EXPERIMENTAL INVESTIGATION OF A PARTICULAR TRAVELING BUBBLE CAVITATION

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ABSTRACT

In the present paper, we focus on a specific type of bubble cavitation over a lifting hydrofoil generated in a periodic way, which turns into attached spot cavitation for high generation frequency. The aim of our work is a better understanding of the inception mechanism of such cavitation as well as its interaction with the liquid flow. Tests are conducted in EPFL cavitation tunnel on a 2-D Naca0009 hydrofoil equipped with miniature pressure sensors. Flow visualisation and pressure transient are recorded in synchronous way for several test conditions. For a given hydrodynamic conditions, the frequency of bubble generation is found to be different for two neighboring bubble sources. Generation frequencies, as high as 5 kHz were measured. We have shown that periodic bubble cavitation originates from a local vaporization process, which takes place within the surface roughness in the minimum pressure area. The pressure transient caused by a traveling bubble passage over the hydrofoil was analyzed. It turns out that the pressure beneath the bubble is always negative and well below the expected vapor pressure. Therefore, a thin film of liquid, which could correspond to the boundary layer, stands between the bubble and the solid surface. Moreover, we have shown that a moving 3-D boundary layer separation is produced behind the bubble.

INTRODUCTION

Cavitation phenomenon is usually defined as the vapor formation in liquid flows by a decrease in pressure at constant temperature. Although the cavitation definition appears to be simple, there is a big complexity in physical mechanism of cavities inception and development. Cavitation can exhibit several physical forms. Among cavitation forms generated on a 2D hydrofoil, traveling bubble cavitation has received great deal of attention. Kermeen et. al. [1] have investigated cavitation inception and pointed out that bubbles may result either from free stream nuclei or from nuclei originating from surface roughness. Kuhn De Chizelle et al. [2] have observed the production of attached streaks in the wake of traveling bubbles and a thin film separating the bubble from the surface. Briançon-Marjolet et. al. [3] and Li et. al. [4] have investigated the interaction of exploding bubble with the boundary layer and attached cavitation; they both observed that traveling bubbles can stimulate local attached cavitation through the generation of a transient region of turbulence, which may sweeps the cavity. Farhat et. al. [5] have shown that, under specific flow conditions, bubble cavitation may be generated in a periodic way and may transit to attached spot cavitation for high generation frequencies as illustrated on Figure 1.

Fig. 1 : Transition from bubble to attached cavitation on a by increasing incidence C=15 m/s, σ=0.3 (After [5])

The focus of the present paper is the inception and dynamic of periodic traveling bubble cavitation over a lifting hydrofoil. Experiments are carried out in the EPFL high speed cavitation tunnel. First, experimental set-up is presented; this involves instrumented hydrofoil as well as the use of a light intensified CCD camera for flow visualization. Second, flow observation and pressure measurements are analyzed and discussed with regard to the process of periodic generation of traveling bubbles.

NOMENCLATURE

C Upstream velocity [m/s]
L Hydrofoil chord length [m]
R Radius of a bubble at its basis [m]
Vd Displacement velocity of a bubble [m/s]
Ve Expansion velocity of a bubble [m/s]
xi Chord of sensor N° i [mm]
Cpi Pressure coefficient on sensor N° i [bar]

\[ p_{in} = \frac{p_{in} - p_{v}}{C_{pi}} \]

pin Pressure at inlet of the test section [bar]

pv Water vapor pressure [bar]

pi Pressure on sensor N° i [bar]

τ Exposure time of camera [µs]

α Incidence angle [°]

σ Cavitation number [-]

\[ \rho = \frac{V_{d} - V_{e}}{C_{pi}} \]

ρ Water density [kg/m3]
EXPERIMENTAL SETUP:
Experiments are carried out in the EPFL High Speed Cavitation Tunnel (Avellan et. al. [6]) having a squared test section of 150 mm side length. A maximum flow velocity of 50 m/s may be reached at the test section inlet corresponding to 1.25 m³/s flow rate. The operating parameters are the upstream velocity \( C \), the cavitation number \( \sigma \) and the incidence angle of the hydrofoil \( \alpha \).

