Observations and measurements in cloud cavitating flows

G H Chen, G Y Wang, C L Hu, B Huang and M D Zhang
Department of Thermal Energy Engineering, Beijing Institute of Technology, Beijing 100081, China
E-mail: chenguanghao@bit.edu.cn

Abstract. The main purpose of this study is to shed light on the cloud cavitating flow and associated characteristic of pressure fluctuation near wall. A simultaneous sampling technique is used to synchronize the observations of cavitation instantaneous behaviour and the measurements of pressure signals near wall in a convergent-divergent channel. The results show that, a typical quasi-periodical sheet/cloud cavitation can be categorized into three stages: (1) the growth of attached cavity; (2) the shedding of the attached cavity; (3) the development and collapse of the detached cavities. At the stage one, the magnitudes of pressure fluctuation under the attached cavity are limited. However, they become significant in the closure region of attached cavity, especially, when attached cavity reaches its maximum length. At the stage two, the attached cavity begins to shed small detached cavity, leading to the generation of small local pressure fluctuations with higher frequency. At the stage three, a large detached cavity is gradually formed in the rear of the channel. When it collapses rapidly in the downstream, pressure pulses with the magnitudes of the order of several atmospheres are detected. The propagation speeds of pressure pulses in different region are found to be related with the bubble density in the flow field.

1. Introduction

In liquid flows, cavitation generally occurs if the pressure in low-pressure regions of high-speed fluid machinery drops below the vapor pressure, and consequently the negative pressures are relieved by means of forming gas filled or gas and vapor filled cavities. The very destructive effects which are observed to occur when such cavitation form and collapse in a flow have been documented by Soyama and Kato[1].

By decreasing the cavitation numbers, four regimes can be identified: inception cavitation, sheet cavitation, cloud cavitation, and super cavitation[2]. Sheet/cloud cavitation usually causes the severe oscillating phenomena known as cavitation instabilities, which can result in severe pressure fluctuations, noise, vibration and erosion. A lot of researchers have analyzed experimentally the sheet/cloud cavitating flow in cavitation tunnels[3-7]. Venturi-type sections and two-dimensional foil sections are usually used to study unsteady sheet/cloud cavitation mechanism. Kubota et al.[3] have investigated the unsteady structure of cloud cavitation. The velocity field can be characterized by large-scale and small-scale structures. The overall cloud cavitation structure is associated with the large-scale velocity, while the small-scale velocity is noticeable around cavity boundaries. Furthermore, the structure of cloud cavitation moves at a velocity smaller than the mean free stream velocity and has a concentrated vorticity region at its centre. Stutz and Reboud[8] have experimentally studied the two-phase cavitating flow structure. Both quasi-steady sheet cavitation and large-scale, unsteady cavitation in convergent-divergent nozzles have been examined. The mean values of the void
fraction, flow velocity and bubble size inside the cavities have been measured. The occurrence of a re-entrant jet under the cavity, that flows upstream and results periodically in cavity break off, is demonstrated for example by Stutz et al.[8] with double optical probe measurements and by Pham et al.[9] with electrical impedance probes. More recently, the pressure fluctuation in sheet/cloud cavitation has been investigated around a hydrofoil by Leroux et al.[6], shock waves produced by cloud cavity collapse is believed to influence the frequency of sheet/cloud cavitation. Reisman and Brennen et al.[10] discuss the pressure pulses of large amplitude and short duration during the rapid collapse of cloud cavitation that are very similar to pressure pulses in the present study, several types of propagating structures, the so-called bubbly shock waves, have been observed. The largest impulsive and radiated noise has been attributed to the coherent collapse of a well-defined separate cloud in regions of high pressure. A brief review of these recent works indicates that we still have inadequate understanding on the correlation between pressure fluctuation signal variation and unsteady cavitation behaviours, since it’s difficult to measure the unsteady pressure fluctuation and moreover synchronize cavitation behaviours with pressure fluctuation.

The present study focuses on the unsteady cavitating flows in a convergent-divergent channel by experiment method. A high-speed camera is synchronized with four piezo-electric pressure transducers by a simultaneous sampling technique to study the correlation between unsteady cavitation behaviours and unsteady wall-pressure fluctuation. Corresponding post-processing method is used to analyze the power spectral density and magnitude of pressure impulse. Both quasi-periodic pressure fluctuations and pressure pulses are analyzed together with the corresponding sheet/cloud cavitation structures.

