Slamming Force on A Planing Hull: Comparison between 3D and 2D Solutions

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Introduction

The prediction of slamming forces is important in the simulation of planing hull motions. The computation of slamming forces is usually based on two-dimensional potential flow theory and CFD solutions. For example, Dobrovol'skaya (1969) developed an analytical solution in terms of a nonlinear singular integral equation for the symmetrical entry of a wedge into calm water. Greenhow (1987) used Cauchy's formula to solve the wedge entry problem. Zhao and Faltinsen (1993) studied the water entry of a wedge using nonlinear boundary element method with constant elements.

Due to the difficulties for the potential flow theories to treat highly distorted or breaking free surface, efforts have been made to solve the Navier-Stokes equations for the 2D water entry problems. For example, Kim et al. (2007) used the SPH method to simulate the water entry of 2D asymmetric bodies. Kleefsman et al. (2005) solved the 2D slamming problem of symmetric bodies by the VOF method. Hu and Kashiwagi (2004) developed a pressure-based algorithm coupled with the Constrained Interpolation Profile (CIP) method to solve slamming problems. Yang and Qiu (2007) solved the 2D water entry problems of symmetric and asymmetric wedges with various deadrise angles using the CIP method. The effect of the air compressibility for small deadrise angles was also discussed in their work (Yang and Qiu, 2008).

The computations of slamming forces based on three-dimensional methods are relatively rare. Furthermore, the discrepancies between the 2D and 3D solutions of slamming problems for general bodies are not very clear. The objective of this work is to investigate the slamming force on a planing hull using 2D and 3D numerical methods, experimental results and empirical formulae.

The slamming forces on a planing hull are computed using the strip theory, in which the impact force on each 2D section is calculated with the 2D CIP method, and the 3D CIP method. Impact tests of the planing hull model entering the calm water are being carried out. The numerical solutions by the 2D and 3D methods and their comparison with model test results and those based on empirical formulae will be presented at the Workshop.

Mathematical Formulation

In the 2D and 3D CIP methods, the highly nonlinear water entry problem, governed by the Navier-Stokes equations, was solved by the finite difference method on a fixed Cartesian grid. In the computation, the CIP method was employed for the advection calculations and a pressured based algorithm was applied for the non-advection calculations. The solid body and free surface interfaces were identified by density functions. For the pressure calculation, a Poisson-type equation was solved at each time step by the Conjugate Gradient iterative method with a Jacobi pre-conditioner.

The differential equations governing the 3D compressible and viscous fluid are given as:

$$\frac{\partial \rho}{\partial t} + u_i \frac{\partial \rho}{\partial x_i} = -\rho \frac{\partial u_i}{\partial x_i} \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \sigma_{ij}}{\partial x_j} + f_i \quad (2)$$

where t is the time; x_i $(i = 1, 2, 3)$ are the coordinates in a Cartesian coordinate system; ρ is the density; u_i are the velocity components; f_i are the body forces.

As the temperature variation can be neglected, the equation of state for the 3D water-entry problem is written as $p = f(\rho)$. Applying the equation of state to Eq. (1), the pressure equation can be obtained as

$$\frac{\partial p}{\partial t} + u_i \frac{\partial p}{\partial x_i} = -\rho c_s^2 \frac{\partial u_i}{\partial x_i} \quad (3)$$

where $c_s = \sqrt{\partial p / \partial \rho}$ is the sound speed and p is the pressure.

The governing equations are solved by the fractional step approach used by Hu and Kashiwagi (2004).

The free surface is captured by solving the following advection equation with the CIP method,

$$\frac{\partial \phi_f}{\partial t} + u_i \frac{\partial \phi_f}{\partial x_i} = 0 \quad (4)$$

where the density function for the fluid, ϕ_f, has a value between 0 and 1.

Based on a compact upwind high-order scheme, the density function and its spatial derivatives are used as dependent variables to construct the interface profile.

The body surface is represented by a set of panels. The density function for the solid surface, ϕ_s, is calculated by $\phi_s = \sum_{i=1}^{i=N} \varepsilon_i$ where N is the total number of panels in the computational cell, $\varepsilon_i = \int_{panel_i} F ds$. The density function for air, ϕ_a, can be also obtained from $\phi_a = 1 - \phi_f - \phi_s$.

