A Method to Get Capture Area of a Waterjet Propulsor Inlet Duct Based on Grid Filter Weighting

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Abstract—In order to get capture area and calculate performance of a waterjet propulsor inlet duct conveniently and fast, grid filter weighting method is proposed based on Computational Fluid Dynamic (CFD) technology in this paper. Numerical simulating of the inlet duct is carried out. Implementation process of this method is discussed in detail. With processing the data of solving results, parameters in capture area are got under different Inlet Velocity Ratio (IVR) condition with this method. Efficiency and hydraulic loss of the inlet duct are calculated for the waterjet propulsor. The results are compared with that got with semi-elliptical fitting method. The calculation results obtained with both methods show good consistency. When IVR equals to 0.6, the efficiency reaches a maximum value, about 0.943. And the hydraulic loss reaches a minimum value, about 0.76. In the whole IVR range, the relative error of efficiency between these two methods is less than 0.2%. The relative error of hydraulic loss of the inlet duct between these two methods is less than 1.3%. The calculating process and results show that this method is convenient to calculate efficiency and hydraulic loss of the waterjet propulsor inlet duct. It can be easily inserted into automatic optimization process of an inlet duct to improve thrust performance of vehicles equipped with waterjet propulsors.

Keywords—Waterjet propulsion; Inlet duct; Capture area; CFD

I. INTRODUCTION

As one kind of efficient propulsion equipment, waterjet propulsors have been widely used on high-speed ships. Especially on waterjet propelled unmanned surface vehicles, researchers have paid a high degree of attention and put a lot of research effort [1, 2]. In order to improve the efficiency of thrust system, an effective inlet duct is required for a waterjet propulsor. The 24th International Towing Tank Conference (ITTC) defined the efficiency of an inlet duct as the ratio of outlet area average velocity to inlet average velocity. Set the value of IVR to 0.8. Then methods to get capture area include test method and numerical methods. Test method is generally using carbon monoxide to track route of fluid and getting the shape of flow tube [6]. Equipments of test method are complex and uneconomic. It is difficult to achieve. Currently, numerical methods are commonly used. Numerical methods include reverse tracing streamline method [7] and solving the additional scalar equation method [8]. The 24th ITTC recommended using a semi-elliptical shape to fit the capture area [3]. Reference [9] also proved this method. Wang et al [10] calculated efficiency of a waterjet propulsor inlet duct with semi-elliptical fitting method. Numerical methods which researchers have used need to adjust a correction parameter by manual work. It is not convenient to calculate efficiency of an inlet duct fast, especially to build an automatic optimization process for an inlet duct.

In order to get capture area of a waterjet propulsor inlet duct, calculate its performances conveniently and fast, and achieve an automatic and programmed process, more appropriate method is imminently required. In this paper, grid filter weighting method is proposed based on CFD technology. Its implementation process is discussed in detail. And it is used to calculate efficiency and hydraulic loss of an inlet duct under different IVR conditions. The results are compared with that obtained with semi-elliptical fitting method.

II. CFD SIMULATION

The inlet duct model, CFD domain and boundary conditions are shown in Fig. 1. The fluid domain is set to be 20D long, 8D wide and 6D high based on experience [11]. D is diameter of impeller. Unstructured mesh is generated for the fluid domain. Due to little impact of prism grid for inlet duct performance and we just explore the method of getting the capture area, prism grids are not generated when simulating the inlet duct. The inlet speed is set to be 15 knots, equal to cruising speed of vessels. Define inlet velocity ratio IVR as the ratio of outlet area average velocity to inlet average velocity. Set the value of IVR to 0.8. Then we can get boundary condition of mass flow outlet based on IVR, inlet speed and water density. Ship hull and inlet duct
wall are set to no-slip wall. Other three sides of the fluid domain are set to free-slip wall. With CFD solving and post, all parameters of every grid in the fluid domain can be obtained.

Fig. 1. The CFD domain and boundary conditions

III. GETTING CAPTURE AREA

A. Semi-elliptical Fitting Method

Based on ITTC suggestion, Streamlines built from outlet area and location of capture area plane are shown in Fig. 2. Semi-elliptical fitting method which reference [9] has used is fitting the edge of streamline area on the plane with a semi-ellipse. By introducing an offset value $M$, and setting $M$ to be minimum, ensuring the mass flow through capture area equal to that through outlet area of the inlet duct synchronously, the major and minor axis size of the semi-ellipse are determined. The capture area got with this method is shown in Fig. 3.

