The effect of time discretization on the propeller hydrodynamic performance simulation in self-propulsion and open water conditions

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Abstract. Numerical simulation technology is widely used in the field of naval architect and marine engineering. The flow induced by the propeller is unsteady. In order to demonstrate the effect of time discretization format and time step on the simulation of the flow, this paper takes an oil tanker and its propeller as the research objects, and simulations have been conducted by using OpenFoam. By comparing the thrust, torque and the vortex after the propeller, the effects of the time discretization format and time step on the numerical simulations are analyzed. This paper believes that changing the discretization format of the time term while keep the time step unchanged has little effect on the calculation results in the condition of open water test simulation. It is beneficial to simulate of the vortex after the propeller hub by using a small time step. The first-order backward Euler discretization format in the condition of self propulsion simulation is recommended. If the error of thrust compared with experiment data is larger than expected, the second-order discretization format should be considered. In order to improve the accuracy of numerical simulation, a smaller time step could be considered.

1. Introduction
With the advancement of numerical simulation technology and the improvement of computing power, in recent years, numerical simulation technology has been widely used in the field of marine engineering. Guo[1], SHEN[2],conducted resistance performance simulations on different types of ships resistance. Their research results show that the numerical simulation technology can be used to simulate the resistance of ships. Tahara[3], Yan[4], Yang[5] optimized the energy-saving devices such as energy saving duct, pre-swirl stator, rudder bulb thrust fins by using numerical simulation technology.

Under the influence of the rotating propeller, the flow is unsteady, vortex will be generated and fall off in the non-uniform flow. Unsteady problems have the following characteristics: First, the flow is usually multi-scale, that is, the flow field may contain vortex of different scales; Second, the flow field contains multi-frequency motion, that is, the flow field may contain oscillatory movements with different frequencies; Third, the flow is variable, and the flow field can be changed from periodic oscillation to multi-period, quasi-periodic, or chaotic motion with the parameters. Therefore, compared with steady flow, the study of unsteady flow is much more complicated. In the simulation of this kind of unsteady flow problem, researchers should focus on not only the mesh but also the discretization of time terms which has a very important effect on the accuracy of the results. Gaggero[6] studied the influence of the time step by using the RANS/BEM coupling approach. The
results show that with respect to the equivalent 4 deg. simulation, the use of a five time larger time step produces only slightly overestimated values of propulsion. Song[7] studied the choice of the time step from the aspect of temporal convergence. According to the numerical uncertainties of the flat plate and hull simulations, the smallest time step is used. Hrvoje[8] used a fixed time step to conduct self propulsion simulations according to the CFL (Courant Friedrichs Lewy) number. It is of note that the ITTC[9] recommend the use of at least 180 time steps per revolution.

This paper takes an 80,000-ton oil tanker and its propeller as the research object, the open source software OpenFoam is used to simulate the propeller hydrodynamic performance in open water and self propulsion condition. The effects of the first-order and second-order implicit time discretization formats and different time steps on the calculation accuracy are analyzed, and the vortex structure in the wake is analyzed with different time discretization formats and time step.

2. Research objects
This paper takes an 80,000-ton oil tanker and its propeller as the research objects. The main dimensions of the tanker and the propeller are shown in table 1 and table 2 respectively, the geometries of the ship and propeller is shown in figure 1 and figure 2. All the simulations have been conducted in model scale.

| Parameter | Symbol | Value | Unit |
|-----------|--------|-------|------|
| Length between perpendiculars | Lpp | 224.9 | m |
| Length of waterline | Lwl | 228.4 | m |
| Breadth moulded | B | 32.26 | m |
| Draft fore | TF | 12.2 | m |
| Draft aft | TA | 12.2 | m |
| Scale Ratio | λ | 23.94 | - |

| Parameter | Symbol | Value | Unit |
|-----------|--------|-------|------|
| Diameter | D | 6.120 | m |
| Pitch at 0.7R | P0.7 | 5.471 | m |
| Pitch ratio at 0.7R | P0.7/D | 0.8940 | - |
| Disc area ratio | AE/AO | 0.430 | - |
| Number of blades | Z | 4 | - |
| Scale Ratio | λ | 23.94 | - |

Figure 1. The geometry of the ship.
3. Research methods

3.1. Governing equations

In this paper the open source software OpenFoam is used to simulate the hydrodynamic performance of the propeller in open water and self propulsion condition. This software uses finite volume method to solve the governing equations. In terms of the unsteady incompressible fluid, the governing equations adopted here is the Unsteady Reynolds-Average Naiver-Stokes (URANS) equations. The equations consist of a mass conservation equation and a momentum conservation equation.

