Pressurized air injection in an axial hydro-turbine model for the mitigation of tip leakage cavitation

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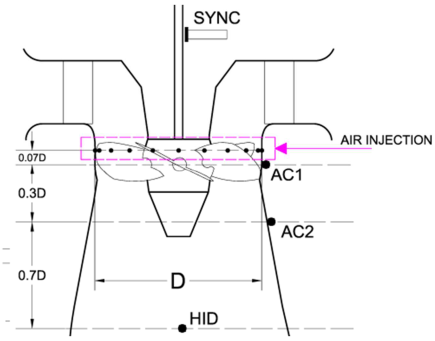
Abstract. Tip leakage vortex cavitation in axial hydro-turbines may cause erosion, noise and vibration. Damage due to cavitation can be found at the tip of the runner blades on the low pressure side and the discharge ring. In some cases, the erosion follows an oscillatory pattern that is related to the number of guide vanes. That might suggest that a relationship exists between the flow through the guide vanes and the tip vortex cavitating core that induces this kind of erosion.
On the other hand, it is known that air injection has a beneficial effect on reducing the damage by cavitation. In this paper, a methodology to identify the interaction between guide vanes and tip vortex cavitation is presented and the effect of air injection in reducing this particular kind of erosion was studied over a range of operating conditions on a Kaplan scale model.
It was found that air injection, at the expense of slightly reducing the efficiency of the turbine, mitigates the erosive potential of tip leakage cavitation, attenuates the interaction between the flow through the guide vanes and the tip vortex and decreases the level of vibration of the structural components.

1. Introduction

Axial hydro-turbines present a clearance between the runner blades and the discharge ring. This feature in combination with the high pressure gradient among both sides of the blade, induce a secondary flow known as tip vortex, which has been studied by several authors [1].
The high intensity of the vortex and the low pressure at the outlet of the runner may generate cavitation of the vortex core [2]. As a consequence, erosion issues at the runner blades and discharge ring can occur at the prototype machine. Moreover, the tip vortex can interact with the wakes generated by the flow leaving the guide vanes giving rise to a phenomenon of interaction that is similar to well-known rotor stator interaction (RSI). The existence of this interaction is suggested in the prototype machine by the presence of as many erosion patches at the discharge ring (on a horizontal plane) as guide vanes [3]. Some mitigation methods, such as anti-cavitation lips, have been tried but their effectiveness has not always been ensured. The use of air injection is an interesting option for cavitation problems, as it has been used in many industrial applications. Arndt et al. [4] examined the effect of air injection on NACA profiles for the mitigation of cloud cavitation, and found that it was an effective method of minimizing the potential of erosion.
In this work, experimental investigation of pressurized air injection in a physical model of a Kaplan turbine is studied. The main objectives are the mitigation of tip vortex cavitation and the suppression of the RSI. In the first part, the experimental setup and the test procedure are presented. Then, the trajectory of the air in the flow is characterized with the aid of high speed visualization and the main results are summarized in terms of efficiency and vibrations. Finally, the RSI pattern is analyzed.

2. Methods and materials

Experiments were carried out at the test rig facility in the Hydromechanics Laboratory of La Plata, Argentina. The circuit is equipped with a feeding pump with variable rotational speed, allowing for the regulation of the specific energy (E) and the flow rate (Q). Experimental investigations on the test rig were based on IEC 60193-standard [5]. The Kaplan model is located between the high and low pressure tanks. The diameter of the runner (D) was 0.34 m and the rotational speed was 1000 rpm, reaching a Reynolds number of 6.05E6 based on the blade tip velocity. The discharge ring was manufactured with a transparent material for the sake of visualization.
The model was instrumented with two accelerometers located at the discharge ring, one hydrophone at the draft tube inlet, and a phase sensor at the runner shaft (Figure 1). The sampling frequency of the signal was 50 kHz. An air compressor was connected, through a pressurized manifold, to 20 evenly spaced 3-mm-diameter holes located on a horizontal plane above the runner centerline. A ball air flow-meter was placed between the compressor and the manifold.
In Figure 1b the operating points tested over the hill chart are shown. Air was injected at each operating point for 8 different air flow rates (Q_a=0.2, 0.3, 0.4, 0.8, 1.3, 1.7 and 2.1‰) in combination with 11 σ numbers ranging from cavitation-free conditions to a fully developed cavitating regime. Finally, a high-speed camera (PHOTRON SA4) was used to analyze the air trajectory.



