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Ship hydrodynamics computations with the CIP method based on adaptive Soroban grids

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SUMMARY

The constrained interpolation profile/cubic interpolated pseudo-particle (CIP) combined unified procedure (CCUP) method (*J. Phys. Soc. Jpn.* 1991; **60**:2105–2108), which is based on the CIP method (*J. Comput. Phys.* 1985; **61**:261–268; *J. Comput. Phys.* 1987; **70**:355–372; *Comput. Phys. Commun.* 1991; **66**:219–232; *J. Comput. Phys.* 2001; **169**:556–593) and the adaptive Soroban grid technique (*J. Comput. Phys.* 2004; **194**:55–77) were combined in (*Comput. Mech.* 2006; published online) for computation of 3D fluid–object and fluid–structure interactions in the presence of free surfaces and fluid–fluid interfaces. Although the grid system is unstructured, it still has a very simple data structure and this facilitates computational efficiency. Despite the unstructured and collocated features of the grid, the method maintains high-order accuracy and computational robustness. Furthermore, the meshless feature of the combined technique brings freedom from mesh moving and distortion issues. In this paper, the combined technique is extended to ship hydrodynamics computations. We introduce a new way of computing the advective terms to increase the efficiency in that part of the computations. This is essential in ship hydrodynamics computations where the level of grid refinement needed near the ship surface and at the free surface results in very large grid sizes. The test cases presented are a test computation with a wave-making wedge and simulation of the hydrodynamics of a container ship. Copyright © 2007 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Ship hydrodynamics computations involve a number of numerical challenges that need to be addressed to make computer modelling a viable tool in this field. These challenges include

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generating a suitable grid around a complex shape and moving that grid following the motion of the ship, properly resolving the boundary layers near the fluid–solid interfaces formed by the ship surface, accurately advecting the vortices generated, calculating the free surfaces in a robust and accurate fashion, and maintaining the computational efficiency while doing all that.

A good number of successful finite element interface-tracking (mesh moving) techniques have been developed in recent decades for computation of fluid–object and fluid–structure interactions (see, e.g. [1–19]), which would be appropriate to use for computation of the fluid–solid interfaces in ship hydrodynamics. But an interface-capturing (non-moving mesh) technique would be more appropriate for the complex, unsteady free surfaces encountered in ship hydrodynamics. The Mixed Interface-Tracking/Interface-Capturing Technique (MITICT) was introduced in [20] for cases where both the fluid–solid and fluid–fluid interfaces (or free surfaces) are present. The MITICT provides an interface tracking for the fluid–solid interfaces and an interface capturing for the fluid–fluid interfaces. Test computations with the MITICT were reported in [21].

Accurate methods with more freedom from mesh moving and distortion concerns are always more desirable. A method with such features was recently introduced in [22] by combining the CCUP[§] method [23], which is based on the constrained interpolation profile/cubic interpolated pseudo-particle (CIP) method developed by Yabe *et al.* [24–27] for solving hyperbolic equations, and the adaptive 'Soroban grid' technique [28], which is an unstructured and collocated grid technique. The CIP method has superior accuracy in dealing with the advection terms. The Soroban grid technique does not have any elements or cells connecting the grid points, and is therefore free from mesh distortion limitations. Even though the grid system is unstructured, it still has a very simple data structure and this makes the computations very efficient. Furthermore, the method maintains computational robustness and high-order accuracy even though the grid system is collocated and unstructured. The combined technique can accurately resolve the boundary layers near the fluid–solid interfaces and also calculate, in a robust and accurate fashion, even the most complex and unsteady free surfaces and two-fluid interfaces.

In this paper, the combined technique is extended to ship hydrodynamics computations. We also introduce in this paper a new way of calculating the advective terms with increased computational efficiency. This is another feature that makes the technique effective in ship hydrodynamics computations, where the level of grid refinement needed near the ship surface and at the free surface results in a very large number of grid points. As test cases, we present in this paper a test computation with a wave-making wedge and simulation of the hydrodynamics of a container ship. Because the computational techniques used in this paper are mostly those described in [22], we only provide here what goes beyond the techniques described in [22]. This is the new, more efficient way of calculating the advective terms, which is covered in Section 2. The test computations are presented in Section 3 and the concluding remarks are given in Section 4.

