ON THE DETACHMENT OF A LEADING EDGE CAVITATION

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ABSTRACT

In the present paper we present an experimental investigation of the onset and detachment of leading edge cavitation. Tests are conducted in the LMH high speed cavitation tunnel on a 2-D Naca0009 hydrofoil having 100 mm chord length. Both Particle Image Velocimetry and flow visualisation are conducted for different test conditions. At low incidence angles, in the case of non cavitating flow, the velocity field do not show any laminar separation of the boundary layer in the suction side of the hydrofoil. In the case of well developed attached cavitation, we have clearly shown that the distance between the separation and the cavity detachment points is less than our PIV spatial resolution (5.10^{-4} m). We have also shown through flow visualisation that an increase of the incidence angle of the hydrofoil leads to an unstable transition from bubble cavitation to attached cavitation. These observations let us believe that, in our specific experimental set-up, the flow separation is generated during the transition process from bubble to attached cavitation with a significant influence of the surface roughness and physical properties of the hydrofoil material as well as the wall pressure distribution along the suction side of hydrofoil.

1 Introduction

The cavitation phenomenon, which is due to a pressure drop in liquid flows, may be responsible of noise and vibration as well as efficiency drop and material erosion. Among the cavitation types that may develop in a flow around a lifting body, the so-called “attached cavitation” or “leading edge cavitation” is known to be responsible of severe erosive. This type of cavitation is characterised by a partial vapour cavity that detaches from the leading edge of a lifting body and extends downstream (see Figure 1). The interaction of the main vapour cavity with the turbulent flow is responsible of Kelvin-Helmholtz like instabilities. U-shaped vapour vortices are thus generated and transported by the mean flow to the pressure recovery region where they collapse violently. These cavitating vortices remain in contact with the solid surface according to Kelvin’s theorem, which leads to vapour collapse close to the surface. This observation explains the aggressiveness of the leading edge cavitation. The shedding process of travelling vortices is highly related to the stability of the main cavity. Unstable cavitation, associated with re-entrant jet, leads to a periodic shedding of transient cavities. In this case, the shedding frequency is found to be governed by a Strouhal law based on the main cavity length (Farhat et. al. 1993). The origin of the leading edge cavitation instability is not yet fully understood. Nevertheless, it is well known that cavitation instability is highly influenced by the upstream velocity, the incidence angle, the cavity length as well as the surface roughness. An increase of one of these parameters promotes instabilities.

The leading edge cavitation over a lifting body has been widely investigated in both theoretical and experimental ways. Shen and Peterson (1978, 1980) have conducted extensive work on the influence of flow unsteadiness on cavitation development. They have shown that unsteady cavitation inception is a function of the ratio of dynamic and static pressure gradients as well as the phase shift between the foil angle and the pressure response. They have also demonstrated that the magnitude of pressure fluctuation in transition and turbulent regions do not depend on oscillation amplitude and frequency. Arakeri et. al. (1978) have pointed out the influence of the boundary layer on the cavitation development and stated that the leading edge cavity may not detach unless a laminar separation occurs. This criteria has been confirmed by several authors, such as Franc ad Michel (1988) who have also observed that the leading edge cavitation may be fully suppressed whenever the laminar separation turns into turbulent state.

Tassin et. al. (1998) have investigated the effect of physical ad chemical properties of the solid surface on the cavitation detachment. They have pointed out a significant difference between “hydrophobic” and “hydrophilic” surfaces on the detachment point location. Recently, Caron et. al. (1999, 2000) have investigated the effect of flow unsteadiness on the dynamics of a leading edge cavitation. For this purpose, an oscillating 2-D hydrofoil has been developed. The maximum oscillation frequency is 50 Hz. They have pointed out a significant influence of such unsteadiness and have showed that cavitation may be fully suppressed for specific flow conditions and oscillation frequency despite the fact that the static pressure is probably below the vapour pressure. The reason of this cavitation suppression remains not yet fully understood. Furthermore, they have shown that the surface roughness in the leading edge area affects not only the onset and detachment of a leading edge cavitation but influence also significantly its dynamic and consequently its erosion aggressiveness.

