Simulation and selection of fin stabilizers for polar cruise ships based on Computational Fluid Dynamics

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Abstract: Polar cruise ships have high requirements for comfort, so it is an important problem to select fin stabilizers matching with the target ship. The underwater movement under the maximum sailing speed and the active anti-rolling of the fin stabilizers under the low sailing speed of an 8035 gross tonnage polar cruise ship are simulated by means of Computational Fluid Dynamics (CFD) simulation, and the hydrodynamic characteristics of the fin stabilizers are explored. The fin type of NACA0012 is selected for the target ship by analyzing the lift and drag characteristics of two common fin types of NACA0012 and NACA0015. The limiting fin angle of fin stabilizers is found to be about 15–20° at the maximum speed and about 30–35° at the low speed. The research results can provide a reference for the design and selection of fin stabilize.

1. Introduction
Polar cruise vessel has higher requirements in safety, comfort and environmental protection by comparing with ordinary cruise ships when it crosses the rough seas (SHI G J et al., 2018). As an active anti-roll device, fin stabilizers are divided into retractable and non-retractable stabilizers, which has important significance in reducing ship rolling motion and improving stability and tourist comfort. Considering the variability of polar environment and the safety of polar ships, the traditional non-retractable active fin stabilizers are not enough to meet the needs of polar navigation, and the marine environment such as floating ice may cause irreversible damage to them. At the same time, polar cruise ships require to maintain certain stability while berthing, so retractable active fin stabilizers have become the key equipment of polar cruise ships.

The fins of fin stabilizers are used as a device to provide stabilizing moment of the fin stabilizers, and its hydrodynamic performance will directly affect the anti-rolling ability of fin stabilizers. For the fin type, A model was established to determine the optimal maximum angle of the fin at about 20°, and the hydrodynamic performance of the fin is simulated under different sea conditions (Kraus, 2012). Andersen et al. concluded that the wake flow of the two fin types is similar through numerical and experimental studies on the swing and heaving of the symmetrical fin type (Andersen et al., 2017). Regarding the fin profile studied in this paper, Ohtake et al. obtained the fin shape parameters in steady flow field through a lot of research work. In this paper, the fin stabilizer matched with the target ship is studied and the hydrodynamic characteristics of the fin are obtained under the limitation of...
navigation area and maximum speed of polar cruise ship (Ohtake et al., 2007).

In this paper, the fin type selection is analyzed for the fin stabilizers of an 8035 gross tonnage polar cruise ship, and the relevant parameters of the fin type of the ship are discussed, which can provide reference for the fin stabilizers design of the polar cruise ships in the future.

2. Numerical calculation principle and method of fin stabilization

2.1. Governing equation

In this paper, the Navier-Stokes (N-S) equation is needed to solve the research problem, the time-average continuity equation RANS (Reynolds-Averaged Navier-Stoke) is obtained by applying the Reynolds time-average method, which is used to solve the external flows in conventional geometric models and has better convergence.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i \right) = 0
\]  

where, \( \rho \) is fluid density, \( u_i \) and \( u_j \) are respectively the rate of velocity change of fluid velocity in \( i \) and \( j \) direction, \( \rho u_i \) and \( \rho u_j \) are respectively the velocity pulsation in fluid velocity \( i \) and \( j \) direction, \( \delta_{ij} \) is the Kronecker delta tensor symbol.

2.2. Turbulence model

As the speed and angle of attack increase, turbulence will occur at the tail of the fin stabilizers, so the turbulence model adopted in this paper is the standard \( k-\varepsilon \) turbulence model, which is proposed by Launder and Spalding in 1972 after introducing a new equation about turbulence dissipation rate \( \varepsilon \) on the basis of the standard equation model. This model is currently the most widely used turbulence model:

\[
\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \varepsilon - Y_M
\]

\[
\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} \left( G_k + C_3 \varepsilon \right) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}
\]

where, \( k \) is turbulent kinetic energy, \( \varepsilon \) is dissipation rate, \( G_k \) is generated term of the turbulent kinetic energy \( k \) caused by the average velocity gradient, \( G_b \) is generated term of turbulent kinetic energy \( k \) caused by buoyancy effect, \( Y_M \) is the influence of compressible velocity turbulent pulsating expansion on the total dissipation rate, \( \mu_t \) is the turbulent viscosity coefficient varying with time, The values used as default constants in Fluent are \( C_{1\varepsilon} = 1.44 \), \( C_{2\varepsilon} = 1.92 \), \( C_3 = 2.0 \), \( \sigma_k = 1.0 \).

2.3. Numerical methods

Finite volume method is adopted for discretization method, the pressure equation is discretized in a standard discrete format. The momentum equation, dissipation equation and turbulent kinetic energy equation are discretized by the second-order upwind scheme. SIMPLE algorithm is used for pressure
and velocity coupling algorithm (YONEMOTO K, 2008). Unstructured grid is used to divide the whole basin at maximum speed, and the grid near the contact surface between the flow field and the fin is encrypted. At low speed, the inner domain is divided into structured grids to ensure the accuracy of calculation, while the outer domain is divided into unstructured grids.