2. CALCULATION OF THE ADVECTIVE TERMS WITH INCREASED COMPUTATIONAL EFFICIENCY

As described in [22], the advection update of the dependent variables is computed with the method of characteristics based on the CIP method (see [22, Section 3.1]). The advection-updated value

[§] 'CCUP' is the acronym for 'CIP combined unified procedure'.

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of a dependent variable at position $\mathbf{x}^{n+1}$ and time level $n+1$ is set equal to the known value of that variable at time level n at position $\mathbf{x}^n$, which is calculated by using the following expression:

$$\mathbf{x}^n = \mathbf{x}^{n+1} - \int_{t^n}^{t^{n+1}} \mathbf{u}\, \mathrm{d}t \tag{1}$$

In carrying out the calculation given by Equation (1), we subdivide the time step into LL sub-steps and use the following recursive relationship:

$$\mathbf{x}^{n+1-kk/LL} = \mathbf{x}^{n+1-(kk-1)/LL} - \Delta t \mathbf{u}(\mathbf{x}^{n+1-(kk-1)/LL}, t^{n+1-(kk-1)/LL}) \tag{2}$$

Here kk is the counter for the sub-steps, ranging from $kk=1$ to $kk=LL$, and the velocity is interpolated by using the expression

$$\mathbf{u}(\mathbf{x}, t) = \frac{(t-t^n)\mathbf{u}^{n+1}(\mathbf{x}) - (t^{n+1}-t)\mathbf{u}^n(\mathbf{x})}{t^{n+1}-t^n} \tag{3}$$

and the CIP method with the Soroban grid technique (see [22]). We note that because $\mathbf{u}^{n+1}$ is unknown, as described in Section 3.2.4 in [22], the computations given by Equations (2) and (3) are carried out iteratively, where the 0th-iteration value of $\mathbf{u}^{n+1}$ is set equal to $\mathbf{u}^n$. For the test computations reported in this paper, the number of iterations is 3.

To increase the computational efficiency, the number of sub-steps is determined locally by using the following formula:

$$LL = \left\lceil \Delta t \left(\mathrm{CFL} \frac{\min(\Delta x, \Delta y, \Delta z)}{\|\mathbf{u}\|} \right)^{-1} \right\rceil \tag{4}$$

where $\lceil \chi \rceil$ is the smallest integer greater than or equal to χ, and Courant–Friedrichs–Lewy (CFL) is the desired value of the CFL number defined based on the sub-step size. We typically set $\mathrm{CFL}=0.5$.

3. TEST COMPUTATIONS

The test computations are carried on a single-processor computer with Pentium 4 (3.4 GHz).

3.1. Test with a wave-making wedge

In this 2D test computation, we consider a wedge-shaped object with mass M undergoing a prescribed oscillatory motion at a free surface. The prescribed motion is given by the expression

$$y = A \sin(\omega t) \tag{5}$$

where A and ω are the amplitude and frequency of the oscillations. Figure 1 shows the problem setup. The number of grid points in the Soroban grid is around 10 000. The time-step size is selected in such a way that we have 200 time steps during one period of the prescribed motion. From our flow computation with the prescribed motion given by Equation (5), we calculate the

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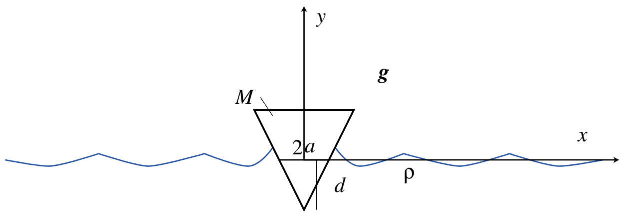

Figure 1. Test with a wave-making wedge. Problem setup. Here d represents the vertical dimension of the submerged part of the wedge at the beginning when the free surface is flat at $y=0$, and $2a$ represents the width of the wedge at the free surface level. The water depth is $3d$, ρ is the water density, and g is the gravity. The dimensions d and a are related by the expression $d=2.5a$.