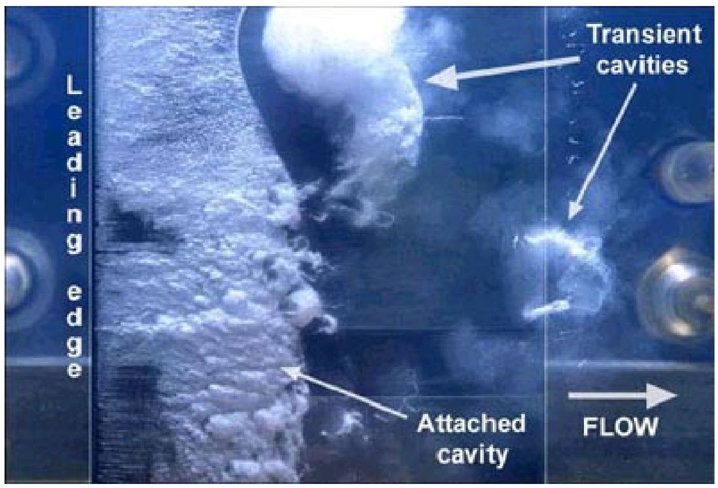

Figure 1: Top view of leading edge cavitation on a NACA0009 hydrofoil
Upstream velocity=30 m/s; Incidence angle=3.5^{o}; σ=0.9

The physics of the onset and detachment of a leading edge cavity on a lifting hydrofoil is a complex problem. Figure 2 illustrates this phenomenon in the case of a flow over a symmetric hydrofoil performed in the IMHEF high speed cavitation tunnel. Due to the low incidence angle, both bubble cavitation and attached cavitation occur at the same time in two locations of the hydrofoil while a cavitation free flow is observed elsewhere[1]. Obviously, macroscopic parameters, such as incidence angle, flow velocity, pressure level, nuclei distribution as well as surface roughness, are the same along the leading edge. We have presented in Figure 3 another illustration of a vapour cavity detachment occurring near the tip of an elliptic hydrofoil. One may easily observe on this figure still droplets, within the vapour cavity, attached to the solid surface. obviously, the pressure inside these droplets is slightly higher that the vapour pressure and their mechanical equilibrium is mainly ensured by the surface tension forces. The water-vapour interface presents a transparent aspect near the detachment point and a foamy aspect downstream. The change in the interface aspect is due to the water-vapour mixing resulting from the interaction of the cavity with the surrounding liquid flow field.

In the present paper, we focus on the onset and detachment of the leading edge cavitation over a 2-D hydrofoil placed in the test section of the IMHEF high speed cavitation tunnel. PIV as well as flow visualisation are performed in order to analyse the flow field in the neighbourhood of the cavity detachment.

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[1] *Figure 1 shows that the length of attached cavitation is almost the same as the length of the envelope of travelling bubbles. This result is in accordance with the hypothesis that have been already accepted by Hirschi et. al.(1998) for leading edge cavitation modelling based on Rayleigh-Plesset theory.*

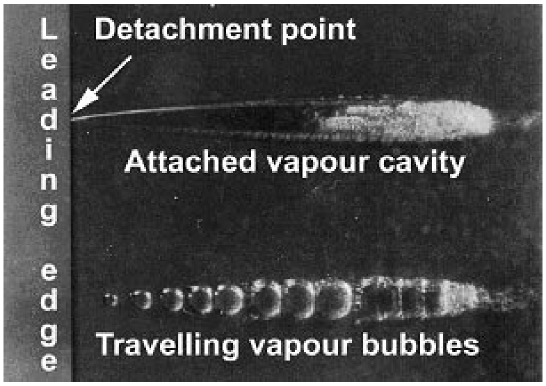


Figure 2: Attached cavitation and travelling vapour bubbles on a symmetric NACA hydrofoil. Velocity: 20 m/s, incidence angle= 1^o; σ=0.8