3. Geometric modeling and meshing

3.1. Geometric models and computational domain division

The research object is a polar cruise ship with 8035 gross tonnages. The fin types of most fin stabilizers of ships are NACA0012 and NACA0015. Therefore, the fin types studied in this paper are NACA0012 and NACA0015 symmetrical fin types. The relevant data of the target ship is as follows:

| Ship form parameters                  | Parameter values |
|---------------------------------------|------------------|
| Ship length (L/m)                     | 104.4m           |
| Length between perpendiculars (Lbp/m) | 100.2m           |
| Molded breadth (B/m)                  | 18.2m            |
| Initial metacentric (GM/m)            | 1.516m           |
| Roll period (T/s)                     | 12s              |
| Service speed (v/kn)                  | 14kn             |
| Maximum speed (v/kn)                  | 16 kn            |
| Moulded depth (D/m)                   | 8.2m             |
| Designed draft (d/m)                  | 5.1m             |
| Ship gross tonnage (t)                | 8035t            |

In this paper, Profili2 is used to construct the standard fin types of NACA, with the maximum fin thickness at 30% chord length. The constructed data is taken into Solid Works to draw the fin type figure. The two-dimensional model of the fin stabilizers is shown in Fig. 1.

![Fig. 1. Fin plans of NACA0012 and NACA0015](image)

3.2. Meshing

3.2.1. Meshing of fin stabilizers at maximum speed

Meshing software MESHING of ANSYS is used to part the fins. The external fluid domain is established, the length of the fluid domain is 20 times the chord length in the X direction and 10 times the chord length in the Y direction. Non-structural mesh is used to part the fins, and mesh encryption is carried out on the surface of the fins to ensure the precision and accuracy of the later calculation. The grid is shown in Fig. 2.
3.2.2. Meshing of fin stabilizers at low speed

The sliding mesh technology is used to divide the fins at low speed, a two-dimensional mesh is used to divide the fin of NACA0012 (WU J L et al., 2017). Two computational domains are generated near the fin stabilizers and the outflow field. Sliding mesh technology is used between domain grids, which can not only realize the given motion but also save computing resources. High-quality mesh is adopted to capture the flow field details, because the flow is unsteady flow when fins themselves swing, and the fins are in a stall state at some angles. For this reason, the inner domain around the fins is divided by structured mesh and properly intensified, the other computing domains are unstructured mesh to simplify the meshing process. The meshing results are shown in Fig. 3.

3.3. Grid independence verification

It is necessary to verify the mesh independence after mesh division. The main purpose is to ensure the accuracy and rationality of model calculation, and the simulation results at 0° fin angle are selected to verify the grid independence.

| Table 2 Grid types and numbers |
|-------------------------------|------------------|------------------|
| Name of the grid | Total number of grids | Pitching moment coefficient (C_m) |
|-------------------|------------------------|-------------------------------|
| The grid 1        | 10,000                 | 0.772                         |
| The grid 2        | 20,000                 | 0.778                         |
| The grid 3        | 30,000                 | 0.777                         |

As can be seen from Table 2, the value of pitching moment coefficient basically remains stable when the number of grids is around 20,000 and 30,000. In order to accelerate the calculation speed,
grid 2, which is relatively accurate and has a fast calculation convergence speed, is used for calculation.

4. Selection and simulation results analysis

4.1. Analysis of lift coefficient and aspect ratio of fin stabilizers

The lifting force formula for calculating the regular speed of fin stabilizers is (China State Shipbuilding Corporation., 2013):

$$L = C_L \cdot \frac{1}{2} \rho V^2 \cdot S$$  \hspace{1cm} (5)

Where, \( \rho \) is seawater density (\( \text{kg/m}^3 \)), \( V \) is incoming flow velocity (m/s), \( S \) is fin area (m\(^2\)), and \( C_L \) is lift coefficient.

The slope of the lift curve, the relation between \( C_L \) and \( \alpha \) of the two-dimensional large aspect ratio fin, is almost linear before the stall angle. But it is often nonlinear for small aspect ratio (SONG J G et al., 2013). It is also related to aspect ratio \( \lambda \), sweep angle \( \alpha_s \) and many other factors. The formula for calculating the lift coefficient of fin stabilizers is summarized as follows:

$$C_L = \left[ \frac{a_0 \lambda}{\cos \alpha_s \left( \frac{\lambda^2}{4} + 4 + \frac{57.3 d_0}{\pi} \right)} \right] \alpha + \frac{C_{DC}}{\lambda} \left( \frac{\alpha}{57.3} \right)^2$$  \hspace{1cm} (6)

Where, \( a_0 = 0.9(2\pi/57.3)/(\degree) \) is the slope correction coefficient of lift curve, and \( C_{DC} \) is the square tip coefficient, which is related to the fin tip cutting ratio \( T \) and the shape of the fin tip. The square tip is set as \( C_{DC} = 0.8 \), and the smooth fin tip is set as \( C_{DC} = 0.4 \). The aspect ratio has the greatest effect on the slope of lift curve. In general, the smaller aspect ratio is, the smaller slope of the lift curve is. Fig. 4 is obtained from the above empirical formula.

