Experimental study on unsteady cloud cavity behaviour and induced pressure fluctuation in a convergent-divergent channel using simultaneous measurement technique

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Abstract. To address the unsteady cavity behaviour and induced pressure fluctuation in cloud cavitating flow, cavitation images and pressure fluctuation signals are simultaneously acquired by high speed visualization system and 4 piezo-electric transducers in a convergent-divergent channel. The cavitation images are processed by using a home-developed software to obtain the time evolutions of global cavity area. Frequency analysis is conducted for both global cavity area and pressure signal. Bubble dynamics is introduced to analyze the correlation between pressure fluctuation in the downstream and global cavity behaviour. Two conclusions are achieved: First, in cloud cavitating flow, the time evolution of both the cavity behaviour and pressure fluctuation are quasi-periodic, one quasi-period can be divided into three main stages: growth of attached cavity, shedding of attached cavity, coalescence and collapse of detached cavity. Second, the dominant frequency of global cavity area and pressure fluctuation on 4 transducers are the same, it’s 20Hz in this study. Third, it’s found that during the stage of growth of attached cavity and growth, collapse of detached cavity, the correlation between global cavity area and induced pressure in the downstream is similar with that of a single bubble; while, such correlation is not clear when several travelling cavities exist at the same time.

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 [1].

In recent years, due to the speeding up and miniaturization of fluid machinery, cavitation might occur anywhere within the machinery. The very destructive effects which are observed to occur when such cavitation form and collapse in a flow have been documented by, for example, Knapp [2], Bark & van Berlekom [3] and Soyama, Kato & Oba [4]. With the mounting of small, lightweight, high-powered turbopumps in liquid rockets, cavitation is certain to occur in the inducer of the turbopump. Such cavitation will sometimes cause oscillating phenomena known as cavitation instabilities. Typical instabilities include the self-oscillatory behaviour of cavitation which can result in severe pressure fluctuations at the inducer outlet. It’s well known that pressure fluctuations are related to the cavitation behaviour like growing and collapsing of the cavity through a number of empirical and theoretical researches. These phenomena are usually studied experimentally in cavitation tunnels (Kubota [5];
Stutz [6]; Leroux, Coutier-Delgosha & Astolfi [7]) to understand the mechanisms of the fluctuations.

Venturi-type sections and two-dimensional foil sections have both been used to obtain unsteady sheet cavitation and to investigate its behaviour. These studies have considerably improved the understanding of the cavity dynamics: the occurrence of a re-entrant jet under the cavity, that flows upstream and results periodically in cavity break-off was demonstrated for example by Stutz et al.[8] with double optical probe measurements and by Pham, Larrarte et al.[9] with electrical impedance probes. More recently, the pressure wave resulting from the cloud collapse has been investigated by Leroux et al. [10], both experimentally and numerically. The magnitude of this wave has been found to influence significantly the frequency of the periodical cavitation cycle.

However, up to the present time, the mechanism of cavitation instability has not been fully understood. In this paper, the fundamental correlation between cavitations and pressure fluctuations has been studied by simultaneous measurement technique. The power spectral density and pulse magnitude of pressure have also been studied.

2. Experimental set up and method

2.1. Cavitation tunnel

The experiment is carried out in a closed-loop cavitation tunnel. A schematic description of the tunnel is provided in Figure.1. An axial flow pump is located about 5m below the test section, reducing the likelihood of pump cavitation. A tank with a volume of 5m$^3$ is placed upstream of the test section to separate undesired free stream bubbles. The top of the tank is connected to a vacuum pump for controlling the pressure in the tunnel. Between the test section and the tank, a corner cane and a straightening vane are used to reduce the turbulence level.

![Figure1. Schematic of the cavitation tunnel](image1.png)

![Figure 2. Schematic of test section and test model](image2.png)

2.2. Convergent-divergent test section and test model

Experiment is conducted in a rectangular test section of 70mm in width and 190mm in height as shown in figure 2. There are three windows which are made of perspex for optical access. A triangle model is installed on the bottom wall to form a convergent-divergent, the convergent and divergent angle are 20 and 10 degree respectively, and the contraction ratio is 0.5. The sectional-view in this flow-channel can be observed for a separated-vortex type of cavitation generated from the leading edge of the divergent part, and the pressure induced by cavity collapse is measured by transducers installed along the divergent wall. The locations of transducers are marked by white points as shown in figure 2.

The Reynolds number and Cavitation number are defined as follow:

\[
Re = \frac{U_h H}{\nu}
\]

\[
\sigma = \frac{(P_c - P_i)}{(0.5 \rho U_h^2)}
\]
where $U_h$, $P_v$, $P_r$, $\rho_l$, $H_l$ are, respectively, the average velocity at the throat of convergent-divergent test section, the static pressure, the vapor pressure, the water density, and the height of test model. The Reynolds number and cavitation number are held constant at 1.1e6 and 0.83 respectively.

2.3. High-speed visualization system
The cavitation phenomenon is documented by a high-speed digital camera (HG-LE, by Redlake), up to a rate of $10^5$ 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 study.

