Stereo-PIV study of unsteady flow in a laboratory air hydro turbine model over a wide range of operating regimes

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Abstract. Swirl flow with the formation of a precessing vortex core (PVC) in a hydro turbine draft tube model was studied using Stereo-PIV and four acoustic sensors. Experiments were performed on an aerodynamic setup in a wide range of operating conditions of the hydro turbine. Using a spatial Fourier decomposition of pressure pulsation data obtained from four acoustic sensors, a PVC was observed for part-load operating regimes (0.3–0.7Qc). Mean flow features were shown for the range of operating regimes from a deep part-load regime (0.3Qc) to an overload regime (1.5Qc). Based on phase-averaged velocity distributions, the PVC spatial structure was identified for maximum pressure pulsations on the cone walls of the draft tube.

1. Introduction

Extending the range of stable operation of hydro turbines is an important practical problem [1]. Off-design and non-optimal operation of hydro turbines may lead to harmful vortex instability effects in decelerating swirl flows, referred to as the precessing vortex core (PVC) or vortex rope [1–4]. The PVC effect leads to strong periodic pressure pulsations, and the low rotation frequency of PVC may coincide with the natural frequencies of the hydro turbine structure [1].

A detailed experimental study of PVC on full-scale experimental rigs is extremely difficult and expensive. Alternative approaches to studying this effect involve the use of scaled-down laboratory models of hydro turbines [5,6], the use of swirl flow generators (SFGs) to simulate the velocity distributions of real hydro turbines under various operating conditions [7,8], and simplification of experimental modelling by using air as the working medium instead of water [9–11].

In our previous works, an inlet velocity distribution close to the distribution behind the real turbine was produced by a system of two vane swirlers [12,13]. In the present study, we extended the experimental technique to include a Stereo-PIV system with simultaneous recording of pressure pulsations. The objectives of this study are to characterize mean
velocity distributions in a wide range of operating conditions and to identify the spatial structure of the PVC using phase-averaged velocity distributions for part-load regimes with PVC formation.

2. Experimental setup

A detailed description of the aerodynamic setup used in these experiments is presented in [12,13]. To simplify the model design and to facilitate the measurements, experiments may be performed with air as the working medium instead of water [13,14]. The test section consists of a scaled-down geometric model of the Francis-99 draft tube [4] with an inlet diameter $D=100$ mm. Air at atmospheric pressure was used as the working medium. To generate the required flow distribution at the inlet to the cone, we used a pair of swirlers: a stationary swirler acting as guide vanes and a rotary swirler – an analogue of the turbine runner [13]. The pair of swirlers was designed for the optimal operating conditions (the best efficiency point – BEP) corresponding to a volumetric flow rate $Q_c = 48.5$ l/s and a runner rotation speed $n_c = 40.5$ Hz. The experimental setup included a computer-aided system for controlling the airflow and rotation frequency of the rotor with an uncertainty of 1.5% and 0.5%, respectively. The operating parameters of the setup ranged from a flow rate of $0.3Q_c$ to $1.5Q_c$ to vary the operation conditions of the hydro turbine.

The study was carried out using stereoscopic particle image velocimetry (SPIV) and four acoustic pressure sensors. Velocity measurements were carried out in a glass cone placed in the middle vertical cross-section $x–z$ (Fig. 1). To measure instantaneous velocity fields, we used a POLIS SPIV system consisting of a dual Nd:YAG pulsed laser (70 mJ in a 10-ns pulse), two ImperX CCD cameras (4904x3280 pixels), and a synchronizing processor. A laser sheet was formed by focusing (spherical) and cylindrical lenses. A 1-mm-thick laser sheet was placed in the central vertical $x–z$ plane. The PIV system is a low repetition system with 1 Hz frequency. The signal from microphones was a reference signal that tracked the phase of the PVC with a typical frequency of 16 Hz. Thus, an unambiguous relationship between the time of PIV images and the phase of the PVC was provided.

For acoustic measurements, four Behringer ECM 8000 microphones were used. Microphone signals were digitized by an L-Card E-440 ADC and amplified using Tube Microgain M200 preamplifiers. The PVC frequency was extracted via time-resolved pressure signals at a sampling rate of 20 kHz, obtained by four microphones mounted in the draft tube.
cone as shown in Fig. 1. The $j$-th microphone signals $p_j$ are decomposed into azimuthal spatial Fourier modes, according to [15]:

$$P_m = \sum_{j=1}^{4} p_j \cdot e^{-ijm(2\pi/4)}$$

(1)

where $m = 0, 1,$ and 2 refer to the azimuthal wave numbers that can be resolved using four microphones per circumference, and $P_m$ is a complex vector. The modes are then transformed into the frequency domain in the form of power spectral density (PSD) using a fast Fourier transform.

3. Results

The first focus of the study was to identify the operating modes involving maximum pressure pulsations on the cone walls of the draft tube model, which are usually observed under conditions far from the design (BEP) mode defined by $Q_c$ and $n_c$. To this, four different combinations of the flow rate $Q/Q_c$ in the range of 0.3 to 1.5 at constant frequency of rotation $n_c$ were considered. Figure 2 shows the PSD for azimuthal modes $m = 0, 1, 2$ calculated using Eq. (1) for four cases with flow rates of 0.3 $Q_c$, 0.5 $Q_c$, $Q_c$, and 1.5$Q_c$.

