Combined Numerical and Experimental Investigation of the Cavitation and Erosion of Submerged Self-resonating Waterjet

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Abstract. In ocean exploitation of deep-sea mineral, cavitation always occurs. In this paper, a model based on the Rayleigh-Plesset equation for researching the cavitation of the self-resonating waterjet was build up. A three-dimensional Computational Fluid Dynamic (CFD) analysis method to demonstrate the possibly of using the pressure distribution phenomenon prediction the evolution of cavitation bubbles. Frequency bands of numerical simulations were in good agreement with experimental data. Based on this, we obtain the shedding frequency of the bubbles, researched the erosions effect. The results validate the proposed scheme, which could be used to adjust the erosions domains.

1. Introduction

The applications of submerged self-resonating waterjet are widely distributed in industrial engineering [1], especially has a good future in the exploitation of deep-sea mineral resources [2]. As we know the organ pipe type self-resonating water jet is based on the theory of fluid transients and hydro-acoustics [3]. It has advantages of simple structure, non-thermal and environmental protection [4], the submerged self-resonating waterjet had gained the concern from many researchers.

Oscillations occurred when water passed through the self-resonating waterjet nozzle. However, the resonance frequency of the nozzle is a major problem when designing an organ-pipe type nozzle [5]. Johnson gain an empirical formula for natural frequency of nozzle based the feedback mechanism of acoustic oscillation [6, 7]. When the frequency of the self-resonating waterjet wave is near the critical jet structuring frequency, the resonance in the nozzle will appear [8]. Which result in the fluctuating pressure as the fluid moves down [9].

The pressure fluctuating produce low-pressure region, when it is lower than the vapour pressure, cavitation would be happened [10]. With oscillation and cavitation, bubbles inception, transition, shedding and collapse [11, 12]. Cavitation has been conveniently classified into two types, stable and transient [13]. There are several previous studies on the bubble dynamics and erosion over the past few years to predict the behaviour of water jet that exhibit cavitation. The first dynamic model of bubble oscillations developed in 1950[14]. The noise level can be used as a mean to evaluate the cavitation intensity, highly erosion and a broadband discrete noise [15]. Recently, E. Hutli researched the effects of the hydrodynamic parameters and the nozzle geometry on the erosion process, give a better understanding of the cavitation jet [16]. The collapse of cavitation bubbles near a solid boundary leads...
to high amplitude and small duration impulsive loads [17]. Especially, when strong oscillations happened, bubble dynamics released broadband noise, ranging from 20~200 kHz [18]. The erosion effects changed with the frequencies bands. However, frequency band is not so clearly identification. The present work we are trying to identification the causes noise frequency bands, shows a great potential for future development of techniques for accurate predictions of cavitation erosion by numerical means only.

2. Numerical Method
Cavitation of a 3D self-resonating waterjet nozzle is considered here. The flow within the cavity is incompressible flow here.

2.1. Governing equations
The unsteady Reynolds-averaged Navier–Stokes equations which consist of the continuity and momentum governing equations of the flow field can be expressed as (1) and (2) [19, 20],

\[ \frac{\partial \rho_m}{\partial t} + \frac{\partial (\rho_m u_j)}{\partial x_j} = 0 \]  
(1)

\[ \frac{\partial (\rho_m u_j)}{\partial t} + \nabla \cdot (\rho_m u_j u_k) = -\nabla p + \nabla \cdot \left[ \mu (\nabla u + \nabla u^T) \right] + \rho_m g + F \]  
(2)

Where \( \rho_m \) is the mixture density, \( t \) represents time, \( g \) is the gravitational acceleration, \( u \) is the velocity vector, \( p \) is the pressure, \( \mu \) is the molecular viscosity, \( F \) is the body force vector.

2.2. Cavitation Model
For cavitation modeling, the Rayleigh-Plesset equation is often abbreviated as the following form [21, 22],

\[ R_b \frac{d^2 R_b}{dt^2} + \frac{3}{2} \left( \frac{d R_b}{dt} \right)^2 + \frac{4\nu_j}{R_b} \frac{d R_b}{dt} + \frac{2S}{\rho_f R_b} = \frac{P_b - P}{\rho_f} \]  
(3)

where, \( R_b \) is the bubble radius, \( \nu_j \) stands for the liquid kinematic viscosity, \( S \) represents the liquid surface tension coefficient, \( \rho_f \) represents the liquid density, \( P_b \) is the bubble surface pressure, \( P \) is the local far-field pressure.

