Vortex rope patterns at different load of hydro turbine model

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Abstract. Operation of hydraulic turbines beyond optimal conditions leads to formation of precessing vortex core in a draft tube that generates powerful pressure pulsations in a hydraulic system. In case of resonance it leads to stability decreasing of hydraulic unit and electrical grid on the whole. In present work, such regimes are explored in a conical part of simplified turbine model. Studies are performed at constant flowrate $Q = 70$ m^3/h and varying the runner rotational speed to explore different loads of the hydroturbine unit. The experiments involve pressure measurements, high speed-visualization and velocity measurements by means of laser Doppler anemometer technique. Interesting finding is related with abrupt increasing precession frequency at low swirl parameter of flow near optimal regime.

1 Introduction

The integration of new energy sources into the existing electrical grid requires the expansion of hydraulic turbine operating range. However most of the installed hydropower units are optimized for their Best Efficiency Point (BEP). When the output flowrate of turbine is changed to execute the regulation function a residual swirl at the draft tube inlet remains, that results in emergence of phenomenon known as precessing vortex core (PVC). PVC leads to uneven pressure distribution in the draft tube that decreases the hydro turbine efficiency and safety.

Depending on the turbine discharge relative to the discharge at BEP a number of operating zones are distinguished at which the flow pattern is differed. With discharge decreasing relative to BEP there are upper part load, part load and deep part load. At increasing discharge, there is overload regime which rarely occurs in real turbines. Computational fluid dynamics (CFD) techniques and scaled down experimental modeling significantly enhances the understanding of PVC phenomena in a hydraulic turbine [1-3]. Nevertheless, CFD requires experimental data for verification but experimental data obtained on scaled model requires a valid theory for interpreting and transferring data to full-scale models that makes experimental modelling of flow structures still highly demanded.

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2 Experimental setup and measurement equipment

The test case is a reduced-scale simplified hydraulic turbine model, designed for an analogous test case, developed at Politehnical University of Timisoara [4]. It is designed to produce a flow similar to the one downstream a Francis turbine runner, operating at part load conditions. Detailed description of experimental set-up can be found in work [5]. Centrifugal pump with a flow rate up to 150 m3/h is used as a feed pump, and the flow rate is controlled by a feedback system that includes an electromagnetic flow meter and a frequency inverter. Runner rotational speed is controlled by electric motor through magnetic couple. Different flow regimes can be obtained changing parameters such as flow rate, runner rotational speed and geometry of stationary swirler. Commonly the flow rate is varied in a scaled hydro turbine model with a fixed rotation speed, thus outside the turbine's best efficiency point the flow in a draft tube inlet has a significant degree of swirl. In contrast, in the current study, the fixed flow rate is used with the aim to keep Reynolds number constant, and excess residual swirl is created by forcibly rotating runner.

Flow visualization techniques, laser Doppler anemometer (LDA) measurements and draft tube wall pressure measurements are employed to study the swirling flow characteristics. The flow exits the runner into the Plexiglas draft tube cone with full optical access for LDA measurements and visualizations. The axial and tangential velocity components used for the calculation of the flow swirl in the inlet cross-sections of the draft tube cone are obtained by performing LDA measurements in a 2-D mode traversing the measurement point between the cone wall and the centerline with regular steps. The velocities are measured every 5 mm, completing each measurement with a last point located on the cone centerline. Flat outer walls of the draft tube cone significantly decrease optical distortions appearing because of inner cone wall curvature. Nevertheless, tangential velocity is recalculated according methodologic proposed by Z. Zhang [6]. Maximum correction of 8% of measured velocity was applied near the central axis of the draft tube cone. Based on mean velocity distribution, the integral swirl parameter characterizing a flow regime is calculated as follows:

$$S = \frac{\int_0^R V_{tg} V_{ax} r^2 dr}{R \int_0^R U_{ax}^2 r dr} \tag{1}$$

where V_{tg} is the mean tangential velocity, V_{ax} is the mean axial velocity, and R is the radius of the cross-sectional area.

Under 70 m^3/h and runner 400 rpm the integral swirl parameter S is close to zero, i.e. the regime is defined as optimal in the turbine model. Experiments show that increasing of swirl parameter, which is directly proportional to runner rotational speed, is analogous to shifting the flow regime towards part load conditions.

3 Results

The modeling of several flow regimes is conducted with fixed flowrate and changing the runner rotational speed. Under flowrate Q = 70 m3/h and runner rotational speed N = 450 rpm (S = 0.45) the swirling flow with well-developed PVC is observed (fig 1.a). One can see the drastically different flow pattern at the same flowrate but at larger N = 700 rpm which corresponds to high swirl parameter S = 1.2 fig 1(b).
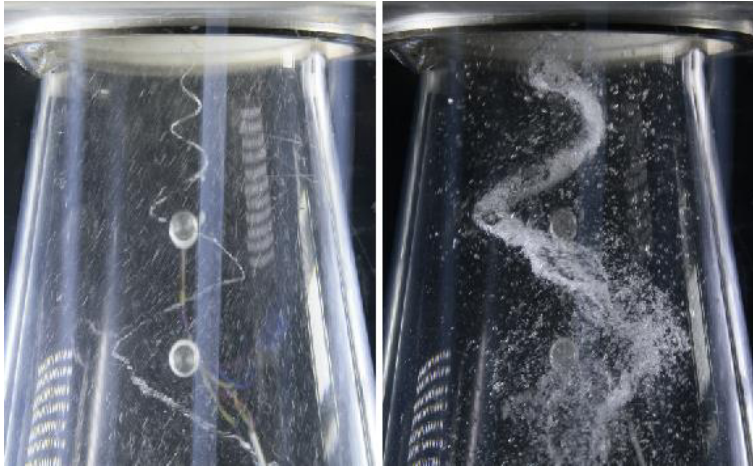
Fig. 1. Instant photo visualization, Q = 70 m^3/h, left – N = 450 rpm, S = 0.45, right N = 700 rpm, S = 1.2