**Instrumented Hydrofoil:**
The instrumented hydrofoil has a Naca 009-7.38 45 /1.95 thickness distribution. It is 100 mm long, 150 mm wide and truncated at 90% of its chord. 14 piezo resistive pressure sensors, having 3 mm diameter, 2 mm height and 7 bar pressure range, are embedded in the hydrofoil suction side close to the stagnation point and throughout the chord. Coordinates of sensors near leading edge have been computed to correspond to the location of minimum pressure at the incidence angle of 3°.

A specific procedure has been developed for the sensors mounting in order to fulfill the following requirements:
- **R1.** Sensors should withstand and operate for negative levels of liquid pressure.
- **R2.** Sensors should fit in curved areas of the hydrofoil without significant alteration of local geometry.
- **R3.** Sensors should withstand cavitation aggressiveness when located in the bubbles collapse area.

Each sensor is mounted in a chamber connected to the hydrofoil surface through a tap of 1 mm diameter and 0.5 mm height (Figure 3). These chambers as well as the cable paths are first drilled in the hydrofoil. The sensors are then directly manufactured in their chambers. The sensing element is first tightly fixed then a protecting plastic compound having the same density as water is introduced from the pressure tap. This allows providing the sensor with a top surface shape close to the original one and preventing its pull-up when subjected to negative pressure. Thereby, requirements R1 and R2 are fulfilled. Obviously, since cavitation may damage any industrial alloy, it is not possible to fulfill the requirement R3. Nevertheless, the fact that the sensing element is not flush-mounted, the life duration of pressure transducers is improved. It should be noticed that 6 sensors out of 14 have been damaged after the end of tests. Figure 2 shows sensors location and numbering. Figure 3 illustrates their mounting procedure.

The output signals for pressure sensors are amplified and filtered before being synchronously digitized by 80-channels waveform recorder at a maximum sampling frequency of 51.2 kHz. Moreover, the hydrodynamic parameters are recorded and averaged during pressure signals recording.

**Static and dynamic calibration of the transducers**
Static calibration of pressure transducers is performed with the instrumented hydrofoil mounted in test section of the cavitation tunnel and by comparing transducers output voltage to the readings of a high precision reference pressure transducer. An excellent linear response is obtained with a measurement error of less than 0.2 % of the measurement range. Moreover, we have also calibrated the pressure sensors for negative values of the pressure according to a specific procedure already described by Farhat [5]. Pressure sensors maintained an excellent linear response down to -1 bar absolute.

The dynamic calibration of the transducers is carried out in a large vessel with the help a spark-generated bubble. An explosive growth of a vapor bubble generated by an underwater discharge allows a wide band excitation of the pressure sensors. The result of such a calibration (Farhat et. al. [7]) shows an good linear response up to 25 kHz bandwidth.

**Visualisation system:**
An intensified light video camera, QUICK 05A, is used for the visualisations. The camera is equipped with a Phosphor Micro Channel Plate (MCP) for the light intensification stage, which is coupled with a video CCD image sensor via high quality optic. The shutter can be triggered by a TTL signal for acquisition on external events and the time delay for effective triggering is 30 ns. The camera allows single shot as well as multiple exposure sequences with programmable delay and inter-fame intervals.

The light source is provided by a Cordin xenon flash lamp. The maximum energy is 1100 J and the flash duration may be set between 0.5 to 11 milliseconds.

The synchronization of the signal acquisition and image recording is ensured according to the following procedure. Once the pressure signal \( p_2 \) is beyond a certain threshold, the camera is triggered, which in its turn triggers both the flash lamp and the signal recorder. By doing so, the electric noise due the flash ignition is avoided. At the same time, the averaging of the operating parameters of the cavitation tunnel is launched.
RESULTS

Mean wall pressure for cavitation free flows:
Figure 4 shows pressure coefficient along the suction side of the hydrofoil for different values of incidence angles and a flow velocity of 20 m/s. The sigma value is set high enough to ensure a non cavitating flow. We have plotted in the same graph the result of flow computation for $\alpha=2.5^\circ$. Computation is achieved with the help of TASCflow commercial CFD code using RANS scheme, $k$-$\varepsilon$ turbulence model, and finite volume discretisation. These graphs show how the minimum pressure decreases when the incidence angle increases.