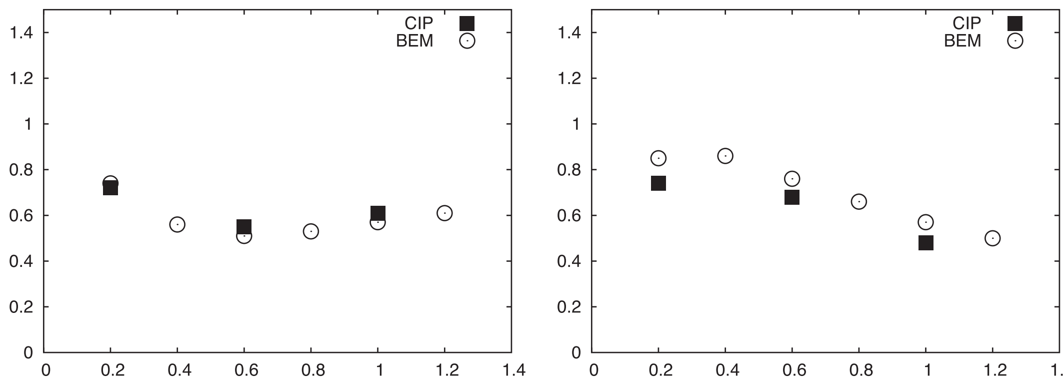

Figure 2. Test with a wave-making wedge. Values of $\widetilde{M}$ (left) and $\widetilde{C}$ (right) computed for $A=0.4$ with the CIP technique and boundary element method (BEM), displayed as functions of ω^2. All values are normalized.

fluid dynamics force $F(t)$ acting on the wedge. By Fourier transformation, we write the fluctuating part of $F(t)$ as $F_1\sin(\omega t)+F_2\cos(\omega t)$, and use that in the following equation:

$$F_1\sin(\omega t)+F_2\cos(\omega t)=-2ay\rho g-\widetilde{M}\ddot{y}-\widetilde{C}\dot{y} \tag{6}$$

where $\widetilde{M}$ is the 'added mass' (also known as A_{33}) and $\widetilde{C}$ is the damping coefficient (also known as B_{33}). With the expressions for y, $\dot{y}$ and $\ddot{y}$ coming from Equation (5) and its time derivatives, by balancing the coefficients of $\sin(\omega t)$ and $\cos(\omega t)$ in Equation (6), we determine $\widetilde{M}$ and $\widetilde{C}$ as functions of F_1 and F_2 and the other parameters seen in Equation (6).

Figures 2 and 3 show, for $A=0.4$ and $A=0.6$, $\widetilde{M}$ and $\widetilde{C}$ as functions of ω^2. All values are normalized, where the length and time scales are a and $\sqrt{a/g}$. In the figures, we compare our CIP results with those obtained with a boundary element method (BEM) and reported in [29]. The comparisons show that the CIP and BEM results are in reasonably good agreement. With $A=0.6$, the discrepancy is somewhat larger for $\widetilde{M}$ at $\omega^2=0.2$ and for $\widetilde{C}$ at $\omega^2=0.6$. In the case of the first discrepancy, the comparison with experimental data shows that the CIP Soroban grid solution is better than the BEM solution. For the second discrepancy the situation is the other way around, and this is something we plan to investigate further in the future.

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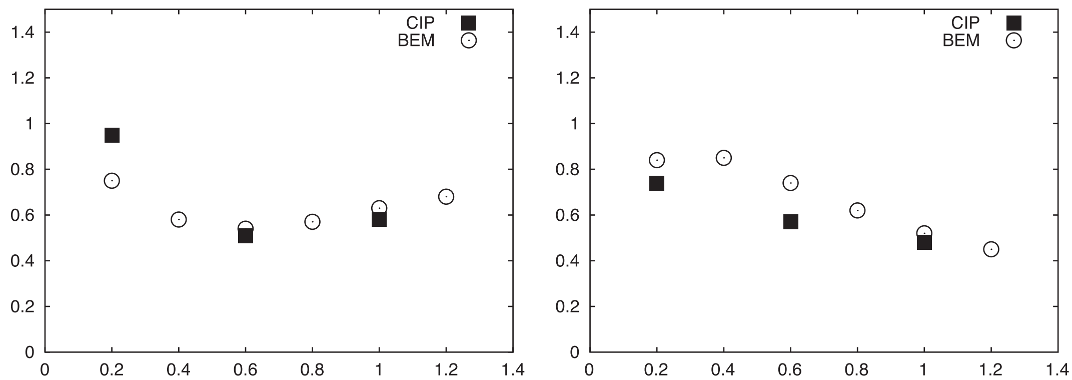