At S = 0.45 the precession radius is decreased in two times; also spatial wavelength is decreased in more than two times compared with regime at S = 1.2. As a result, precession frequency registered by high-speed visualization technique at S = 0.45 is higher than at S = 1.2. The same behavior of PVC at low swirl number was observed by Fernandes et al. [7] for axial swirl generator with variable blade angles. Fernandes et al. showed that there was critical swirl number below which the precession frequency increased with swirl number decreasing while the stable PVC existed. This has a good correlation with figure 2 (left) where dependence of PVC frequency on runner rotational speed is presented. Note that the swirl number increased linearly with rotational speed from N = 400 rpm. At low swirl the precession frequency can be determined only based on high-speed visualization, performed at 500 fps because of weak periodical mode of the pressure signal, recorded at N below 500 rpm (figure 2 b). Note that the visualization technique shows a good agreement with Fast Fourier transform of pressure signal at higher N.
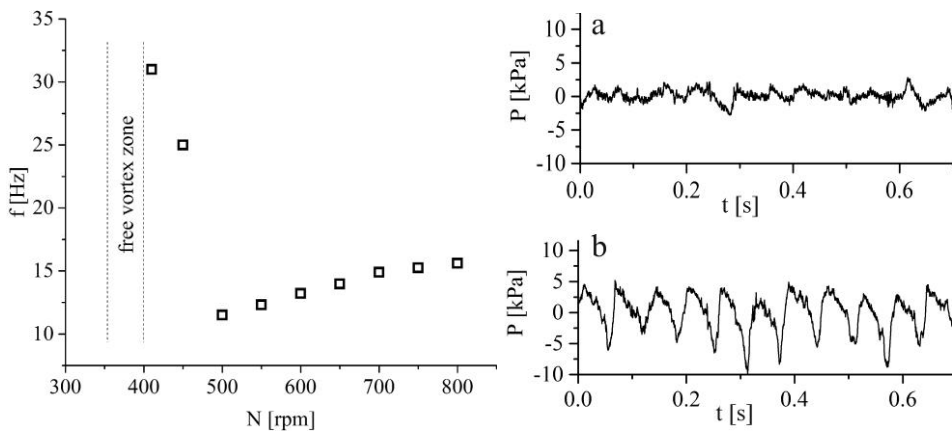

Fig. 2. Left – dependence of PVC frequency on runner rotational speed, right – draft tube wall pressure pulsations, Q = 70 m^3/h, a – 450 rpm, b – 700 rpm

Figures 3 shows the quantitative information obtained by the LDA measurements. Velocities were nondimensionilesd using bulk velocity U = 2.47 m/s. One can see in both

cases there is a narrow region of the central reverse flow. At higher rotational speed the back flow zone is more developed that correlates with flow visualization on figure 1.
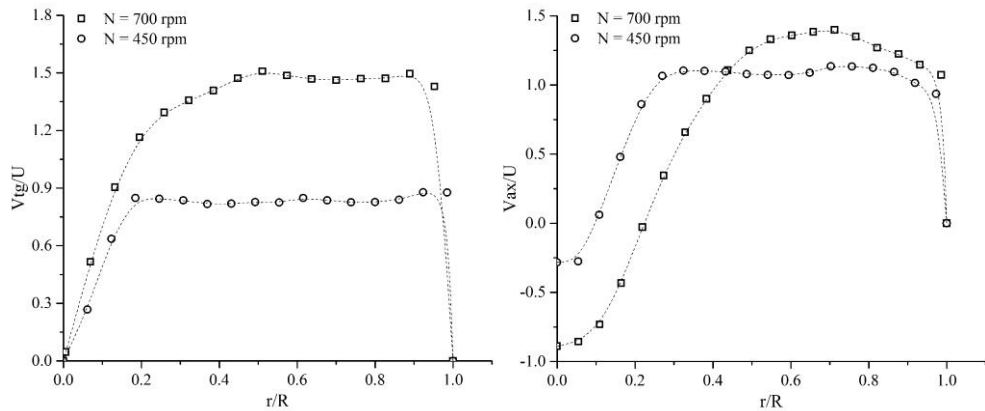

Fig. 2. Dimensionless tangential (left) and axial (right) mean velocity, Q = 70 m3/h.

4 Conclusion

Observation of the PVC in the conical draft tube model provides some new information regarding the vortex structure at low swirl parameter. As it turned out there is a narrow region below critical swirl parameter where precession frequency of the PVC grows up with decreasing swirl parameter. It is not related to an increase in tangential velocity component but can be explained by a drastical change of the PVC pattern. At low swirl the spiral vortex is formed with a smaller radius and shorter spatial wavelength.

Although the observed effect of high precession frequency with low amplitude does not pose any practical direct problem, it can become an additional source of pressure disturbances, which are sensitive to cavitation number.

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