2. Approach and set-up
The experiments are carried out in a closed-loop cavitation tunnel[11].

**Figure 1.** (a) Transducer mounting. (b) Schematic of test section and test model. Units in millimeter.

**Figure 2.** Layout of simultaneous sampling system.

Experiments are conducted in a rectangular test section of 70mm in width and 190mm in height as shown in Figure1(b). There are two windows, one on the top and one on the side, which are made of perspex for optical access. A triangle model is installed on the bottom wall to form a convergent-divergent channel, the convergent and divergent angle are 20 and 10 degree respectively, contraction ratio is 0.5. A separated-vortex type of cavitation generated from the leading edge of the divergent part can be observed from both top and side wall of the channel. The pressure fluctuations induced by unsteady cavity behaviours are measured by piezo-electric transducers installed flush with the wall surface as illustrated in Figure 1(a).

The Reynolds number and Cavitation number are defined as below:
\[ Re = \frac{U}{H} \]  
\[ \sigma = \frac{(P_\infty - P)}{(0.5 \rho U^2)} \]  

where, \( U, P_\infty, P, \rho \) are, respectively, the average velocity at the throat of convergent-divergent test section, the static pressure, the vapor pressure, and the water density. The Reynolds number is fixed at 1.14×10^6.

The experimental conditions are maintained to within 1% uncertainty on the angle of convergent-divergent section, and 2% uncertainty on both the flow velocity and the upstream pressure. Together, the Cavitation number can be controlled to within 5% uncertainty.

The cavitation phenomena are documented by a high-speed digital camera (HG-LE, by Redlake), up to a rate of 105 frames per second (fps). In order to maintain desirable spatial resolutions, much lower recording speed is adopted. Specially, depending on the focus of the investigation, 3000 fps is used in the present study.

The unsteady wall-pressure fluctuations generated by the sheet/cloud cavitation behaviours are measured by 4 piezo-electric pressure transducers (sensibility 7.3mV/kPa), and the sampling rate is 1.024MHz.

Figure 2 shows the layout of simultaneous sampling system, a high-speed visualization and unsteady pressure fluctuation measurement set ups are combined by a controller. When the controller is triggered, the cavitation images and unsteady wall-pressure will be captured simultaneously, but at a different sampling rate. Even though the sampling rate of high-speed camera is far less than that of piezo-electric transducers, each cavity image has its own corresponding pressure fluctuation value, and the uncertainty of simultaneous sampling is negligible compared with the unsteady sheet/cloud cavitation development period.

3. Experiment results and discussion

3.1. Quasi-periodic behaviours of sheet/cloud cavitation

About one and a half cycles of sheet/cloud cavitation images captured from plane-view are shown in Figure 3. A typical quasi-periodic sheet/cloud cavitation development process can be divided into three main stages: (1) the process of growth of attached cavity, (2) the process of shedding of attached cavity, (3) the process of development and collapse of detached cavities, which are marked by line 1, 2, 3, correspondingly.

In the stage one, as shown in Figure 3, the cavity image at \( T_1+0\)ms refers to the origin of a cycle. During \( t \in [T_1+0\)ms, \( T_1+8\)ms], the small vortex cavities coalesce with each other to form an attached cavity behind the throat. As the time develops, the attached cavity gradually grows and covers the wall surface. It reaches its maximum length at about \( T_1+32\)ms, while the four transducers are covered by attached cavity. In the stage two, the attached cavity begins to shed at the rear part and some small detached cavities are observed, finally, it’s broken up totally at about \( T_1+48\)ms. In the stage three, a new cycle of growth begins when vortex cavities reappear near the throat and immediately form a new attached cavity. The small detached cavities in the rear of attached cavity gradually grows into a large detached cavity, and the growth of the large detached cavity is basically in phase with that of the newly formed attached cavity until it reaches its maximum size at about \( T_1+72\)ms. Finally, the large detached cavity collapses rapidly when it’s convected to the downstream. It should be noted that, between \( T_1+0\)ms and \( T_1+28\)ms, small detached cavities also show a similar process of development and collapse in the rear of attached cavity.

3.2. Unsteady wall-pressure fluctuation

3.2.1. Pressure fluctuations associated with the unsteady sheet/cloud cavitation behaviours. As shown in Figure 4, about one and a half cycles of pressure fluctuation measured simultaneously with the
Sheet/cloud cavitation images in Figure 3 are presented. As marked by the number 1, 2, 3 on the top of Figure 4, they correspond separately to the three stages of sheet/cloud cavitation: (1) the process of growth of attached cavity, (2) shedding of attached cavity, (3) development and collapse of detached cavity as indicated in Figure 3(a).