![Figure 4](image)

Mechanism of periodic generation of cavitation bubbles:

Effect of surface roughness and nuclei content

Figure 5 illustrates two different kind of bubble cavitation obtained for an upstream velocity of 13 m/s, $\sigma$ is 0.3 and $\alpha$ is 1°. For the first photograph, the leading edge of the hydrofoil has an averaged surface roughness of 1 $\mu$m RMS and the water is well degassed. In the second photograph, the water is not degassed and the leading edge is polished with an averaged surface roughness of 0.2 $\mu$m RMS. It should be noticed that with polished leading edge, no bubble cavitation could be obtained for well degassed water.

These photographs illustrate well the major role of surface roughness on the bubble formation. In the case of well polished leading edge, since bubbles could be generated only with non degassed water, we may state that they originate from nuclei contained in the upstream liquid. This explains why their occurrence is random both in space and time and also why their size is varying significantly from one bubble to the other at a given location along the hydrofoil chord.

For well degassed water, bubble cavitation may only originate from a fixed roughness element close to the minimum pressure location. In this case, bubbles are found to be generated in a periodic way and have the same size at any given location along the hydrofoil chord. Moreover, as soon as the bubble frequency is high enough, a smooth transition to an attached cavitation spot occurs as already shown on Figure 1.

![Figure 5](image)

The frequency of bubble generation:

Figure 6 shows a bubble growth as it travels along the hydrofoil suction side. The bubble explodes on the pressure sensor N°1 and passes over sensors N°2 and 3. The micro-roughness due to the sensor N°1, which is located in the minimum pressure area, allows a periodic generation of cavitation bubbles similar to the one presented in Figure 5. Frequencies of bubble generation as high as 5 KHz have been measured for upstream velocity of 13 m/s. Assuming that active nuclei concentration may not exceed 5 nuclei per 1 cm³, one may never expect such high frequency of bubble generation originating only from upstream nuclei. This result confirms that periodic bubbles originate from a local nucleation/vaporization process.

We have investigated the influence of operating parameters on the periodicity of bubble generation and could not find any clear relationship. We have even noticed that for a given fixed test conditions, the generation frequency may vary significantly from one test to the other. This observation let us believe that the generation process of periodic bubbles is a local phenomenon, which depends on the flow structure around micro-roughness elements.

![Figure 6](image)

It should be noticed that periodic generation of cavitation bubbles was easier to obtain for flow velocities ranging from 10 to 15 m/s. For flow velocities higher than 20 m/s, no periodic bubbles could be obtained and only attached cavitation spots were observed. This observation illustrates that the occurrence of periodic bubble cavitation depends not only on the minimum pressure level and surface roughness, but also on the local rate of vaporization. In fact, the rate of vaporization in a nucleation site, which is directly related to the frequency of bubble generation, is enhanced by the flow turbulence. Once this rate is high enough, transition to attached spot cavitation is obtained. This explains why high Reynolds numbers do not allow occurrence of bubble cavitation (Billard, Farhat et al. [8]).
**Attached cavitation spots**

In this test, we have set the velocity to 16 m/s and the incidence angle to 3°. The sigma value is set high enough to ensure cavitation free flow. The pressure $p_{in}$ in the test section inlet has been gradually decreased from cavitation free to well developed attached cavitation conditions. Pressure signals have been recorded during 40 seconds with sampling frequency of 200 Hz. Pressure signals $p_1, p_2, ..., p_6$ are presented on Figure 7 along with a top view of a well developed cavitation.

Obviously, as far as the flow is free of cavitation, the pressure on all sensors and the upstream pressure ($p_{in}$) decrease with the same slope. It should be noticed that pressure on sensor N°1 reaches negative values as low as -0.48 bar without any cavitation. This confirms, once again, that industrial water may withstand substantial tension without vaporization. The cavitation inception on sensor N°1 causes a sudden increase of the pressure $p_1$, which remains constant with a negative value. This pressure does not reach vapor pressure because the sensor is not totally covered by vapour. Nevertheless, the negative value confirms that the liquid upstream to the detachment point is in tension.

