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# Study of swirling flow in the simplified turbine model under different operating conditions

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## Abstract

Operating hydraulic turbines under non-optimal conditions leads to the emergence of the precessing vortex rope behind the turbine runner. This experimental study examine cavitating turbulent flow in a simplified hydraulic turbine to reveal flow features in a wide range of speed and discharge conditions. A swirling device that allows reproducing the speed distribution behind the runner of a real turbine was manufactured using a rapid prototyping technology. Laser Doppler anemometry velocity measurements were performed at the runner outlet for various operating regimes. The details of velocity distributions at high swirl number were investigated and discussed.

## 1 Introduction

The integration of new energy sources like wind or solar energy into the electrical grid requires the flexible regulation of electrical grid. This possibility can be realized by hydro turbines capable of rapidly changing the output power. Most of the installed hydropower units are optimized for their Best Efficiency Point (BEP) but for regulation, they work beyond optimal conditions. 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. PVC rotates around draft tube axis and generates pressure surge resulting in a resonance conditions. It diminishes efficiency and robustness of hydraulic unit. Also interacting with the draft tube elbow, the vortex rope creates oscillations of the liquid column leading to a dangerous power swing. Rheingans (1940) was one of the first who drew attention to this phenomenon. Since then, the problems of the appearance of non-stationary phenomena in a swirling flow behind the runner of a hydro turbine have been paid much attention. The strong impact that the vortex rope has on the power plant performance requires studying the mechanism of the PVC formation that is necessary for advancing hydropower plant efficiency and preventing undesirable vibrations. Because of the complexity and high cost of experiments on real hydroturbines, reduced and simplified models are used.

Nishi and Liu (2013) have generalized the description of the different vortex rope patterns observed at different turbine loads. The development of contactless optical flow diagnostic methods (PIV, LDV, high-speed visualization) significantly increased the understanding of the complex structure of the flow. Favrel et al. (2015) performed PIV measurements and phase averaging procedure in order to examine the dynamic of PVC in one revolution in different cross sections for various $Q/Q_{BEP}$. Tridon et al. (2010) paid attention to measuring the radial velocity component. Commonly this component is not consider due to the complexity of the required measurement setup and significant curvature of the draft tube cone for LDV application. A strong asymmetry of the radial velocity has been shown, which is usually not taken into account in analytical models. Müller et al. (2017) applied Laser Doppler Velocimetry and high-speed

visualizations for two-phase flow field at the runner exit. The complex interplay of wall pressure, the flow swirl, the torque, the vortex rope volume was shown.
Another way to understand complex effects and phenomena arising in a turbulent, multiphase swirling flow is the use of numerical simulation. Thus, the CFD methods solve not only the problems of geometry optimization Ciocan et al. (2016), Lyutov et al. (2015), Wei et al. (2014), but also the important task is to obtain quantitative information on the flow structure in those areas in which the use of optical technique becomes problematic Zuo et al. (2015), Shingai et al. (2014), Minakov et al. (2017). Despite the advantages of numerical simulation, it requires ongoing verification by experimental data.

## 2 Experimental setup

Measurements are carried out at the test facilities of the Kutateladze Institute of Thermophysics, Laboratory of Ecological Problems of Heat Power Industry, on a vertical closed-loop experimental test rig with scaled simplified model of a hydraulic turbine (figure 1). The main purpose of the simplified turbine model examined in this paper is to reproduce the flow behind a real turbine runner in the cone of the draft tube. The draft tube cone was made of Plexiglas, providing an optical access for optical methods of flow diagnostic, such as the LDA technique and high-speed visualization. Using the straight conical draft tube neglects the effects of the complex interaction of the vortex rope with the elbow.
The swirl generator (instead of guide vane and turbine runner) designed to simulate flow in a Francis turbine operated at different discharge conditions. Magnetic couple provides the contactless transmissions of the torque from the external electromotor to the runner inside the flow. The stationary swirler creates a tangential velocity component, which is further redistributed by an externally rotated runner. The stationary guide vanes and runner were made by means of three-dimensional rapid prototyping technology that allows that allows you to precisely create a complex blade geometry. The centrifugal pump 3LMH 80- 160/18.5 from Ebara Corp., (Tokyo, Japan) supplies a flow rate up to 200 $m^3/h$ ($Re_{max} \approx 10^6$); runner speed is varied in a range of 0 – 2000 rpm.

Figure 1: Photo of test section. Transparent part of draft tube cone for LDA and pressure measurements.