Governing equations are listed as follows:

Mass conservation equation:
\[ \frac{\partial u_i}{\partial t} = 0 \]  

Momentum equation:
\[ \frac{\partial}{\partial t} \left( \rho u_i \right) + \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i} \left( \mu \frac{\partial u_i}{\partial x_j} - \frac{\tau_{ij}}{\rho} \right) + f_i \]

where \( u_i \) and \( u_j \) are the Reynolds average of the velocity components, \( x_i \) and \( x_j \) are the component of coordinate, \( i (i = 1,2,3) \) and \( j (j = 1,2,3) \) indicate different directions; \( t \) is time; \( \rho \) is the fluid density; \( p \) is the average pressure of the fluid; \( \mu \) is the hydrodynamic viscosity; \( f_i \) is the body force; \( -\rho u_i u_j \) represents the Reynolds stress.

During the open water and self-propulsion tests, the propeller has a certain depth from the water surface, and the effect of the water-air interface (such as waves) on the propeller hydrodynamic performance is negligible. In order to eliminate the unnecessary impact of two-phase flow calculation on the results and efficiency, only one-phase flow simulation was carried out in the numerical simulation of open water and self-propulsion tests. The SST k-\( \omega \) turbulence model is used to close the governing equations. The discretization of the convection term \( \text{div}(\phi, \text{U}) \) in the mass conservation equation is selected as the second-order upwind scheme, the discretization of the convection term \( \text{div}(\phi, \text{k}) \) in the momentum conservation equation and the convection term in the omega equation are selected as the first-order upwind schemes.

3.2. Time discretization

Time discretization refers to the integration of each term of the partial differential equation in a time step of \( \Delta t \). During time development, the general variable \( \phi \) can be expressed as follows:
\[ \frac{\partial \phi}{\partial t} = F (\phi) \]

where the function \( F(\phi) \) contains arbitrary space discretization.

If the time derivative is backwards differentiated, the time dispersion of first-order precision as follows:
\[
\frac{\phi^{n+1} - \phi^n}{\Delta t} = F(\phi)
\]

(4)

the time dispersion of second-order precision as follows:

\[
\frac{3\phi^{n+1} - 4\phi^n + \phi^{n-1}}{2\Delta t} = F(\phi)
\]

(5)

where \(\phi^{n+1}\) is the scalar value at time \(n+1\), \(\phi^n\) is the scalar value at time \(n\), and \(\phi^{n-1}\) is the scalar value at time \(n-1\).

After the time derivative discretization is completed, we must choose how to calculate \(F(\phi)\), that is, choose which time step of \(\phi\) to calculate \(F(\phi)\). One way is the implicit method which uses the value of \(\phi\) in the future time step to calculate \(F(\phi)\) as follows:

\[
\frac{\phi^{n+1} - \phi^n}{\Delta t} = F(\phi^{n+1})
\]

(6)

Another way is the explicit method which uses the value of \(\phi\) at the current time step to calculate \(F(\phi)\) as follows:

\[
\frac{\phi^{n+1} - \phi^n}{\Delta t} = F(\phi^n)
\]

(7)

3.3. Mesh

Snappyhexmesh, a meshing tool of OpenFoam is used to generate the mesh. The mesh used to simulate the open water test is shown in figure 3 and figure 4. Figure 5 shows the stern mesh used to simulate the self propulsion test.