![Diagram showing cavitation stages](image_url)

**Figure 3.** Plane view observation of sheet/cloud cavitation during about one and a half cycles. $\sigma = 0.75$

The locations of transducers in streamwise direction are indicated by the black points as shown in the schematic in Figure 3(a). After $T_1+0$ms, an attached cavity appears near the throat, as the attached cavity grows, it covers transducer 1# and 2# in succession. Accordingly, transducer 1# and 2# experience, one after another, a decrease in pressure fluctuation as indicated by the declining arrow as shown in Figure 4. When attached cavity obtains its maximum length at about $T_1+30$ms, severe cavity fluctuation is observed in the rear of attached cavity, accordingly, strong pressure fluctuations are captured on transducer 3# and 4# as shown in the rectangle frame labeled by c. This characteristic is consistent with that by Leroux et al.[6].

At about $T_1+30$ms, the attached cavity begins to shed and produce some small detached cavities. Due to the variation of these small detached cavities, small local pressure fluctuations are detected as indicated by the black vertical arrows.

After $T_1+48$ms, a large detached cavity is formed in the rear of a newly generated attached cavity, as it moves downstream gradually, a decrease, followed by an increase in pressure fluctuation is detected as shown by the lines labeled by d and e. (see also, for instance, label a and b between $T_1+0$ms and $T_1+30$ms). Such kind of correlation between detached cavity and pressure wave propagation agrees well with previous numerical results[12-14].
3.2.2. Pressure pulses associated with the collapse of detached cavity. Figure 5 shows the cavitation structures in the process of rapid and coherent collapse of large detached cavity associated with the larger pressure pulses. The large detached cavity is also amplified for better observation, and the collapse region is indicated by the ellipse frame. As can be seen in the rectangle frame region, the large detached cavity collapses rapidly near transducer 3#. As the time develops, the collapse region becomes larger and larger. It should be noted that the collapse of large detached cavity does not involve large change in the overall dimensions of the cloud, rather, collapse involves large changes in the bubble density within the cloud. As shown in Figure 6, the pressure pulse with the magnitude of the order of several atmospheres are detected on transducer 3# which is located in the collapse region, three other transducers also detect the same pressure pulse as indicated by the black arrows with a discernible time delay. The significant difference of magnitudes of pressure pulse detected on the 4 transducers may due to the energy dissipation in the propagation process. By examining the time intervals separating the arrival of pressure pulses at the neighbouring transducers, it is possible to obtain the propagation speeds of the pulses. As presented by the bar graphs in Figure 7, the propagation speeds represent the rates at which the pressure pulses are propagated away from the detached cavity collapse region. In all cases, the propagation speeds are smaller than the sonic speed in the pure liquid. In the region between transducer 1# and 2#, the bubble density is high inside the attached cavity (as can be seen in Figure 5), and the corresponding propagation speed is about 240m/s. The bubble density is much lower in the region between transducer 2# and 3#, and the corresponding propagation speed is about 600m/s. In the region where large detached cavity collapses, the propagation speed is about 410m/s. The difference of propagation speed in different region may due to the fact that the sonic speed is decreased with the increase of bubble density in the flow field.
Figure 5. Cavitation structure in the process of rapid and coherent collapse of large detached cavity.

Figure 6. Time evolution of pressure pulse.

Figure 7. Propagation speed of pressure pulse.

4. Conclusion

The unsteady cavitating flows and corresponding wall-pressure fluctuation in a convergent-divergent channel is studied by a simultaneous sampling system. The following is a summary of the main findings:

(1) A typical quasi-periodic sheet/cavitation development process is characterized by three stages: (1) the process of growth of attached cavity, (2) the shedding of attached cavity, (3) the development and collapse of detached cavities.

(2) In the stage one, the magnitude of pressure fluctuations under the attached cavity are small,
however, it’s large in the closure region of attached cavity, especially, when attached cavity obtains its maximum length. In the stage two, the attached cavity begins to shed and produce some small detached cavities. Due to the variation of these small detached cavities, small local pressure fluctuations with higher frequency are detected. In the stage three, a large detached cavity is formed in the rear of the channel, as it moves downstream gradually, a decrease, followed by an increase in pressure fluctuation is detected.

(3) When the detached cavity collapses in the downstream, and pressure pulses with the magnitude of the order of several atmospheres are detected. The difference in the propagation speed of pressure pulse in different cavitation region is found to be related with the bubble density in the flow field.

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