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# Assessment of cavitation regime in divergent vortex flows

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**Abstract.** The analysis of a cavitating swirling flow in a configuration similar to the flow at the entrance of a hydraulic turbine draft tube, except the rotational component, is proposed. This flow behaviour is essential for the hydraulic turbine operation in extended range and its understanding is essential for the turbine design improvement. Advanced 2D measurements of the velocity field using PIV techniques and unsteady pressure measurements are used to determine the  $\sigma$  number and velocity field for various stages of cavitation development.

## 1. Introduction

The cavitation in hydraulic machines is an actual concern for the manufacturers and power plant users. The energy market imposes a price driving operation and the turbines in operation are often outside the optimum range, in cavitation regimes [1], [2], [3], [4]. For the new turbines, an extended operating range is requested and the cavitation is one of the main design parameters.

The cavitation phenomenon is mostly associated to the  $\sigma$ , sigma number (cavitation coefficient), and international codes are considering this similitude parameter for the cavitation transposition. In hydraulic machines, at the runner outlet, the flow is complex: rotating, turbulent, cavitating and in a pressure adverse gradient environment (divergent flow) and for this reason the transposition from prototype to site is not accurate.

In hydraulic turbines, the runner outlet swirling flow can be represented analytical taking the discharge as independent variable and consider the flow as a superposition of three distinct vortices [2]. The superposition of two Batchelor vortex with a rigid body rotation vortex give an accurate description of the runner outlet velocity profile [2] perform the development for Francis turbine. This development was extended for helix turbines [6] and improved by [7], considering radial velocity and runner blades wake influence. The next step is to associate the cavitation behaviour in relation with the flow structure and cavitation number. The transposition will be also accurate for all operating regimes.

To study this complex behaviour, experiments were performed on a reduced scale test bench simulating the flow in the draft tube. A swirling flow apparatus was proposed by [5], for the flow control in hydraulic turbines. The study was conducted both experimental and numerical to propose an improvement of the cavitation flow behaviour by water jet injection.

To introduce the cavitation in the analytical representation of the flow, a test bench is used for the study of biphasic flow with adverse pressure gradient, similar to the flow in the draft tube of hydraulic



turbines except, in this study, of the rotation component. The flow is induced by the stator and develops a vortex that becomes cavitation with the increase the water velocity in the hydraulic circuit. By water flow rate variation, the different cavitation regimes: non-cavitating, incipient cavitation and fully develop cavitation are studied.

The test bench is designed to study some innovative aeration devices to be mounted on the hydraulic turbines to reduce the dissolved oxygen deficiency from turbined water - [8]. Therefore, the study of the cavitation phenomenon is necessary for a complete understanding of the flow through the turbine. This preliminary study was conducted to define the cavitation regimes and obtain the associated velocity field in a simplified configuration – only a stator is generating the swirling flow.

On the test bench transparent area allows visualization of the emergence and evolution of the cavitation vortex and the implementation of advanced measurement systems for multiphase flows to have the cavitation behaviour. Thus, a 2D PIV system was implemented to measure the flow velocity at the stator outlet.

The pressure measurement was performed in order to obtain the cavitation number  $\sigma$ . A correlation in the range of Reynolds numbers  $3 \cdot 10^4 \div 4 \cdot 10^5$ , between the cavitation structure and Sigma number as well as the analysis of the physical flow behaviour is obtained.

## 2. Experimental setup

A test bench (Figure 1) is designed for the study of vortex biphasic flow with adverse pressure gradient, similar to the flow in the draft tube of hydraulic turbines. The bench described in detail in [8] consists of a water supply tank from which, by means of an electro-pump and a cleaning water filter, the water is introduced into a hydraulic circuit provided with a study area. This section consists in a conical geometry ( $\gamma/2 = 7^\circ$ ) on the inside and rectangular on the outside, provided with a stator located upstream of the divergent. To improve the optical behavior of the section, the study area, designed for PIV measurements, is made from bulk Plexiglas®, with plane exterior faces for the optical access (both camera and laser sheet). As tracers, S-HGS particles - silver coated hollow glass spheres of 10  $\mu\text{m}$ . For the camera a filter is used in the laser wave length, to cat all ambient light perturbation.

