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Hydrodynamic interactions between two ships travelling or stationary in shallow waters

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ABSTRACT

In this paper, a boundary element programme MHydro, which is based on 3-D Rankine source method, was developed to investigate the ship-to-ship interaction problem. The method developed considers both stationary and forward speed cases. A new radiation condition, which takes Doppler shift into account, is imposed on the control surface. For the stationary case, the validations were carried out both in head sea and beam sea conditions. The experimental measurements, as well as the published numerical results, were used for the comparison. For the ship-to-ship with forward speed case, we validated our method through the experimental tests. Good agreement was achieved except the roll motion. The hydrodynamic coefficients and wave excitation forces were investigated and a very large sway force was predicted when the transverse distance between two ships equalled to the wave length. The wave elevations in the gap were also calculated. Discussions are highlighted on the shallow water effects.

1. Introduction

Lightering operations with forward speed are important for the transfer of fuel in naval operations. Nowadays, lighting operations without forward speed is important for the LNG offloading from LNG FPSOs or FSRUs (Floating Storage and Regassification Units). The loads in the mooring lines between the two vessels, the loads in the floating fenders and the relative motions at the manifold location are the most critical issues during this operation. These are determined by the wave, wind and current loads on the two vessels in close proximity, as well as by the strong hydrodynamic interaction between the vessels. Even in head seas, the two vessels could be subjected to a very large separating force as the waves run between the two hulls. The resulting motions and mooring loads determine the operability of the operation in certain environmental conditions.

Early studies on the hydrodynamic interaction problem focused on 2-D strip theory. Ohkusu (1974) used the multipoles method and theory to calculate the response of parallel, slender, ship like bodies in beam waves. His results clearly illustrated the effect of position of a smaller body on the weather and lee side against a large body. Kodan (1984) extended Ohkusu's theory (Ohkusu, 1974) to hydrodynamic interaction between two parallel structures in oblique waves by strip method. Fang and Kim (1986) analysed the hydrodynamically coupled motions of two longitudinally parallel barges advancing in oblique waves by strip method. His analysis showed that the coupled motions of two advancing ships depend on the speed, wave heading and distance. The 2-D method was a simple and effective tool in predicting the hydrodynamic interaction between two adjacent ships. Ronæss (2002) applied a unified slender body theory to investigate the ship-to-ship with forward speed problem. Her results showed good agreement with her model tests at the Marine Technology Centre in Trondheim, Norway. However, the limitations of applying 2-D methods in the ship-to-ship interaction problem in waves have been confirmed by Fang and Kim (1986). The two ships were assumed to be in each other's near-field. The 2-D method overestimated the interaction effects due to the wave energy trapping between the two hulls in the frequency range which is important for ship motions, which also leads to the overestimation of the mean second-order wave loads on each ship. Besides, the strip theory can only predict the motion responses of conventional monohull ship in waves at low to moderate Froude numbers. However at high Froude numbers, three-dimensional (3-D) effects become dominant and strip theory fails to predict the hydrodynamic performance of vessels travelling with high forward speed. Under these circumstances, an

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advanced computational technique which accounts for the 3D flow interactions is necessary for motion and loading prediction.

Chen and Fang (2001) extended Fang's method (Fang and Kim, 1986) to 3-D. They used a 3-D Green function method to investigate the hydrodynamic problems between two moving ships in waves. It was found that the hydrodynamic interactions calculated by a 3-D method were more reasonable in the resonance region, where the responses were overestimated by 2-D method. However, their method was only validated by model tests with zero speed. More rigorous validation should be made by further experiments. Kim and Ha (2002) used 3-D pulsating source distribution techniques to calculate twelve coupled linear motion responses and relative motions of the barge and the ship in oblique waves. Their computational results gave a good correlation with the experimental results and also with other numerical results. McTaggart et al. (2003) and Li (2007) developed a frequency domain code based on 3-D Green function method. They validated their numerical predictions by model tests conducted at the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland. It was showed that the presence of a larger ship could significantly influence the motions of a smaller ship in close proximity. But the numerical prediction of roll motion was not accurate. Kashiwagi et al. (2005) investigated the wave drift forces and moments on two ships stationary in waves by using 3D HOBEM. They compared their method to the model test results and obtained a good agreement. Xu and Faltinsen (2011) used a 3-D Rankine source method to solve the linear initial-boundary value problem of two ships advancing in waves. The time domain analysis was validated through the frequency solution via Fourier transform, and also the model test results. Recently, within the frame work of Green function, Xu and Dong (2013) developed a 3-D translating-pulsating (3DTP) source method to calculate wave loads and free motions of two ships advancing in waves. Model tests were carried out to measure the wave loads and the heave, roll and pitch motions for a pair of side-by-side arranged ship models advancing with an identical speed in head regular waves. Both the experiment and the numerical prediction showed that hydrodynamic interaction effects on wave loads and motions were significant. They also pointed out that the prediction accuracy of the 3DTP method was much better than that of 3DP, especially for peak values of the motion responses.

