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Investigation on the unsteady hydrodynamic loads of ship passing by bridge piers by a 3-D boundary element method

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ABSTRACT

A 3-D Rankine type Green function boundary element method is developed to estimate the unsteady hydrodynamic interaction during ship passing piers process. To address this moving boundary problem, a free surface re-meshing algorithm based on the combination of local mesh and global mesh is proposed to update fluid boundary and the boundary value formula is solved at each time step. Two alternative numerical models for ship passing piers problem are compared with the current analysis method. Based on the three numerical models, the characteristics of the hydrodynamic loads acting on the passing ship are specified and the critical positions for the peak values have been identified. Simulation results demonstrate that the fluid disturbance induced by the piers is of importance. Therefore, the study of ship–piers hydrodynamic interaction in a river must be handled as a different forward speeds problem. Additionally, the wave elevation effect can only be neglected on condition that the forward speed is very low.

1. Introduction

The unsteady fluid interaction between two moving bodies during a passing by process has long been investigated, mainly in terms of aerodynamics and hydrodynamics. Based on 3-D compressible Euler/Naiver–Stokes equations, Fujii and Ogawa [1] simulated the flow filed induced by two trains passing by each other in a tunnel. The basic characteristics of the time history of pressure distributions and the aerodynamic forces were identified. Mancini and Malfatti [2] performed a full-scale field measurement of the unsteady aerodynamic pressure generated by a train passing at high speed in open air and in tunnels. Watanabe and Matsuno [3] investigated the flows driven by a high-speed car passing through a hairpin corner. A so-called 'Moving Computational Domain Method' was proposed and the whole computational domain including bodies inside moved in the physical space without the limit of region size. Yeung and Tan [4] studied the hydrodynamic interaction of ships with fixed obstacle. The slender-body theory was used with the assumption that the free surface was rigid. Kijima [5] investigated the ship–piers interaction in close proximity with the asymptotic expansions method. Time series of wave forces and ship motions were obtained.

Research on multi-body hydrodynamic interaction during passing by process was firstly started decades ago with model test approach. Newton [6] carried out model test of two ships during overtaking operations in deep water. Müller [7] studied overtaking and encountering problem in restricted water channel. Vantorre et al. [8] carried out extensive model tests on the hydrodynamic interaction between two ships during overtaking, passing by, and encountering operations. A specially designed twin-carriage system was applied to implement the complicated operations. Model test program was launched by Mousaviraad et al. [9] to investigate ship-to-ship interactions in the calm water and waves during overtaking operations. Effect of configuration, speed and heading angle were studied.

Alongside with model test method, analytical and empirical approaches mostly based on the slender-body theory have been developed and validated. Tuck and Newman [10] extended the slender-body theory to predict the hydrodynamic lateral force and yaw moment acting on each of the two ships while they were moving along parallel paths. Yeung [11] used similar approach to investigate the unsteady hydrodynamic interaction of two ships moving in shallow water. Brix [12] proposed an approximate empirical formula to estimate the maximum values of longitudinal and transverse forces during overtaking operations. Wang [13] expanded Yeung's [11] study to investigated the irrotational flow around two slender bodies with revolution angles of yaw, which were travelling along parallel paths in close proximity.

More recently, the boundary element method is applied in an increasing number of numerical studies on unsteady hydrodynamic interaction within the framework of potential flow theory. Xiang and Faltinsen [14] developed a 3-D Rankine source method with consideration of the linear wave effect to solve the boundary value problem of two

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ships advancing in waves. Sutulo et al. [15] developed a potential-flow method to estimate the hydrodynamic interaction forces. The general estimation method was validated against experimental data obtained in deep and shallow water towing tanks for the case of a tug operating near a larger vessel. Yuan et al. [16] proposed a methodology to predict the ship-to-ship interaction during overtaking operations in shallow water. To deal with the different forward speeds, they divided the velocity potential into two independent components and addressed each component separately. Yao and Dong [17] developed a frequency domain analysis method with consideration of local steady flow effect to investigate wave forces of two parallel advancing ships. They showed that the flow speed is an important factor relating to the hydrodynamic interaction. Xu et al. [18] used high-order element method to predict hydrodynamic interaction of two cylindroids moving along parallel courses in shallow water. Since free surface elevation was neglected in their work, only low forward speed problem was addressed. Pinkster and Bhawsinka [19] proposed a real-time simulation technique for ship–ship interaction based on a double-body flow method. Wang and Zou [20] studied the hydrodynamic interaction between a passing ship and a berthed ship in a single way lock.

The hydrodynamic interaction involved in the ship passing piers process has not been fully studied due to its complexity. The speed of river flow could make the coordinate system complicated. The bridge piers cannot be treated as fixed obstacles and the 'passing by' process turns to an encountering problem, which is a different forward speeds problem by nature. Also, the ship usually passes by the piers with a moderate or even high forward speed so that the wave elevation effect must be considered. This study aims to address these issues involved in the ship passing piers problem. A 3-D boundary element method based on Rankine type Green function is developed. Since it is an unsteady and moving boundary problem, a re-meshing algorithm is developed to update boundary of fluid domain at each time step. To fully capture the free surface disturbance effect, the Neumann–Kelvin condition is applied on the free water surface. The current analysis method will be compared with another two numerical models to illustrate the wave elevation effect and the importance of fluid disturbance induced by the piers in river flow.