2.4. Pressure measurement system
The near wall unsteady pressure generated by the cavitation are measured by means of four piezoelectric pressure transducer (resonant frequency 250khz, sensibility 7.3mV/kPa). A signal conditioner is used to power the transducers. A data acquisition board whose largest sampling rate is 2.5M per channel is used to transform the output of transducers into digital values.

2.5. Simultaneous measurement system
Figure 3 shows the schematic of simultaneous measurement system, the pressure transducer and high-speed camera are synchronized by a controller.

![Figure 3. Schematic of the layout of simultaneous measurement system](image)

3. Experiment results and discussion

3.1. Quasi-periodic characteristic of unsteady cavity behaviour and pressure
Figure 4 shows a typical example of the growth and collapse of cavitation for a convergent-divergent nozzle with the diffuser angle of 10°. In these photographs, white colored number 1, 2, 3, 4 indicate the location of transducer #1, #2, #3, #4 respectively. As marked by dotted line1, line2 and line3, one period can be divided into three main stages: growth of attached cavity, shedding of attached cavity, and coalescence and collapse of detached cavity.

Between $T_0+0ms$ and $T_0+20ms$, the new generated small vortex cavities grow into a single attached cavitation sheet and moves toward the downstream gradually, the attached cavity obtains its largest length at about $T_0+20ms$. Between $T_0+20ms$ and $T_0+28ms$, the attached cavitation sheet maintains its maximum length. Between $T_0+28ms$ and $T_0+42ms$, a re-entrant liquid jet penetrates the attached cavity from the downstream edge and flows toward upstream, attached cavity is broken up into many small travelling cavities. As can be seen in figure 4, after $T_0+42ms$, the small travelling cavities are observed to persist after the shedding of the attached cavity. In the subsequent frames, some new generated vortex cavity will coalesce with the travelling cloud cavity, one major detached cavity is formed like the detached cavity indicated by a red arrow, and the detached cavity grows in size and moves downstream gradually. It should be noted that, between $T_0+0ms$ and $T_0+24ms$, small travelling
cavities also shows a typical coalescence, growth and collapse process in the downstream of the attached cavity.

| Time 1  | Time 2  | Time 3  |
|--------|--------|--------|
| $T_0 + 0$ ms | $T_0 + 18$ ms | $T_0 + 36$ ms |
| $T_0 + 2$ ms | $T_0 + 20$ ms | $T_0 + 38$ ms |
| $T_0 + 4$ ms | $T_0 + 22$ ms | $T_0 + 40$ ms |
| $T_0 + 6$ ms | $T_0 + 24$ ms | $T_0 + 42$ ms |
| $T_0 + 8$ ms | $T_0 + 26$ ms | $T_0 + 44$ ms |
| $T_0 + 10$ ms | $T_0 + 28$ ms | $T_0 + 46$ ms |
| $T_0 + 12$ ms | $T_0 + 30$ ms | $T_0 + 48$ ms |
| $T_0 + 14$ ms | $T_0 + 32$ ms | $T_0 + 50$ ms |
| $T_0 + 16$ ms | $T_0 + 34$ ms | $T_0 + 52$ ms |

**Figure 4.** Periodic process of cavity shape in convergent-divergent channel

The cavity area in flow field can be estimated based on image gray and extracted by a home-developed software [11]. Figure 5 presents a general quasi-periodic time evolution process of cavity
area. As can be seen, cycle to cycle variations in the details of the cavity area are significant, but the overall characteristic is quite repeatable.

Figure 6 clearly visualizes the power distribution in the frequency domain. A peak exists at the frequency of about 20hz which indicates the dominate frequency of the periodic cavity evolution mentioned above.

**Figure 5.** Periodic development process of cavity area  **Figure 6.** Power spectral density of cavity area

Pressure fluctuation in both non-cavitating flow and cloud cavitation flow are measured at a sampling frequency of 1.024MHz, as shown in figure 7(a) and figure 7(b), the horizontal axis varies from 0 to 0.5s, the vertical axis scale is 30kpa per diversion for all transducers. For non-cavitating flow, there is no significant fluctuation on 4 transducers. However, in the case of cloud cavitation flow, both periodic pressure fluctuation of long duration and large pressure pulses of very short duration are captured due to unsteady cavity behaviours.

As to the long duration pulse, the magnitudes are of the order of about 20kPa to 50kPa, durations measured on the four transducers vary from a few milliseconds to tens of milliseconds. Compare with the pressure on three other transducers, the pressure on transducer #4 shows the most violent fluctuation.

As to the short duration pulses, the magnitudes are of the order of several atmospheres with typical durations of the order of tens of milliseconds. It's clear that there is very large difference in the amplitudes of the short duration pulses measured on the four transducers. The largest pulse magnitude is about 12atm in this experiment. The occurrence of short duration pulse is relatively random on the four transducers.

