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On the hysteresis of cavitation incipience and desinence in hydraulic machines

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Abstract. The omnipresent vortical structures in hydraulic machines are extremely prone to the occurrence of cavitation. It is well known that besides the flow parameters, the incipience, development, and disappearance of cavitation within a vortex is very sensitive to the gas content. It is also known that the pressure threshold for vortex cavitation desinence may be significantly higher than that of its incipience. This hysteresis, which is not yet well understood, is the scope of the current work. The case study is made of an elliptical NACA 16020 hydrofoil, placed in the test section of EPFL high-speed cavitation tunnel. We have observed the inception and the desinence of tip vortex cavitation (TVC) for different flow conditions and gas contents. We found that the pressure threshold for the TVC desinence increases with the dissolved gas content. We have also found that this pressure threshold strongly depends on the flow parameters and may reach atmospheric pressure for specific conditions. We argue that the persistence of a cavity at pressure levels higher than the vapor pressure is due to an outgassing process that sucks air from of the surrounding supersaturated liquid to feed the cavity. The gas diffusion is likely enhanced when a laminar separation of the boundary layer is formed at the tip of the hydrofoil on the suction side.

1. Introduction

Occurrence of cavitation in turbines, pumps and marine propellers can lead to severe erosions of the impeller blades and/or the discharge ring of the machine, with a significant increase in maintenance costs. One of the cavitation-prone flow structures that is very common in hydraulic machines is the vortex flow, as illustrated on Figure 1 [1][2]. For instance, one may mention the off-design inter-blade vortices and the vortex rope in Francis turbines, tip vortices in axial hydraulic machines such as Kaplan turbines and marine propellers. Karman vortices, which develop in the wake of an impeller blades, are another example of vortical structures that may initiate cavitation in hydraulic machines. Due to their rotational motion and the resulting pressure decrease in their core, vortices are extremely vulnerable to the inception and development of cavitation. In addition to the bulk flow parameters, it is well known that the level of the dissolved gases in water significantly affects the cavitation behavior, although its role is not yet well explained. In particular, large differences between the pressure thresholds for the cavitation incipience and desinence of vortices may be observed under specific conditions. Such unpredictable hysteresis is a challenging issue, when testing hydraulic machines at reduced scale. There is no consensus between incipience index and desinence index to evaluate cavitation performances. Moreover, even the definition of cavitation phenomenon becomes questionable with the existence of incipience-desinence hysteresis. In fact, with the persistence of a gaseous phase at pressure levels higher than vapor pressure, there is a need to distinguish between (i) “true cavitation” with vapor production and condensation and (ii) “gaseous cavitation”, which is made of only non-condensable gas.

Among various types of vortex cavitation, the so-called Tip Vortex Cavitation (TVC), which may develop at the tip of impeller blades, is highly relevant because it is usually the first to appear in axial turbines, pumps and propellers [3][4][5][6]. It is also always associated with extensive noise emission and structural vibrations [7]. Owing to early research performed by McCormick [8], the viscous core of a tip vortex scales with the boundary layer thickness on the pressure side of hydrofoils. Later on, several authors proposed empirical correlations for the inception cavitation number for tip vortices generated by elliptical hydrofoils, which were based on the Reynolds number and the lift coefficient [9][10][11]. Nonetheless, it is well known that besides the flow parameters, the gas content of water also plays a major role in the cavitation inception, which was not considered in these correlations.

Figure 1. Left: Part-load rope at the outlet of a Francis turbine [1]; Middle: Tip vortex cavitation in a Bulb turbine [2], Right: Inter-blade vortices in a Francis turbine.

Arndt and Maines [12] introduced the terms ‘‘weak’’ and ‘‘strong’’ water on the basis of the size and the distribution of nuclei in water. They demonstrated that in weak water with enough large nuclei, TVC incepts when the pressure in the core of the tip vortex reaches the vapor pressure, however, strong water with fewer and/or smaller nuclei could resist significant tensions. Traditionally, the desinence threshold is believed to be a more reproducible and robust criterion in determining the cavitation-free regime. However, little attention has been paid to distinguish between inception and desinence. Holl et al. [13] investigated the desinence of hub vortex cavitation and observed that it disappeared at higher pressures when water was saturated with air. Recently, Gross et al. [14] examined the role of dissolved gases on the rate of wall nucleation, generated by a single bubble trapped in a small hole. They observed that the bubble did not disappear and continuously produced small nuclei, as long as the flowing liquid was supersaturated. They have shown that the nucleation rate increased with the flow velocity and the level of air saturation.