After the density functions for all phases are determined, the physical properties including viscosity and density can be calculated for each computational cell.

Numerical Results

The 2-D and 3-D water entry problems for a planing hull are solved by the numerical method described above. In the computations, the density and the viscosity of water and air are given as $\rho_1 = 1000 kg/m^3$, $\mu_1 = 10^{-3} kg/s/m$, and $\rho_2 = 1.0 kg/m^3$, $\mu_2 = 10^{-5} kg/s/m$, respectively.

To illustrate the accuracy of 3D CIP simulations, computations were first carried out for the water entry of a 3D wedge with a deadrise angle of 30°. The geometry of the wedge is given in Fig. 1. Zhao et al. (1996) conducted the drop test for such a wedge at MARINTEK. The breadth, B, of the test section was $0.5m$, the total length, L, was $1m$, and the length of the measuring section was $0.2m$. The maximum drop height was about $2m$.

The time series of the computed hydrodynamic forces are compared with the experimental results (Zhao et al., 1996) in Fig. 2(a). The 3D solutions were also compared with the results by the 2D CIP method (Yang and Qiu , 2007). Note that in the 2D CIP solution, the unit slamming force was only computed on the mid transverse section. As shown in the figure, the numerical solutions by the 3D CIP method are a good agreement with experimental results and the 2D CIP results for the test section.

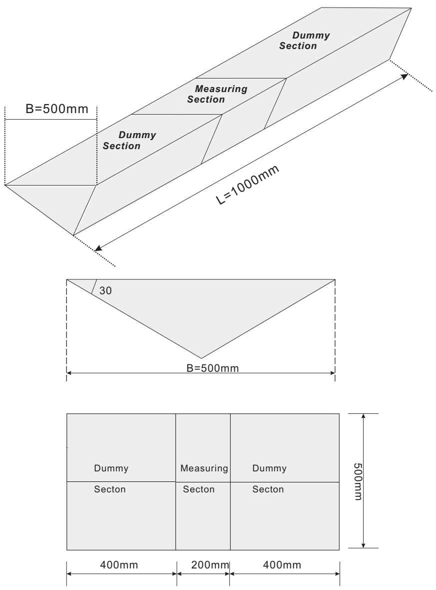
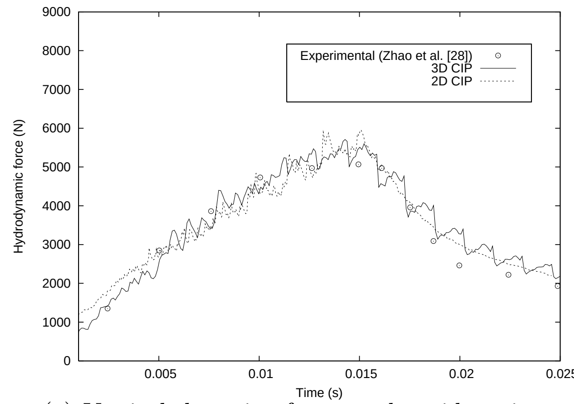


Figure 1: The geometry of a 3D wedge

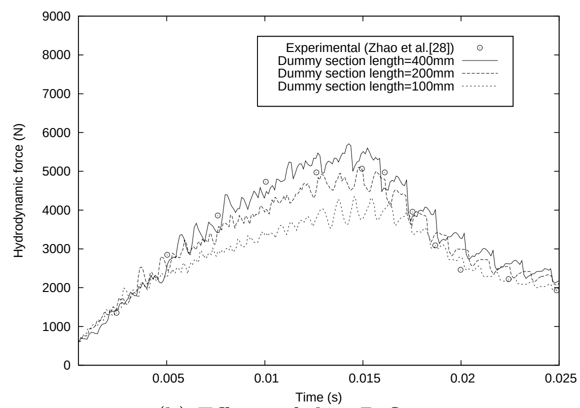
To investigate the effect of 3D flow, the hydrodynamic forces were computed by using various lengths of dummy sections. As shown in Fig. 2 (b), the computed maximum slamming force become smaller as the lengths of dummy sections decrease, and the 3D flow effects tend to be significant. The 3D effects lead to a reduction in the vertical slamming force. As shown in Fig. 2(a), the dummy sections used in the model tests were sufficiently long and the 3D flow effects were eliminated effectively.

