Study of underwater vehicle’s bubbly wake caused by side exhausting

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Abstract. The bubbly wake characteristics of the underwater vehicle are the basic of wake homing techniques. The bubbly wake of the underwater vehicle caused by the side exhausting is simulated based on the Mixture model and the Multiple Reference Frames technology. The results show that due to the side exhausting of the underwater vehicle, a wake with lots of bubbles appears in the sailing through area. The bubbly wake of the underwater vehicle lasts for a long time. As a result, the bubbly wake can be observed in the area far away from the underwater vehicle, which is signification enough to be detected by the bubbly wake detector. Besides, the bubbly wake characteristics for the cases of the underwater vehicle with/without the propeller are much different.

1. Introduction

When the surface ship is sailing in the sea, a wake with lots of bubbles appears in the sailing through area. Similarly, when the underwater vehicle is sailing in the sea, it is also able to cause the bubbly wake. Obvious optical scattering is caused by the bubbly wake of the underwater vehicle, which is the basic of wake homing techniques. As a result, finding out the characteristics of the underwater vehicle’s bubbly wake in the sea is important for the development of anti-underwater vehicle techniques, and draws more and more attentions in recent years [1].

There have been a lot of works on the study of the bubbly wake, including experiments [2] in laboratories and simulations via computers [3]. However, there are few researches on the evolution of the underwater vehicle’s bubbly wake. Jiang has simulated the movement characteristics of single bubble based on VOF model [4]. In order to examine the overall evolution progress of the bubbly wake, the crowd effect of a large number of bubbles should be considered [5].

The bubbly wake of the underwater vehicle caused by the side exhausting is simulated based on the Mixture model, and the influence of the exhausting bubble diameter and the velocity of the underwater vehicle on the evolution of the bubbly wake is analyzed. Besides, the MRF technology is applied to simulate the bubbly wake of the underwater vehicle with propeller. The bubbly wake characteristics of the underwater vehicle with/without propeller are compared. The results obtained by this paper are directive for the counteraction.
2. Math-physical model

2.1. Mathematical model

The evolution progress of the underwater vehicle’s bubbly wake in the sea is complicated, which is related to the underwater vehicle’s shape, flow mechanics, and so on. Mixture model is adopted to simulate the evolution progress of the underwater vehicle’s bubbly wake. The RANS model is adopted to simulate the flow fields. The MRF technology is used to simulate the rotational motion of the underwater vehicle’s propeller.

The control equation of energy, mass and momentum can be written in a uniform equation as fellow.

\[
\frac{d}{dt} \int_{V} \rho \phi dV + \oint_{S} \rho \phi \mathbf{u} \cdot d\mathbf{A} = \int_{V} \nabla \cdot \mathbf{S} dV + \oint_{S} \Gamma \phi d\mathbf{A}
\]

Where, \( \phi \) is the common variable, such as velocity and pressure. \( \rho \) is the density. \( V \) denotes the control volume, and denotes the boundaries of the control volume. \( A \) stands for the normal vector of the boundary surfaces of the control volume. \( \mathbf{u} \) is the velocity. \( \Gamma \) is the diffusion coefficient. \( S \) is the source item with regards to the variable \( \phi \).

2.2. Physical model

The 3D model of the Suboff is used in this paper. The size of the Suboff model is amplified to 110m in length and 12m in diameter. To reduce the boundary effect but save the computational resources simultaneously, the computational domain is set with 1000m in length and 200m in diameter, as shown in Fig.1. There is an exhaust outlet of 1m long and 0.2m wide on the port/starboard, respectively, where the exhausting bubbles come out. The origin of coordinates and the most front of the Suboff overlap, and the back wall is 900m away from the origin.

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Fig. 1 The computational domain

Fig. 2 The side exhaust outlet
3. Calculation and Analysis

3.1. Mesh method
The hybrid meshes are used to discrete the computational zones. Unstructured meshes and structured meshes are generated in the domains around and away from the Suboff, respectively, as shown in Fig.3. The calculations are conducted via the Fluent software. After conducting the mesh size independence verification, 8.5 million meshes are used for the calculation.

![Fig. 3 The generated hybrid meshes](image)

3.2. Boundary conditions
The incoming flow method is used to conduct the calculations, that is, the Suboff remain still, the water flows to the Suboff in at the opposite speed. The incoming flow is along the x axis. Boundary condition for numerical are set as shown in Fig.4.

![Fig. 4 The boundary condition](image)

The inlet of sea water (inlet1), the outlets of exhausting bubbles (inlet2 and inlet3) and far-field boundary (inlet4) are set as velocity inlets. The outlet of two-phase flow (outlet) is set as pressure outlet. The surface of the Suboff is set as non-slip wall. In the computation of the bubbly wake of the underwater vehicle with propeller, the domain around the Suboff rotates around the x axis.