In order to address the issue of cavitation hysteresis in vortical flows, we have experimentally investigated the TVC generated by an elliptical hydrofoil with NACA-16020 cross-section, placed in the test section of EPFL high-speed cavitation tunnel. The choice of such a case study is motivated by the ability of the elliptical hydrofoil to generate a single and well-defined tip vortex. Cavitation inception/desinence tests are performed for two freestream velocities and various angles of attack at different gas content levels. These results are analyzed to explain how the gas content affects the TVC occurrence and desinence.

2. Experimental set-up

The case study is made of an elliptical hydrofoil with a NACA 16-020 cross section, placed in the squared test section (150×150×750 mm) of EPFL high-speed cavitation tunnel. The maximum inlet velocity is 50 m/s and the maximum static pressure is 16 bar. The hydrofoil is made of stainless steel and has a span of 90 mm and a root chord length of 60 mm. The latter is used as the characteristic length in the definition of the Reynolds number. The monitoring of the gas content is performed through the measurement of oxygen concentration, with the help of a Presens O2 Dipping Probe (DP-PSt7), placed upstream to the test section. We use super-cavitation and free-surface regimes to respectively decrease and increase the amount of the dissolved gases in the tunnel. Employing the mentioned methods, the saturation level of water is efficiently varied between 50 and 100 percent. All the measurements are conducted at 18 °C to avoid any changes in the solubility of air in water. In order to perform the cavitation inception/desinence test for a given a flow condition (i.e. any specific upstream velocity and angle of attack), we depart from a high-pressure cavitation-free state and then gradually decrease the static pressure of the test rig until a visible and steady TVC appears (which gives the incipience threshold σ_i). The pressure is then reduced further to allow for a well-developed TVC. Afterwards, the pressure is gradually increased until the TVC disappears (the desinence threshold σ_d). For each working condition, the whole process takes between 5 to 10 minutes, which is slow enough to obtain quasi-steady conditions and to assure that the flow is provided with sufficient time to react to the pressure changes. In order to increase the reliability of the measurements, the cavitation inception/desinence test is performed twice for each flow condition.

3. Results and discussion

We have presented on Figure 2 the cavitation index for TVC incipience (σ_i) and desinence (σ_d) as a function of the incidence angle for 10 and 15 m/s upstream velocity and different values of oxygen content. We clearly observe the hysteresis between the cavitation incipience and desinence, i.e σ_i is always higher than σ_d, for all the tested conditions. Moreover, the hysteresis is very sensitive to the flow parameters and is much more pronounced at 10 m/s of upstream velocity and between 10° and 14° incidence angles. As expected, an increase in the gas content level leads to an increase of both σ_i and σ_d.

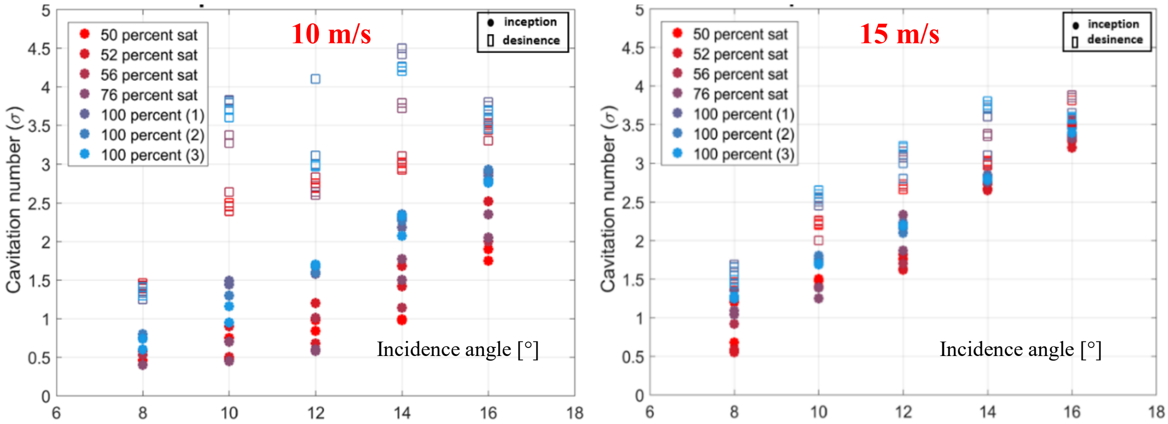

Figure 2. Inception and desinence thresholds of TVC for different incidence angles and gas content levels measured at 10 and 15 m/s of freestream velocity.