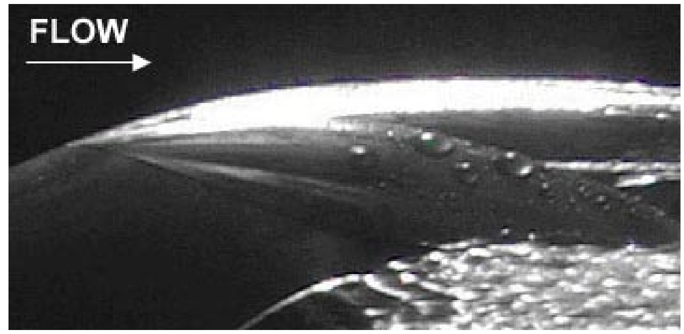


Figure 3: Leading edge cavity detaching from tip of an elliptic hydrofoil. Upstream velocity: 25 m/s, incidence angle= 2^o; σ=0.4

2 Experimental Set-up

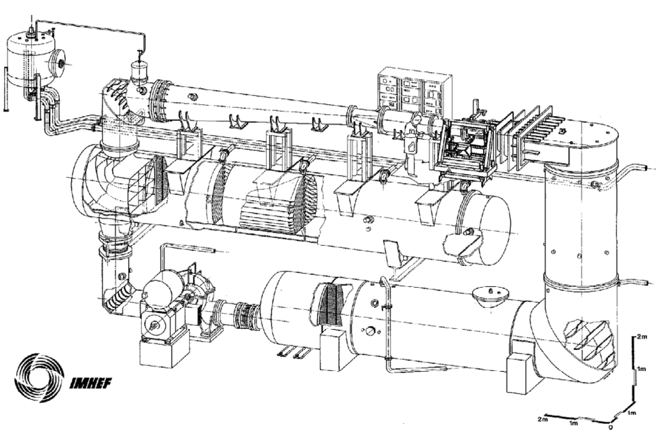
Tests are carried out in the IMHEF high speed cavitation tunnel presented in Figure 4 and described by Avellan et. al. (1984). The test section is a150x150 mm and 750 mm long. The maximum upstream velocity is 50 m/s. The operating parameters are the upstream velocity C_{ref}, the incidence angle α and the cavitation index σ defined as follows:

$$\sigma = (p_{ref} - p_v(T)) / (0.5\, \rho\, C_{ref}^2)$$

where C_{ref} and p_{ref} are the reference velocity and pressure both measured at the test section inlet. The $p_v(T)$ is the vapour pressure corresponding to the water temperature T.

The experimental hydrofoil is a NACA0009 having 100 mm chord length and 10 mm maximum thickness.

The velocity field is captured with the help of a 2-D *Dantec* Particle Image Velocimeter (PIV). In the case of cavitating flows, laser diffraction on the cavity interface leads to a saturation of the PIV digital camera. To overcome this problem, we have installed a mask that prevents from vapour cavity illumination (Figure 5). Thus, velocity measurements could be achieved upstream of the leading edge cavity as close as 0.5 mm from its detachment point. Furthermore, flow visualisation is also achieved with the help of a digital camera and a xenon flash lamp having 5 μs duration.



