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RE-ENTRY JET AND SHOCK INDUCED CAVITY SHEDDING IN CLOUD CAVITATING FLOW AROUND AN AXISYMMETRIC PROJECTILE

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ABSTRACT

Shedding is one of the most important expressions of the instability of cavitating flow. Most previous research works were focused on the shedding mechanism induced by the re-entry jet. Shock induced shedding on a wedge is identified recently by using time resolved X-ray densitometry which attracted lots of attention. In the present paper, cavitation dynamics around an axisymmetric body are investigated. Both shock propagation and re-entry jet as inducing factors of shedding are observed in different cycles in a single experiment. Relevant numerical simulations are carried out based on a fully compressible approach under the framework of the open-source code OpenFOAM. Numerical and experimental results agree well with each other. Results indicate shedding is induced by the re-entry jet in the first cycle. Re-entry jet occurs and cut the cavity off on the should which induces the shedding of cloud cavity in the first cycle. However in the second and subsequent cycles, shocks are generated by the collapse of shedding cavities and propagate to the cavity closure and induces stronger re-entry jet. Its effect on cavity instability is indirect which still needs a strong re-entry jet as the medium media.

INTRODUCTION

Cavitation instability always attracts a lot of attention, which often appears as cavity shedding and sheet to cloud transition. Most previous research works were focused on the shedding mechanism induced by the re-entry jet, which is usually considered as the most important factor on the transition [1]. Stuts and Reboud [2-4] carried out a series tests with venturi-type test section. They confirmed the existence of re-entry jet by measuring the void fraction and velocity inside the two phases flow structure by suing a double optical probe. Callenaere[5] studied the re-entry jet instability and associated cloud cavitation on a plano-convex hydrofoil, and carried out a variety of different classifications and analyses about these phenomena.

Besides the re-entry jet, other factors are also regarded as impossible factors. For example, Arndt et al [6] found there are two different Strouhal numbers for the cavitating flows around the hydrofoil in various conditions. The shedding phenomenon for one on them was possibly generated by the shock propagation. This phenomenon and mechanism were found to commonly exist in many researchers' works. Genesh et al [7] developed a high temporal resolution X-ray device and measured the density evolution inside the unsteady cavitating flow around a wedge. They confirmed that with certain caviation number, the shock was generated, and its propagation could cause the shedding of the cavity and the transition from sheet to cloud cavity. Moreover, the collapse of shedding cavity was also considered as an important factor of cavitation instability[8,9].

Considering the latest development and Understanding of shock propagation as a cause of cavity shedding, we want to examine some previous results and confirm the mechanism. A fully compressible algorithm is established on the cavitating flow around the axisymmetric projectile. By a joint investigation on experimental and numerical results, different mechanisms of cavity shedding were found in the various flow conditions. The effects of re-entry jet, shock and collapse on the cavitation instability are compared and discussed.

1. EXPERIMENTAL AND NUMERICAL METHODS

The typical experiments are performed by using a launching device based on the SHPB technology. Detailed of the method can be found in the reference [8]. The typical photographs in the experiment are shown in Fig.1, in which the re-entry jet and the shedding cavity collapse can be seen clearly and there are suspected shock propagations in the second and third cycles.

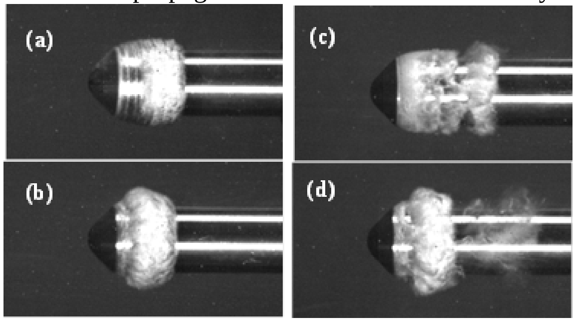

Fig.1 Typical snapshots with different mechanisms of cavity shedding (a, re-entry jet in the first cycle; b, shedding in the first cycle induced by the re-entry jet; c, suspected shock propagation in the second cycle after shedding cavity collapses; d, cavity shedding in the third cycle.)