The pressure signals $p_2, ..., p_6$ exhibit a similar behavior as the vapor cavity grows. We may observe a slight increase of the pressure on every sensor, one after the other, followed by a decrease down to the vapour pressure as soon as the sensor is covered by the cavity. The pressure increase may be related to the stagnation point of the liquid flow over the cavity closure as already reported by Franc J. P. [9].

**Bubble Dynamic**

**Pressure disturbance induced by bubble passage:**

Pressure signals are recorded simultaneously with a multiple-exposure visualisation. Camera and system recorder are triggered on pulses generated by bubble explosion on sensor N°1. The camera is programmed to overlap five frames with 1 µs exposure time. The frames, labelled A through E, are spaced in time as follows:

<table>
<thead>
<tr>
<th>A-B</th>
<th>B-C</th>
<th>C-D</th>
<th>D-E</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>150</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>

We have presented in Figure 8 pressure signals $p_1$ and $p_2$ along with the corresponding overlapped frames of a travelling bubble. The incidence is 1.5°, the upstream velocity is 13.5 m/s and sigma is set to 0.3. Vertical lines plotted on pressure graphs help in locating the occurrence of each frame.

The bubble explodes on the sensor N°1 and grows as it travels towards the sensor N°2. One may easily observe that the frame D corresponds to the bubble covering sensor N°2. The pressure signals reveal that the liquid withstand a negative pressure up to the location of sensor N°2. The generation and explosion of the bubble on the sensor N°1 leads to a fast increase of the pressure followed by a slower decay as the bubble leaves the sensor. Then the pressure $p_1$ returns to its original cavitation free level. For the pressure signal $p_2$, one may...
observe that the pressure starts to increase gradually while the bubble is still on the sensor N°1. This could be related to an interaction of the shock wave generated by the bubble explosion and the boundary layer, which may cause a transient boundary layer separation. As soon as the front interface of the bubble reaches the sensor N°2 (Frame C), a slight drop of the pressure is systematically observed followed by a constant pressure that lasts as far as the bubble covers the sensor (Frame D). In the contrary, the rear interface of the bubble causes a slight increase and decrease of the pressure as the bubble leaves the sensor. Once the bubble has left the sensor by about 2 mm, a substantial increase of the pressure is observed; whose duration is around 300 µs.

The pressure disturbance produced by the bubble interface may be explained by the fact that the liquid near the bubble front is accelerated while it is decelerated near its tail. It should be noticed that the pressure measured during the bubble passage over the sensor is negative (~80 mbar) and well below the expected vapor pressure. This result, which is systematically observed on a large number of tests, let us suppose that the bubble is not in contact with the hydrofoil and there should be a thin film of liquid between the bubble and the solid surface.

The pressure increase observed after the bubble has left the sensor is a signature of a complex interaction between the moving bubble and the boundary layer. As the rear interface of an exploding bubble is moving backward, the liquid in this area is decelerated and the pressure is consequently increased. The positive pressure gradient thus generated upstream to the bubble may trigger a boundary layer separation, which travels with the bubble. Thus, the liquid upstream should flow over the bubble.

**Effect of incidence angle:**

We have presented in Figure 9 pressure signals \( p_1 \), \( p_2 \), \( p_3 \) and \( p_5 \) corresponding to 2 test conditions in order to follow the interaction of the bubble with the pressure field along the hydrofoil chord. The flow velocity is 13 m/s and the incidence angle is 1° and 2°.

In the case of 1° incidence angle, a periodic bubble generation is observed with a frequency of 420 Hz. Again one may observe a behavior of the pressure signals \( p_1 \) and \( p_2 \) similar to the previous case. As the bubble heads to the sensor N°3, the pressure decreases from its cavitation free level down to a negative value when the bubble covers the sensor. As for pressure signal \( p_3 \), the pressure signal \( p_1 \) exhibits a significant increase of the pressure once the bubble has left the sensor. The amplitude and duration of this pressure disturbance are found to be higher than with \( p_2 \). According to our assumption on the origin of this pressure increase, this shows that the length corresponding to the boundary layer separation behind the bubble is increasing as it travels over the foil. For this test conditions, the bubble collapse occurs on the sensor N°4, which by the way has caused its destruction. The shock overpressure caused by the collapse is well detected by the sensor N°5, which exhibits large pressure peaks.

