Study on Re-entrant Jet Pressure Characteristics of Ventilated Cavitating Vehicles

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Abstract. When the re-entrant jet phenomenon generation at the end of ventilated cavity, body surface form high pressure under the meanflow impact. This high pressure moves downstream with the development of ventilated cavitation, and will arouses significant effect on the motion stability of the body. Based on this, this paper through the experimental observation of the reentrant jet phenomenon, captures the characteristics of the pressure surface, the dynamic changes of the re-entrant jet pressure of the underwater vehicle during the development of the cavity are studied. The relationship between the velocity of the cavity and the characteristics of the re-entrant jet pressure is obtained, and under the condition of the vehicle at the angle of water shot back pressure feature. The results show that the re-entrant jet pressure is much higher than the pressure inside the cavity, and the re-entrant jet pressure is obviously changed with the development of the cavities. There are differences in the pressure characteristics between the surface and the back surface.

Introduction

There are broad application prospects by using of ventilated cavity drag reduction and load shedding in the militarily. A large number of studies have been conducted on cavitation flow by worldwide researchers in recent years[1-3]. In the development and generation of ventilated cavity, the re-entrant jet phenomenon generates at the end of ventilated cavity, and body surface form high pressure under the mean-flow impact. The re-entrant jet pressure affects the deflating rate of the cavitation tail and is an important factor affecting the stability of the cavitation. There-entrant jet pressure moves downstream with the development and collapses of ventilated cavitation, and will arouses significant effect on the motion stability of the body. Therefore, it is deeply theoretical and practical significance to study on re-entrant jet pressure characteristics.

A large number of studies have carried out on the re-entrant jet phenomenon at the end of ventilated cavity. In theoretical research, researchers conduct cavitation flow research based on potential flow theory. The method can obtain the re-entrant jet pressure distribution on the surface of the vehicle by theoretical calculation of the cavity closure model[4-5]. In the experimental research, the researchers have carried out a lot of research on the development speed of the re-entrant jet, the unsteady change characteristics, the influence on the stability of the cavity, and the passive control of the re-entrant jet. Knapp[6] first studied the phenomenon of re-entrant jet flow around a cylindrical cloud cavitation, and obtained the change rule of the flow field of there-entrant jet flow. Callenaere[7] studied the phenomenon of unsteady re-entrant jet in hydrofoil and Venturi tubes, and found that the recurrent flows in the cloud and flaky cavitation flow displayed periodic variation trends. Franc[8] studied the relationship between the stability of the local cavity around the hydrofoil and the re-entrant jet flow. The study shows that the re-entrant jet is an important factor affecting the stability of the cavity. Sato[9] controlled the re-entrant jet flow by adding obstacles on the surface of the model. The experimental results showed that the re-entrant jet phenomenon could be prevented by placing obstacles, but the frequency of cavitation shedding did not change. Stutz[10] gave a quantitative measure of the velocity of the upstream movement of the re-entrant jet, and found that the velocity of the re-entrant jet was of the same order as the mainstream velocity. Huang[11] used the particle imaging velocimetry system to test the development process of unsteady cloud cavitation.
The results showed that the unsteady cavitation presents a quasi-periodic process of generation-development-breaking-shedding, and the vortex motion of the cavitation tail itself led to the generation of the re-entrant jet, the interaction of the retro reflective stream and the main stream caused periodic shedding of the cavitation. Wang [12] used the simultaneous measurement technology of full flow field display system and dynamic pressure measurement system to study the mechanism of the adhesion cavity collapse and shedding caused by the re-entrant jet. It is indicated that the re-entrant jet is formed at the tail of the attached cavitation, the thickness was much smaller than the thickness of the cavity, and when the re-entrant jet moved to the leading edge of the attached cavity, the "cutting" of the attached cavity was "cut", causing the hole to break and fall off.

In summary, the existing research mainly focused on the formation mechanism of re-entrant jet, the influence of re-entrant jet on the development of cavitation and the stability of cavity, the flow characteristics of re-entrant jet, and the control of re-entrant jet. However, there are fewer published literatures on the effects of re-entrant jet about the hydrodynamic characteristics of underwater vehicles. Based on this, the re-entrant jet phenomenon is observed by the cavitation water tunnel experiment, and the pressure of each measuring point on the surface of the underwater vehicle is captured in real time. The characteristics of the re-entrant jet pressure on the surface of the navigation body during the development of the cavitation are studied. Considering the asymmetrical stress, the re-entrant jet pressure will affect the stability of the motion of the vehicle. At the same time, the variation characteristics of the re-entrant jet pressure of the navigation body under the angle of attack are studied.

**Experimental Equipment and Experimental Methods**

Ventilated cavity experiments carry out in a closed water tunnel equipped with a pressure relief tank and a degassing device. The working section of the water tunnel is 2.6 meters long and has a square cross section of 0.6m×0.6m. It is equipped with 8 large-size detachable plexiglass observation windows. The adjustment range of water tunnel pressure is from 0Kpa to 200Kpa. The working section velocity uniformity and stability are all less than or equal to 1%, and the water tunnel background noise is low. The water tunnel is equipped with a computer control and management system, a degassing device and a data acquisition system.

