Suppression of cavity volume and its oscillation using adaptive geometry

Tezhuan Du *, Yiwei Wang, Chenguang Huang

1 Institute of Mechanics, Chinese Academy of Sciences, Beijing, China;
2 University of Chinese Academy of Sciences, China.

Abstract

Many researchers are interested in cloud cavitation because of its instability which can cause vibration and noise, and even lead to structural damages. In the present work, cavitating flows over a hollow projectile with adaptive shape is simulated to study the effectiveness of re-entrant jet suppression and cloud cavitation control. A fluid-structure coupling model is established to study the performance of adaptive shape on control of cavitation. The proposed model is then applied to simulate cavitating flows over a hollow projectile with the adaptive shape. The adaptive shape is achieved by deformation of an elastic membrane under internal-external pressure difference. The membrane bulges and recovers while cavitation grows and collapses respectively. Conversely, deformation of membrane affects the evolution of cavitation. Different Young modulus is adopted to analysis the interaction between cavitating flow and the elastic membrane. The results show that adaptive shape can reduce the total volume of cavitation and collapse pressure under specific parameters.

Keywords: cavitation suppression, adaptive shape, fluid-structure interaction, collapse pressure

Introduction

Cloud cavitation is the most regular and coherent regime of oscillation of partial cavities. The detachment of bubble cloud will cause significant fluctuation of pressure [1]-[4], and pressure pulse generated by bubble collapse in cloud cavitation is usually considered to be the major cause of structure failure. Many researchers are interested in cloud cavitation because of its instability which can cause vibration and noise, and even lead to structural damages [5]. The instability of a partial cavity is usually considered to be induced by the development of a re-entrant jet [6]. Tanimura [7], Kawanami [8], Pham [9] and Zhang [10] set up barriers in the hydrofoil surface to impede the development of re-entrant jet and control the instability of cavitation.

In the present work, cavitating flows over a hollow projectile with adaptive shape is simulated to study the effectiveness of re-entrant jet suppression and cloud cavitation control.

1. Numerical model

1.1 Problem Description

Simulation of cavitating flow over a cylindrical body with 90° blunt conical head is presented in this study. The cylindrical section of a hollow projectile is covered by an elastic membrane. The boundary conditions are shown in Figure 1.
The diameter of the cylinder is \( D = 37.5 \) mm, and the thickness of the membrane is \( h = 0.5 \) mm. The material of membrane is rubber, density \( \rho_s = 930 \) kg/m\(^3\), Young’s modulus \( E = 4\sim16 \) Mpa. The free-stream velocity is \( U_\infty = 18 \) m/s and the ambient pressure is 101325pa. Physical properties of liquid, vapor and air are listed as follows:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Density (kg/m(^3))</th>
<th>Viscosity (kg/m(\cdot)s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid</td>
<td>998.2</td>
<td>1.00(\times)10(^{-3})</td>
</tr>
<tr>
<td>vapor</td>
<td>0.5542</td>
<td>1.34(\times)10(^{-5})</td>
</tr>
<tr>
<td>air</td>
<td>ideal gas</td>
<td>1.79(\times)10(^{-5})</td>
</tr>
</tbody>
</table>

The saturation pressure of water is set as 2367pa. The corresponding cavitation number and Reynolds number are \( \Sigma = 0.611 \) and \( Re = 6.75 \times 10^5 \), respectively.

The 2-D axisymmetric model is utilized in the simulation. The coupling model consists of a fluid solver, a structure solver and a data interface.

### 1.2 Flow Model

The flow field is divided by the membrane into two regions. The outer flow is cavitating flow, and the inner flow is expansion and contraction of gas. The approach for cavitating flows consists of unsteady Reynolds Averaged Navier-Stokes equations of mixture phase, continuity equation of vapor phase and “full cavitation model” developed by Singhal et al \([11]\).

\[
\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \nabla) = 0 \\
\frac{\partial}{\partial t} (\rho_m \nabla) + \nabla \cdot (\rho_m \nabla \nabla V) = -\nabla p + \nabla \cdot [\mu_m (\nabla V + \nabla V^T)] + \nabla \cdot (-\rho_m \nabla V^V) \\
\text{where } \mu_m = \alpha_v \mu_v + \alpha_g \mu_g + (1 - \alpha_v - \alpha_g) \mu_l \\
\text{is the equivalent viscosity of the mixture phase. In the present work, the Modified RNG} \ k - \varepsilon \text{ model} \([12]\) \text{is used to simulate the turbulent effect on cavitating.} \\
\]

For inner flow, based on quasi-static hypothesis, the pressure is assumed uniform inside projectile, which is given by:

\[
p_{in} = \frac{p_0 V_0}{(V_0 + dV)} \\
\text{where } p_0 \text{ is initial pressure inside, } V_0 \text{ is initial volume of air inside, } dV \text{ is volume difference.}
\]