For 2° incidence angle, we observe a periodic generation of bubbles with a higher frequency (~960 Hz). In fact, increasing the incidence angle leads to a decrease of the minimum pressure and thereby to an increase of the rate of local vaporization. As bubbles grow, they start to merge on sensor N°3 and become completely mixed to form a single fluctuating cavity whose closure is located on the sensor N°5. Pressure pulses on sensor N°1 are found to be higher than in the case of 1° incidence. Furthermore, the increase of the pressure after the bubble passage over the sensor N°2 is narrower. This is due to the fact that the distance between two successive bubbles is shorter since their frequency is larger. As the bubbles start to merge on sensor N°3, \( p_3 \) signal feels successive passages of bubbles interface. The pressure N°5 illustrates the cavity fluctuation. It should be noticed that this fluctuation frequency is the same as the bubble generation frequency. The cavity oscillation is highly modulated by the bubble passage.

**Fig. 9:** Pressure measurements for two operating condition allowing travelling bubble cavitation

**Bubble shape:**

During early stage of bubble growth, a strong effect of the incidence angle on bubble shape was found. We have presented in figure 10 pressure signals \( p_1 \) and \( p_2 \) for fixed values of flow velocity and \( \sigma \), and two different incidence angles. The corresponding overlapped frames, as seen from top, are also presented with a sketch of the same bubble as seen from the side. The bubble exhibits a different shape at 1.5° and 2.5°. In fact, for 1° incidence angle, the bubble is hemispheric and starts...
to grow faster in the downstream direction as it travels beyond the sensor N°2. For 2.5° incidence angle, the bubble tail remains attached to the hydrofoil while growing exhibiting a conic shape whose summit is attached to the nucleation site. Once the bubble reaches a specific dimension, it is swept by upstream flow and becomes hemispherical before it starts to grow faster in the downstream direction as for 1.5° incidence angle. The fact that the bubble remains attached for a while during its early growth may be due to the surface tension forces acting between liquid solid and vapour as reported by Farhat et. al. [10]. The final shape of the bubble, elongated in the downstream direction, may be explained by the fact that the boundary layer separation upstream to the bubble and the resulting pressure increase, acts as a barrier for bubble expansion. This is why the bubble grows faster in the downstream direction.

As the bubble travels over the hydrofoil, its interaction with the boundary layer and the solid surface cause the development of a cavitating “twin tails” visible of frame sequences of Figure 10 as well as on Figure 12. Ceccio [11] has already reported this phenomenon. He supposed that the origin of these vapour structures could be related to the development of vortices by the liquid flow over the bubble.

The photograph presented on Figure 11 illustrates an elongated bubble during its collapse. One may observe the micro-jet, which develop inside the bubble towards the hydrofoil.

**Bubble motion :**

Digital photographs of traveling bubbles, taken from the top, are used to derive expansion and displacement velocities during the growth phase. The camera is set overlap two frames with 1 µs exposure time and an inter-frame (τ) of 500 µs. Digital images are processed to extract the contact line that the bubble forms with the hydrofoil. The contact line is then approximated by a circle having a radius R(t) and center coordinates (xc(t), yc(t)). This image processing is performed on both overlapped bubbles. The displacement velocity in the stream direction Vd and the expansion velocity Ve, at a given time t, may be estimated as follows:

\[ V_d(t) = \frac{x_c(t) - x_c(t - \tau)}{\tau}, \quad V_e(t) = \frac{R(t) - R(t - \tau)}{\tau} \quad \text{with} \quad \tau = 500 \mu s \]