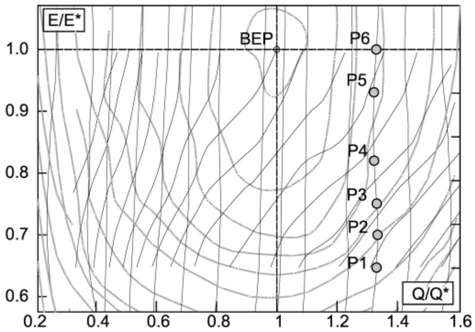


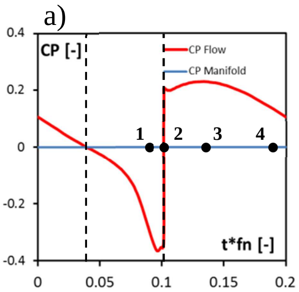
Figure 1. a) Instrumentation and air injection location on the model. b) Measured points in the hill chart. AC1, AC2 and HID denote the position of the accelerometers and the hydrophone, respectively. E* and Q* are the nominal value for specific energy and flow rate.

3. Results

3.1. Flow visualization

Figure 2 presents high-speed visualization snapshots at different positions of the runner blade with air injection for a free-cavitation regime. Air entrance occurs when the pressure at the manifold is greater than the fluctuating fluid pressure (Figure 2a). Fluid pressure is seen to rise due to the high gradient between both sides of the blade as the leading edge interferes with the air jet (snapshot 2). Air travels along the edge of the blade (snapshot 3) until getting immersed into the vortex core (snapshot 4).

a)



b)

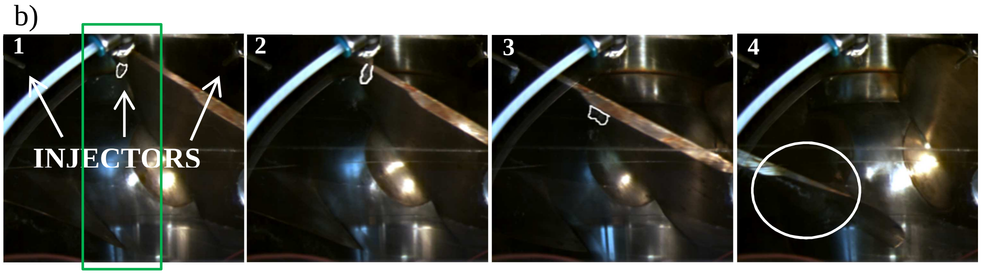


Figure 2. a) Fluid pressure fluctuations at the location of one injector and in the manifold for one blade passage, as a function of the pressure coefficient (CP) and time (*t*fn*), where *fn* is the runner rotational frequency. b) Snapshots of air injection for the blade position (1, 2, 3 and 4) indicated in 2.a) for a cavitation-free regime.

3.2. Hydrophone measurements

For a cavitation-free regime, the ensemble average of the hydrophone signal remains essentially flat (Figure 3a), which implies a random behavior. For σ = 1.40, there is an incipient tip leakage cavitation. The oscillatory pattern is driven by a frequency of 25 *fn* (Figure 2b) and remains the same as the amplitude increases with decreasing values of σ (Figure 2c). Simultaneously, an increase of the random component is observed, which is in agreement with the higher development of tip cavitation. When air is injected, the frequency of 25 *fn* vanishes, giving rise to components of 20 and 5 *fn*.

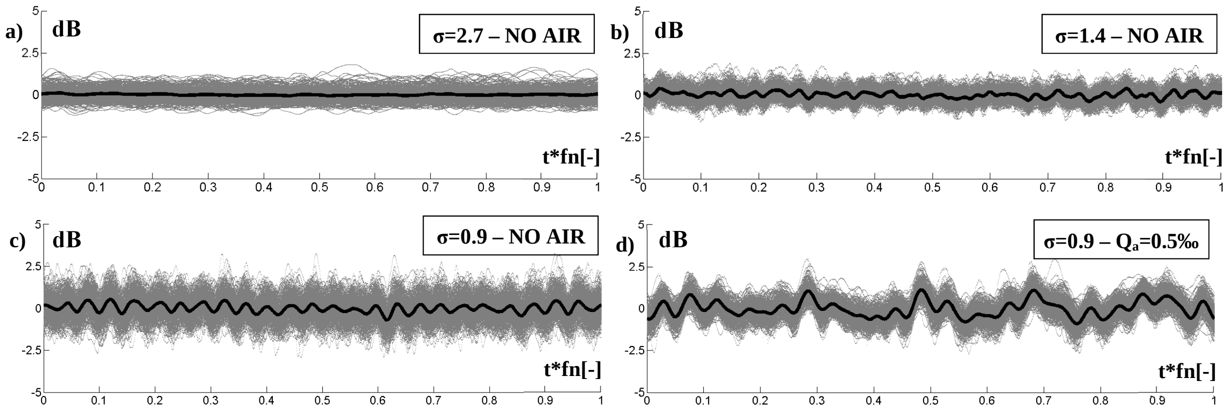


Figure 3. Hydrophone signal for the operating condition P2: ensemble average (black line) and instant values (gray dots) for different σ values with and without air.