Fig. 2. Streamlines and capture area location

Fig. 3. Capture area got with semi-elliptical fitting method

B. Grid Filter Weighting Method

When building and optimizing an inlet duct model, it needs to calculate performances of the inlet duct repeatedly. Semi-elliptical fitting method needs to determine the offset value $M$ artificially in each calculation, which is inconvenient. To solve this problem, we propose a fully programmed calculation method – grid filter weighting method.

The idea of grid filter weighting method is filtering all elements on the capture area plane shown in Fig. 2. Elements meeting a filter rule are retained. Others not meeting the rule are removed. Then the retained elements form capture area of the inlet duct. The filter rule is comparing the minimum distance from each element on the plane to streamlines with average distance among all streamlines. Then whether an element is entirely or partly in the capture area is determined.

In Fig. 4, the semi-ellipse represents the edge of streamlines distribution shown in Fig. 2. Minimum distance from each element on the plane to streamlines is set to $d_{\text{min}}$. A weighting parameter $\lambda_i$ is assigned to each element. The value of weighting parameter $\lambda_i$ depends on the compare result between the minimize distance $d_{\text{min}}$ and average distance among streamlines.

Fig. 4. Elements of different weighting parameter

The average distance between the streamlines is $\bar{d}$

$$\bar{d} = \sqrt{\frac{\pi D^2 \cdot VR}{4n}}$$

(1)

The variable $n$ is the number of streamlines. Calculate the minimize distance $d_{\text{min}}$ from each element point on the capture area plane to the streamlines, and filter the points that

$$d_{\text{min}} < \bar{d} \leq d_{\text{min}} < 2\bar{d}$$

(2)

The weighting parameter $\lambda_i$ of elements satisfying $d_{\text{min}} < \bar{d}$ is set to 1, just like point $P_3$ in Fig. 4. The weighting parameter of elements satisfying $\bar{d} \leq d_{\text{min}} < 2\bar{d}$ is set to $\lambda_i$, just like the point $P_2$ in Fig. 4, where
The weighting parameter \( \lambda_i \) of elements satisfying \( d_{\text{min}} \geq 2\bar{d} \) is set to 0, just like the point \( P_1 \) in Fig. 4. Then the distribution of these points is obtained, as shown in Fig. 5. It is the capture area shape.

\[
\lambda = \frac{2\bar{d} - d_{\text{min}}}{\bar{d}}
\]

The weighting parameter \( \lambda_i \) of elements satisfying \( d_{\text{min}} \geq 2\bar{d} \) is set to 0, just like the point \( P_1 \) in Fig. 4. Then the distribution of these points is obtained, as shown in Fig. 5. It is the capture area shape.

\[
\lambda = \frac{2\bar{d} - d_{\text{min}}}{\bar{d}}
\]

For the points \( \bar{d} \leq d_{\text{min}} < 2\bar{d} \), a total weighting parameter \( \bar{\lambda} \) is introduced to keep mass flow through the capture area equal to that through the outlet area, scilicet

\[
\begin{align*}
Q_{\text{inlet}} &= \sum Q_{d_{\text{min}} < \bar{d}} + \bar{\lambda} \sum Q_{d_{\text{min}} < 2\bar{d}} = Q_{\text{outlet}}
\end{align*}
\]

When the efficiency and hydraulic loss of the inlet duct are calculated, the pressure and velocity parameters of elements in the capture area are unchanging. But the mass flow and area value of each element in the capture area are changed to

\[
\begin{align*}
Q &= \begin{cases} 
Q_i & d_{\text{min}} < \bar{d} \\
\bar{\lambda}_i Q_i & \bar{d} \leq d_{\text{min}} < 2\bar{d}
\end{cases} \\
A &= \begin{cases} 
A_i & d_{\text{min}} < \bar{d} \\
\bar{\lambda}_i A_i & \bar{d} \leq d_{\text{min}} < 2\bar{d}
\end{cases}
\end{align*}
\]