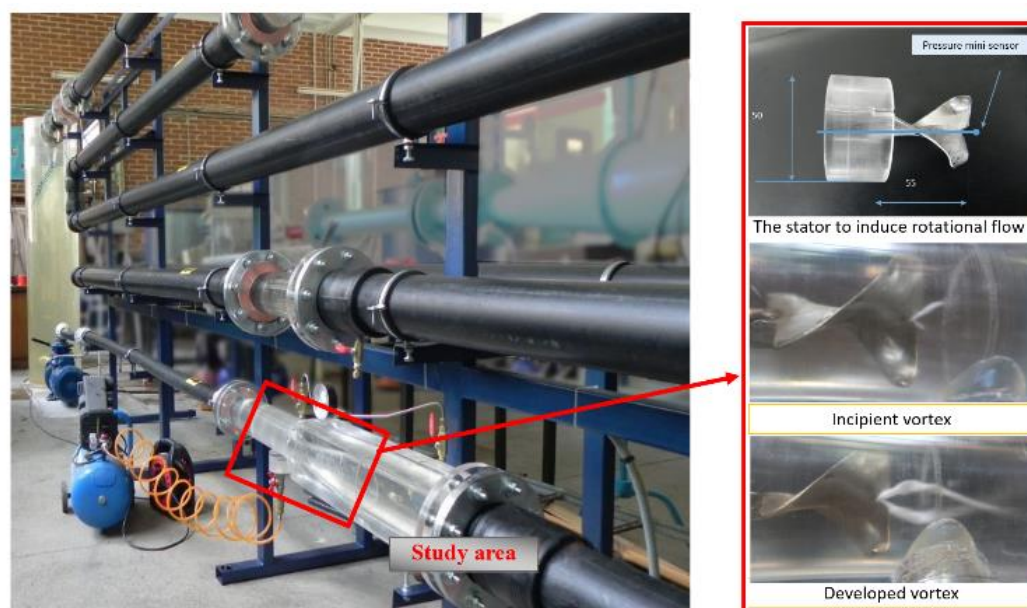


Figure 1 Test bench for study of vortex biphasic flow study with adverse pressure gradient

The rotational flow induced by the stator develops a vortex that becomes cavitation with the increase of the water velocity in hydraulic circuit [9]. By varying the water flow rate, different flow

regimes are obtained: non-cavitating, incipient cavitation and fully developed cavitation and can be studied.

The study area allows the visualization of the emergence and evolution of the cavitation vortex and the implementation of advanced measurement systems for multiphase flows as 2D PIV – Figure 1.

The pressure measurement is performed in order to obtain the cavitation number  $\sigma$ . The reference pressure ( $p_{ref}$ ) and reference velocity ( $v_{ref}$ ) are considered at the pump outlet. A miniature pressure sensor, UNISENSOR AG, is placed axially downstream of the stator shaft to measure the pressure in the vortex,  $p_v$ . This sensor is characterized by its small size, of 3 mm in diameter. Its sensitivity is 25.3 mV/bar at a supply voltage of 5 V, and input range of 0 - 3.5 bar absolute.

Cavitation number  $\sigma$  (1) are calculated [10] using the following equation:

$$\sigma = \frac{2(p_{ref} - p_v)}{\rho v_{ref}^2}. \quad (1)$$

The measurement system is composed of a fast acquisition board, two pressure sensors and a flow meter connected to the analog input channels of the board. The acquisition board, ADLINK USB-1210, was set at 100 kHz sampling frequency on each analog channel.

A TDS-100M ultrasonic flow meter with 1% accuracy and 0.2% repeatability, is used for the flowrate measurement.

For each measurement set it was recorded 60s of data. The repeatability was checked and the results is into the measurement accuracy range.

The study area allows the visualization of the emergence and evolution of the cavitation vortex. Investigations of the flow field was performed using a 2D PIV system (Figure 2). The detailed measurement, setup presentation and the image processing developed to catch the vapors zone are presented in [11]. The image calibration is realized with a customized white dots target (Figure 2), designed to fit fast inside the study segment, on the measurement plane. The calibration is also performed using an order two polynomial fit. In this way all optical distortion due to different optical indices between air, Plexiglas and water are corrected. The target is also used to align the laser sheet in the symmetry plane of the circular section.

