Transient phenomena in the draft tube model of a Francis hydro-turbine

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Abstract. This article is devoted to the study of pressure pulsations behind the runner of a hydro turbine model caused by the precessing vortex core (PVC). Pressure pulsations are investigated under conditions of stationary load and transient modes of the hydro-turbine operation. Studies were performed in model conditions on the aerodynamic setup. The map of pressure pulsations was built for stationary modes using acoustic sensors and served to find rotational speeds of the swirler and flow rates at which the PVC occurs. On the basis of the data presented by parametric dependences, the initial and final parameters of the transition process were chosen. In the article, a sudden (fast) transition from part-load regime to the best efficiency point and back was considered. The characteristic times for the formation of PVC and the establishment of the flow regime when changing the controlling parameters of the installation have been determined using a continuous wavelet transform.

1. Introduction

Increasing the share of renewable energy sources, such as wind and solar, requires the application of energy generation units to compensate changes in weather conditions entirely governing operation of wind turbines or photovoltaic elements. Hydropower plants are a well suited energy source for balancing intermittent energy contributions due to their flexible operation capabilities [1,2]. Basically the hydro-turbines are designed for nominal operation conditions when they work stably and with maximum efficiency (best efficiency point - BEP) [3]. When performing regulating function the hydro-turbines are forced to operate at nonoptimal conditions. In the off-design (non-optimal) modes of the turbine operation behind the runner, critical hydrodynamic instabilities may take place in the form of unsteady vortex phenomena, such as the precessing vortex core, PVC [4]. When switching the hydro-turbine operation modes a transient flow regime occurs [5], in some cases provoking high amplitude pressure pulsations [6]. To analyze the transient processes developing in hydro-turbines at operation mode changing the Computational Fluid Dynamic (CFD) tools are widely used [1,5]. However, it has been commonly recognized that empirical data are needed for validation of the CFD results [2,6].

In this context, this work investigates pressure pulsations, caused by PVC in cone part of the model draft tube of a Francis hydro-turbine, under conditions of stationary load and in the cyclic transient operation from part-load to BEP. PVC is identified as a source of powerful flow pulsations, which have negative influence on the equipment and can lead to their serious damages [7,8]. At the same time, the literature contains almost no data on the PVC evolution at transient operating modes of hydro-turbines (start and stop, regulation of load).
2. Experimental set-up

The experimental setup is described in detail in [9]. The real flow behind the hydro-turbine is simulated using a system of two swirlers [10-13]. One of them is resting, and the other is forced to rotate with a given frequency. The in-house software was developed to control the speed of the rotation and air flow. It allows maintaining two regime parameters for the required time with an uncertainty of 1.5% and 0.5% for setting the flow rate $Q$, m$^3$/s and the speed $n$, respectively. For transient regimes, the software has reproduced the required cycle according to specific governing law of the flow rate change. Rotation frequency was constant in all regimes.

The flow passes through a system of two swirlers and then enters the test section. The test section is a cone of the draft tube with a diameter of 100 mm. After the cone, the flow enters elbow, then rectangular diffuser and then exits to the surrounding atmosphere. The model draft tube and the swirlers were produced by the rapid prototyping technique. The velocity distribution in the flow inside the cone is measured by a laser-Doppler anemometer. In order to provide optical access for the LDA laser beams into the test section, a part of the wall in the cone is replaced by a transparent glass window. For the LDA measurements the air flow has to be seeded with paraffin oil aerosol. The number of reliable bursts was 10 thousand for each point at which the velocity was measured. To measure pressure pulsations the acoustic sensors based on microphones Behringer ECM 8000 were used; their signals were digitized by the ADC L-Card E-440. In the experiments, two acoustic sensors were placed in the middle of the cone diametrically on the opposite sides flush with the cone walls.

3. Results

3.1. Steady-state regimes

Before studying the transitional regimes, flow characteristics such as pressure pulsations were studied in stationary regimes. This was done to confine the parametric space of the flow regime variations to the most interesting modes with the most pronounced effects of transition. With the help of a system of two acoustic sensors facing each other, a map of pressure pulsations of 1000 points was plotted. At each point, the air flow rate and rotational speed of the swirler were kept constant. A map of frequencies corresponding to the pressure pulsations was built as well (Figure 1). Figure 1 shows the area corresponding to the PVC (marked with a solid line). Frequency values obtained in this experiment agree well with the data obtained earlier in [9].

![Figure 1](image-url). On the left – map of frequencies (Hz) corresponding to the largest pressure pulsations at each point, and on the right – pressure pulsation map (in a.u.).
3.2. Transient regimes
Based on the obtained map of pressure pulsations, regimes with partial load of the hydro-turbine \((Q = 0.51Q_c = 0.025 \text{ m}^3/\text{s})\) and with the highest efficiency of the hydro-turbine (BEP) \([7]\) \((Q = Q_c = 0.049 \text{ m}^3/\text{s})\) were chosen as start and finish points of the transient process. There is a PVC at the point of partial load of the hydro-turbine, as we can see on the map (Figure 1). At the BEP point PVC is not observed. An example of the transition process is shown in Figure 2. During the experiments, different times of steady-state conditions as well as different acceleration and deceleration times were set. Each cycle was repeated 50 times, then, the obtained data were averaged over all cycles.

Since we are dealing with a non-stationary signal, it was decided to use the wavelet transform. This operation will allow one to clearly see the beginning of the PVC formation and the end of the PVC life, as well as to define the amplitude of the pulsations. An example of the wavelet diagram is shown in Figure 3.

A total of about 50 different transient regimes were recorded with different transition times and steady-state times. For each regime, a wavelet transform was performed on a difference signal from two microphones \([9]\). As a result of the wavelet transform of the signal, two-dimensional arrays were obtained, each of them containing 40 rows and approximately 500 thousand columns. A string (scale parameter) has the meaning of a reciprocal of the signal frequency. For each array, a string was searched the maximum sum of absolute values of the amplitudes of the difference signal received from the
microphones (P_1-P_2). Thus, a search was made for the frequency at which the amplitude of the pulsations is the greatest, assuming that this frequency corresponds to the PVC frequency. Then, for the found row, a probability density function was constructed to find the magnitude of the amplitude in this row. If the function had one well-defined peak, then the PVC was absent. This peak corresponds to the probability to find time with noise of the swirler blades and the servo drive, which are not considered in this study. If the function had two well-defined peaks, then the PVC was present in that period of time. Figure 4 shows an example of the source signal processed according to the algorithm described above.

![Figure 4](image)

**Figure 4.** Regime with transient flow rate and fixed rotation speed and PVC evolution.

The lifetime of the PVC was calculated for each transient cycle. Figure 5 shows the graphs of the dependence of the PVC lifetime on the transition time. It is shown that the dependence of the PVC lifetime in a transient mode is inversely proportional to the speed of transition.

![Figure 5](image)

**Figure 5.** Time dependence of PVC lifetime for different transition times (t = 1, 3 and 5 s, respectively).
Conclusions
Pressure pulsations caused by the PVC in the model of hydro-turbine have been considered and investigated under steady-state and transient conditions. The transition from part-load mode ($Q = 0.51Q_c$) to the BEP point ($Q = Q_c$) and back has been described. The development of the PVC is shown under transient conditions. It has been found that the lifetime of the PVC in the transient modes ($t=1,3,$ and $5\text{ s}$) is proportional to the transient process time.

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