Abstract

An unsteady Reynolds averaged Navier–Stokes method is developed to account for sinkage and trim effects in the calculation of steadily advancing surface ship. Volume of fluid method (VOF) is devised for the treatment of free surface. The sinkage and trim were predicted by using dynamic mesh technology, and the motion of ship is controlled by six degrees of freedom (6DOF) code. Predicted results for sinkage and trim and resistance at seven Froude numbers (from $F_r=0.15$ to $F_r=0.45$) were compared against experimental data, showing good agreement. A plenty of numerical simulations for resistance of ship model under different running attitudes are carried out. On these bases, the results of numerical simulation and the factors which affect ship resistance are analyzed, the formulas for calculating the ship resistance under different drafts and longitudinal trims and arbitrary drift-trim coupled running attitudes are deduced and validated.

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Keywords: Computational fluid dynamics; Ship motion; Resistance; Sinkage and trim;

1. Introduction

The running attitude of surface ship always changes, for commercial ship, the change of draft and trim will take place when the stowage or the ballast are different, for naval ship, the change of heel will also occur for the consume of ammo or the damage of body. These changes have effect on the ship resistance,
and affect the ship rapidity sequentially [1][2]. However, it is a difficulty to predicate the ship resistance at different running attitude considering free surface at present.

The most typical running attitude mentioned above is the draft-trim coupled form. To obtain the rule of ship resistance under draft-trim coupled running attitude precisely and efficiently, a plenty of numerical simulations for captive ship model test under different drafts and trims based on CFD (Computational Fluid Dynamics) theory are carried out, and the computational formulas for ship resistance under different running attitudes are deduced.

The numerical method is achieved by solving three-dimensional incompressible viscous fluid of Reynolds average Navier-Stokes equation with a finite-volume method for the discretization of differential equations, the SIMPLE [3] algorithm is adopted, and the SST $\kappa-\omega$ turbulence model [4] is used, and turbulence model, and the volume of fluid method (VOF) [5] is devised for the treatment of free surface. In order to obtain higher precision results, second-order upwind dispersion for the momentum, and second-order upwind scheme for the turbulence kinetic energy and specific dissipation rate are set.

### Nomenclature

- $C_q$ : volume fraction
- $f_i$ : body force component of fluid
- $F_a$ : Froude number
- $F_{CGi}$ : forces acting at the centre of mass of the body
- $I_i$ : moment of inertia
- $L_{CGi}$ : moments acting at the centre of mass of the body
- $L_i$ : length of ship
- $m$ : mass of ship
- $P$ : pressure
- $R, R_0$ : $R$ is the total resistance, $R_0$ is the resistance of normal attitude
- $\Delta R_{\Delta T}$ : resistance increment for draft change
- $\Delta R^T_{\Delta T}$ : resistance increment for trim change based on draft change
- $T, \Delta T$ : $T$ is the draft, $\Delta T$ is the draft increment
- $u$ : temporal averaged velocity component
- $u'$ : fluctuation velocity component
- $\nu$ : kinematic viscosity
- $x_{CGi}$ : distance from the centre of gravity to the amidships section
- $\theta_{CGi}$ : rotations of the body
- $\Delta, \Delta_0$ : $\Delta$ is the present displacement, $\Delta_0$ is the normal displacement
- $\eta$ : resistance increment rate for trim change
- $\rho$ : density of water
2. Mathematical Model

The governing equations of incompressible viscous flow can be modeled with the continuity equation coupled with the RANS equations:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]  

\[
\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} \left( u_i u_j \right) = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} - u'_i u'_j \right) + f_i
\] 

Where: \( u_i \) is the temporal averaged velocity component; \( P \) is the pressure; \( f_i \) is the body force component of fluid; \( \rho \) is the fluid density; \( \nu \) is the kinematic viscosity; \( u'_i \) is the fluctuation velocity component; \( -\rho u'_i u'_j \) is the Reynolds stress.

The VOF method is used to simulate the free surface, Transport equations of volume fraction \( C_q \) can also be solved by governing equations.

\[
\frac{\partial C_q}{\partial t} + u_i \frac{\partial C_q}{\partial x_i} = 0
\] 

The turbulent viscosity was computed using SST \( \kappa-\omega \) turbulence model, the turbulence model equations are shown in reference [4].

3. Geometry and solution domain

In the present study, a model surface ship (INSEAN 2340) advancing in calm water was simulated. INSEAN 2340 is a model of a modern US Navy combatant surface ship and has been selected by the International Towing Tank (ITTC) as a recommended benchmark for CFD validation for resistance and propulsion (ITTC, 1996). The principal dimensions of the model can be seen in reference [6].

The solution domain is set to be a cube shape. The locations between ship models and the various boundaries of the solution domain are shown as figure 1 (a).