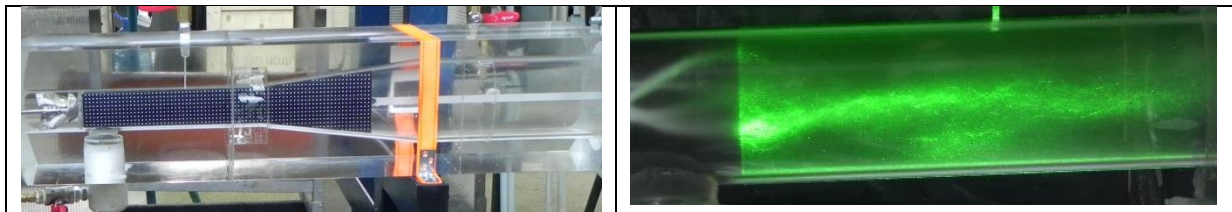


Figure 2 PIV calibration setup and measure

To improve the accuracy in the post processing data, done in Matlab, only values in 3 STD (STD = standard deviation) range were considered, as expressed by:

$$v_{avg} - 3STD < v_i < v_{avg} + 3STD \quad (2)$$

### 3. Experimental results

The pressure measurement in the centre of the experimental section show the evolution of the pressure with the mean flow velocity increasing – see Figure 3. The  $\sigma$  was also calculated related to the mean flow velocity evolution – see Figure 4. A  $\sigma$  decreasing is observed and  $\sigma_{inception}$  is 30, considered at 3.3 m/s, that corresponds with the incipience of the cavitation observed on flow visualisation.

The measurement data was fitted with a second-degree polynomial curve, which was also used in evaluation of  $\sigma$ .

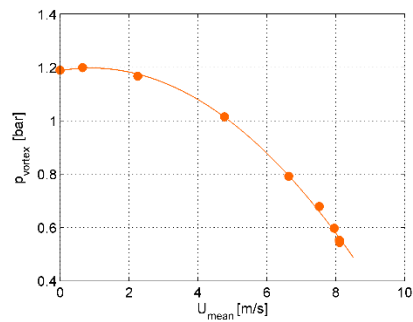


Figure 3 Pressure evolution at stator outlet

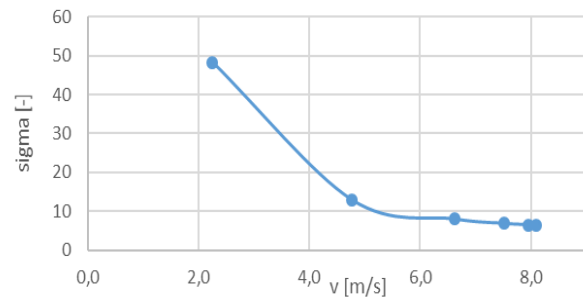


Figure 4 Sigma evolution with velocity increase

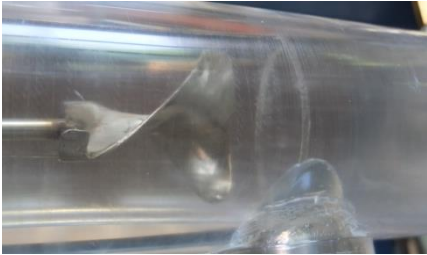
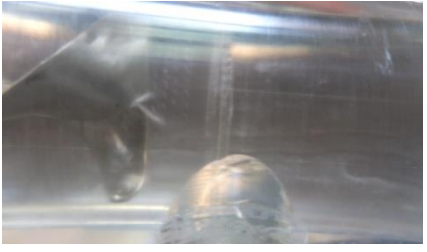



$U_{mean}$ [m/s]	Cavitation observation	Cavitation type
2.6 m/s		Cavitation free
5.3 m/s		Incipient cavitation
7.4 m/s		Developped cavitation
8.1 m/s		Developped cavitation
8.9 m/s		Developped cavitation

Figure 5 Cavitation visualization



In parallel with measurement cavitation, visualisation permit to detect the different cavitation regimes – see Figure 5.  $\sigma_{\text{inception}}$  is corresponding with the cavitation incipience, but  $\sigma$  don't give supplementary information related to the cavitation stages and development.