In order to analyze the shock propagation and its effect in the flow field, a fully compressible algorithm for unsteady cavitating flow is established based on the open source code OpenFOAM. The barotropic equations of state for liquid, gas and the mixture phase are adopted to describe the variations of density and sound speed of the mixture phase under various pressure, which can give more accurate simulation on shock propagation and phase change rather than the commonly used incompressible scheme.

Continuity and momentum equations for the mixture are established as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho U) = 0 \tag{1}$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \bullet (\rho U U) = -\nabla P + \nabla \bullet \left[\mu (\nabla U + (\nabla U)^T) \right] \tag{2}$$

where ρ, μ, t, U and P denote the fluid density, viscosity, time, velocity and pressure, respectively.

A homogeneous equilibrium model (HEM) with the barotropic closure is adopted.

$$\frac{D\rho}{Dt} = \psi \frac{DP}{Dt} \tag{3}$$

The Ψ refers to the compressibility of the mixture and corresponds to the inverse of the sound speed squared.

$$\psi = \frac{1}{a^2} \tag{4}$$

The speed of the sound is calculated by using the Wallis model, which can represent the low sound speed characteristic of the mixture inside the cavity. The transport equation of the water vapor volume fraction is,

$$a = \frac{1}{\sqrt{\gamma \rho_{vsat} + (1-\gamma)\rho_{lsat})(\gamma \frac{\psi_v}{\rho_{vsat}} + (1-\gamma)\frac{\psi_l}{\rho_{lsat}})}} \tag{5}$$

Subscripts v and l denote the vapor and liquid phase, respectively. The vapor mass faction γ is calculated by local pressure.

$$\gamma = \max[\min[\frac{\rho - \rho_{lsat}}{\rho_{vsat} - \rho_{lsat}}, 1], 0] \tag{6}$$

where ρ_{lsat} and ρ_{lsat} demonstrate liquid and vapor densities at saturation, respectively.

For the turbulence, an one equation explicit large eddy simulation (LES) approach is used which is the same as that in reference [10]. For simplicity, an axisymmetirc case is used. The grid and boundary conditions are shown in Fig.2. For the typical experimental and numerical conditions, the inflow velocity is 18.5 m/s.

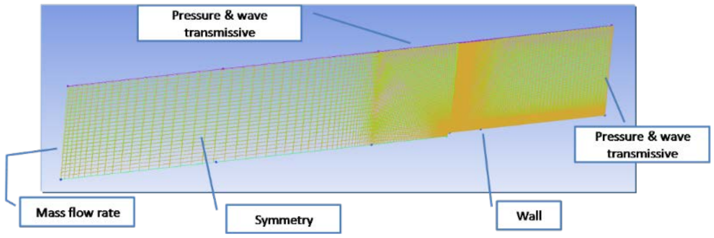

Fig. 2 Grid and boundary conditions used in the numerical simulation

The open source code OpenFOAM is used with the second order implicit scheme for time discretization and Gauss linear interpolation for spatial discretization. The advections terms are discretized by using the Gauss vanLeer scheme. The time step is adjustable and limited by both the Courant number *Co* and the acoustic Courant number $Co_{acoustic}$ with maximum values of 0.5 and 50, respectively.

2. RESULTS AND DISCUSSION

3.1 Overall evolution of the cavity

The overall evolutions of the cavitating flow around the axisymmetric projectile are obtained both numerically and experimentally, which include two typical cycles. Transparent sheet cavity is generated initially in the first cycle, and then the re-entry jet is generated as a foam-like stream and flows to the leading edge inside the cavity (as shown in Fig.1 (a)). The cavity is cut off by the re-entry jet and sheds from the leading edge (as shown in Fig.1 (b)). The shedding cavity collapses after flow a certain distance away from the newly generated main cavity, which causes high pressure at the cavity closure and induces cavity shedding in the next cycle (as shown in Fig.1 (c) & (d)).

3.2 Cavity shedding induced by the re-entry jet in the first cycle

The detailed pressure and velocity fields can be obtained in the numerical results, which can be used to analyze the mechanisms more clearly. The pressure becomes higher and higher during the cavity growth at the cavity closure and form a negative pressure gradient (as shown in Fig.3 (a) and (b)). The re-entry jet is generated by the negative pressure gradient, which shows as a negative U value in Fig.3 (c) and (d).