We have plotted on Figure 13 the bubble radius at different location as well as its displacement and expansion velocities. The corresponding incidence angle is 1°, the upstream velocity is 13 m/s and the sigma value is 0.42. For any given location on the hydrofoil, the bubble radius is almost the same for all tests. This confirms that for periodic bubble cavitation, the bubbles behave in very similar way. The displacement velocity may be compared to the liquid velocity plotted in the same graph. The liquid velocity is derived from the wall pressure distribution with help of Bernoulli equation (figure 4). One may easily observe that the bubble velocity is lower than the liquid velocity in the very beginning of the bubble growth. Around 20 % of chord length, the bubble move at almost the same velocity as the...
liquid. Obviously, the expansion velocity of the bubble decreases as the bubble travels. It drops from 4 m/s to almost zero at 25% of chord length. The ratio between the expansion and the displacement velocities is the tangent of the angle of the ultimate displacement of the ultimate cavitation spot, which forms when the bubble frequency increases.

\[
\begin{align*}
R [\text{mm}] & \quad \text{Measured radius} \\
X [\text{mm}] & \quad \text{Displacement velocity of bubble} \\
V_d [\text{m/s}] & \quad \text{Local velocity} \\
V_e [\text{m/s}] & \quad \text{Expansion velocity of bubble}
\end{align*}
\]

\*Fig. 13 : Kinematics measurement of traveling bubble cavitation, \( C = 13 \text{m/s}, \sigma = 0.42 \) and \( \alpha = 1^\circ \)

DISCUSSION

The observation of periodic traveling bubbles, which turn into cavitation spots as soon as the generation frequency is high enough, shows that this type of cavitation originates locally on micro-roughness element in the minimum pressure area. Since the water wettability is not perfect, small amount of gas remains trapped inside the surface as shown on Figure 14. This remaining gas acts as vaporization catalyst. In fact, as soon as the local pressure is low enough with respect to the surface tension forces at the liquid-gas interface, the trapped gas may grow and trigger local vaporization of the liquid inside the surface roughness. For a given local pressure level, an exploding bubble is generated if the amount of vaporized liquid has a critical pressure above the local pressure. This explains why no bubble cavitation could be produced with polished leading edge hydrofoil. When a bubble explodes, it is swept by upcoming flow while an amount of gas remains in the nucleation site because of surface tension forces that prevent from a perfect wettability. This “auto nucleation” process provide a sustained way to produce cavitation bubbles in a periodic way for unlimited time.

The parameters that govern the generation frequency of the bubbles remain unknown. For a given hydrodynamic conditions, a large difference in generation frequency was observed between two neighbouring nucleation sites leading us to believe that the nucleation process is rather a local phenomenon. A possible explanation of the frequency variation could be the volume of gas trapped in the micro-roughness as well as the local flow structure around the micro-roughness element. Further micro scale investigations of the flow around the nucleation site is needed to clarify the periodicity of bubble generation.

\*Fig. 14 : Nucleation process

CONCLUSION

In the present study, an experimental investigation of the periodic generation of traveling bubbles is performed. Tests are carried out on a 2-D hydrofoil equipped with miniature pressure sensors. An intensified camera is used to visualize the complex motion of traveling bubbles. The main conclusions may be summarized as follows:

- Bubble cavitation may originate from upstream nuclei contained in water or from a local nucleation/vaporization process. In the later case, the bubble generation is found to be periodic and turns into an attached spot when the generation frequency of bubbles is high enough.
- The generation frequency of periodic bubbles was found to vary significantly from one nucleation site to the other for fixed hydrodynamic conditions. The nucleation process is thereby a local phenomenon, which depends on the amount of gas trapped in the micro roughness as well as the local flow structure and the pressure level.
• The pressure measured at different location of the hydrofoil suction side during the bubble passage reveals a very complex interaction of the bubble with the liquid flow. The pressure in the bubble measured beneath the bubble is always negative and well below the vapor pressure. Thereby, a thin liquid film stands between the bubble and the solid surface.

• The pressure measurements also illustrate a boundary layer separation behind the bubble, which travels with the bubble. This 3-D flow separation is caused by a positive pressure gradient resulting from the bubble expansion.

• During the beginning of the bubble growth, the displacement velocity of the bubble center is found to be lower than the local liquid velocity. The liquid flows over the bubble leading to the formation of “twin vortices”, which detach from its tail.

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