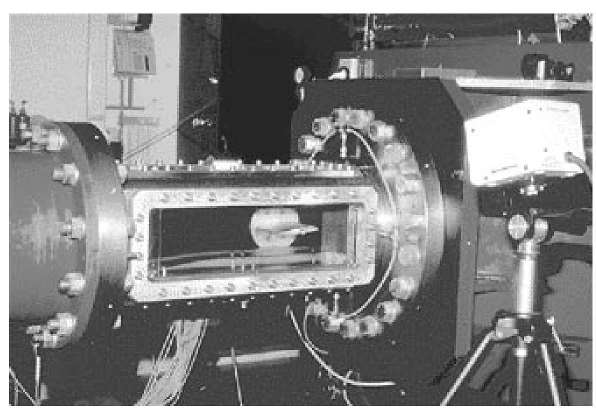


Figure 4: The IMHEF high speed cavitation tunnel

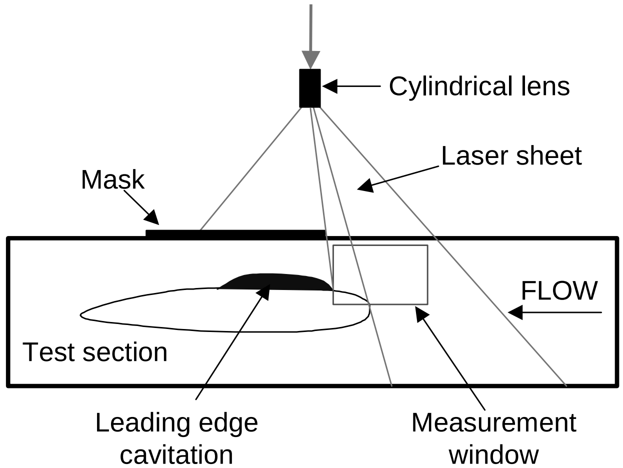


Figure 5: PIV set-up for velocity field measurement with a leading edge cavitation

3 Results

3.1 The velocity field

Measurement of the velocity field upstream to the hydrofoil is performed for 2.5° incidence angle and 25 m/s upstream velocity. Three σ values are tested, corresponding to cavitation free condition (σ=1.5) and 2 cavitating flows corresponding to different leading edge cavity lengths (σ=0.7 and σ=0.64). The velocity at every node is obtained through an averaging of 1024 samples.

We have presented in Figure 6 a the velocity field in the case of a well developed leading edge cavitation (σ=0.7). A top view of the corresponding flow is presented on the same figure. According to the PIV spatial resolution of 5. 10^{-4} m, this result shows that the flow in the leading edge area remains attached to the hydrofoil and no boundary layer separation could be observed. It should be noticed that analysis of the velocity field in the case of a non cavitating flow (σ=1.5) also show no flow separation on the suction side of the hydrofoil. This result is well confirmed by flow computation.