Ignoring the viscous term and surface tension force term, the Rayleigh-Plesset equation always simplified as equation(4),

\[ \frac{d R_b}{dt} = \sqrt{\frac{2 [P_b - P]}{3 \rho_f}} \]  
(4)

The equation build up the relation of the bubble dynamics and the cavitation simulation, which can describe the bubble dynamics. The volume fraction equation, solved for both phases can be calculated from (5) [23],

\[ \rho_m = \alpha \rho_v + (1 - \alpha) \rho_f \]  
(5)

where \( \alpha \) is the vapor volume fraction, \( \rho_v \) is the vapor density.

For different numerical models, the cavitation model is different in terms of the mass transfer. In this research, we choose the Schnerr-Sauer cavitation model [24], the mass transfer equation is given by (6),

\[ \frac{\partial}{\partial t} (\alpha \rho_v) + \nabla (\alpha \rho_v u_j) = R_p - R_c \]  
(6)
These source terms defined as (7) and (8),

When \( P \leq P_\varepsilon \),
\[
R_p = \frac{\rho_l \rho_{l_0}}{\rho_m} \alpha (1-\alpha) \frac{3}{R_b} \sqrt{\frac{2(P_\varepsilon - P)}{3 \rho_l}}
\] (7)

When \( P > P_\varepsilon \),
\[
R_c = \frac{\rho_l \rho_{l_0}}{\rho_m} \alpha (1-\alpha) \frac{3}{R_b} \sqrt{\frac{2(P - P_\varepsilon)}{3 \rho_l}}
\] (8)

Where bubble radius is given by
\[
R_b = \left[ \frac{3 \alpha}{4\pi n_b (1-\alpha)} \right]^{\frac{1}{3}},
\]
and \( n_b \) the nuclei density per volume of liquid.

2.3. Mesh and Boundary Conditions
The computation grid used in the paper shown in Fig. 1, we applying HyperMesh commercial software to acquire the structured grid of the fluid domain. The grid is refined at the outlet of the nozzle and the number of the grids is 14465,000. Here the simulation of the CFD flow domain was half-model using symmetry boundary conditions. The SIMPLE algorithm for unsteady simulations was employed to solve the coupling between pressure and velocity. Boundary conditions were shown in Fig. 2.

**Figure 1.** Numerical mesh for the 3D simulations.

**Figure 2.** Boundary conditions.
3. Experimental and Validation

3.1. Experimental Setup
An experimental test system was designed to generate low confining pressure in our former research with high-pressure tank, and the sketch was shown in Figure 3. In this paper we focusing on the vibration and the cavitation noise based a RHS-20 hydrophone, the flat response of it up to 120 kHz and ± 3dB oscillations up to 200 kHz. During the experiment, the hydrophone was installed 100 mm as the radius centered on the nozzle, and it parallel to the nozzle.

We choose the organ-pipe type nozzle as the self-resonating nozzle and the geometry schematic description of it was shown in Fig.4, the structure parameters was shown in Table 1. According the research of Johnson [25] the acoustic natural frequency of the nozzle is about 14 kHz.

![Figure 3. The experimental test system.](image_url)

![Figure 4. Self-resonating Nozzle geometry schematic description.](image_url)
Table 1. Parameters of the experiment nozzle (mm).

| \( D_x/mm \) | \( D/mm \) | \( L/mm \) | \( d1/mm \) | \( l \) | \( \theta \) |
|-----------|-------|---------|--------|--|-----|
| 23        | 10    | 24      | 2      | 0.7 | 21   |

3.2. Validation

The experiment data with the simulation were, the mean value of inlet pressure is \( \overline{P_{in}} = 15.51 \) Mpa, the mean value of measured confining pressure is \( \overline{P_a} = 1.503 \) Mpa, the mean value of measured flow rate of the pump is \( \overline{Q} = 19.98 \) L/min, the distance between the hit plate and the nozzle is 6mm, and the sample frequency \( f_a = 204800 \) Hz.

