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Unsteady hydrodynamic interaction between two cylindroids in shallow water based on high-order panel method

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ABSTRACT

A NURBS-based high-order panel method is developed for predicting the hydrodynamic interaction of two bodies moving along parallel courses in shallow water. Source and dipole are distributed on the body surfaces, while dipole is distributed on the wake surfaces; the singularity strengths are determined by satisfying the boundary condition on the body surfaces and the Kutta condition at the trailing edges. The wave-making effect is neglected under the low speed assumption; the image method is used to deal with the effects of finite water depth and undisturbed free surface. The time-stepping method is used to update the velocity potential and the position of each body. Firstly, calculations are carried out for a cylindroid passing a stationary cylindroid and two cylindroids moving in the same direction with the same speed. Detailed convergence study with respect to panel size, time step and truncated mirrored images is carried out. On the basis of convergence study, numerical results are compared with experimental measurements to validate the numerical method. Then, calculations are conducted for two cylindroids during passing, meeting and overtaking under different lateral distances between cylindroids, different water depths and different cylindroid geometry. Numerical results are presented to demonstrate the effects of these factors.

1. Introduction

Ship-to-ship hydrodynamic interactions will occur when two ships are travelling in close proximity. Particular cases of special interest are the unsteady-state situation of two ships moving in tandem in a re-fuelling or lighting operation, and the situations of two ships meeting or overtaking in restricted waters. In these cases, the hydrodynamic interaction forces and moments on the ships will cause safety issues in navigation and operation, and in the worst case may lead to collision accidents. Therefore, it is of greatest importance to understand clearly the phenomena of ship-to-ship hydrodynamic interaction.

Many previous studies are based on experimental method since it directly produces reliable and realistic results. Oltmann [1] carried out an extensive experimental study on two cylindroids interacting in shallow water. Hydrodynamic interaction forces on the cylindroids were measured for the steady case of two cylindroids moving in the same direction with the same speed at various relative distances and the unsteady case of one cylindroid passing by another stationary one. Series of Froude number (*Fr*) from 0.143 to 0.571 were investigated. Vantorre et al. [2] carried out an extensive experimental study with different manipulating parameters on the ship-to-ship interaction in shallow water involving various ship types.

Theoretical studies on ship-to-ship hydrodynamic interaction are traditionally based on the potential flow theory. Collatz [3] applied the potential flow theory to investigate the hydrodynamic interaction of two two-dimensional cylindroids meeting and overtaking in shallow water. Tuck and Newman [4] extended the slender-body theory to predict the hydrodynamic lateral force and yaw moment acting on each of two ships moving along parallel courses. Yeung [5] applied the slender-body theory to examine the unsteady hydrodynamic interaction of two bodies moving in shallow water, with the effects of circulation included. Kijima and Yasukawa [6] examined the hydrodynamic behaviour of ships meeting and passing in narrow water channel by using the slender-body theory with consideration of vortex shedding. Important factors, such as water depth and lateral distance between ships, were investigated.

Numerical studies involving three-dimensional panel method with consideration of lifting effects are the main concern of the present paper. Hess [7] described a method for calculating the potential flow about an arbitrary three-dimensional lifting body by

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Nomenclature

a	semi-major axis of the cylindroids
b	semi-minor axis of the cylindroids
CF_x	non-dimensionalized longitudinal force
CF_y	non-dimensionalized lateral force
C_n	non-dimensionalized yaw moment
D	draught of the cylindroids
Fr	Froude number
h	water depth
N	yaw moment
p	pressure
S_i	hull surface of Cylindroid i
Sp	lateral distance between the cylindroids
ST	longitudinal distance between the cylindroids
SW_i	wake surface of Cylindroid i
U_i	speed of Cylindroid i
X	longitudinal force
Y	lateral force
y_{bb}	broadside distance between the cylindroids
ξ	non-dimensionalized longitudinal distance
ρ	density of water
ϕ	velocity potential

using finite-strength surface vorticity distributions instead of concentrated line vorticity interior to the body and applying the Kutta condition at the trailing edge of the body. King [8] investigated two two-dimensional thin cylindrical bodies in unsteady motion along straight parallel paths with the effects of circulation considered. Korsmeyer et al. [9] studied the ship-to-ship interaction in a canal by using three-dimensional Rankine source method; a particular Green function was used for canal with rectangular cross section, while a conventional Green function was used for canal with sloping sides. Zhang and Wu [10] studied hydrodynamic interactions between ships during meeting and overtaking in narrow waterway by using boundary element method, where the lifting potential flow was represented by surface dipole and source, as well as free vortex distributions. Yuan et al. [11,12] developed a boundary element programme based on three-dimensional Rankine source method, and investigated ship-to-ship interaction during overtaking operation in shallow water, with consideration of wave-making effects. All numerical studies cited above are based on constant panel method, and the C^1-continuity on the body surface cannot be satisfied; thus a kind of high-order panel method is needed.