![Fig. 4. \( C_{DC} = 0.4 \) and \( C_{DC} = 0.8 \), influence chart of aspect ratio and lift coefficient](image)

For the fin type with large aspect ratio, the relationship between lift coefficient and attack angle is approximately linear in the range of stall angle, and the degree of linearity and the slope of the curve gradually increase with the increase of aspect ratio (SONG J G et al., 2020). For the fin type with small aspect ratio, the degree of nonlinearity of lift characteristic curve is obviously enhanced, and the slope of the curve at zero angle of attack gradually increases with the increase of aspect ratio \( \lambda \).

It can be seen from Fig. 4 that maximum lift coefficient at the same fin angle is increased by decreasing aspect ratio, but too small aspect ratio will lead to lower lift coefficient in the range of...
small fin angle, and larger fin angle swing amplitude at low speed; The sensitivity distribution of lift coefficient to the angle of attack is unbalanced (the small fin angle is not sensitive, but the large fin angle is more sensitive), and the control stability decreases; At the same time, the maximum lift-drag ratio and the fin efficiency decreases, the navigation drag increases by decreasing aspect ratio.

The 8,035 gross tons polar cruise ship is scheduled to sail annually from Svalbard to Franz Josef Land Islands and Greenland from May to September; The annual planned sailing area is from the South Antarctic Peninsula to Mount Erebus in the Antarctic Strait, and from the West to Mount Trol from the end of October to the end of March, which requires a higher comfort for ships. For small yachts, the fin stabilizers are generally non-retractable due to the limitation of internal space, and the aspect ratio is generally about 0.35–1. For the purpose of this article, the choice of fin stabilizers should be retractable, because it should be able to recover fin box when smooth sailing. The type of low speed fin stabilizers is chosen as fin stabilizers need to have damping effect under the zero speed. Aspect ratio of retractable fin stabilizers is selected generally about 2, at the same time, the linear degree of lift curve is better.

4.2 Analysis of fin types selection
For NACA0012 and NACA0015 fin types, the curves of lift coefficient $c_l$, drag coefficient $c_d$ and lift-drag ratio $c_l/c_d$ under the maximum airspeed of fins are calculated by CFD software (Lv Y B et al., 2018), so as to analyze the use of two commonly used fin types on fin stabilizers.

As shown in Fig. 5–6, NACA0012 fin type has a better lift coefficient and a smaller aspect ratio at the same angle of attack, which is also reflected in the better performance of NACA0012 fin type in lift-drag ratio. In the range of 0–30° angle of attack, the hydrodynamic performance of NACA0012 fin type is better than that of NACA0015 fin type. Therefore, the fin type should be NACA0012 fin type for this target ship.
4.3. Constraint of fin angle analysis

Simulation analysis of NACA0012 fin stabilizers type at 0°, 10°, 20° and 30° is carried out at maximum speed, and the simulation cloud map is shown in Fig. 7~8.

Fig. 7. Velocity (m/s) cloud map of NACA0012 fin type at maximum speed

Fig. 8. Pressure (Pa) cloud map of NACA0012 fin type at maximum speed

At low speed, the simulation analysis of NACA0012 fin stabilizers type at 10°, 20°, 30° and 40° is shown in Fig. 9.
Fig. 9. NACA0012 fin type of fin stabilizers speed cloud map (m/s) at low speed

Taking the maximum speed of 16 knots of polar cruise ships as an example, the conversion flow velocity is 8.23 m/s, and the flow field is water flow. The water flow and the pressure on the fin surface of the fin stabilizers are simulated at the maximum speed. As can be seen from Fig. 7–8, negative pressure is generated on the upper fin surface of the fin stabilizers and serious eddy is formed on the upper fin surface of the tail of the fin tip. At the same time, too large local pressure is generated on the lower fin surface when the fin angle is 20°–30°, which leads to stalling (Mao L F et al., 2019). It is believed that the fin angle of the fin stabilizers should be controlled within 15°–20° at the maximum speed. Fig. 9 shows the active swing of the fin at a low speed with a swing speed of 0.5 rad/s. The vortex occurs at 35°–40° and the stall occurs. The fin angle swing is better controlled within 30°–35° at a low speed. In this way, the maximum fin angle of the fin stabilizers is found and it should be limited.

5. Conclusions

For a polar cruise ship with 8,035 gross tonnage, the hydrodynamic analysis of NACA0012 and NACA0015 two types of stabilizer fins is conducted by CFD method. It is confirmed that NACA0012 is more recommended to be used as the fin stabilizers of the polar cruise ships, and the retractable fin stabilizers with an aspect ratio about \( \lambda = 2 \) should be selected. In fin stabilizers design, the fin angle should be controlled within 15°–20° at the maximum speed and within 30°–35° when the active swing is at low speed. This conclusion can provide theoretical reference for the selection and design of fin stabilizers and has certain engineering practical significance.

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