As shown in Fig. 2, the most energetic peak in the spectra occurs for the cases of 0.3$Q_c$ and 0.5$Q_c$. The spectra have two distinct peaks. The first ($\approx$16–19 Hz) and second (32–36 Hz) peaks exhibit similar amplitudes and can be associated with the PVC. According to [16], the azimuthal mode $m=1$ is a suitable marker of PVC formation in the flow. These parts of coherent pressure pulsations are caused by the PVC formed in the cone of the draft tube in non-optimal regimes (0.3$Q_c$ and 0.5$Q_c$). For the cases with $Q_c$ and 1.5$Q_c$, the PVC effect does not occur and the azimuthal mode $m=0$ is prevalent for in this flow type.

![Figure 2. PSD spectra of pressure pulsations for 0.3$Q_c$, 0.5$Q_c$, $Q_c$, and 1.5$Q_c$.](image-url)
Figure 3 presents the maximum peak-to-peak amplitude of the dominant peak in the spectrum of the \( m=1 \) azimuthal mode as a function of flow rate in the range of \( 0.35Q_c \) to \( 1.5Q_c \) for more than 100 points. According to this figure, the maximum influence of the PVC on the cone walls is observed at a flow rate of \( 0.5Q_c \); the same result was obtained in [13] using a two-point array of microphones.

![Figure 3](image)

**Figure 3.** Peak-to-peak amplitude of pressure pulsations \((m=1)\) as a function of flow rate.

Mean flows were examined for the same flow rates \((0.3Q_c, 0.5Q_c, Q_c, \text{ and } 1.5Q_c)\). Figure 4 shows a sequence of mean flows (in terms of streamlines and the tangential velocity component \( V_y \)) from the deep part-load regime \((0.3Q_c)\) to the overload regime \((1.5Q_c)\). All velocity values were normalized by the bulk flow velocity \( U_0=Q/(\pi D^2/4) \), where \( Q \) is flowrate and \( D \) is the inlet diameter of cone.

![Figure 4](image)

**Figure 4.** Mean flows for the different flow rate regimes \((0.3Q_c, 0.5Q_c, Q_c, \text{ and } 1.5Q_c)\).
The deep part-load regime \((0.3Q_c)\) is characterized by a wide area of the central recirculation zone (the whole cone area is exposed to the opposite axial flow), while the swirl strongly presses the flow against the cone walls. In this regime, the PVC effect occurs in the flow, but the pressure pulsation on the cone walls is rather weak as in the case of \(0.5Q_c\), as shown in Fig.3.

The strong PVC regime \((0.5Q_c)\) is characterized by a compact recirculation zone of length \(0.2D\). The influence of the strong PVC effect on the mean flow is seen at the stagnation point and also a near-zero tangential velocity component \(V_y\) (marked with white color in the legend) in the central region of the cone.

The BEP regime \((Q_c)\) is characterized by a small recirculation region \((0.1D)\), the formation of which is associated with the flow past the cowl. The inner swirl with a diameter of about \(0.2D\) rotates in the counterclockwise direction, opposite to the runner rotation direction. The external flow has a clockwise swirling motion that follows the direction imposed by the stationary swirler, as shown in [13]. For the overload regime \((1.5Q_c)\), the counterclockwise swirl intensity increases while the clockwise swirling pushes on the cone walls. This mean flow looks like the formation of a stationary central vortex with a thin concentrated core.

To better visualize the PVC, we employed a phase-averaged representation of the velocity field. The real part of pressure pulsation \(P_{m=1}\) of the \(m = 1\) mode was a reference signal that tracked the phase of the vortex core precession. Phase-averaging of 8 000 velocity distributions was performed with a resolution \(\Delta \phi = \pm 3^\circ\) using approximately 40 snapshots per each phase step (totally 120 phases were considered).

![Phase-averaging velocity field](image)

**Figure 5.** Phase-averaging velocity field for the \(0.5Q_c\) regime (strong PVC).

Figure 5 shows the phase-averaged velocity distribution obtained for the case of a strong PVC with \(0.5Q_c\) for angles \(\phi \approx 0^\circ, 90^\circ, 180^\circ,\) and \(270^\circ\). For a phase angle \(\phi \approx 0^\circ\), the vortex core appears near the left side of the cowl edge and rapidly propagates further downstream. At
φ ≈ 90°, the PVC becomes invisible on the left side due to a rapid change in the helical pitch of the vortex core. The PVC motion causes periodic intermittent flow from right to left. At phases φ ≈ 180° and φ ≈ 270° PVC, the motion repeats itself, causing flow from right to left.

4. Conclusions

Air swirl flow with the formation of a precessing vortex core (PVC) in the hydro turbine draft tube model was studied using Stereo-PIV and four acoustic sensors. Using a spatial Fourier decomposition of pressure pulsation data obtained from four acoustic sensors, a PVC was observed for part-load operating regimes (0.3–0.7Qc). Mean flow features were shown for a wide range of operating regimes from a deep part-load regime (0.3Qc) to an overload regime (1.5Qc). Based on phase-averaged velocity distribution, were the PVC spatial structure was identified for the case of maximum pressure pulsations on the cone walls of the draft tube (0.5Qc).

The preliminary experimental results can be useful for recent developments in linear stability theory to identify the PVC structure as a globally unstable mode triggered by a hydrodynamic feedback process in hydro turbine draft tubes.

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