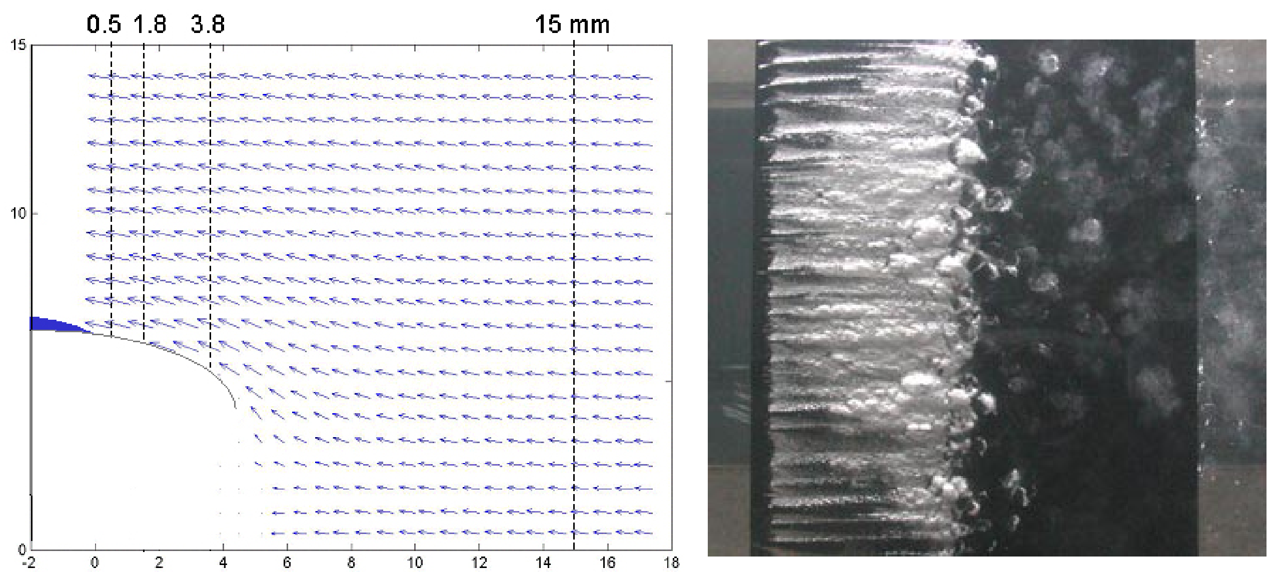


Figure 6: Velocity field in the vicinity of the hydrofoil leading edge (left) and the corresponding top view of leading edge cavitation development (right). Upstream velocity: 25 m/s, incidence = 2.5^{o}; σ=0.7

We have presented in Figure 7 cross section velocity profiles obtained for a cavitating and non cavitating flows at –15.5, -3.8, -1.8 and 0.5 mm from the vapour cavity detachment. Both horizontal and vertical components of the velocity, scaled by the upstream velocity, are plotted for 25 m/s upstream velocity and 2.5° incidence angle. We have also presented the pressure profile derived from Bernouilli's equation.