Obtaining flow parameters in capture area with this method needs to calculate the distance from each element to each streamline. In order to save computing time and improve the computational efficiency, a location comparing process is carried out. Comparing coordinate \((x, y)\) of each element on capture area plane with coordinate extremum \((x_{\text{min}}, y_{\text{min}}), (x_{\text{max}}, y_{\text{max}})\) of streamline distribution, elements satisfying (7) are separated. It can greatly improve computing speed for the inlet duct performance and reduce time of calculation.

\[
\begin{align*}
x_{\text{min}} - 2\bar{d} &< x < x_{\text{max}} + 2\bar{d} \\
y_{\text{min}} - 2\bar{d} &< y < y_{\text{max}} + 2\bar{d}
\end{align*}
\]

This method does not need to adjust a correction parameter with manual work. The weighting parameter of each element can be calculated with EXCEL VBA program easily.

**IV. Calculating Efficiency and Hydraulic Loss of the Inlet Duct**

The 24th ITTC defined the efficiency of an inlet duct as follow:

\[
\eta_{\text{out}} = \frac{\int \frac{1}{2} \rho u_i^2 + (p_i - p_0) - \rho g z_i \, dQ_i}{\int \frac{1}{2} \rho u_0^2 + (p_0 - p_0) - \rho g z_0 \, dQ_i}
\]

The subscripts 1, 2 represent capture area and outlet area of the inlet duct, and the variable \( p_0 \) represent reference pressure.

Another coefficient to evaluate performance of the inlet duct is hydraulic loss \( \Delta h \), which is the difference between energy on capture area and energy on outlet area. \( \Delta h \) can be written as follow:

\[
\Delta h = \frac{\sum \left[ Z_i + \frac{p_i}{\rho g} + \frac{v_i^2}{2g} \right] A_i}{\sum A_i} - \frac{\sum \left[ Z_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} \right] A_2} {\sum A_2}
\]

\( A_i \) is the area of each element in the capture area.

Calculating efficiency and hydraulic loss of the inlet duct with grid filter weighting method, comparing the results with that calculated with semi-elliptical fitting method which ITTC suggested, the efficiency and hydraulic loss curves corresponding under different \( IVR \) conditions can be obtained, as shown in Fig. 6 and Fig. 7.

From Fig. 6 and Fig. 7, it can be seen that the efficiency and hydraulic loss curves show good consistency between these two methods. All curves can reflect performance of the inlet duct corresponding to \( IVR \). When \( IVR \) equals to 0.6, the efficiency reach a maximum value, about 0.943. And the hydraulic loss reach a minimum value, about 0.76. In whole \( IVR \) range, the inlet duct has best performance at this condition.
When $IVR$ is equal to 0.8, the capture area shape got with semi-elliptical fitting method and the capture area distribution got with grid filter weighting method are shown in Fig. 8. The solid line is the edge of the capture area got with semi-elliptical fitting method. Different marked points represent different elements satisfying filter rules. It can be seen that elements satisfying $d_{\min} < \bar{d}$ are all inside the semi-ellipse. Other elements satisfying $\bar{d} \leq d_{\min} < 2\bar{d}$ are near the semi-ellipse edge. Capture areas with these two methods are basically the same.

Efficiency and hydraulic loss calculated with these two methods have some error. The error depends on the mesh types, mesh density, flow conditions, boundary conditions, etc. Relative error corresponding with $IVR$ between the results calculated with these two methods are shown in Fig. 9. It can be seen that relative error of efficiency is less than 0.2% and relative error of hydraulic loss is less than 1.3%. It proves that accuracy of grid filter weighting method is acceptable. The method can be applied to engineering computing.

V. CONCLUSION

Grid filter weighting method can be used to get capture area and automatically calculate performance of an inlet duct. Compared with semi-elliptical fitting method, it is more convenient as it does not require manual adjustment of a correction factor. Using recorded script and data processing program, performance of inlet ducts can be calculated quickly. Its accuracy is acceptable. Relative errors are within the allowable range of engineering computing. It is significant that it can be inserted into an automatic optimization process to optimize an inlet duct and improve the thrust performance of vehicles equipped with waterjet propulsors.

REFERENCES

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