A visual illustration of the hysteresis phenomenon is provided on Figure 3, where top views of TVC are presented for 10 m/s freestream velocity (Re = 600,000), 12° incidence angle and 100% air saturation. The cavitation index is gradually decreased from $\sigma = 4.2$ (cavitation-free) down to $\sigma = 1.7$, which corresponds to TVC inception. The cavitation index is further decreased to $\sigma = 1.3$ to allow for a fully developed TVC. The bottom row of the photographs of Figure 3 provide a clear evidence of the hysteresis phenomenon. As the cavitation index is increased back to its initial value ($\sigma = 4.2$), TVC sustains at levels of cavitation index much higher than σ_i, with a desinence threshold $\sigma_d \sim 4.0$. The static pressure measured at the tip of the hydrofoil associated with this cavitation number is even higher than one bar [15].

According to a previous work on a similar case study [2], the pressure coefficient at the vortex axis for the same flow conditions as in Figure 3 was experimentally evaluated to be $Cp_{core} \sim -2.1$. Owing to this estimation, we may observe that cavitation inception occurs at a pressure slightly below the vapor pressure. This is in line with the expectation, since the tested water is fully saturated with air, which provides nuclei for the cavity initiation. Surprisingly, for this specific flow condition, cavitation desinence occurs at a pressure within the vortex core as high as atmospheric pressure. Obviously, the cavity observed at such a high level of pressure does not contain water vapor anymore, but it must be filled with non-condensable gas only. We argue that this cavity is sustained by an outgassing process: The liquid in the vicinity of the vortex axis is in a state of super-saturation and part of its gas content diffuses through the cavity interface. The rate of this gas diffusion, which is proportional to the pressure difference (p_{atm}-p_{core}), decreases as the pressure is increased leading to the TVC desinence when atmospheric pressure is reached at the vortex axis.

It should be noticed that the outgassing process does not occur during the pressure decreasing from the initial cavitation-free state down to the cavitation incipience, even though the liquid is in super-saturation state. In fact, with the lack of a cavity interface, no gas diffusion is possible. It is only after the formation of a well-developed TVC that the outgassing process can take place leading to the observed hysteresis. It should be also noted that the case presented on Figure 3 is an extreme situation corresponding to the largest observed hysteresis. Besides the gas content, the flow parameters have a significant effect on the TVC hysteresis, as already seen on Figure 2.

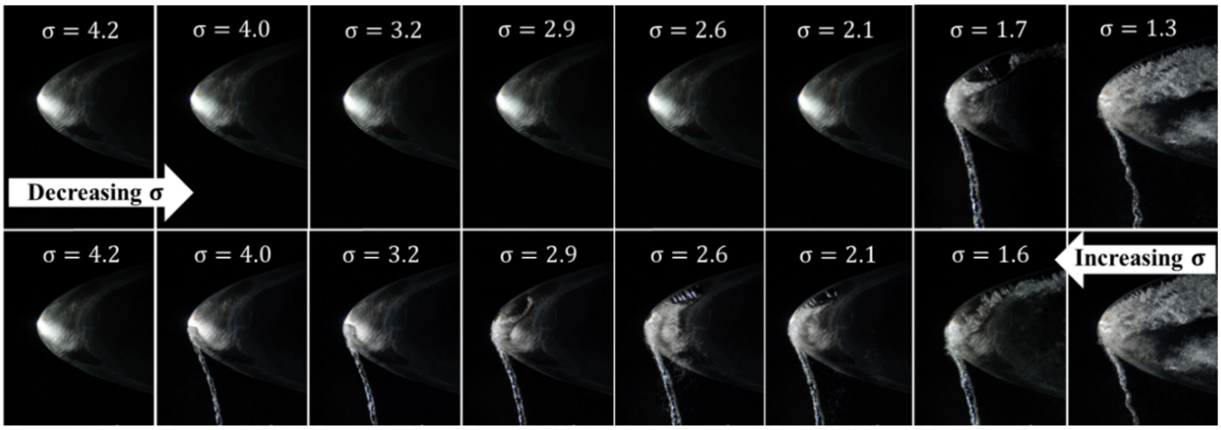

Figure 3. Illustration of the large gap between the inception and the desinence of TVC $V_\infty = 10\ \mathrm{m/s}$, $\alpha = 12°$ and 100 % of O_2 saturation.