**Figure 7.** Time evolution of pressure from 4 transducers

The power spectrum density distribution for both non-cavitating and cloud cavitation are shown in figure 8. In the case of non-cavitating flow, there is no dominant frequency, energy is distributed in a wide range. However, in the case of cloud cavitating flow, energy is distributed in a narrow range, a
peak exists at about 20hz on four transducers, it reveals that the pressure fluctuation on four transducers are periodic, and the frequency is about 20hz which is identical to that of global cavitation area. It should be noted that the power of dominant frequency on transducer #4 is significantly larger than those of three other transducers. This is consistent with pressure fluctuation in figure 7(b). As can be seen from figure 4, transducer #4 is located in the rear of attached cavity, and it’s near the region where large scale detached cavity collapse.

![Power spectral density of pressure](image)

(a) $\sigma = 1.6$ (non-cavitation)  
(b) $\sigma = 0.75$ (cloud cavitation)

**Figure 8.** Power spectral density of pressure

3.2. Correlation analysis between global cavity area and induced pressure in the downstream

In order to investigate the correlation between cavity and induced pressure in cavitating flow, the output signal of transducer #4 is chosen to correlate with cavity area variation, because transducer #4 is located in the downstream of diffuser and influenced by the global cavity behaviour in flow field, It also has the largest power at dominant frequency which means it’s strongly correlated with the periodic development of cloud cavitating flow.

![Relation between volume change of bubble and pressure induced](image)

**Figure 9.** Relation between volume change of bubble and pressure induced

![Time evolution of cavity area and pressure from transducer #4](image)

**Figure 10.** Time evolution of cavity area and pressure from transducer #4

Figure 9 shows the time evolution of pressure on transducer #4 and global cavity area, the section marked by vertical line A and C corresponds to the cavitation development period on figure 4. According to the correlation between cavity and induced pressure, this period can be seperated into two sentions.
Bubble dynamics of Brennen [4] is introduced to explain the correlation between the global cavity area and the pressure signal in the downstream. Equation (1) represents the relation between bubble volume change and pressure induced in time domain.

\[
\frac{p_{\text{a}}(r/R_{M}, t/\tau_{c})}{p(r)} = \frac{\partial^2 (v/R_{M}^3)}{\partial (t/\tau_{c})^2}
\]

(1)

Typical example of the relation between volume change of a bubble and pressure is shown in figure 10. According to this figure, in the growing stage of bubble volume, the pressure ascends to the summit. After this turning point, the level of pressure get down and finally reach to the minimum at the moment the cavity has been fully developed. After this growing stage, the bubble experiences the collapsing process, accordingly, the pressure goes up to the peak point as the volume shrinks.

As shown in figure 9, the section between vertical line A and line B corresponds to the high-speed motion photographs between \(T_{0}+0\)ms and \(T_{0}+34\)ms in figure 4. In this period, the cavitation experiences the two stages marked by line1 and line2 in figure 4, an attached cavity and only one major large scale travelling cavity exist in flow field, when the attached cavity and travelling cavity grows in size, the global cavity area grows accordingly which represents the growth of all cavities in the flow field, and the induced pressure on transducer \#4 gets down and reaches to the minimum when the global cavity area goes up and reaches to the maximum; after the turning point, the travelling cloud cavity and attached cavity begin to collapse and shed successively, accordingly, the global cavity area goes up which represents the collapse of all cavities in the flow field, and the pressure on transducer \#4 goes up. As mentioned above, the correlation between the global cavity area and the induced pressure on transducer \#4 is similar with that of a single bubble.

However, the section between vertical line B and line C correspond to the high-speed motion photographs between \(T_{0}+36\)ms and \(T_{0}+52\)ms in figure 4, several small travelling cavities remain after the attached cavity shedding, in this process, the growth and collapse of these travelling cavities are out of phase with each other. Because the global cavity area and the pressure induced on transducer \#4 are affected by all these travelling cavities, so the correlation between global cavity area and pressure induced on transducer \#4 is not very clear.

4. Conclusion
Cavitation images and pressure fluctuation signals are simultaneously acquired by high speed visualization system and pressure transducers to address the unsteady cavity behaviour and induced pressure fluctuation in cloud cavitating flow. Frequency analysis is conducted for global cavity area and pressure signal. Bubble dynamics is also introduced to analyze the correlation between pressure fluctuation in the downstream and global cavity behaviour. Three main conclusions are achieved:

First, at cavitation number of 0.83, the evolution of both the cavity shape and pressure fluctuation are quasi-periodic, one quasi-period can be divided into three main stages: growth of attached cavity, shedding of attached cavity, and coalescence and collapse of detached cavity.

Second, by frequency analysis for global cavity area and pressure signal, it’s found that the dominant frequency of global cavity area and induced pressure fluctuation on 4 transducers are the same, and it’s 20Hz in this study.

Third, it’s found that during the stage of growth of attached cavity and the stage of coalescence and collapse of detached cavity, the growth and collapse for attached cavity and detached cavity are in phase with each other basically, thus the correlation between global cavity area and induced pressure in the downstream is similar with that of a single bubble; while in the stage of shedding of attached cavity, several travelling cavities exist at the same time, the growth and collapse for these travelling cavities are out of phase with each other, thus, the correlation between global cavity area and induced pressure in the downstream is not very clear.

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