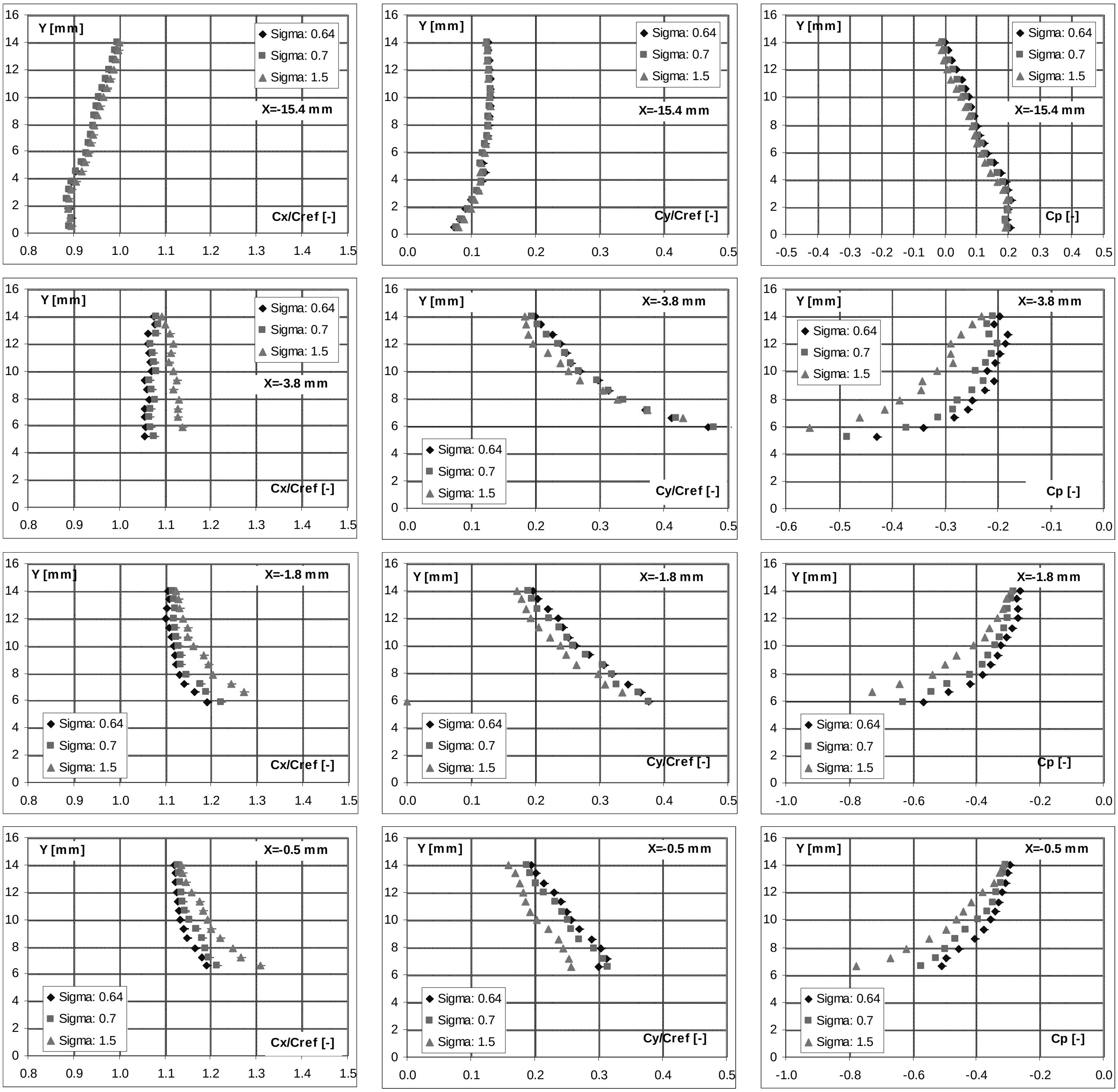


Figure 7: Horizontal and vertical velocity as well as pressure coefficient profiles at different locations (X = -15.4, -3.8, -1.8 and -0.5 mm) upstream to the main cavity detachment for 2.5 incidence angle, 25 m/s upstream velocity and 2 different cavity lengths (σ=0.64, σ=0.7) and cavitation free (σ=1.5).

Velocity profiles at X=-15.4 mm upstream to the cavity detachment point shows no significant influence of the vapour cavity on the velocity field. For X=-3.8 mm, a decrease of the fluid velocity in the horizontal direction may be observed for cavitating flows while the vertical component of the velocity remains almost unchanged. At X=-1.8 and X=-0.5 mm, the leading edge cavity causes a decrease of the fluid velocity in the horizontal direction as well as a substantial increase of the flow velocity in the vertical direction. These results do not show any flow separation of the boundary layer up to 5. 10^{-4} m from the detachment point. Obviously, a separation of the boundary layer has to exist since a flow stagnation point on the vapour cavity would lead to a hydrodynamic paradox. Therefore, the distance between this separation point and the cavity detachment point is less than 5. 10^{-4} m, which is in accordance with Arakeri's results (1974). Plots of pressure coefficients shows a substantial increase of the pressure upstream to the leading edge cavity compared with cavitation free regime. These observations raise the following question: is the flow separation a *sine qua non* condition or is it created during the cavity generation ? We will address this question later in the present paper.

3.2 Flow analysis near the cavity detachment

Figure 8 illustrates flow visualisation obtained for an upstream velocity of 13.5 m/s and a σ value of 0.3. These photographs show how bubble cavitation turns into leading edge cavitation in a very complex manner by slightly increasing the incidence angle from 1° to 1.25°. We have selected this particular hydrodynamic condition because bubble cavitation may easily develop in a well visible way. First, we may observe (photo A) isolated bubbles that explode on the suction side of the hydrofoil and collapse separately. As the incidence angle is increased, the density of vapour bubbles increases leading to bubbles coalescence during their implosion (photo B). Surprisingly, those bubbles are found to be generated in a well periodic way. This is due to the hydrofoil low amplitude oscillation resulting from the well visible cavitating Von Karman vortices shed from the hydrofoil trailing edge. In fact, if we assume that the bubbles travel with the flow, their generation rate may be roughly estimated form the photograph (B) and found to be around 900 Hz, which is close to the hydrofoil resonance frequency (~ 850 Hz).

