Numerical Study on Air-involved Cavity during Water Exit of Underwater Vehicle

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Abstract

In the underwater vehicle launching process, some air in the launch tube will be involved in the low-pressure cavity formed at the shoulder part of the vehicle. This cavity mixed with air will collapse during water exit, causing dramatic change of flow field, which has a certain impact on the load environment. Based on homogeneous multiphase flow model, numerical simulation of the collapse of the cavity filled with vapor and involved air has been conducted. The results show that the nose shape with stronger cavitation ability is much easier to make the air in the launching tube involved in the low-pressure cavity. When air is mixed with vapor in the cavity, the rebound phenomenon will occur in the cavity collapse process. And there will also be multiple peaks of surface pressure.

Keywords: cavitation; water exit; multiphase flow; underwater vehicle; numerical simulation

1. Introduction

During the water exit process of underwater vehicle, there will be complex intense external load impressed on the vehicle, leading to the perturbation in attitude [1]. If there are cavities attached to the vehicle, the shrinkage and collapse of the cavities is one of the major phenomena at the water-exit stage. The water around the cavity will impact the vehicle surface under pressure gradient, leading to a pressure pulse [2]. Cavity collapse will cause noise and material damage, become an important research topic [3].

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However, the research largely confined to the collapse of a single cavity bubble at present [4-6], analysis combined with the circumstances during underwater launch and water exit are rarely conducted. While the underwater launched vehicle moves in the water, the local pressure drops, triggering the formation of cavity at the vehicle surface [7-8]. But, Cavitation is a very broad phenomenon, not limited to the cavity filled with vapor. In any effective pressure, the cavity can be filled with any permanent gas [9]. In the underwater launch process, when the vehicle comes into water from launch tube, some air in the launch tube will be involved in the low-pressure cavity. Numerical simulation of the air-involved cavitating flow around the vehicle with different nose shapes has been conducted by a viscous flow solver with homogeneous multiphase flow model. Besides, further analysis of the effect of the involved air on the cavity collapse during water exit has been carried out.

2. Computational methodology and validation

The set of governing equations under the homogeneous-fluid modeling consists of the conservative form of the Favre-averaged Navier-Stokes equations, the \( k-\varepsilon \) two-equation turbulence closure, and a transport equation for the liquid volume fraction.

The continuity, momentum, turbulence closure, and transport-based cavitation model equations are given below.

The continuity equation:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0
\]  

(1)

The momentum equation:
\[
\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathbf{U}^T) = -\nabla p + \mathbf{B} + \nabla \cdot \left( \mu_{\text{eff}} \left( \nabla \mathbf{U} + (\nabla \mathbf{U})^T \right) \right)
\]

(2)

The turbulence closure equation:
\[
\begin{align*}
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{U} k) &= \nabla \cdot \left( \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \nabla k \right) + P_k - \rho \varepsilon \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{U}) &= \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} \left( C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon \right)
\end{align*}
\]

(3)

Where, \( \mathbf{U} \) and \( p \) are velocity and pressure; \( t \) is time; \( \mu_{\text{eff}} = \mu + \mu_t \) is the effective viscosity; \( \mu = \sum_{i=1}^{N_p} \alpha_i \mu_i \) is the mixture viscosity; \( \mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon} \) is the turbulence viscosity; \( \rho = \sum_{i=1}^{N_p} \alpha_i \rho_i \) is the mixture density; \( N_p \) is phase number; \( \mathbf{B} \) is the body force; \( \alpha_i \) is the volume fraction of phase \( i \); \( C_{\mu}, C_{\varepsilon 1}, C_{\varepsilon 2}, \) and \( \sigma_\varepsilon \) are empirical constants. \( P_k = \mu_t \nabla \cdot (\nabla \mathbf{U} + (\nabla \mathbf{U})^T) = \frac{2}{3} \nabla \cdot \mathbf{U} (3 \mu \nabla \cdot \mathbf{U} + \rho k) \) is the turbulence production due to viscous and buoyancy forces.

The cavitation model equation:
\[
\frac{\partial}{\partial t} (\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \mathbf{U}) = S_i + \Gamma_j
\]

(5)

Where, \( S_i \) is the mass sources of phase \( i \); \( \Gamma_j \) is the interface mass transfer per unit volume into phase \( i \). And, the interface mass transfer per unit volume satisfies the relation of
\[ \Gamma_i = \sum_{b=1}^{N_p} \dot{m}_{ib} A_{ib} \]  \hspace{1cm} (6)

Where, \( A_{ib} \) is interfacial area density between the phases; \( \dot{m}_{ib} \) is flow rate per unit interfacial area from phase \( b \) to phase \( i \).

The Rayleigh-Plesset equation provides the basis for the rate equation controlling vapor generation and condensation, which can be written as follow.

\[ \dot{m}_{tg} = F \frac{3r_{mc}(1-r_c) \rho_g}{R_B} \sqrt{\frac{2}{3}} \frac{|p_v - p|}{\rho_w} \text{sgn}(p_v - p) \]  \hspace{1cm} (7)

Where, \( p_v \) is the saturation vapor pressure of water; \( r_{mc} \) is the volume fraction of the nucleation sites; \( F \) is an empirical factor.