## 3 Velocity and pressure measurements

Experimental data containing velocity distribution on more than 100 operating points are collected. For each flow rate, ten runner speeds are analyzed. Velocities are presented in non- dimensional form using bulk velocity; it allows to compare the influence of different runner speed at one Reynolds number. The cross section in which the measurements are carried out is located 60 mm downstream the inlet cross section. In view of the symmetry of the draft tube cone axial and tangential velocities are assumed to be axisymmetric and measurements are taken from the wall to the central axis.
The tangential profile in the swirl free conditions (figure 2, black squares) has an S-shaped velocity profile, and the zero-velocity point is shifted to the wall. It is possible to distinguish two groups of velocity distributions for a given flow, up to 900 revolutions per minute and after. In these two areas the velocity patterns are different. This applies to both tangential and axial components. The tangential component in the 0-0.3R region for large runner speeds has a slope in the opposite direction. The axial component also has an interesting feature. When the critical speed of rotation is reached, the recirculation region abruptly disappears; nevertheless, the pulsations associated with the precession of the vortex rope are still recorded.

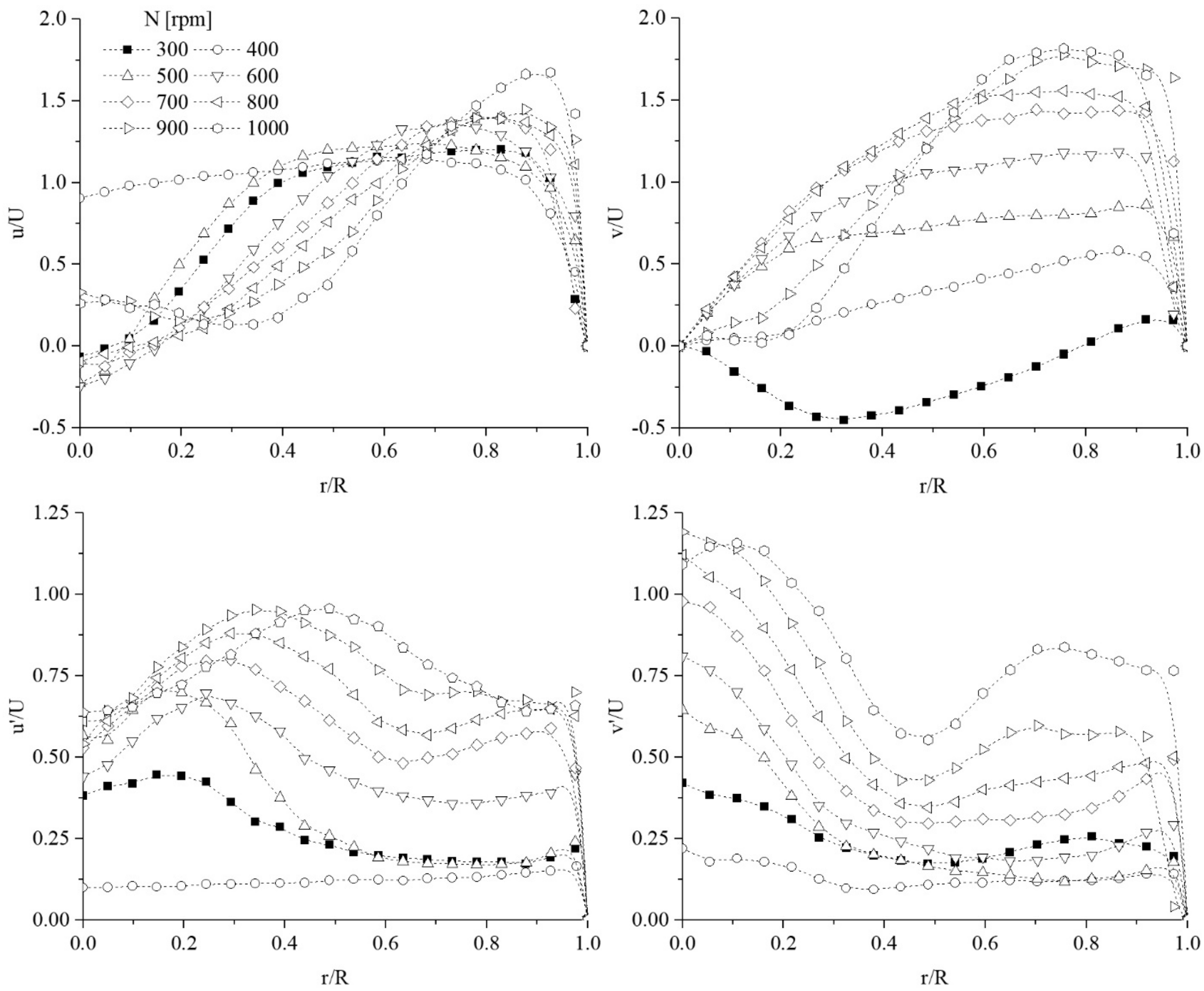


Figure 2: axial (u) and tangential (v) velocity distributions (and RMS their fluctuations u', v') at different runner rotational speed and constant flowrate (Re ~ $2.4 \cdot 10^5$), U – bulk velocity (2.42 m/s). Black squares correspond to regime with zero swirl.

