Resistance analysis of underwater towing cable based on overset grid

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Abstract. The method of overset grid is used to calculate the lift and drag of towing cable at various angles of attack. Compared with the past method, it effectively solves the problem of mesh distortion at high angles of attack. Overset grid is more effective, and most of the grids are formed by regular hexahedron, so the accuracy of calculation is more guaranteed. When calculating the special angle of attack, the cubic spline interpolation method is used to solve the problem.

1. Introduction

As an underwater equipment, towing cable plays a huge role and it’s often used in various underwater equipments. In order to calculate the performance of the whole cable, it is necessary to parameterize it, calculate the performance of each cable, and sum its whole vector.

In the past, empirical formulas were used to calculate the drag performance of towed cables. The empirical formula is to decompose the velocity into tangential and normal directions, and then calculate the tangential and normal forces from the formula. This method is not accurate because it does not take into account the mutual interference between tangential and normal velocities. In addition, the empirical formulas are larger than the real values when calculating the direction force of the algorithm. With the development of computational fluid dynamics technology, this method can solve this problem well. When the towline moves at different angles of attack, the traditional mesh generation method is easy to cause grid deflection, and the calculation results are not accurate enough. With the development of overset grid computing, this problem can be solved better.

2. Basic theory of fluid mechanics

2.1. Control equation

The continuity equation and momentum equation for incompressible viscous fluid are:

\[ \frac{\partial \mathbf{u}}{\partial t} = 0 \]  
\[ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) \]
Where, \( \rho \) is density, \( \mu \) is Viscosity Coefficient, \( \overline{p} \) is average pressure, \( \overline{F}_i \) is external force, \( \overline{u}_i \) is mean velocity, \( u'_i \) is fluctuating velocity, \( -\rho u_i u_j \) is reynolds stress.

2.2. Turbulence model

In order to make the equation closed, a new turbulent model equation must be introduced to link the fluctuating values with the time average in the stress terms. There, we chose the RNG\( k - \varepsilon \) equations. The transport equations of turbulent kinetic energy and turbulent fluctuation intensity in the RNG\( k - \varepsilon \) equation are:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_{\text{eff}} \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon + S_k \tag{3}
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_{\text{eff}} \frac{\partial \varepsilon}{\partial x_j} \right] + G_{1k} \frac{\varepsilon}{k} - C_{2\kappa} \rho \varepsilon^2 - R_{\varepsilon} + S_{\varepsilon} \tag{4}
\]

Where, \( \mu_{\text{eff}} = \mu + \mu_t \), \( \mu_t = \rho C \mu \frac{k^2}{\varepsilon} \), \( G_k = -\rho \mu_j \frac{\partial u_i}{\partial x_j} \), \( R_{\varepsilon} = \frac{C_\mu \rho \eta^3 (1 - \eta) \varepsilon^2}{k} \), \( \eta = \frac{S_k}{\varepsilon} \), \( S = \sqrt{2S_x S_y} \), \( S_x = \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \), \( S_y \) and \( S_{\varepsilon} \) are user-defined source terms.

Constant, \( G_{1k} = 1.42 \), \( G_{2\kappa} = 1.68 \), \( C_\mu = 0.0845 \), \( \sigma_k = 1.0 \), \( \sigma_\varepsilon = 1.3 \), \( \eta_0 = 4.38 \), \( \beta = 0.012 \)

3. CFD Simulation

3.1. Fluid Computing Domain

The angle of attack between the towline and the upflow velocity varies from 0 to 90. The case of 0 degree and 90 degree is relatively simple, and the structured grid can be obtained quickly. The more complex case is between 0 degree and 90 degree. In the past, the velocity direction was modified and the inflow surface was specially treated. However, due to the problem of velocity and mesh angle, the calculation results are not accurate enough. The fluid computing domain is shown in Figure 1.

![Figure 1. Fluid Computing Domain and Boundary Setting](image-url)
3.2. Boundary condition
The setting of boundary conditions is one of the necessary conditions to ensure the realization of CFD. The boundary conditions of the computational domain in this paper are given in Fig. 1, including velocity inlet, pressure outlet and wall.

(1) Velocity entrance: setting the magnitude and direction of upflow velocity on the inflow surface \( V_{in} = V_0 \);

(2) Pressure outlet: hydrostatic pressure set at the outflow surface relative to the reference pressure point, \( p_{out} = 0 \)

(3) Wall Conditions: Non-slip boundary conditions are set on the surface of the towline and around the flow field. \( u = v = w = 0 \)

3.3. Mesh generation
This problem can be effectively solved by using overset grid. When the angle of attack of the towline changes, the quality of the grids remains good (Figure 2).