To validate the computational methodology, the cavitating flows around the hemisphere nose vehicle with the diameter of \( d \) at three different cavitation numbers \( \sigma = 2(p_v - p)/\rho \nu^2 \) have been simulated. Fig. 1 shows the results of both predicted and measured surface pressure distributions, conducted by Rouse and McNown [10]. Where, \( C_p = 2(p - p_v)/\rho \nu^2 \) is pressure coefficient, and \( zd^{-1} \) is the nondimensional distance from the tip of the vehicle to measuring point. As the figure indicates, the numerical results and experimental results agree well.

**Fig. 1 Comparison of predicted and measured surface pressure distributions**

### 3. Results and Discussion

#### 3.1. Effect of underwater vehicle nose shape on the flow pattern of involved air in the cavity

During the underwater launch process, when the vehicle comes into water from the launch tube, some air in the launch tube will be involved in the low-pressure cavity. But the nose shape of the vehicle will affect the flow pattern of the involved air. As shown in Fig. 2a, for the vehicle with spherical nose, the pressure at shoulder area is still not low enough to make the vapor and the involved air fully mixed in the cavity. Instead, the involved air in the cavity gradually leaks from the cavity closure zone, and eventually detaches from the cavity. As shown in Fig. 2b, for the underwater vehicle with roughly conical nose, curvature radius of shoulder part between the cone part and the cylindrical part is small, which causes very low pressure formed at this site. The low pressure at shoulder part makes part of the air in the launcher tube involved in this area. A relatively stable cavity filled with vapor and air is formed, attached to the shoulder part of the vehicle, and moving upward with the vehicle.
3.2. Flow field around underwater vehicle during water exit

For the situation that there is a certain amount of air mixed in the cavity, the time evolution of volume fraction for each phase during the water exit process is shown in Fig. 3. Where, \( \text{St} = \frac{vt}{d} \) is the nondimensional time, \( v \) is the velocity of water exit.

![Fig. 3 Contour of volume fraction for each phase while air is mixed in the cavity](image)

For the circumstance that there is no air trapped in the cavity, the time evolution of volume fraction for each phase during the water exit process is shown in Fig. 4.

The results show that there are some commons between the cavity collapse processes for above situations. While the nose part crosses free surface, the surrounding water moves upward with the vehicle, causing the uplift of free surface. The relative velocity between the vehicle and the adjacent fluid decreases, leading to the increase of static pressure. The cavity starts to shrink and finally collapse. There are obvious differences between the cavity collapse processes for above situations. There is rebound phenomenon of the cavity for the first situation. As shown in Fig. 3, at the time of \( \text{St}=1.29 \), the cavity...
shrinks to minimum volume, then the cavity begins to rebound. At the time of \( St = 1.65 \), cavity volume reaches its maximum again and gradually shrink. At the time of \( St = 2.05 \), it shrinks to its minimum size. And then the cavity starts to rebound again.

![Contour of volume fraction for each phase while there is no air mixed in the cavity](image)

This kind of cavity collapse and rebound phenomenon is consistent with previous studies on cavity life cycle, which indicates that cavity life cycle generally includes a regeneration stage of rebound [9]. In the water tunnel experiment, the rebound phenomenon can be frequently observed. However, experiments that cavity does not rebound have been observed. For example, in the venturi tube nozzle experiment conducted by Harrison [11], micro-cavity bubbles were found, and no obvious rebound after the collapse of the bubbles has been found. The collapse speed of these cavities is very consistent with Raleigh theoretical result. The special technology used in this experiment can guarantee that there is little permanent gas in the spark generated cavity. Then, when the cavity Collapse, no significant rebound is observed. On the contrary, the spark-induced cavity, which contains a certain amount of air, showed rebound phenomenon.

### 3.3. Pressure distribution during water exit of underwater vehicle

![The distribution of surface pressure coefficient while air is mixed in the cavity](image)

When the nose of underwater vehicle cross free surface, the relative velocity between the vehicle and the adjacent fluid decreases, leading to the increase of static pressure and the collapse of cavity. At the cavity collapse stage, water around the cavity impacts the vehicle surface, causing the surface pressure changing dramatically. Fig. 5 and Fig. 6 show the dependences of vehicle surface pressure coefficient on \( St \) in the situation with or without air mixed in the cavity respectively. In both cases, as the cavity shrinks to minimum volume, the compressed fluid will lead to the instant high pressure. The comparisons also show that, if some air is mixed in the cavity, there will be rebound phenomenon. During the collapse and rebound process, the fluid around the cavity repeatedly impacts on the hull of vehicle, causing double peak value of surface pressure.
4. Conclusion

Based on homogeneous multiphase flow model, the numerical simulation of cavitating flow during the water exit process of underwater vehicle has been conducted. The results show that:

The nose shape of underwater vehicle with stronger cavitation capability is easier to make some air in the launcher tube involved in the shoulder cavity. And the cavity will attach to vertical moving vehicle and eventually collapse.

By comparison of the situation whether the air is fully mixed with vapor in the cavity, the results show that there will be rebound phenomenon during the cavity collapse process, while air is mixed in the cavity. On the contrary, the rebound phenomenon does not exist.

When the cavity shrinks to its minimum size after it rebounds, the surface pressure at the collapse location will increase suddenly to a peak value. This phenomenon indicates that there will be multiple peaks of surface pressure during the cavity collapse procedure.

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