Figure 3. Test with a wave-making wedge. Values of $\widetilde{M}$ (left) and $\widetilde{C}$ (right) computed for $A = 0.6$ with the CIP technique and boundary element method (BEM), displayed as functions of ω^2. All values are normalized.

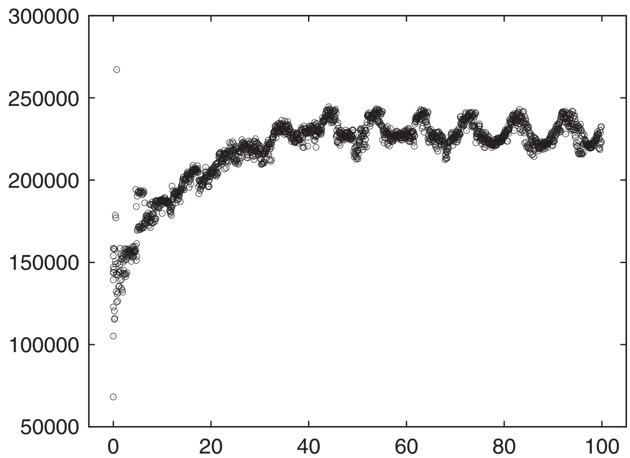

Figure 4. Hydrodynamics of a container ship. Number of grid points as a function of time (s).

3.2. *Hydrodynamics of a container ship*

The ship used in this test computation is modelled after a 5500 twenty-foot equivalent units (TEU) container ship and is 284 m long. It is cruising at 10 m/s and is undergoing rigid-body motion with 5 degrees-of-freedom. The water depth is 50 m. The Froude number is 0.19. The computational domain is translating with the ship. The condition we specify at the inflow boundary is the third-order Stokes wave with the wavelength and height set at 284 and 16 m. The lateral boundaries have slip conditions, and the outflow boundary has no condition specified.

The computation is carried out for 100 s, with a time-step size of 0.1 s. Figure 4 shows the number of grid points as a function of time. Despite the large number of grid points involved, the computation takes 2–4 min per time step. Figures 5 and 6 show the heave (vertical) position and velocity of the centre of mass as a function of time. Figures 7 and 8 show the ship and the water

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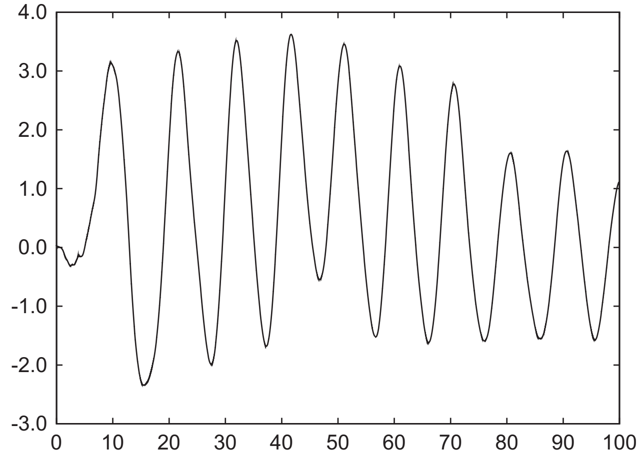

Figure 5. Hydrodynamics of a container ship. Heave position (m) of the centre of mass as a function of time (s).