**Figure 3.** Mesh for the simulation of open water test.

**Figure 4.** The surface mesh of the propeller.

**Figure 5.** Mesh for the simulation of self propulsion test.

4. Time discretization schemes
4.1. Explicit and implicit time discretization

Due to the characteristics of the algorithm, the explicit discretization must meet a certain condition to ensure numerical stability. Otherwise, calculation divergence will occur. The condition for ensuring numerical stability is that the propagation distance of the fastest disturbance in the fluid cannot exceed k times the size of a grid cell, where k is a constant (for some of the simple explicit algorithms, k is equal to 1). This is the famous CFL condition (Courant-Friedrichs-Lewy condition) in CFD. Because of this condition, the time step of the explicit algorithm is severely restricted. For most unsteady problems, due to the strict limitation of the time step in the explicit algorithm, it takes a long time to reach the calculation convergence, thus the implicit algorithm is more suitable.

4.2. The comparison between first-order and second-order time discretization schemes

For the unsteady problem, the discretization in the time domain mainly has the following formats: The first-order backward Euler format (implicit format), the second-order backward Euler format (implicit format), and the Crank-Nicolson format. Although the Crank-Nicolson format has second-order accuracy and is unconditionally stable, it needs to be given an appropriate time step. If the time step is too large, it will cause oscillation of numerical calculation results. In comparison, the implicit Euler format has better stability. Therefore, the effects of the first-order backward Euler format and the second-order backward Euler format on numerical calculation accuracy are studied.

4.2.1. The effect of time discretization format on open water test simulation

While keeping other numerical simulation conditions unchanged, the effects of the first-order backward Euler format and the second-order backward Euler format on the calculation results at the same time step are studied, as shown in table 3.

Table 3. Open water test simulation results by using two time discretization formats.

| Discretization format                  | Time step (ms) | Thrust (N)   | Torque (N·m) |
|----------------------------------------|----------------|--------------|--------------|
| the first-order backward Euler format  | 0.02           | 209.02       | 7.3221       |
| the second-order backward Euler format | 0.02           | 209.28       | 7.3336       |

It can be seen from table 3 that under the same time step, there is almost no effect on the calculation results in this case by changing the time discretization format alone. Under the calculation conditions in this paper, the open water test simulation of the propeller is not sensitive to the time discretization format, so the first-order backward Euler format or the second-order backward Euler format can be used for these kinds of simulation. Considering that the second-order backward Euler format is more time consuming, this paper recommends the first-order backward Euler format for the open water test simulation of propeller.

4.2.2. The effect of time discretization format on self propulsion simulation

While keeping other numerical simulation conditions unchanged, the effects of the first-order backward Euler format and the second-order backward Euler format on the calculation results at the same time step are studied, as shown in table 4. It can be seen that the thrust and torque calculated by using the second-order backward Euler format are smaller than those calculated by using the first-order backward Euler format. Table 5 shows the thrust and torque at the forced self-propulsion point analyzed by ITTC1978 recommendation. It can be seen that under the same time step, the time discretization format has a greater influence on the thrust than the torque which isn’t affected almost.

Table 4. Self propulsion simulation results by using two time discretization formats.

| Time discretization format | Time step (ms) | Rotation (rps) | Thrust (N) | Torque (N·m) |
|----------------------------|----------------|---------------|-----------|-------------|
| the first-order backward Euler | 0.1            | 7.5           | 44.195    | 1.600       |
Table 5. Self-propulsion analysis results by using two time discretization formats.

| Time discretization format               | Time step (ms) | Thrust (N) | Torque (N·m) |
|-----------------------------------------|----------------|------------|--------------|
| the first-order backward Euler format   | 0.1            | 65.65      | 2.290        |
| the second-order backward Euler format  | 0.1            | 64.40      | 2.284        |
| difference                              | -              | 1.9%       | 0.3%         |

Figure 6 shows the simulated vortex under different viewing angles when the time discretization format is the first-order backward Euler format. Figure 7 shows the simulated vortex under different viewing angles when the time term is the second-order backward Euler format. By comparing these four figures, regardless of the first-order backward Euler format or the second-order backward Euler format, the structure of the simulated vortex is basically the same. However, the vortex simulated by using the second-order backward Euler format is more complicated.