3.3. Results and analysis

3.3.1. The overall distribution of the bubbly wake. The bubbly wake is the crowd effect of a large number of bubbles, which is characterized by the air volume fraction in seawater. The overall distribution of bubbly wake of the Suboff without propeller is shown in Fig.5, where the speed of the Suboff is 3m/s, the speed of exhausting is 0.01m/s and the radius of bubbles is 0.001mm. Due to the side exhausting of the underwater vehicle, a wake with lots of bubbles appears in the sailing through area, as shown in Fig.5. As the result of buoyancy and diffusion effect, the bubbles rise and spread over time, which performance as a decrease in the z coordinate of the maximum air volume fraction of the plane x section and an increase in the maximum air volume fraction of the plane x with x increases, respectively, as shown in Fig.6 and Fig.7.

![Fig. 5 Air volume fraction of the plane z=0](image)
3.3.2. The influence of the bubble radius on the bubbly wake. Assuming the speed of the Suboff is 3m/s and the speed of exhausting is 0.01m/s, the bubbly wakes of the Suboff with the radius of exhausting bubbles r=0.0001m, 0.0005m, and 0.001m are simulated, respectively.
As mentioned earlier, the maximum air volume fraction of the plane x decreases from $3.70 \times 10^{-5}$ to $0.70 \times 10^{-5}$ as x increases from 150m to 900m for r=0.001m. For r=0.0001m and 0.0005m, there are similar situations. The maximum air volume fraction of the plane x=900m section decreases from $5.56 \times 10^{-5}$ to $3.25 \times 10^{-5}$ with the radius of exhausting bubbles increases from 0.0001m to 0.001m. There are similar trends for other x sections, as shown in Fig.8.

Fig. 9 Influence of the bubble radius on z coordinate of the maximum air volume fraction of x planes

The z coordinate of the maximum air volume fraction of the plane x decreases from 3.75m to 31.9m as x increases for r=0.001m. For r=0.0001m and 0.0005, there are similar situations. The z coordinate of the maximum air volume fraction of the plane x=900m section increases from 3.83m to 31.9m with the radius of bubble increases from 0.0001m to 0.001m. There are similar trends for other x sections, as shown in Fig. 9.

The simulated results show that the bubbles in the bubbly wake rise and spread accelerate as the radius of exhausting bubble increases.

3.3.3. The influence of speed of the Suboff on the bubbly wake. Assuming the radius of exhausting bubbles is 0.0005m and the speed of exhausting is 0.01m/s, the bubbly wakes of the Suboff with the speed of the Suboff v=3m/s, 4.5m/s, and 6m/s are simulated, respectively.

Fig. 10 Influence of the speed of the Suboff on the maximum air volume fraction of x planes
The maximum air volume fraction in the plane $x=200\text{m}$ section decreases from $4.01 \times 10^{-5}$ to $2.37 \times 10^{-5}$ with the speed of the Suboff increases from 3m/s to 6m/s, there are similar trends for other $x$ sections, as shown in Fig.10.

![Graph](image1.png)

**Fig. 10** Influence of the speed of the Suboff on the $z$ coordinate of the maximum air volume fraction of $x$ planes

The $z$ coordinate of the maximum air volume fraction of the plane $x=900\text{m}$ section increases from 17.46m to 9.45m with the speed of the Suboff increases from 3m/s to 6m/s, there are similar trends for other $x$ sections, as shown in Fig.11.

The simulated results show that the bubbles in the bubbly wake rise and spread accelerate as the speed of the Suboff increases.

**3.3.4. The comparison of with propeller and without propeller.** To make a comparison, the maximum air volume fraction of the $x$ planes with/without propeller are given by Fig. 12, and the $z$ coordinate of the maximum air volume fraction of the $x$ planes are shown in Fig. 13. Where the radius of exhausting bubbles is 0.0001m and the speed of exhausting is 0.012m/s and the speed of the Suboff is 3m/s. The results show that the propeller’s stirring effect accelerates the spread of bubbly wake, and celebrates the rise of bubbly wake.

![Graph](image2.png)

**Fig. 12** The maximum air volume fraction of $x$ planes with/without propeller
4. Conclusion

In this paper, a method based on Mixture model is used to simulate the bubbly wake of the Suboff in the sea. The results show that due to buoyancy and diffusion effects, the exhausting bubbles appear to rise and spread over time. The exhausting bubbles rise and to spread accelerate as the radius of exhausting bubbles and the speed of the Suboff increase. For the Suboff with propeller the distribution of bubbly wake is much different from the case of without propeller.

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