A structured/unstructured [7] hybrid mesh consisting of about 1.15 millions cells was generated for the whole solution domain. The overall view of the mesh around the model ship is shown in figure 1 (b).

![Fig. 1 (a) Solution domain; (b) Overall view of the mesh around the model ship](image)

4. Body motions

Two coordinate systems are used to evaluate the motions [8][9]: An inertial system (\( E\xi\eta\zeta \)) which moves forward at a constant velocity, and a non-inertial coordinate system (\( O\xi\eta\zeta \)), called body coordinate system which moves according to the ship’s motion. The vector in the ship coordinate system
can be expressed in the earth system by the transformation matrix composed by trigonometric function of Euler angles [10].

The ship hull can be regarded as a rigid body, according to the momentum theorem and angular momentum theorem of rigid body. The 6DOF motions of a rigid body in body coordinate system are governed by equations of linear and angular momentum referred to center of gravity.

\[
\begin{align*}
F_{CG_i} &= m \frac{d^2 x_{CG_i}}{dt^2} \\
L_{CG_i} &= \frac{d}{dt} (I_i \frac{d \theta_{CG_i}}{dt})
\end{align*}
\]

(4)

where \(x_{CG_i}\) and \(\theta_{CG_i}\) are the Cartesian translations and rotations of the body, respectively, while \(F_{CG_i}\) and \(L_{CG_i}\) are the Cartesian resultant forces and moments acting at the center of mass of the body. Modes \(i=1\rightarrow3\) represent the translational motions of the center of gravity for surge, sway, and heave, while \(i=4\rightarrow6\) represent the rotational motions of roll, pitch, and yaw.

To obtain the trim and sinkage of ship moving forward, only 2DOF equations related to heave and pitch are used in this paper.

5. Results of ship motion with running attitude automatic adjustment

5.1. Resistance

Table 1 shows the numerical calculation results of ship resistance with running attitude automatic adjustment. It can be find that calculation results are in good agreement with the experiment results and the error is less than 4%.

| \(F_n\) | Simulation (N) | Experiment (N) | Relative error (%) |
|--------|----------------|----------------|--------------------|
| 0.15   | 12.25          | 12.11          | 1.15               |
| 0.20   | 21.11          | 21.58          | -2.18              |
| 0.25   | 33.91          | 34.68          | -2.22              |
| 0.28   | 43.57          | 45.18          | -3.56              |
| 0.35   | 78.14          | 80.66          | -3.12              |
| 0.41   | 147.92         | 152.70         | -3.13              |
| 0.45   | 211.37         | 216.33         | -2.29              |

5.2. Sinkage

Figure 2 (a) shows the comparison of the CFD sinkage calculation with the experiment results at different speeds. The positive value of sinkage corresponds to an increase of draft from its at-rest position. It can be found that a small amount of sinkage is occurred when the ship is towing at a low speed, but with the speed increasing, the sinkage increased significantly. The CFD sinkage calculation results agree well with the experiment data.

5.3. Trim

Figure 2 (b) shows the comparison of the CFD trim calculation with the experiment at different speeds. A positive trim corresponds to bow-up in this paper. When \(F_n<0.35\), the ship has a tiny stem incline, and when \(F_n>0.35\), it become to stern incline. As the \(F_n\) increases, the trim angle increases rapidly. The results of numerical calculation agree well with the experiment data.
5.4. Waveform

Figure 3 (a) compares the wave height of side surface between numerical simulation and experiment, while figure 3 (b) shows the free surface wave distribution of numerical simulation. It presents that using VOF method to simulate free surface is accurate in this paper.

6. Computational Formulas for Ship Resistance with different running attitudes

6.1. Resistance computational formula for draft change

The resistances of ship model under five drafts and five Froude numbers are simulated, and the results are conversed to the real ship resistances through the Froude conversion method (see reference [11]). By analyzing the results, the resistance computational formula for draft change is deduced as follow:

\[
\begin{align*}
R &= R_0 \left( \Delta / \Delta_0 \right)^y \\
y &= (1 + K) \cdot \overline{y} \\
\overline{y} &= -1.64760419 \times F_n^2 + 2.01313417 \times F_n + 0.88911441 \\
K &= -1.31821222 \times \Delta T / T + 0.14832171
\end{align*}
\]

(5)

Where: \( R \) is the total resistance, \( R_0 \) is the resistance of normal running attitude, \( \Delta \) is the present displacement, \( \Delta_0 \) is the normal displacement, \( F_n \) is the Froude number, \( T \) is the draft, \( \Delta T \) is the draft increment.
6.2. Resistance computational formula for trim change

The ship model resistances under eleven drafts and five Froude numbers are simulated, and the results are conversed to the real ship resistance through the Froude conversion.