The re-entry jet intersects with the cavity boundary and forms an isolated bubble near the leading edge. Then the bubble shrinks and collapse at the shoulder of the projectile (as shown in Fig.3 (e) and (f)), which may further cause the transition from the sheet cavity to the cloud cavity.

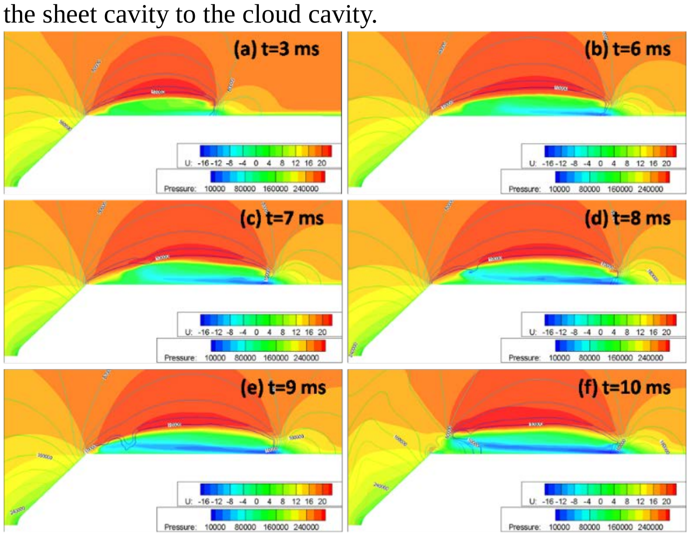

Fig. 3 Re-entry jet development and cavity evolution in the first cycle in the numerical results. The variable U denotes the velocity in the flow direction, so the negative value means the stream flows from the trailing edge to the leading edge.

3.3 shock induced shedding and transition

The cavity which is cut off in the last cycle sheds from the leading edge together with the growth of the new cavtiy. The shedding cavity is affected a large vortex comprised by both the main inflow and the re-entry jet which is generated in the last cycle(as shown in Fig.4 (a) and (b)).

The low pressure region inside the vortex becomes weaker and weaker when it flows far away from the shoulder of the projectile. So the shedding cavity shrinks and finally collapse at the cavity closure region, which forms a high pressure region(as shown in Fig.4 (c) and (d)).

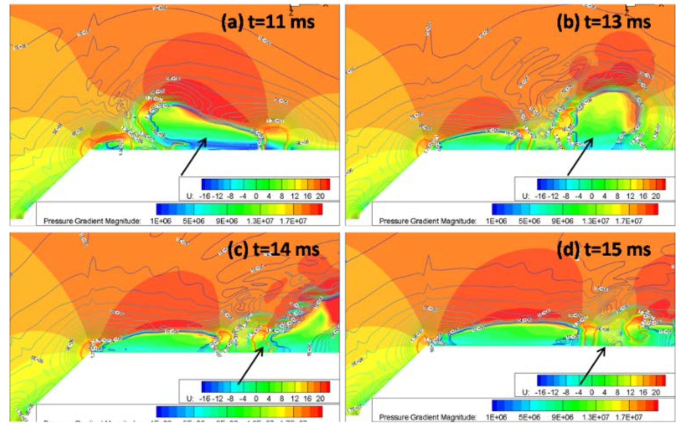

Fig.4 Time sequences of cavity shedding and collapse. The color contour represents the velocity in the flow direction and the line contour represents the pressure gradient. The shedding cavity is pointed by the black arrow.

Strong shock with high pressure is generated by the cavity collapse and propagates to the surrounding area (as shown in Fig.5 (a)). Because the wave resistance inside the cavity is remarkably lower than the liquid water, the shock propagates around the cavity closure and through the liquid water. When the shock intersects with the cavity boundary, very high pressure and strong negative pressure gradient is generated at the cavity closure. So new strong re-entry jet is formed at the same time when the shock arrives at the boundary (as shown in Fig.5 (b)).