The initial computations are being carried out to a 1.2m planing hull entering the calm water at various angles with the 3D CIP method. The geometry of the hull is presented in Fig. 3. Figure 4 shows the vertical slamming force on the planing hull entering water at zero degree. The computed wave elevation at t=0.165s is given in Fig. 5.

Efforts are also being made to compute the slamming forces on the planing hull based on the 2D CIP method, and to compare the 2D and 3D solutions with those by empirical



(a) Vertical slamming force on the mid section



(b) Effects of the 3D flow

Figure 2: Vertical slamming forces on the 3D wedge

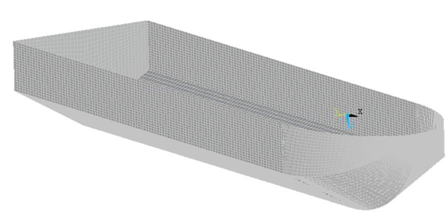


Figure 3: Geometry of a planing hull

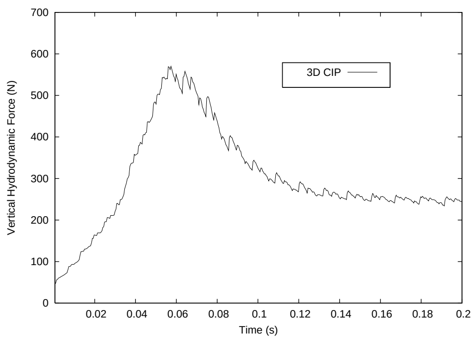


Figure 4: Slamming force on the planing hull at zero-degree angle of entry

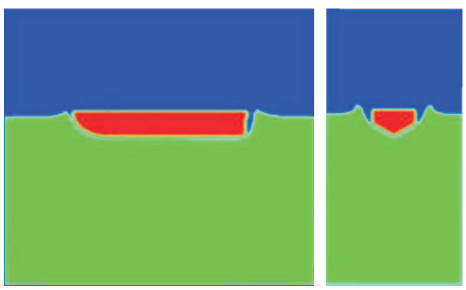


Figure 5: Free surface elevation at t=0.165s

formulae. Impact tests for the planing hull model are in progress. It is anticipated that the comparison of the 2D and 3D numerical solutions with experimental results and those by empirical formulae will be presented at the Workshop.

Acknowledgment

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References

Dobrovol'skaya, Z.N., 1969. On Some Problems of Similarity Flow of Fluid with a Free Surface. Journal of Fluid Mechanics, Vol. 36, pp. 805-829.

Greenhow, M., 1987. Wedge Entry into Initially Calm Water. Applied Ocean Research, Vol. 9, pp. 214-223.

Hu, C. and Kashiwagi, M., 2004. A CIP-Based Method for Numerical Simulations of Violent Free-Surface Flow. Journal of Marine Science and Technology, Vol. 9, pp.143-157.

Kim, Y.W., Kim, Y., Liu, Y.M., and Yue, D., 2007. On the Water-Entry Impact Problem of Asymmetric Bodies. Proceedings of 9th International Conference on Numerical Ship Hydrodynamics, Ann Arbor, Michigan.

Kleefsman, K.M.T., Fekken, G., Veldman, A.E.P., Iwanowski, B. and Buchner, B., 2005. A Volume-of-Fluid based Simulation Method for Wave Impact Problems. Journal of Computational Physics, Vol. 206, pp. 363-393.

Yang, Q. and Qiu, W., 2007. Numerical Solution of 2-D Slamming Problem with a CIP Method. Proceedings of VF-2007 International Conference on Violent Flows, Research Institute for Applied Mechanics, Kyushu University, Japan.

Yang, Q. and Qiu, W., 2008. Computational of Slamming Forces on Wedges of Small Deadrise Angles Using a CIP Method. Proceedings of the 18th International Offshore and Polar Engineering Conference, Vancouver, Canada.

Zhao, R., Faltinsen, O. and Aarsnes, J., 1996. Water Entry of Arbitrary Two-dimensional Sections with and without Flow Separation. Proceedings of 21st Symposium on Naval Hydrodynamics, Trondheim, Norway.