The experiment uses an external ventilation system, a pressure measurement system, and a photographic camera system. The ventilation system uses the air compressor as the air source. The compressed air flowing out from the air compressor enters the air reservoir through the pressure reducing control valve, and after been regulated by the air reservoir, flows through the flow controller to the ventilation chamber of the navigation body, ejected from the model head vent. The air flow meter MFC-1000LPM-D/5V mass flow controller used in the test can control the ventilation flow by programming. The flow controller's range is 0-1000L/min respectively. The pressure measurement system consists of a pressure sensor and a data acquisition system. The pressure sensors are arranged on the surface of the model. The outer diameter of the sensor is 5mm, the length is 15mm, the range is 0-300kPa, the nonlinear error and repeatability error are all less than or equal to 0.5%, and the frequency response is greater than 2KHz. The whole process of the test is carried out by color high-speed photography that the shooting frequency is 2000 frames/s.

In this experiment, under the condition of steady flow velocity and working section pressure, the ventilating system is used to ventilate the shoulder of the model. The time history of the model surface pressure recorded by the pressure measuring system, and the development history of the cavity morphology is observed by the high-speed photography system. The NI acquisition processor is used to simultaneously process water tunnel velocity, water tunnel pressure, surface pressure of the vehicle, ventilation flow, and high-speed camera system acquisition signals, as shown in Figure 1. The pressure sensor at 10 different sections of the model surface uses to capture there-entrant jet pressure at different locations of the model.
Re-entrant Jet and Re-entrant Jet Pressure Phenomenon of Ventilated Cavity

The experimental results show that when the re-entrant jet phenomenon generation at the end of ventilated cavity, the surface of the model will also form a higher pressure due to the impact of the mainstream fluid, which is the re-entrant jet pressure. Figure 2 shows the curves of pressure of the two measuring points on the surface of the model changing with operating time. In this diagram, x is the distance from the measuring point to the vertex of the model head, and D is the diameter of the model. It can see from the figure that as time passes, the pressures of the two measuring points on the surface of the vehicles body successively appear peaks, the pressure of the measuring point near the head of the model first appears peak, and then the peak of the measuring point farther away from the model appears. Figure 3 shows the cavitation morphology corresponding to the pressure peak at two measuring points. Comparing the two figures, we can see that when t=3.4604s, the pressure at the measuring point 1 reaches a peak (see Figure 2). At this time, the measuring point 1 is located at the closure of the cavitation tail, and the cavitation tail produces the phenomenon of re-entrant jet. The pressure peak captured by the measuring point 1 is the re-entrant jet pressure, and the value is 32.40KPa. When t=3.4961s, the pressure at measuring point 2 peaked, the cavitation tail developed to measuring point 2, and the re-entrant jet pressure captured by measuring point 2 is 33.89kpa. When t>3.5356s, as the cavitation continues to develop, both measuring points wrapped by cavity, and the pressure at both measuring points is the pressure inside the cavitation. Since the pressure at each position in the cavitation is basically the same at the same time, the pressure change law of the two measuring points is also consistent. It can also see from experimental that the pressure at the measuring point on the surface of the body decreases after the cavitation wrapped, and the re-entrant jet pressure is much higher than the pressure inside the cavitation. The re-entrant jet pressure and the pressure inside the cavitation work together to form a higher adverse pressure gradient. Under the action of the adverse pressure gradient, the water flow will enter the cavitation, that is, the re-entrant jet described above.
Characteristics of Re-entrant Jet Pressure on the Surface of the Vehicle

When the cavitation wraps from the head of the model to the tail, the development speed of the cavitation gradually increases, as shown in table 1. L is the model length, V is the cavitation development velocity, $V_\infty$ is the flow velocity, $P_{jet,c}$ is the re-entrant jet pressure, and $P_c$ is the pressure inside the cavitation. When the cavitation wraps in the middle of the model, the development velocity of the cavitation is 0.723 times of the velocity of the mainstream fluid, and the re-entrant jet pressure is 1.347 times of the pressure inside the cavitation. When the cavitation wraps to the tail of the vehicle, the development velocity of the cavitation is 0.913 times of the velocity of the mainstream fluid, and the re-entrant jet pressure is 1.214 times of the pressure inside the cavitation. That as time goes on, the development of cavitation velocity increases. This is because when the cavitation not wrapped, affected by the low pressure at the bottom of the model, the low surface pressure at the back of the model is conducive to the development of the cavitation. As shown in figure 2, the pressure of measuring point 2 before the cavitation wrapping is significantly lower than that of measuring point 1 at the front of the model, which causes the speed of the cavitation moving towards the tail of the model to increase. It can also be seen from table 1 that with the increase of the development velocity of cavitation, the re-entrant jet pressure captured on the model surface gradually decreases.
Table 1. Cavity development rate.