3.3. Global results

The intensity of vibration rises as σ decreases, reaching a local maximum for σ ~ 1.2. A further decrease in σ results in levels of vibration going down until σ ~ 0.9 upon which a new rise is observed, in coincidence with full cavitation conditions (Figure 4a). The level of vibration is also seen to decrease as the rate of air injection increases for a constant σ regardless of the operating conditions (Figure 4b). Beyond approximately Q_a= 0.5‰, air injection has no further influence on the level of vibration and the efficiency drop becomes greater than 1%. The evolution of the amplitude of the hydrophone signal corresponding to a frequency of 25 *fn* rises as the guide vane opening (α) increases (Figure 4c). The trend is positive except for the maximum guide vane opening conditions (P1).

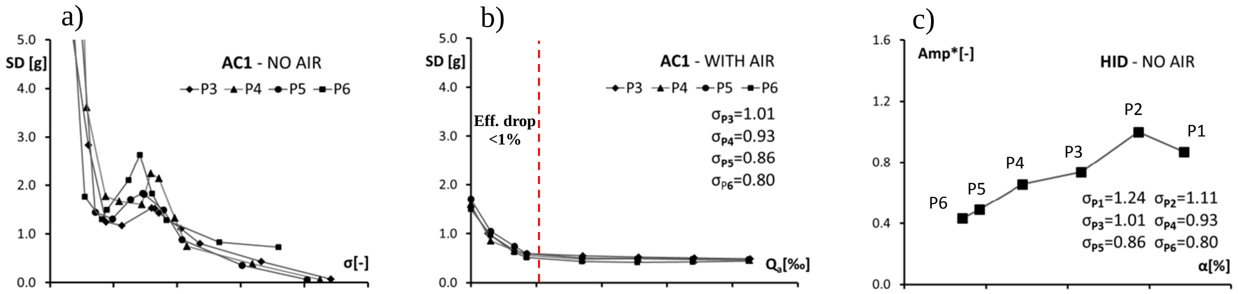


Figure 4. a) Influence of the development of cavitation on the vibration level as a function of the standard deviation of the acceleration signal (SD) and σ; b) Influence of air injection rates on the vibration level for constant σ values; c) Amplitude of the hydrophone signal corresponding to a frequency of *25 fn* as a function of the guide vane opening. Pi (i = 1,2,…,6) denote the operating conditions shown in Figure. 1.

4. Discussion

4.1. RSI analysis

As σ decreases, cavitation develops mainly as tip leakage cavitation. The influence of the non-uniform flow leaving the guide vanes can be identified by the analysis of the modulation process generated by the stationary flow field of the 24 guide vanes (Z_0), and the rotating flow field due to the 5 runner blades (Z_b), as proposed by Ruchonnet et al. [6]. Table 1a shows the RSI patterns for several orders of harmonics for the first diametrical mode number k_1. The highest amplitude expected is for the first order of harmonics of flow through the guide vanes (n = 1) and the fifth order of harmonics of flow through the runner (m = 5), since k_1 is the minimum. The characteristic frequency of 25 *fn*, given by the expression $f/fn = mZ_b$, has to be present if the interaction exists. When air is injected, there is a novel interaction between the 20 injectors (Z_i) and the blade passage, which is summarized in table 1b. In this case, *k1* is minimum for *m*= 4 and *n*=1, and the characteristic frequency is 20 *fn*, where $f/fn = m$Zi.

Table 1. First diametrical mode number k_1 according to harmonic order *m* for the runner blades (Z_b=5) and *m.* a) For the guide vanes (Z_0=24); b) For the injectors (Z_i=20).

a)

	$k1=mZ_b-nZ_0$				
n/m	1	2	3	4	5
1	-19	-14	-9	-4	1
2	-43	-38	-33	-28	
3	-67	-62	-57	-52	-47

b)

	$k1=mZb-nZ_i$				
n/m	1	2	3	4	5
1	-15	-10	-5	0	5
2	-35	-30	-25	-20	-15
3	-55	-50	-45	-40	-35

5. Conclusions

The tip vortex cavitation that develops at lower cavitation numbers was singled out as one of the main causes of the increase of vibration levels.

The analysis of the signal of the hydrophone reveals the presence of RSI-related phenomena which becomes apparent when tip vortex cavitation develops.

Air injection was found to fluctuate in correspondence with periodic oscillations of fluid pressure due to the blade passage. Regardless, it can be an effective tool both in eradicating the influence of the flow driven by the guide vanes and in reducing the level of vibration. This may have a beneficial effect on the mitigation of the erosion due to its related tip vortex cavitation.

Vibration levels were reduced 50 % for an air flow rate of Q_a = 0.5 ‰ at the expense of an efficiency drop of less than 1 %.

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