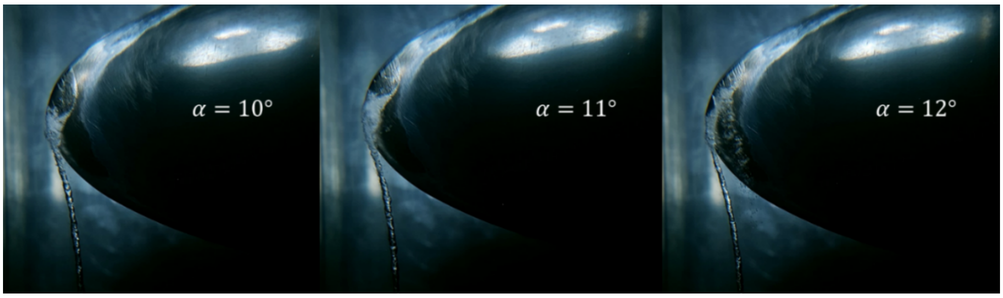

Figure 4. Evolution of the shape and the aspect of the leading edge cavity formed at the tip of the hydrofoil vs the incidence angle ($V_\infty = 10\ \mathrm{m/s}$ and $\sigma = 3$) [15].

We believe that the key element is the boundary layer state at the tip of the hydrofoil. As illustrated on Figure 4, the tip vortex is connected to a gas cavity attached to the leading edge. As the incidence angle is increased from 10° to 12°, this cavity does not grow but rather shrinks and starts losing its transparent aspect. We believe that this is an indication that a laminar boundary layer develops on the hydrofoil tip. As the upstream velocity is increased, the laminar separation vanishes and the boundary layer becomes turbulent, leading to a foggy leading edge cavity and a significant decrease of the hysteresis. Nevertheless, it is not yet clear how a laminar separation of the boundary layer may enhance the outgassing process and produce a larger hysteresis.

The hysteresis observed between TVC incipence and desinence raises fundamental questions that need to be addressed. First, the classic definition of cavitation phenomenon becomes questionable. Indeed, while cavitation is always defined as a liquid vaporization due to a pressure decrease, the present study shows that a cavity may take place without any liquid vaporization. There is a need to distinguish between these two cavitation types, which we may be called "vaporous cavitation" and "gaseous cavitation" for instance. Second, there is also a need to evaluate the difference between these two types of cavitation in terms of erosion risk, radiated noise and flow induced vibration. In other words: Is the gaseous cavitation as dangerous as vapor cavitation? Moreover, the TVC hysteresis also raises practical questions. For instance, it is not yet clear which of the incipience and desinence indices should be considered when testing hydraulic machines at a reduced scale. It is also not clear how to scale up the results to the full-size machine. In fact, besides the gas content, the flow structure and mainly the boundary layer may differ drastically from the model to the full-scale machine with tremendous consequences on the occurrence of the gaseous cavitation.

4. Conclusion

In the present study, we have investigated the incipience/desinence hysteresis of TVC and the role of the gas content. The case study is an elliptical Naca-16020 hydrofoil, placed in the test section of the EPFL high-speed cavitation tunnel. The TVC incipience and desinence were measured experimentally for various flow conditions and gas content levels. The observations clearly reveal the existence of a hysteresis between the inception and the desinence of the TVC, which is strongly dependent on the air saturation level of water and the flow parameters, as well. For a specific condition, the cavitation desinence may require a static pressure within the vortex as high as atmospheric pressure. We argue that (i) the observed cavity is made of non-condensable gases without any water vapor and (ii) the cavity sustains high pressure because of gas diffusion from the super-saturated water close to the vortex axis. Our research also reveals a strong influence of the flow parameters on the hysteresis amplitude. Owing to the flow visualizations, we believe that a laminar separation of the boundary layer in the tip area of the hydrofoil enhances the outgassing process and contribute to sustaining the gas cavity. Further investigations are needed to validate this explanation and clarify the difference between "vaporous cavitation" and "gaseous cavitation" in terms of erosion risk, radiated noise and flow induced vibration. Form the practical point of view, our results raise the question about how to carry out model testing of hydraulic machines with a clear distinction between these two cavitation types.

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