Viscous force and added mass for complex configuration with an implicit dual time method

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Abstract This article obtains the viscous force and added mass for a complex configuration. Its subject is a small AUV propelled by four pumps at stern, which is used to survey the ocean. The model in simulation is similar to actual body without any simplification in order to get high resolution result, with Meshing by unstructured grids based on advancing front method. The steady viscous force is calculated by integrating RANS equation by cell centered finite volume scheme, and compared with that of experiment. The simulation data is within 1.7 percent with respect to that of experiment. Motivated by this, we apply this method to calculate the unsteady force of AUV. In order to achieve high resolution for unsteady viscous flow, an implicit dual time approach, which is proved to be more stable, is applied to discretize the time-dependent conserved variables. Applying this method to the complex pump-propelled AUV unsteady motion, its resistant force and corresponding velocity are obtained at each time step. With curve fitting method, we acquire the added mass. At the same time, the experiment data of max velocity, total time and total displacement are got as AUV slips from max velocity without thrust, which agrees well with that of simulation. The emphasis of the paper is placed on the practicality of the methodology for accurately predicting viscous drag data and added mass for complex configuration.

1 Introduction

The hydrodynamic characteristics of an AUV, which are comprised of the viscous force and inertia force have to be estimated under various cruise conditions by constructing maneuvering equations. In general, CFD will be a candidate to treat this problem prior to the usual experiment or estimation by simplified model with experience. To simulate such problem, CFD must have a capability to model actual complex AUV. For complex geometry, hybrid meshes are the prior\textsuperscript{[1-3]}. In this article, unstructured hybrid meshes comprised of tetrahedral, prisms and pyramids are adopted to model the flow field.

To get the dynamic response of an AUV resulting from its inertial mass, there are four ways, e.g., additional source methods, overset meshes\textsuperscript{[6]}, deforming meshes\textsuperscript{[5]}, and the Cartesian approach\textsuperscript{[6]}. The last three methods are based on the mesh moving, which need more time and may be unstable in numeral simulation, while the additional source methods solve the problem
by adding moment source in moment equations, which are validated by experiment and need less numerical time.

2 Model

Shenyang Institute of Automation (SIA) in China has been developing small AUVs to research the ocean. The AUV propelled by four stern pumps studied in this paper is a new propelling AUV, which is only 750 mm long, with diameter 75 mm. Figure 1 is the real AUV, its model is pictured in Fig.2. The complex stern section is zoomed in the Fig.3. In order to capture the layer flow characters, prismatic mesh is built near the AUV boundary layer, while other flow field is filled with tetrahedral mesh. The mesh is sketched in Fig.4.

3 Governing equations

The set of governing equations are the unsteady Navier-Stokes equations in their conservation forms, which consist of the conservation of mass and momentum for an incompressible fluid, as expressed in Eqs.(1) and (2).

\[ \nabla \cdot U = 0, \]

\[ \frac{\partial U}{\partial t} + \nabla \cdot (U \otimes U) = \nabla \cdot \left( -p\delta + \mu \left( \nabla U + (\nabla U)^T \right) \right) + S_M. \]

Where \( U \) is the velocity vector, \( \delta \) is the \( 3 \times 3 \) identity matrix, \( S_M \) is the moment source, in the unsteady flow simulation, its value is \( \rho \times a \), where \( \rho \), \( a \) are fluid density, acceleration respectively. \( \nabla \cdot (U \otimes U) \) is the advection term, expressed as in Eq.(3).
\[ \nabla \cdot (U \otimes U) = \left[ \frac{\partial}{\partial x} (U_x U_x) + \frac{\partial}{\partial y} (U_y U_y) + \frac{\partial}{\partial z} (U_z U_z) \right] \]

4 Temporal discretization

In order to accelerate the convergence and improve the accuracy of unsteady flow, implicit dual time method is adopted for the time dependent term discretization. A dual time formulation\(^{[7,8]}\) was developed for the time-dependent scheme, as is expressed by

\[
\frac{dQ}{dt} + R^*(Q) = 0, \quad (4)
\]

\[
R^*(Q) = \frac{\partial Q}{\partial t} + R(Q). \quad (5)
\]

Where \(\tau\) is referred to as “pseudo-time”, and is the iterative parameter, \(t\) is the physical time. \(Q\) is the vector of conservative variables and \(R(Q)\) is an appropriate numerical quadrature of the flux divergence. The temporal discretization involving the integration of every term in the differential equations over a time step \(t\) are outlined by Beam and Warming\(^{[9]}\) as Eq.(6), a partial list of a stable three time methods are listed in Table referred to \(^{[6]}\). In this paper, 2nd order backward discretization method is used, where \(\theta, \xi, \phi\) are 1, 1/2, 0 respectively.

\[
R^*(Q) = \frac{(1 + \xi) Q^{n+1} - (1 + 2\xi) Q^n + \xi Q^{n-1}}{t} + \theta R(Q^{n+1}) + (1 - \theta + \phi) R(Q^n) - \phi R(Q^{n-1}). \quad (6)
\]

5 Results

In order to get the viscous force of the complex AUV, we build the model shown in Fig.2 without any simplification, and mesh the flow field more finely to describe the geometry. AUV stern surface mesh is pictured in Fig.5, with nearly 2.6 million for total mesh nodes. Because cruise velocity is less than 2 knot confined by the energy, the velocity in simulation is chosen as 0.5 knot/s. From numerical simulation, viscous force is 0.0913 N. Its velocity vector of the complex stern section is viewed in Fig.6. At the same time, we measured the relation between voltage and the force pumped out, viewed as Fig.7. With the result of simulation, we estimate that its motion velocity is nearly 0.4 m/s under the propelling of left and right pumps. While at first, the velocity in experiment is near 0.25 m/s, which is measured with a line tied on the AUV during experiment, the disagreement is due to the resistance of the line. The result measured in an experiment without the line agrees well with that of the simulation, with error of 1.7%.
After that, we apply this method to calculate the unsteady force of the AUV. In unsteady simulation, AUV is moving from stationary to the max velocity, which is equal to that of the steady motion referred above. Its unsteady velocity and acceleration are listed in Eqs.(7) and (8) respectively, with plotting outlined in Fig.8. Equation (9) is the moment source used in governing moment equation. Applying the implicit dual time to discrete time-dependent term, we get the contour of velocity in different time. Figure 9 is the velocity contour at 15 s. Figure 10 is its resistance force with time increasing, in which we can see the terminal force is near constant related to that of the steady motion. With curve fitting method, the complex configuration added mass is obtained. Dealing with this value, we gain the total time of AUV slipping from the max velocity to nearly stationary by integrating the Eqs.(10), which agrees well with that over experiment.

\[
V' = V_{\text{max}}(1 - \exp(-t/3.0)),
\]

\[
a = \frac{V_{\text{max}}}{3.0} \exp(-t/3.0),
\]

\[
S_M = \rho \times a,
\]

\[
(m + \lambda_1)\ddot{u} = X_{\text{au}} u^2.
\]
6 Conclusions

This paper presents a method to get viscous force and its added mass of complex geometry by simulation. Modeling the complex AUV without simplification, and mesh the flow field by hybrid grid, we can acquire the viscous force more exactly. Compared the simulation with experiment, we should emphasis that any tie to the AUV will give relative large load to AUV for its essential small body and the effect of the line tied to AUV can not be ignored. To get the added mass of the non-regular AUV, the unsteady motion is simulated by discretizing the time dependent term with implicit dual time method, its result is validated.

References