this paper, we aim to provide the exact solution in the numerical sense for motion of a ship freely floating inside the harbour and do not introduce any further approximation within the framework of the linearized potential theory. Here 'exact' in the numerical sense means that as the discretization is continuously refined the solution will converge to the exact one. We shall use the 3-D BEM together with the free surface Green function [20]. However when such a method is used directly, the integral equation will involve the coastal wall boundary tending to infinity, on which a huge number of elements may be needed. Therefore, a simpler domain decomposition method to account for wave/harbour interaction [4] is reintroduced in this paper to remove the need of elements along the infinite straight coastal line. The matching condition will be imposed on their interface to enforce flow and pressure continuity condition.

In the next section, the basic theory including mathematical equations and the numerical procedure are first described. In Section 3, to verify the accuracy of the present numerical model and solution, comparisons are made with the published results in a rectangular basin. Computations are then carried out for a floating FPSO, and extensive numerical results are provided, including the hydrodynamic forces and ship motions. The highly oscillatory behaviour of the results are observed and its mechanics are detailly discussed. The effect of incident wave frequency and direction, ship location as well as the harbour topography are investigated respectively. Finally, conclusions are drawn in Section 4.

2. Mathematical model and numerical procedure

2.1. Mathematical model

We consider the problem of motion of a ship floating in a harbour, as sketched in Fig. 1. The fluid is assumed to be inviscid and incompressible with constant density ρ_0, and the flow to be irrotational. The velocity potential theory can then be used. When the amplitudes of the wave and body motions are small compared with the wavelength and characteristic length of the body, the boundary conditions can be linearized, in which all the nonlinear terms can be ignored and the conditions can be imposed on the mean position of the boundary. To describe the problem and develop the numerical procedure, the total fluid domain Ω_A is divided into two sub-domains, the interior domain of harbour Ω_1 and the exterior domain of open water Ω_2. A Cartesian coordinate system $o-xyz$ is defined in which its origin is on the mean free surface, y-axis is along the interface of the two sub-domains and z-axis points vertically upwards. The coastal wall along y-axis is a straight line and tends to infinity. We also define a body fixed Cartesian coordinate system $O_g-x'y'z'$, with its origin at the centre of gravity of the ship (x_g, y_g, z_g), x' along the ship length, y' along the beam and z' pointing vertically upwards. The orientation of the ship in the harbour is denoted by the angle γ between x' and x.

The velocity potential in each sub-domain can be decomposed into those due to incident, diffraction and radiation

$$\Phi^{(l)}(x,y,z,t)=\mathrm{Re}\{[\phi_0^{(l)}(x,y,z)+\sum_{j=1}^{6}\mathrm{i}\omega\eta_j^{(l)}\phi_j^{(l)}(x,y,z)]e^{\mathrm{i}\omega t}\}, \tag{1}$$

where periodic motion in time with frequency ω has been assumed, and $\mathrm{i}=\sqrt{-1}$, $l=1$, 2 correspond to interior and exterior domains,