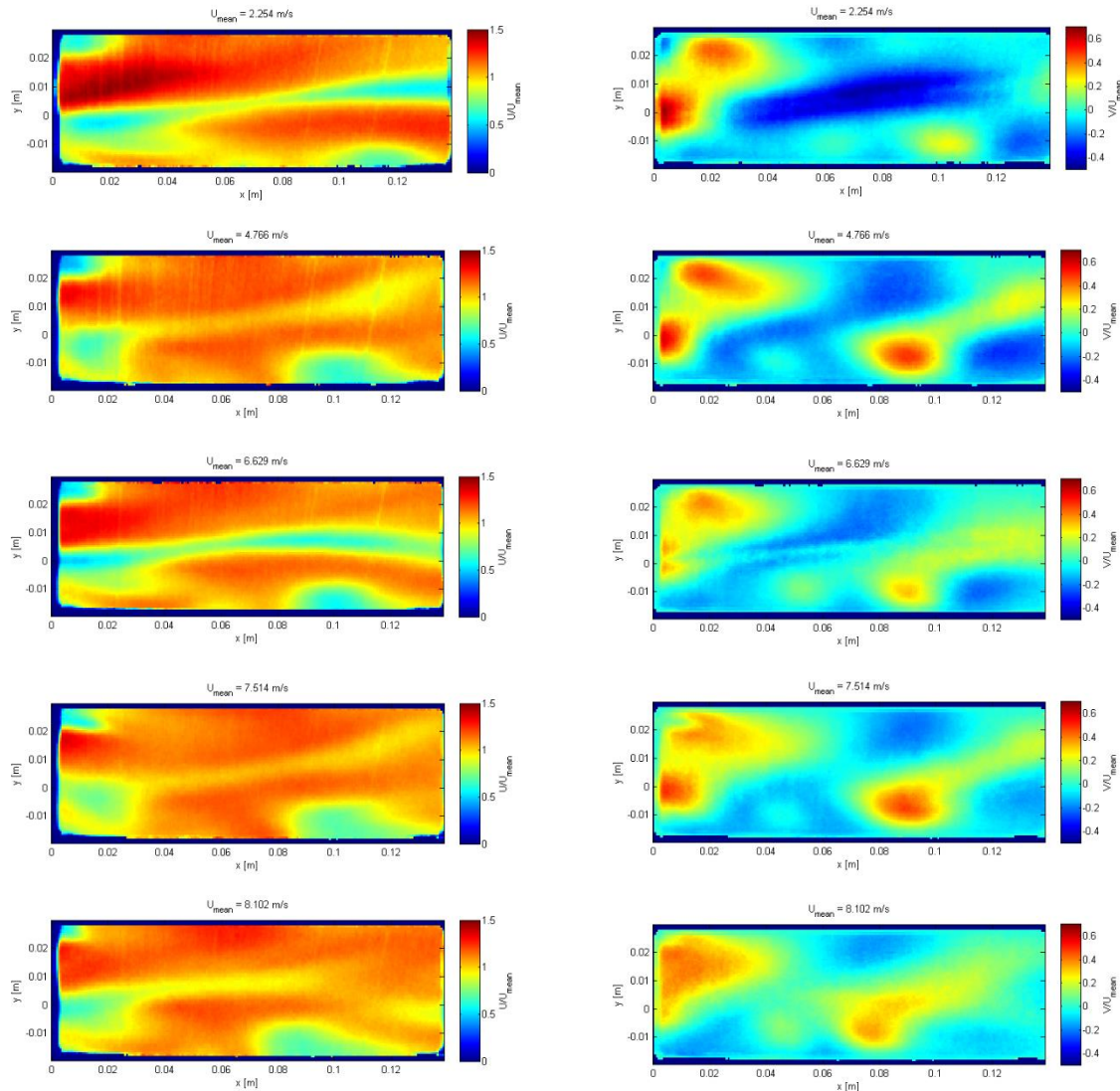


Figure 6 Velocity field downstream the stator –  $U$  axial component,  $V$  radial component

Using a 2D PIV system, two velocity components was measured.  $U$  is the axial component and  $V$  the radial one. In Figure 6 the velocity components, for each operating point, was divided with the mean flow velocity in the section of measure (the mean flow rate measured with ultrasonic flowmeter divides by the area of measurement section). It can be observed that the flow morphology is maintained. In non-cavitating flow or incipient cavitation the velocity gradients are stronger and are decreasing with the development of the cavitation. It can be observed the vortex development downstream and the maintain of blade wake. The swirling flow structure is also obtained and it is not changing with the flowrate increase (the vortex has the same morphological characteristics).

#### 4. Conclusion

To qualify the cavitation behaviour at the runner outlet of Francis turbines and permit an accurate transposition between model and prototype, the integration of cavitation in the analytical representation of velocity profiles will be studied. In a first step a test bench was qualified to perform

cavitation study. A stator generates the swirling flow and by variation of the flow rate, the different cavitation stages are investigated. The flow morphology, as well as the cavitation behaviour and pressure evolution was measured. The cavitation figures (volume), for each regime, are under process.

To perform the analysis of the analytical velocity profile, the tangential velocity is needed. In the next step, 3D PIV measurements will be performed in the same configuration with the characterization of the vapours phase, and finally a rotor will be implemented to can evaluate the rotational effect on the cavitation behaviour. The influence of aeration on the cavitation will also be studied too.

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