The occurrence of cavitation, following the difference between the inlet pressure and confine pressure and the vapor pressure of the fluid, has been assessed through the cavitation number, the vapor pressure set as \( P_c = 3169 \) Pa in the simulation, the cavitation number can be calculated by equation (9), and combining with experimental data, the result is \( \sigma = 0.085 \).

\[
\sigma = \frac{\overline{P_a} - P_c}{\overline{P_{in}} - \overline{P_a}},
\]

(9)

The fast Fourier transform (FFT) way was used to processing the experiment and simulation data, to find out the vibration and the cavitation noise frequency band. The results were shown in Figure 5 and Figure 6, \( f_{experiment} = 47490 \) Hz, \( f_{simulation} = 51930 \) Hz. Absolute error evaluation method was provided according to the frequency band of the experimental and simulation result. The absolute error was prediction by equation (10), the result is \( E = 8.55\% \), the simulation model can adequately predict the cavitation of the self-resonating waterjet.

\[
E = \left| \frac{f_{simulation} - f_{experiment}}{f_{experiment}} \right| \times 100\%,
\]

(10)

Figure 5. FFT result of Experiment data.
4. Simulation Results and Discussions

4.1. Pressure Distribution
The cavitation always occurs at the local places where the pressure is lower than the vapor pressure. From the result shown in Figure 7, cavitation occurs at outlet of the nozzle throat we focus in other paper, and down the axis of the nozzle the key research of this research, where the bubble inception.

4.2. Bubble dynamics and Cavitation
The time step of our simulation is $5 \times 10^{-7}$ s, the iterative number is 20. As the knowledge that a typical cycle of cavitation bubble evolution contains four stages are inception, transition, shedding and collapse. The whole bubble evolution of the bubbles was obtained in 38 time steps, and we choose the typical steps shown in Figure 8. Depend on the result of the bubble evolution and the simulation parameters, we can calculate the bubble shedding frequency is 52.63 kHz.
a. Bubble inception and transition.

b. Bubble growth and breakoff.

c. Bubble disappeared.

Figure 8. The evolution of cavitation bubble.
4.3. Erosions

Figure 9 gave the experiment result of the erosions on a pure aluminum hit plate. We can concluded that there were two erosions domains, one was aiming the center of the nozzle formation a small circular shaper, another also aiming the center of the nozzle but formation a ring shaper. Contrast two domains, the erosion strength on the ring domain was stronger than that in the circular.

![Figure 9](image1.png)

**Figure 9.** The erosion result of Experimental result on the hit plate.

Figure 10 was the wall shear on the hit plate of the simulation. Figure 10(a) was the wall shear contour bands on the hit plate, and Figure 10(b) is the wall shear shown as contour lines. We can conclude that the highest wall shear was at the ring shape domain the same as the experiment result. And another peak wall shear was in the center of the hit plate. Under the same working conditions, the experiment and simulation model both had two erosions domains.

![Figure 10](image2.png)

a. Wall Shear shown as contour bands on the hit plate.
5. Conclusion
This paper combined numerical and experimental method, based on the Rayleigh-Plesset equation, investment the evolution of the bubble cavitation and the erosion effect of the submerged self-resonating water jet. The main results conclude as follows,

1. Based on the FFT method, we processed the experiment and the simulation data, the absolute error of the frequency band was 8.55%, from which we researched the location of cavitation occurrence, at the outlet of the nozzle throat, and down the axis of the nozzle.

2. We were focus on the cavitation occurrence at the down the axis of the nozzle, the whole evolution of bubble cavitation was obtained, and the frequency is 52.63 kHz, for the similar to the result $f_{\text{experiment}} = 47490$ Hz and $f_{\text{simulation}} = 51930$ Hz, we can conclude that this is the shedding frequency of the bubbles.

3. Experiments and simulation results show that there were two erosion domains, a circulate shape and a ring shape, and in the ring shape the erosion is stronger.

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