<table>
<thead>
<tr>
<th>Cavity morphology</th>
<th>Cavity end wrap position(x/L)</th>
<th>Cavitation dimensionless development(V_c/V_∞)</th>
<th>The ratio of the re-entrant jet pressure to the cavitation pressure( P_{jet,c} / P_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.46</td>
<td>0.723</td>
<td>1.1224</td>
</tr>
<tr>
<td></td>
<td>0.62</td>
<td>0.795</td>
<td>1.0671</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>0.845</td>
<td>1.0383</td>
</tr>
<tr>
<td></td>
<td>0.92</td>
<td>0.913</td>
<td>1.012</td>
</tr>
</tbody>
</table>

Concerning the relationship between there-entrant jet pressure and the development velocity of cavitation, literature [13] deduced that the re-entrant jet pressure point is the stagnation point in the pressure coordinate system based on the potential flow theory, and the absolute flow field velocity of the re-entrant jet pressure point is \( u = V - V_L \). Therefore, with respect to the free surface at infinity, write the Cauchy-Lagrange Integral of the re-entrant jet pressure point, and get:

\[
\frac{\partial^* \phi}{\partial t} - \frac{(V - V_L)^2}{2} + \frac{P_{jet,c}}{\rho} - g(h + L) = \frac{P_0}{\rho}
\]  

(1)

Where \( P_{jet,c} \) is the re-entrant jet pressure, \( P_0 \) is the background pressure, \( h \) is the depth of the water, \( L \) is the model length when launched vertically under water and when launched horizontally is 0 m, \( V \) is the flow velocity, \( V_L \) is the cavitation development velocity, \( \frac{\partial^* \phi}{\partial t} \) is the unsteady term of the re-entrant jet pressure, which is related to the axial additional mass. For the slender body shape or horizontally moving object, it can ignore.

Formula (1) can be simplified as follows:

\[
\frac{P_{jet,c}}{\rho} \approx \frac{P_0}{\rho} + g(h + L) + \frac{(V - V_L)^2}{2}
\]  

(2)

In this paper, the unsteady cavitation morphology obtained by high-speed camera is used to give the development speed of cavitation \( V_L \). The re-entrant jet pressure \( P_{jet,c} \) calculates based on formula (2). The calculated re-entrant jet pressure \( P_{jet,c} \) compares with the re-entrant jet pressure \( P_{jet,c} \) captured by the measurement point in the experiment. Figure 4 shows the comparison results. The calculated re-entrant jet pressure is in good agreement with the experimental results. The experimental and theoretical results show that the re-entrant jet pressure decreases with the increase of the cavitation development velocity.
Influence of Angle of Attack on Re-entrant Jet Pressure

The above test results are mainly for the distribution of the re-entrant jet pressure of the model surface when the angle of attack of the vehicle is 0, the Froude number is large, and the cavitation form is basically symmetrical. However, the underwater vehicle will present asymmetric condition in the process of motion. At this time, the rapid movement of the re-entrant jet pressure on the surface of the vehicle will affect the stability of the vehicle. Therefore, the dynamic pressure characteristics of the surface of the vehicle at the angle of attack are studied. This paper mainly studies the forward angle of attack of the vehicle.

The results show that, when the vehicle has an angle of attack, the length of the upstream surface cavity is shorter than the length of the back surface cavity. The re-entrant jet zone at the end of the upstream surface cavity corresponds to the inner zone of the back surface cavity, and the re-entrant jet zone at the end of the back surface cavity corresponds to the wet zone downstream of the upstream surface, as shown in Figure 5. Figure 6 and Figure 7 respectively show the variation curves of pressure and pressure difference over time on the upstream surface and the back surface. Compared with the re-entrant jet pressure of the upstream surface, the re-entrant jet pressure on the back surface of the water generates earlier, the re-entrant jet pressure is lower, resulting in a relatively small surface pressure difference of the vehicle. The variation of the upstream surface and back surface pressure is affected by ventilation volume, cavitation number, length of the surface cavitation, angle of attack, environmental pressure and other factors. Further analysis of influencing factors is needed in the future.

Figure 4. The experimental results of re-entrant jet pressure are compared with the calculated results.

Figure 5. Cavity shape at attack angle.
Conclusion

The phenomenon of re-entrant jet in the development of cavitation is studied by water tunnel experiment, and the characteristics of re-entrant jet pressure on the surface of vehicle body are analyzed. The main conclusions of this paper are as follows:

1) Under the action of the reverse pressure gradient, the water flow will enter the cavity and form the re-entrant jet.

2) Experimental and theoretical results show that, with the passage of time, the development velocity of cavitation increases, and the re-entrant jet pressure captured on the model surface decreases.

3) When the vehicle has an angle of attack, there are differences in the characteristics of the re-entrant jet pressure between the upstream surface of the water and the back surface. The back surface re-entrant jet pressure is relatively low and the surface pressure difference is relatively small.

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References