During the last decades, high-order panel method based on B-spline or Non-Uniform Rational B-spline (NURBS) has been developed successfully. B-spline and NURBS can provide a more precise description of the body geometry of the ship surface for the purpose of hydrodynamic calculation; moreover, they can be used to represent the source density or velocity potential distribution for potential flow problem, so that the continuity of higher order derivatives of velocity potential on the ship surface can be ensured. Zhang et al. [13] developed a numerical method based on B-splines for the hydrodynamic interaction forces between two ships. He [14] developed a three-dimensional time-domain sea-keeping analysis tool by using a high-order boundary element method with the Rankine source as the kernel function, and investigated the diffraction problem of a Wigley hull travelling with a constant forward speed in waves.

In the present paper, a three-dimensional high-order panel method based on NURBS is developed for calculating the ship-to-ship unsteady hydrodynamic interaction force in shallow water. Vortex-shedding and lifting effects are considered, while the effect of free surface elevation is ignored under the assumption of low speed. An infinite image method is used to deal with the effects of finite water depth and undisturbed free surface. Mathematical formulation and numerical solution procedure are derived. Numerical calculations are conducted for two cylindroids. Firstly, detailed convergence study with respect to panel size, time step and truncated mirrored images is carried out. On the basis of convergence study, the numerical results are compared with Oltmann's experimental results and Collatz's theoretical results for the cases of a moving cylindroid passing by a stationary cylindroid and two cylindroids moving in the same direction with the same speed. Then, particular cases of a moving cylindroid passing by another stationary cylindroid, two cylindroids in meeting and overtaking conditions are investigated, and calculations are conducted for different lateral distances between the cylindroids, different water depths and different 3-D cylindroid geometry. The detailed results are presented to demonstrate the effects of these factors.

2. Mathematical formulation

As shown in Fig. 1, two cylindroids moving along parallel courses in proximity of each other are considered, where Cylindroid i (i=1, 2) travels with a constant speed U_i; a and b are the semi-major axis and the semi-minor axis of the cylindroids, respectively. The right-handed coordinate systems are adopted, where $o-xyz$ is earth-fixed and $o_i-x_iy_iz_i$ is body-fixed, with the x_i-axis pointing from the stern to the bow, y_i-axis to the starboard side; the $o-xy$ and $o_i-x_iy_i$ planes coincide with the undisturbed free surface ($z=0$). The water depth is assumed to be constant and is expressed by $z=h$. The longitudinal and lateral distances between the cylindroids are denoted by ST and Sp, respectively. The broadside distance between the two cylindroids is denoted by y_{bb}.

It is assumed that the fluid is inviscid and the flow is irrotational; and the cylindroids' speeds are very small, so that the effects of free-surface elevation can be ignored. The perturbation velocity potential representing the flow is defined as $\phi(t,x,y,z)$, it satisfies the Laplace equation in the fluid domain and the following boundary conditions:

$$\frac{\partial \phi}{\partial n^{(1)}} = U_1 n_1^{(1)}, \quad \text{on} \quad S_1 \tag{1}$$

$$\frac{\partial \phi}{\partial n^{(2)}} = U_2 n_1^{(2)}, \quad \text{on} \quad S_2 \tag{2}$$

$$\frac{\partial \phi}{\partial z} = 0, \quad \text{on} \quad z=0 \tag{3}$$

$$\frac{\partial \phi}{\partial z} = 0\,, \quad \text{on} \quad z=h \tag{4}$$

where $\vec{n}^{(i)} = (n_1^{(i)}, n_2^{(i)}, n_3^{(i)})$ denotes the outward normal vector on Cylindroid i; S_i denotes the hull surface of Cylindroid i.

Besides, for the lifting potential flow problem considered here, a proper Kutta condition should be satisfied at the trailing edges of the bodies. In the present study, the equal-pressure Kutta condition is applied:

$$p^+ = p^-, \quad \frac{\partial \phi^+}{\partial n} = \frac{\partial \phi^-}{\partial n}, \quad \text{on } SW_1 \text{ and } SW_2 \tag{5}$$