For 1.1° incidence angle, an interesting photograph is obtained where an elongated bubble is clearly observed. This transient phenomenon results from an interaction of the vapour bubble with the boundary layer as well as the solid surface. Indeed, part of the vapour bubble is *attracted* by the solid surface while the rest of the bubble follows the main stream. At the same time, during this bubble elongation, the liquid flow obviously separates upstream of the detachment point. This observation illustrates an origin of the leading edge cavity detachment. It should be noticed that the transition from bubble to attached cavitation is found to be highly unstable leading to a substantial increase of noise and vibration.

For an incidence angle of 1.15° (photo D), an attached cavity is clearly established and extends beyond the trailing edge of the hydrofoil. In fact, due to the low incidence angle, no partial cavity could be obtained on our experimental hydrofoil. As the incidence angle is further increased, the vapour cavity detaches from almost the whole leading edge of the hydrofoil. Nevertheless, at the bottom of the photograph F (1.25° incidence angle), one may still observe separated bubble cavitation development.

At low incidence angles, attached cavitation may not occur because the positive pressure gradient downstream of the minimum pressure point on the suction side is not strong enough to ensure flow separation during transition from bubble to attached cavitation. As soon as this condition may be fulfilled, for higher incidence angles, the cavitation bubble sticks to the solid surface and turns into attached cavitation. Once the attached cavity is established, the detachment is obviously located in the positive pressure gradient corresponding to cavitation free flow. We have already shown through PIV measurements that the flow field upstream of the cavity detachment is significantly affected by the presence of the vapour cavity. The flow velocity in the space between the laminar separation and the detachment points decreases when the leading edge cavity takes place. This might lead to an increase of the minimum pressure above the vapour pressure upstream to the detachment point (see Figure 7). Otherwise, we would have to face a hydrodynamic paradox, already reported by several authors, since the water would remain in the liquid state in the space between the separation and detachment points despite the fact that the static pressure is well below the vapour pressure.