4.3. Time step
Time step is an important part of the control equation after discretization. In this paper, the time step is studied based on the first-order backward Euler format.

4.3.1. The effect of time step on open water test simulation
The effect of different time steps on the calculation results of open water test simulation under operating conditions \( J = 0.5 \) is studied while other numerical simulation conditions remain unchanged. The results by using the first-order backward Euler format are shown in table 6. It can be seen that the thrust and torque are changed with the time step. When the time step is less than 0.1 ms, it has little effect on the calculation results. Figure 8 shows the vortex structure at different time steps. It shows that the time step has little effect on the tip vortex generated from the blade tips. However, it has a great influence on the vortex near the hub, the smaller the time step is, the slower the vortex dissipates in this area.

**Table 6.** Results obtained by using the second-order backward Euler format.

| time step (ms) | Thrust results(N) | Thrust diff. | Torque results(N) | Torque diff. |
|---------------|-------------------|--------------|------------------|--------------|
| 0.3           | 265.47            | 22.65%       | 9.2198           | 21.78%       |
| 0.1           | 216.45            | 0 %          | 7.571            | 0%           |
| 0.05          | 211.04            | -2.50%       | 7.39             | -2.39%       |
| 0.02          | 209.02            | -3.43%       | 7.3221           | -3.29%       |

**Figure 8.** Comparison of vortex structure simulated at different time steps.

4.3.2. *The effect of time step on self propulsion simulation*

The effect of different time steps on the simulated results of the propeller in the self propulsion condition when the rotation is 7.5rps is studied while other numerical simulation conditions remain
unchanged. the simulated results by using the first-order backward Euler format are given in the table 7. It can be seen that the calculated thrust and torque gradually increase as the time step decreases. When the time step is reduced from 0.5 ms to 0.1 ms, the variation of thrust is small, but the variation of torque is large, the effect of time step on torque is greater. The vortex structure simulated in the time steps of 2 ms, 0.5 ms, 0.1 ms is shown in the figure 9, figure 10 and figure 11. It can be seen from these figures that the time step has a great influence on the structure of the vortex. The edge of the vortex close to the propeller is blurred in the time step of 2 ms, it becomes much more clear when the time step is 0.5 ms, the deformation of the tip vortex close to the rudder can also be clearly simulated. When the time step is further reduced to 0.1 ms, hub vortex becomes more. It can be judged that a small time step is beneficial to reduce the influence of numerical dissipation on the vortex simulation.

| time step (ms) | thrust results(N) | diff. | torque results(N) | diff. |
|--------------|------------------|-------|------------------|-------|
| 2            | 25.12            | -42.6%| 1.023            | -34.8%|
| 0.5          | 43.80            | -     | 1.570            | -     |
| 0.1          | 44.195           | 0.9%  | 1.600            | 1.9%  |

**Figure 9.** the vortex in the time step of 2ms.

**Figure 10.** the vortex in the time step of 0.5ms.

**Figure 11.** the vortex in the time step of 0.1ms.
5. Conclusions
The flow induced by the rotation of propeller in open water and self propulsion condition is unsteady, a careful study of time discretization format and time step is very important. In this paper, an 80,000-ton oil tanker and its propeller are studied as the research objects, and the conclusions are drawn as follows:
Considering the engineering application, it is recommended to use the first-order backward Euler time discretization format for the numerical simulation of the open water test. Reducing the time step is beneficial to the hub vortex simulation. A time step of less than 0.1ms for the open water test simulation is recommended.
In terms of self propulsion simulation, for the same time step, the time discretization format has a greater impact on thrust, but has almost no effect on torque. The thrust simulated by using the second order backward Euler format is less than that simulated by using the first order backward Euler format. Considering that the calculation time of the first-order discretization format may be shorter than that of the second-order discretization format, it is recommended to use the first-order discretization format at the beginning of self propulsion simulation. If the error of thrust compared with experiment data is larger than expected, the second-order discretization format should be considered. This paper believes that a small time step will benefit to simulate the vortex. If the time step become smaller, such as from 0.5ms to 0.1ms, the thrust will be less affected, while the torque is more significantly affected.

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