It should be noted that the region with the lowest velocity pulsations, both axial and tangential, is displaced with respect to the zero-swirl flow regime (N = 300 rpm) toward greater swirl (S ~ 0.15, N = 400 rpm). In this regime, a practically uniform profile of the axial velocity is observed, and the model of solid-state rotation well describes tangential velocity. The position of the maximum of the axial velocity component correlates with the position of the precessing vortex rope, in turn, the maximum of pulsations on the axis of the tangential component also confirms the presence of precessing structure displaced relative axis of the draft tube cone. The maximum of the axial component shifts toward the wall, and its value increases. When the critical rotational speed of the runner reaches the growth is not observed, but the maximum is still shifting to the side.
To generalize the data on the measurement of pressure pulsations, the integrated swirl parameter introduced in Chigier and Beer (1964) as the ratio of axial flux of azimuthal momentum to the axial flux of axial momentum multiplied by radius R. Not taking into account the distribution of pressure and Reynolds stress it can be rewritten as:

$$S = \frac{\int_0^\infty \rho u w r^2 \, dr}{R \int_0^R \rho \mathrm{u}^2 \mathrm{r} \, \mathrm{dr}} \tag{1}$$

Draft tube wall pressure pulsation map is presented in figure 3. A coherent component was extracted from the signal, excluding turbulent pulsations in the flow. It can be seen that in the region of zero and moderate swirl S < 0.6, the pressure sensor does not detect pulsations from the vortex rope, despite the fact that, according to the visualization data and indirectly according to the velocity profiles (the presence of a reverse flow), PVC in the flow is present. Starting at S = 0.6, the pressure pulsations become significant and grow with flowrate increasing.

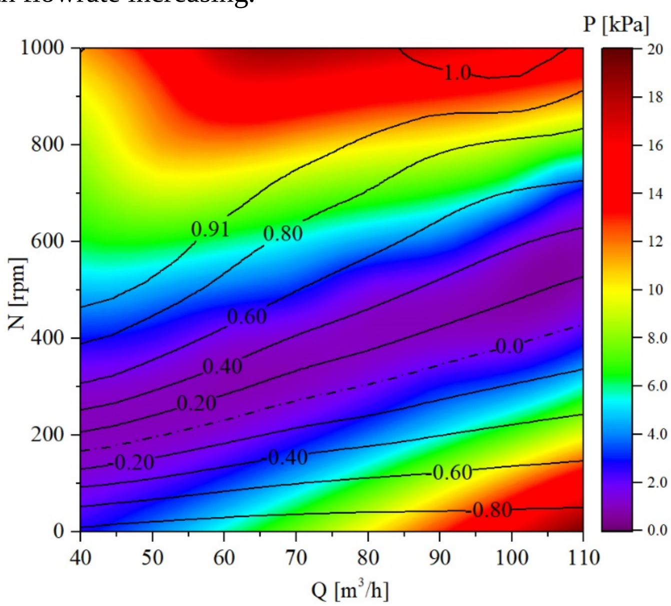


Figure 3: Pressure surge map in Q-N coordinates.

## 4 Conclusion

PVC-induced pressure oscillations are reproduced on a reduced simplified physical model of a hydraulic turbine. The technique of fast 3D prototyping made it possible to create with high accuracy a swirling device that simulates the flow distribution behind the runner of real turbines at various operating modes. More than one hundred operating regimes have been investigated experimentally by means of LDV and pressure measurements. Experimental results show that the large on-axis recirculation region and the high level of velocity fluctuations occur at the shifting towards non-optimal regimes in which the $N/N_0$ ratio differ from 1. The velocity and their pulsations in the draft tube cone showed a different pattern depending on the runner speed. Pressure pulsations have been drawn in color maps in Q – N coordinates; the main feature is the discrepancy between locations of the maximum of flow rate and pressure amplitude. Starting at a critical value S = 0.9, a decrease in flow rate or an increase in the runner rotational speed do not increase the integral swirl parameter.

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