Figure 2. Fluid Computing Domain and Boundary Setting

3.4. Numerical calculation
The governing equations and turbulence modes are discretized by the finite volume method and calculated by the coupled implicit method. In the difference scheme, the pressure term is in the standard format, and the momentum term, turbulent energy term and dissipation lead term are iterated 500 times using the first-order upwind scheme, then using the second-order upwind scheme.

\( RNGk - \epsilon \) turbulence model and finite volume method are used to discretize the governing equations. The pressure-velocity coupling iteration is solved by a consistent SIMPLEC algorithm. Besides the standard discrete scheme, the momentum, turbulent energy and turbulent dissipation rate are solved by a second-order upwind scheme, and the sub-relaxation factor is calculated by default. The wall function method is used in the area near the wall.

Taking the towing cable with diameter of 10 mm and length of 200 m as an example, the velocity is 5 m/s. The pressure field diagram is shown in Figure 3.

Figure 3. Pressure field diagram of towing cable(45 degree, 5m/s)
4. Principle of curve interpolation
Curve interpolation usually has exponential function interpolation, Lagrange interpolation, Cubic spline interpolation, B spline curve, NURBS curve and so on.

4.1. Cubic spline curve interpolation
There, \( a = x_0 < x_1 < \cdots < x_n = b \), if function \( y(x) \) satisfying two condition:

(a) \( y(x) \) is Cubic Polynomial on each interval \( [x_{i-1}, x_i], i = 1, 2, \cdots, n; \)

(b) \( y(x) \) is twice continuously differentiable function on interval \( [a, b] \).

Then, \( y(x) \) is Cubic spline on interval \( [a, b] \). There, \( x_i (i = 0, 1, \cdots, n) \) is the node. The interpolation points are shown in Table 1.

Table 1. Interpolation points.

| \( x \) | \( x_0 \) | \( x_1 \) | \( \cdots \) | \( x_n \) |
|---|---|---|---|---|
| \( y \) | \( y_0 \) | \( y_1 \) | \( \cdots \) | \( y_n \) |

Cubic spline interpolation function:

\[
s(x) = \frac{h_k}{h_k^3} + 2(x - x_k) \frac{(x - x_{k+1})^2}{h_k^3} y_k + \frac{h_k - 2(x - x_{k+1})}{h_k^3} (x - x_k)^2 y_{k+1} \\
+ \frac{(x - x_k)(x - x_{k+1})^2}{h_k^2} m_k + \frac{(x - x_{k+1})(x - x_k)^2}{h_k^2} m_{k+1}
\] (5)

In equality (1),

\[
h_k = x_{k+1} - x_k (k = 0, 1, \cdots, n - 1)
\] (6)

\[
\lambda_k m_{k-1} + 2m_k + \mu_k m_{k+1} = g_k (k = 1, 2, \cdots, n - 1)
\] (7)

Where,

\[
\lambda_k = \frac{h_k}{h_k + h_{k-1}}, \mu_k = \frac{h_{k-1}}{h_k + h_{k-1}}, g_k = 3(\mu_k \frac{y_{k+1} - y_k}{h_k} + \lambda_k \frac{y_k - y_{k-1}}{h_{k-1}})(k = 1, 2, \cdots, n - 1)
\]

5. Analysis of calculation results
Using the above method, the towing cable element is calculated at a speed of 5 m/s and 10 angles of attack. The calculation results are shown in Table 2.

Table 2. Lift and resistance of towing cable element at different angles of attack

| attack° | R/N | L/N |
|---|---|---|
| 0 | 1.05 | 0.00 |
| 10 | 2.65 | 5.95 |
| 20 | 7.50 | 15.00 |
| 30 | 16.50 | 24.50 |
| 40 | 30.50 | 33.00 |
| 50 | 47.50 | 37.50 |
| 60 | 64.00 | 35.00 |
| 70 | 76.00 | 26.50 |
| 80 | 84.00 | 14.00 |
| 90 | 85.50 | 0.00 |
When it is necessary to calculate the lift and drag at different angles of attack, cubic spline interpolation can be used to solve the problem. When the angle of attack is 35°, resistance is 25.50N and lift is 27.47N.

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