New strong re-entry jet flows to the leading edge and cuts off the cavity again, which induce the shedding in the new cycle (as shown in Fig.5 (c) and (d)). Because the cavity is foam-like which means it contains large amounts of bubble and liquid water. So, the density inside the cavity is significantly larger than that in the first cycle which is a transparent sheet cavity, and the re-entry jet can disturb the pressure field and cavity pattern more remarkably in this cycle (as shown in Fig.1 (d), Fig.5 (c) and (d)).

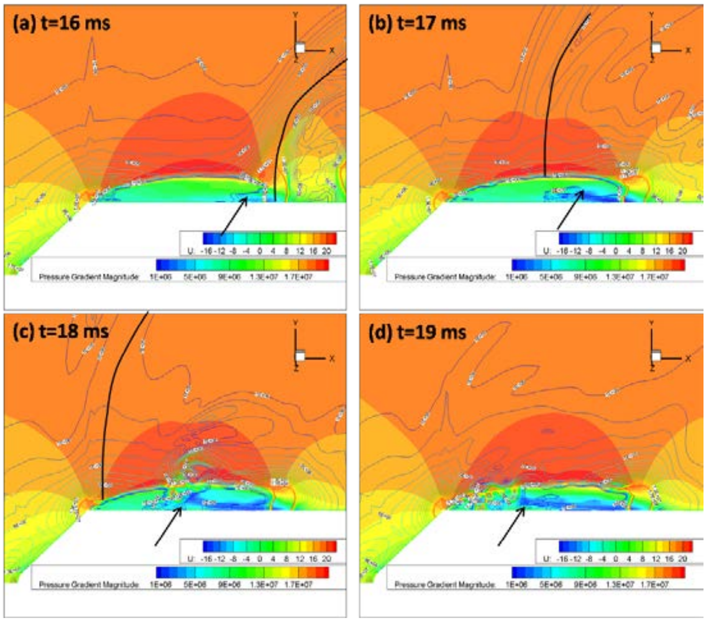

Fig. 5 Time sequences of shock propagation and new re-entry jet generation. The shock represents as large pressure gradient region and is shown by the black curve. The front of the re-entry jet is pointed by the black arrow.

3. CONCLUSIONS

A fully compressible scheme is established and used to investigate the effect of shock on the cavity shedding together with a typical experiment. The transitions from sheet to cloud cavity are found both in numerical and experimental results.

It is confirmed that there are two different shedding patterns in different cycles in a single condition, which are mainly induced by the re-entry jet and shock, respectively.

The strong shock at the cavity closure is generated by the shedding cavity collapse. Its effect on cavity instability is indirect which still needs a strong re-entry jet as the medium media.

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REFERENCES

[1] Brennen, CE (1995). Cavitation and Bubble Dynamics, USA:Oxford University Press.

[2] Stutz B, Legoupil S (2003). X-Ray Measurements within Unsteady Cavitation. Experiments in Fluids 35(2):130-138.

[3] Stutz B, Reboud J (1997). Experiments on Unsteady Cavitation. Experiments in Fluids 22(3): 191-198.

[4] Stutz B, Reboud J (2000). Measurements within Unsteady Cavitation. Experiments in Fluids 29(6): 545-552.

[5] M. Callenaere, J. P. Franc, J. Michel, et al, "The cavitation instability induced by the development of a re-entrant jet", Journal of Fluid Mechanics, Vol. 444, pp. 223-256, (2001).

[6] Arndt, Song et al Instability of partial cavitation- A numerical & experimental

[7] H. Ganesh, "Bubbly shock propagation as a cause of sheet to cloud transition of partial cavitation and stationary cavitation bubbles forming on a delta wing vortex", PhD thesis, University of Michigan, (2015).

[8] Cloud cavitating flow over a submerged axisymmetric projectile and comparison between 2D RANS and 3D LES methods

[9] Iga, Y., Hashizume, K., and Yoshida, Y., 2011, "Numerical analysis of three types of cavitation surge in cascade," ASME J. Fluids Eng., 133(7), 071102.

[10] Yu, X., Huang, C., Du, T., Liao, L., Wu, X., Zheng, Z., and Wang, Y., 2014, "Study of Characteristics of Cloud Cavity Around Axisymmetric Projectile by Large Eddy Simulation," ASME J. Fluids Eng., 136(5), 051303.