Most work on ship-to-ship interaction problem assumes that the water is infinitely deep. In deep water, the major stimulus for systematic study of the phenomenon arose from the needs of the warship replenishing while underway at sea. It has already been pointed out that merchant ships are most likely to be in close quarters situation in shallow water where interaction effects may be larger. Meanwhile, the increasing demands for LNG and the associated safety requirements has resulted in a large number of offshore LNG terminal developments and most of these are located near-shore, in relatively shallow water. In addition to shallow water effects on the waves, the clearance to the bottom might become an issue when the water depth to draft ratio becomes small. Ship motions are directly affected in two ways by the restricted water depth: (1) the incident waves are changed and as a result, the wave exciting forces exerted on ship differ from those in deep water; (2) the hydrodynamic coefficients of the ship (i.e. radiation forces) are changed by the nearness of the sea bottom. We also find that most of the publications on two ships with forward speed problem are based on Green function that satisfies the Kelvin free surface conditions, as well as the radiation condition. It is an effective method for the zero forward problems, but if the vessel is travelling with forward speed, this method still has some limitations. Firstly, it could not account for the near-field flow condition. Although some researchers (Lee and Sclavounos, 1989; Nossen et al., 1991) extended it to include the near-field free surface condition, the so-called irregular frequency still cannot be avoided. This will bring singularity to the coefficient matrix equation. Secondly, it is impossible for the Green function to account for the interaction between the steady and unsteady flow.

In the present study, the Rankine source approach proposed by Hess and Smith (Hess and Smith, 1964) will be applied, which uses a very simple Green function in the boundary integral formulation. This method requires the sources distributed not only on the body surface, but also on the free surface, control surface and sea bottom. Therefore, a flexible choice of free-surface condition and sea bottom condition can be realized in these methods. The forward speed and shallow water effects can be directly taken into the consideration in the boundary value problem. Besides, the near field wave elevations can be directly obtained by boundary integration on the free surface. In order to complete the boundary value problem, a radiation condition should be imposed on the control surface. A commonly used treatment was proposed by Nakos (1990). The free surface was truncated at some upstream points, and two boundary conditions were imposed at these points to ensure the consistency of the upstream truncation of the free surface. Another method to deal with the radiation condition is to move the source points on the free surface at some distance downstream (Jensen et al., 1986). The results from these two methods show very good agreement with published experimental data when the parameter τ ($\tau = \omega_e u/g$, ω_e is the encounter frequency, u is the forward speed, and g is the gravitational acceleration) is greater than 0.25, since they are both based on the assumption that there is no scattered wave travelling ahead of the vessel. However, when the forward speed of the vessel is very low, the parameter τ will be smaller than 0.25 and the scattered waves could travel ahead of the vessel. These traditional radiation conditions could no longer be valid. For ship-to-ship problem, the forward speed is usually limited to a low level for the safe operations. Therefore, a new extensive radiation condition is required to deal with the very low forward speed problem. Here a new modified Sommerfeld radiation condition (Das and Cheung, 2012; Yuan et al., 2014a, 2014b) was used, which was applicable to a wide range of forward speeds, including the very low forward speed problem where the parameter is smaller than 0.25. Yuan et al. (2014a) validated this radiation condition through model experiments and a very satisfactory agreement was obtained. They also computed the wave elevation on the free surface, and a reasonable wave pattern was obtained at $\tau < 0.25$ by using their new radiation condition. In this paper, we will apply this new radiation condition to the ship-to-ship problem. A 3-D panel code MHydro, which is based on Rankine source method, will be developed to investigate the hydrodynamic interaction between two vessels with forward speed arranged side by side in shallow water. The motion responses of both ships will be calculated and compared to these obtained from commercial software and experimental results. Discussions are highlighted on the shallow water effects.

2. Mathematical formulations of the potentials

2.1. Coordinate systems

The corresponding right-handed coordinate systems are shown in Fig. 1. The body coordinate systems $o_a\text{–}x_a y_a z_a$ and $o_b\text{–}{}_b z_b$ are fixed on Ship_a and Ship_b respectively with their origins on the mean free surface at midships. $o_a\text{–}z_a$ and $o_b\text{–}z_b$ are both positive upwards. $O\text{–}XYZ$ is the earth-fixed coordinate system with its origin located on the calm free surface and OZ axis positive upwards. dt and dl denote the transverse and longitudinal distance between the two ships respectively. The incident wave direction is defined as the angle between the wave propagation direction and X-axis. $\beta = 180^\circ$ corresponds to head sea; $\beta = 90^\circ$ corresponds to beam sea. dt denotes the transverse distance between two ships while dl is the longitudinal distance. u_0 is the forward speed.

In the computation, the motions and forces of Ship_a and Ship_b are concerted to the local coordinate system in which the origin is at the centre of gravity of each ship.