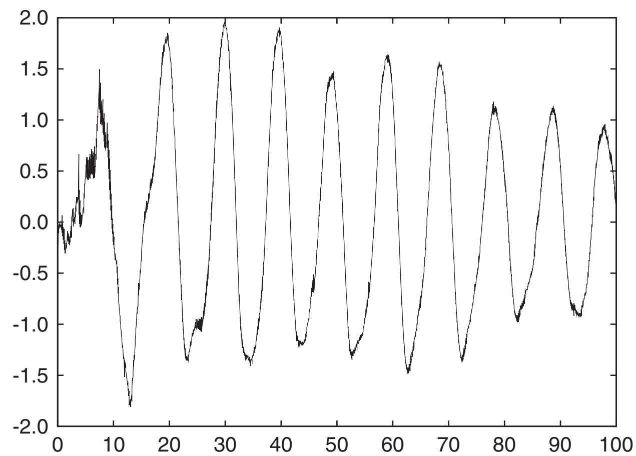

Figure 6. Hydrodynamics of a container ship. Heave velocity (m/s) of the centre of mass as a function of time (s).

surface at $t = 17.9$ and 24.5 s. Figure 9 shows the diver's view of the ship and the water surface at $t = 24.5$ s, together with the Soroban grid lines and points at that instant.

4. CONCLUDING REMARKS

The computational method introduced in [22] for 3D fluid–object and fluid–structure interactions in the presence of free surfaces and fluid–fluid interfaces was developed by combining the CCUP method, which is based on the CIP method, and the adaptive Soroban grid technique. In this paper,

Figure 7. Hydrodynamics of a container ship. The ship and the water surface at $t = 17.9$ s.

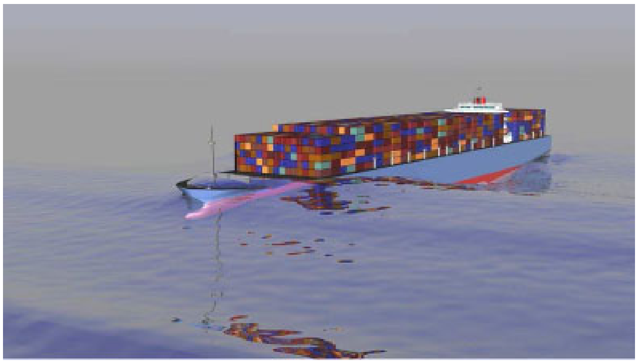

Figure 8. Hydrodynamics of a container ship. The ship and the water surface at $t = 24.5$ s.

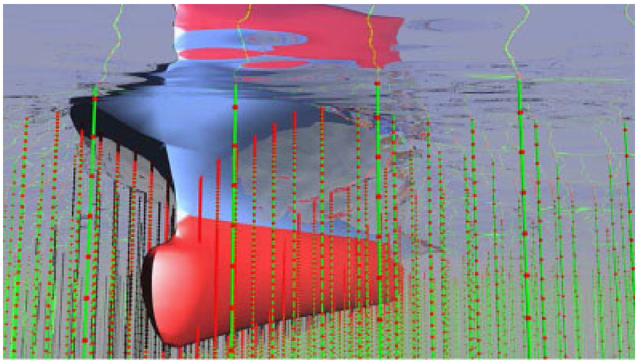

Figure 9. Hydrodynamics of a container ship. Diver's view of the ship and the water surface at $t = 24.5$ s, together with the Soroban grid lines and points at that instant.

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we have extended the combined technique to ship hydrodynamics computations. The technique has a number of desirable features. The CIP method brings superior accuracy in computation of the advection terms. The Soroban grid technique, because of its unstructured nature, brings geometric flexibility and makes it possible to generate suitable grids around complex shapes. Even with this geometric flexibility, because the Soroban grid techniques has a very simple data structure, the combined technique is computationally efficient. Also, because the Soroban grid technique does not have any elements or cells connecting the grid points, it is free from mesh distortion limitations. The combined technique can accurately resolve the boundary layers near the ship surface and also calculate, in a robust and accurate fashion, the complex and unsteady free surfaces. We also introduced in this paper a new way of calculating the advective terms with increased computational efficiency. The enhanced efficiency makes the combined technique even more competitive in ship hydrodynamics computations. We presented two test cases in this paper. The first one is a test computation with a wave-making wedge, and the second one is a realistic simulation of the hydrodynamics of a container ship.

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