2. Mathematical formulations

Theoretically, ship passing pier (involving relative movement) is an unsteady problem, since the boundary of the fluid domain is time-varying. Nevertheless, it can be handled in a quasi-steady approach. The steady boundary value model is set up at each time step, based on the current fluid boundary configuration. The boundary value problem is solved in a step-by-step manner with the update of boundary configuration to consider the unsteady effect.

2.1. Boundary value problem

For a single ship advancing in open calm water with constant forward speed u, a velocity potential ϕ is introduced. Following [21], the dynamic free surface condition and the kinetic free surface condition can be expressed as

$$u\frac{\partial\varphi}{\partial x}+\frac{1}{2}\nabla\varphi\cdot\nabla\varphi+g\xi=0,\ \text{on}\ z=\xi(x,y) \tag{1}$$

$$u\frac{\partial\xi}{\partial x}-\frac{\partial\varphi}{\partial z}+\frac{\partial\varphi}{\partial x}\cdot\frac{\partial\xi}{\partial x}+\frac{\partial\varphi}{\partial y}\cdot\frac{\partial\xi}{\partial y}=0,\ \text{on}\ z=\xi(x,y) \tag{2}$$

where ξ is the wave elevation. Neglecting higher order terms, the classical linear Neumann–Kelvin free surface condition is derived

$$u^2\frac{\partial^2\varphi}{\partial x^2}+g\frac{\partial\varphi}{\partial z}=0,\ \text{on}\ z=0 \tag{3}$$

Assume that a ship is passing by piers with constant forward speed u and the river flow speed is u_0. A river-fixed coordinate system moving together with the river flow is introduced. In the river-fixed coordinate, both the passing ship and the piers are moving with forward speed $u_1=u{-}u_0$ and $u_2=-u_0$, respectively.

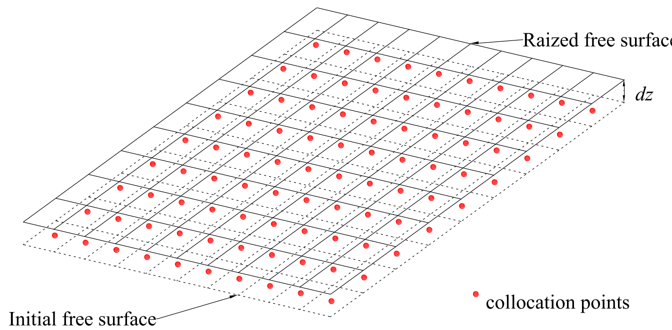

Fig. 1. Raise of the free surface.

Theoretically, it is a body-to-body encountering problem. Nevertheless, it is commonly simplified and described with Eq. (4), where the flow potential induced by the pier is neglected. The main reason of such simplification lies in the speed-dependent term in the Neumann–Kelvin condition, which will cause difficulties in a different forward speeds problem. The simplified model inherently neglects the fluid disturbance induced by the piers although the wave elevation effect is considered. However, no single academic study has been undertaken to check the feasibility of this simplified model.

$$\begin{aligned}
\nabla^2\varphi&=0,\ \text{in fluid domain}\\
\frac{\partial\varphi}{\partial \boldsymbol{n}}&=u_1\cdot n_1,\ \text{on passing ship}\\
\frac{\partial\varphi}{\partial \boldsymbol{n}}&=0,\ \text{on piers}\\
u_1^2\frac{\partial^2\varphi}{\partial x^2}+g\frac{\partial\varphi}{\partial z}&=0,\ \text{on}\ z=0\\
\frac{\partial\varphi}{\partial \boldsymbol{n}}&=0,\ \text{on}\ z=-H\\
\varphi&=0,\ \sqrt{x^2+y^2}\to\infty
\end{aligned} \tag{4}$$

where $\boldsymbol{n}=(n_1,n_2,n_3)$ is the unit normal vector inward on the body surface and H is the water depth.

Another simplification of this problem is the rigid surface model, which neglects the free water surface disturbance. In this way, the speed-dependent terms in the free surface condition are omitted. The boundary value model of the rigid surface model is given as

$$\begin{aligned}
\nabla^2\varphi&=0,\ \text{fluid domain}\\
\frac{\partial\varphi}{\partial \boldsymbol{n}}&=u_1\cdot n_1,\ \text{on passing ship}\\
\frac{\partial\varphi}{\partial \boldsymbol{n}}&=u_2\cdot n_1,\ \text{on piers}\\
\frac{\partial\varphi}{\partial z}&=0,\ \text{on}\ z=0\\
\frac{\partial\varphi}{\partial \boldsymbol{n}}&=0,\ \text{on}\ z=-H\\
\varphi&=0,\ \sqrt{x^2+y^2}\to\infty
\end{aligned} \tag{5}$$

Eq. (5) is the so-called rigid surface model used by a majority of researchers in their studies [10,11,13,18]. Using the rigid surface model, only a single boundary value equation needs to be established regardless of the number of bodies involved and it avoids the different forward speeds problem in this way. However, the wave elevation effect is neglected in the rigid surface model.

The two methods more or less neglect some aspects of the problem, due to the speed terms in the Neumann–Kelvin condition. To deal with the different forward speeds problem, Yuan et al. [16] proposed an