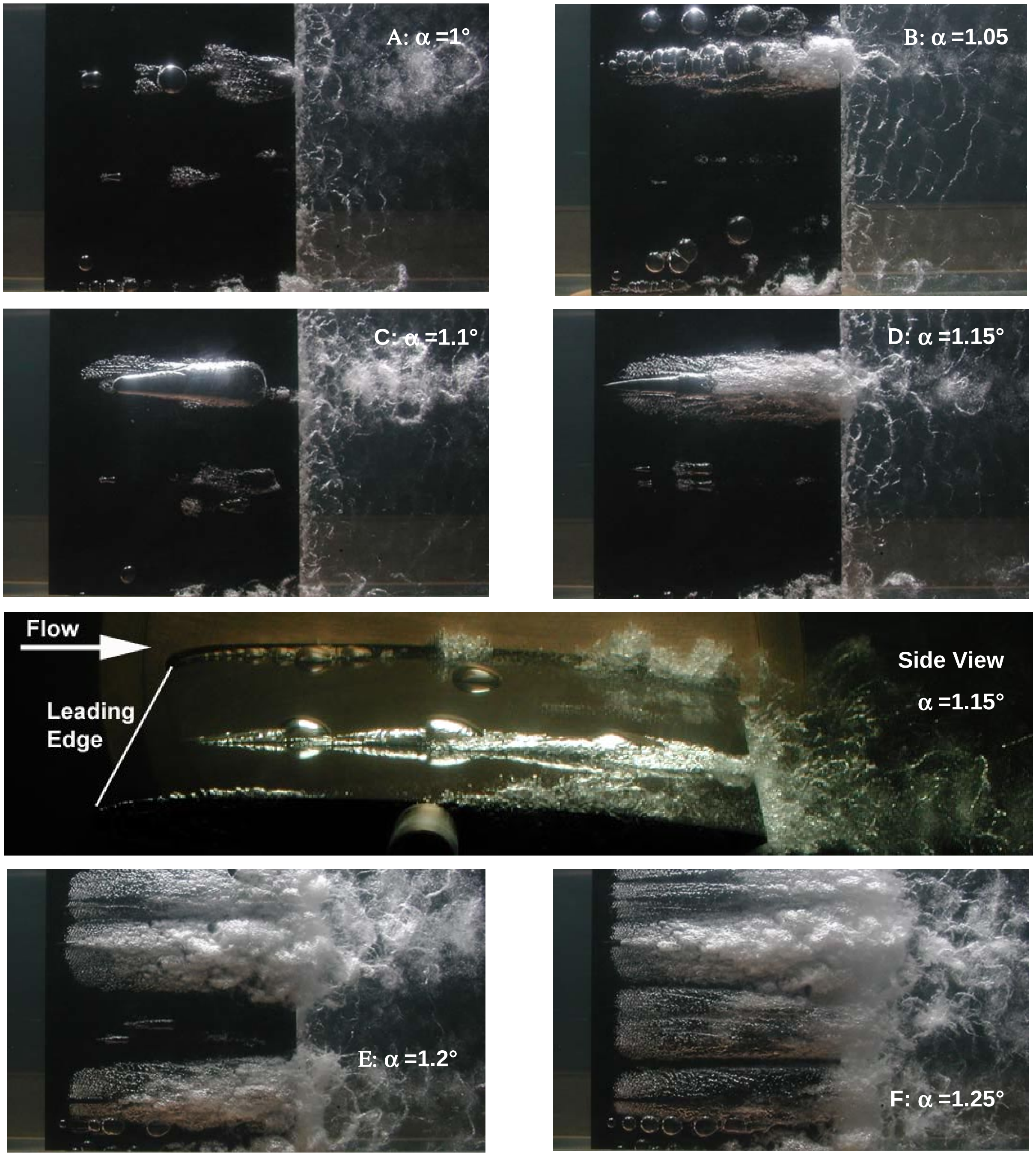


Figure 8: Visualisation of transition from bubble to attached cavitation
Upstream velocity=13.5 m/s, σ=0.3, incidence angle ranging from 1° to 1.25°

During the transition process from bubble to attached cavitation, the interfacial energies between fluids (liquid and vapour) and solid, which play a major role, take into account the chemical heterogeneities and the solid surface roughness. This explains why in the early stage of leading edge cavitation development, the vapour cavity detaches from isolated and non reproducible points. These observations let us believe that the key of the cavity detachment is the result of a complex interaction of isolated bubbles with the solid surface (roughness and physical properties) and the liquid flow (boundary layer and pressure distribution). Furthermore, as we have already shown in former studies (Caron et. al. 1999, 2000), one has to take into account the interaction with a fluctuating pressure field, which may also affect significantly the leading edge cavitation detachment and its development. In fact we have shown that the leading edge cavitation may be completely suppressed for a particular set of hydrodynamic conditions and pressure fluctuation frequency. The influence of a fluctuating pressure field on the leading edge cavitation is still not fully understood.

Conclusion

In the present paper we have investigated the detachment condition of the leading edge cavitation over a 2-D Naca 0009 hydrofoil. The main results may be summarized as follows:

- Particle Image Velocimetry performed on non cavitating flow does not reveal any laminar flow separation. Thus, such separation may not stand as necessary condition for attached cavitation occurrence.
- Particle Image Velocimetry on flow with partial attached cavitation has been performed by masking the vapour cavity to prevent from light diffraction. We have found that the leading edge cavity leads to a decrease of fluid velocity in the axial direction as well as an increase of vertical velocity component as the flow approaches the detachment point. No flow separation could be detected upstream to the detachment point according to our PIV resolution (5. 10^{-4}m).
- Flow visualisation clearly shows that as the incidence angle is increased, bubble cavitation may turns into attached cavitation in a complex way. This transition process, which is found to be highly unstable, depends upon the positive pressure gradient downstream to the minimum pressure location as well as the surface roughness and the physical properties of the hydrofoil material. The leading edge cavity detaches as soon as the flow may separate upstream to a travelling bubble. This observation let us believe that attached cavitation may be initiated by a separated bubble that explodes and interacts with the boundary layer to form an attached cavity. During this transition process, a laminar separation occurs upstream to detachment point.

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