To describe the rule of resistance under different trims, the resistance increment rate \( \eta \) compare with the normal state are used. By analyzing the results, the value of \( \eta \) can be obtained, the result are shown in figure 7. The resistance computational formula for trim change is as followed:

\[
\begin{align*}
R &= R_0 (1 + \eta) \\
\eta &= f(F_n)
\end{align*}
\]

Where: \( \eta \) is the resistance increment rate, the median resistance increment rate for the change of trim can be obtained by linear interpolation.

![Fig. 7. (a) Fitting curves of resistance increment rate for stern incline; (b) Fitting curves of resistance increment rate for stem incline](image)

6.3. Resistance computational formula for draft-trim coupled running attitude

The numerical simulation results of draft-trim coupled running attitudes under two Froude number, 0.280 and 0.410 are shown in reference [11]. The draft-trim coupled influences are very complex, to simplify the coupled influences, the total resistance increment can be resolved into the resistance increment of draft change and the increment of trim change based on draft change, which can be obtain by equation (4) and (5).

\[
R = R_0 + \Delta R_{\Delta T} + \Delta R_{\Delta T}^{\Delta \varphi}
\]

Where: \( \Delta R_{\Delta T} \) is the resistance increment for draft change, \( \Delta R_{\Delta T}^{\Delta \varphi} \) is the resistance increment for trim change based on draft change.

6.4. Validation

To validate the Formula for draft change deduced in this paper, the method of modify the parent ship proposed by Župc [12] are carried out, the comparison are shown in table 2. The value of agreement seems to be satisfactory. Because of lack of experiment data, The Formula for trim change and draft-trim coupled running attitude are not validate at present, the validate work await to be done in the future.
Table 2. The comparison of results for draft-trim coupled running attitude

| Draft change (m) | $F_n=0.210$ | $F_n=0.280$ | $F_n=0.410$ |
|-----------------|-------------|-------------|-------------|
| Present result (N) | 4.1189 | 7.0556 | 23.6340 |
| Γm method (N) | 4.0991 | 7.4456 | 22.6900 |
| Relative error (%) | 0.48 | -5.24 | 4.16 |

7. Conclusion

An unsteady Reynolds averaged Navier–Stokes method is presented to predict the sinkage and trim for steadily advancing surface ship. The body’s automatic adjustment is achieved by using dynamic mesh technology. The resistance, sinkage, trim and waveform agree well with the experiment data. To calculate the resistance of ship with different running attitudes conveniently, a plenty of numerical simulations of ship advancing at different running attitudes and Froude numbers are carried out. By analyzing the results, three computational formulas are deduced.

The method presented for the prediction of ship motion is carried out in calm water. In actually, the free surface of sea is always fluctuant. Therefore, the method provide in this paper will be applied to the research of ship motion in wave in the future study.

References

[1] H Schneekluth. Hydromechanik zum schiffsentwurf, Translated by Xian Peilin. Shanghai: Shanghai Jiao Tong University Press; 1997, pp. 279–281.
[2] Harvald. Sv. Aa. Ship resistance and propulsion. Translated by Huang Dingliang, et al. Dalian: Dalian University of Technology Press; 1989, pp. 110–111.
[3] Patankar, S. V. & Spalding, D. B. 1972 A calculation procedure for heat, mass and momentum transfer in three-dimensional arabolic ows. Int. J. Heat Mass Trans.15, 1787.
[4] F.R. Menter. Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications. AIAA Journal. 32(8). 1598–1605. August 1994.
[5] Hirt,C. W. & Nichols, B. D. Volume of fluid method for the dynamics of free boundaries. Comp. Phys.1981, 39(1): 201–225.
[6] A.Olivieri, F.Pistani, A.Avanzini,et al. Towing tank experiments of resistance, sinkage and trim, boundary layer, wake, and free surface flow around a naval combatant INSEAN 2340 model. IIHR Technical Report No.421, The University of Iowa, 2001.
[7] I. Senocak, G. Iaccarino. Progress towards RANS simulation of free-surface flow around modern ships. Center for Turbulence Research Annual Research Briefs 2005: 151–156.
[8] Carrica, P.M., Wilson, R.V., Stern, F., Ship Motions using Single-Phase Level Set with Dynamic Overset Grids, Comput. Fluids, Vol 36, 2007b, pp. 1415–33
[9] Sato Y, Miyata H, Sato T. CFD simulation of 3-dimensional motion of a ship in waves: application to an advancing ship in regular heading waves. Mar Sci Tech 1999;4:108–16.
[10] Dianpu Li. Ship motion and modeling. Beijing: National Defense Industry Press; 2008, pp. 14–21.
[11] Zhenbang Sheng, Yingzhong Liu. Principle of naval archinery,Vol.1. Shanghai: Shanghai Jiao Tong University Press; 2003, pp. 290–292.
[12] WU Ming, WANG Xiao, YANG Bo, SHI Aiguo, YANG Baozhang. Numerical Calculation Method for Resistance of Ship with Different Floating States. Navigation of China. Vol. 32 No. 3, Sep. 2009.