### 1.3 Structural Model

2D axisymmetric is utilized in the present work, the mode shapes and modal frequencies are given by:

\[
\phi_j = \sqrt{\frac{2}{\rho A L}} \sin \frac{j \pi x}{L} \\
\omega_j = \frac{j \pi}{L} \sqrt{\frac{E}{\rho}} \\
\text{where } \phi_j \text{ is the } j\text{th natural vibration mode, } x \text{ is axial coordinate, } \rho \text{ is the density of membrane, } E \text{ is Young's modulus, } A \text{ is the cross-sectional area of the membrane, and } L \text{ is the length of the membrane. The circumferential constraint can be equivalent to the modified elastic modulus.} \\
\text{The radial displacement of the membrane is calculated using modal superposition method.} \\
\]

\[
u_s(x) = \sum q_{j,n} \phi_j \\
\text{where } q_{j,n} \text{ is the corresponding modal displacement at the } n\text{th time step.}
\]
Owing to the existence of the wall of the projectile, radial displacement of the membrane is subject to the following constraint condition:

\[ u_r(x) \geq 0 \]  \hspace{1cm} (7)

In the present work, only the first three orders of vibration mode are considered. The Runge-Kutta method is adopted to solve equation (6) in time domain\(^{13}\).

### 1.4 Coupling method

Loose coupling approach is employed in this paper. The flow field and solid field are simulated respectively. The interaction between these two fields is achieved by exchanging the data through the fluid-solid interface at every time step. The data exchange through the interface includes the following two parts:

1. Mapping the hydro force onto the solid mesh from the fluid mesh.
2. Mapping the displacement of solid onto fluid mesh from the solid mesh.

In the present work, FLUENT was used to simulate the cavitating flow and SIMPLE algorithm was adopted to solved the velocity-pressure coupled system. The structure solver and coupling interface were programmed and linked to FLUENT as user-defined functions (UDFs). Memory swapping was implemented for data exchange which could enhance the simulation efficiency. The block diagram of fluid-structure coupling method is shown in Figure 2.

![Figure 2: Block diagram of fluid-structure coupling method](image)

### 2. Results

#### 2.1 Influences of shape deformation on cavitation

Owing to the internal-external pressure difference, the membrane bulges, and recovers while cavitation grows and collapses respectively. Conversely, deformation of membrane affects the evolution of cavitation. Different Young modulus is adopted to analyze the interaction between cavitating flow and the elastic membrane. Figure 3 illustrates that the \( q_1 \) is an order of magnitude larger than \( q_2 \) and \( q_3 \), which indicates that the first order mode shape plays a primary role in deformation.
In this paper, the total volume of cavitation is chosen to indicate the effect of cavitation suppression. Non-dimensional volume and non-dimensional time are defined as $V' = \frac{V_{total}}{\frac{1}{4} \pi D^3}$ and $t' = \frac{t U_\infty}{D}$ respectively.

The results show that adaptive shape can reduce the total volume of cavitation and collapse pressure under specific parameters. The vibration amplitude of membrane increase with the decreases of Young's modulus. However, the outlines of cavitation area (Figure 4 dash curve) almost the same. It indicates that the total volume of cavitation decrease with the decreases of Young's modulus (Figure 5). While the deformation of membrane exceeds the outline of cavitation area ($E = 4$ Mpa), newly attached cavitation will appear behind the hump (Figure 6). In this case, the total volume of cavitation will increase.

![Figure 4: Cavitation outlines with different Young’s modulus.](image)
2.2 Influence of deformation on pressure

There are two mechanisms for generating pressure pulses: the re-entrant jet meets the main flow at the shoulder of the projectile and the collapse of the detached cavity. Figure 7 shows that deformation of the membrane can significantly reduce the max pressure $p' = \frac{p_{\text{max}}}{L + U^2_{\infty}}$ in the flow field on certain conditions ($E = 7.8$ Mpa and $E = 10$ Mpa), especially the pressure pulse generated by re-entrant. It’s because the re-entrant jet is restrained by the deformation of the membrane. Meanwhile, the volume of the detached cavity is reduced which may lead to lower collapse pressure.

However, more pressure peaks are generated due to the appearance of locally attached cavitation while $E = 4$ Mpa.
3. Conclusion

In the present work, a fluid-structure coupling model is established to study the performance of adaptive shape on control of cavitation. Different Young modulus is adopted to analyze the interaction between cavitating flow and the elastic membrane. The simulation results show that:

1. The membrane bulges and recovers while cavitation grows and collapses respectively under internal-external pressure difference.

2. The total volume of cavitation decrease with the decreases of Young's modulus. However, while the deformation of membrane exceeds the outline of cavitation area ($E = 4 \text{ Mpa}$), the total volume of cavitation will increase due to the appearance of locally attached cavitation.

3. The deformation of the membrane can restrain the development of re-entrant and reduce the volume of the detached cavity, and hence significantly reduce the max pressure in the flow field on certain conditions ($E = 7.8 \text{ Mpa}$ and $E = 10 \text{ Mpa}$).

Acknowledgements: The authors acknowledge the financial support from the National Natural Science Foundation of China (11402276)

References


