Aperiodic pressure pulsation under non optimal hydraulic turbine regimes at low swirl number

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Abstract. Off-design operating conditions of hydraulic turbines is hindered by pressure fluctuations in the draft tube of the turbine. A precessing helical vortex rope develops, which imperils the mechanical structure and limits the operation flexibility of hydropower station. Understanding of the underlying instabilities of precessing vortex rope at low swirl number is incomplete. In this paper flow regimes with different residual swirl is analysed, particular attention is paid to the regime with a small swirl parameter. Study defines upper and low boundaries of regime where aperiodic pressure surge is observed. Flow field at the runner exit is investigated by Laser Doppler Velocimetry and high-speed visualizations, which are complemented draft tube wall pressure measurements.

1. Introduction

Nowadays, hydropower stations integrated in electrical grid have a very important task to provide flexible changes of electrical grid load. It is ensured by operation hydraulic turbine beyond designed conditions. Under part or over – load or starts-stops turbines the flow downstream the runner has a residual swirl which together with expanding part of draft tube lead to formation of recirculation zone and emergence of spiral vortex breakdown know as precessing vortex core (PVC). It is well recognized that such phenomenon has negative impact on hydraulic turbine operating stability and efficiency of hydraulic unit.

Detailed description and study of physical principle leading to PVC phenomenon are paramount to development flow control techniques, the main task of which to reduce PVC influence on hydraulic system while maintaining the efficiency of the turbine. This phenomenon in hydraulic turbine is widely described in literature; these are investigations of twin vortex rope [1,2], pulsations at upper part load [3], deep part load and low load investigations [4,5], turbine transient processes [6] etc. Due to abundance of various turbines designs and wide operating range in which turbines have to operate under grid regulating, the study of flow under turbine runner are still demanded.

Particular attention should be paid to regimes close to optimal at best efficiency point (BEP), commonly at such regimes whether part or over – load the swirl of flow is quite small and close to 0.2-0.5. Thus precessing vortex rope is formed weak and no intensive. Nevertheless, Dorfler [7] mentions regime near 0.85 Q_{BEP} when precessing vortex rope rotates irregularly, with a stable period no longer than 4 revolutions. At disruption of PVC pattern pressure spikes in the draft tube are observed that correspond to partial collapse of the vortex rope.

Recently it was found that the cause of pressure spikes in regime close to BEP is vortex rings formed due to reconnection of unstable spiral vortex [8,9]. The authors also note PVC instability each
3-4 of vortex rope revolutions in average. Due to induced motion vortex ring moves close to a draft tube wall and generates pressure spike or drop. At that draft tube wall pressure pulsations caused by PVC in observed regime are insignificant.

In that work explored regime is expanded compare to previous study [9] where regime with vortex rings formation was found at free rotating runner, rotational speed is proportional to flow rate. Here runner rotational speed is controlled and varied from 0 to 800 rpm. This allowed us to establish the boundaries of the unstable regime with aperiodic pulsations in terms of the swirl parameter. Experiments are conducted at fixed Reynolds number \( \text{Re} = 10^5 \) (constant flow rate) and inlet flow conditions are changed only by varying runner rotational speed.

2. Methodology
The study are conducted at the experimental set-up of the Kutateladze Institute of Thermophysics. The test rig is designed in a closed loop configuration driven centrifugal pump with a maximum flow rate of up to 150 m³/h. As a hydro turbine prototype simplified model of hydraulic turbine with straight draft tube is used. The flow distribution close to the distribution downstream a Francis turbine runner operating at non-optimal conditions is provided by combination of stationary guide vanes and forcibly rotating runner. An electromotor regulates the rotating speed of the runner through magnetic couple.

Two piezo resistive pressure transmitters are mounted in a draft tube wall to detect pressure disturbance caused by precessing vortex rope. Flow rate is held constant to compare draft tube wall pressure pulsation at constant Reynolds number and different swirl. Various flow regimes are obtained by runner rotational speed regulation. Detailed description and scheme of experimental set-up can be found in works [2, 9].

Contactless technique laser Doppler anemometry (LDA) is used to obtain quantitative information about flow structure which is needed to understand the flow phenomena and verification of numerical simulation. The flow exits the runner into the Plexiglas draft tube cone with full optical access for LDA measurements and visualizations. Flat draft tube cone walls significantly decrease distortions related to cone curative, tangential velocity is specified according methodologic proposed by Z. Zhang [10]. Correction in 8% of measured tangential velocity is specified near central axis of draft tube cone.

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 in regular steps between the cone wall and the centerline. The velocities are measured every 5 mm, completing each measurement with a last point located on the cone centerline. Based on mean axial and tangential velocity distribution integral swirl parameter characterized a flow regime is calculated as follows:

\[
S = \frac{\int_0^R \int_0^{\sqrt{2}} VUr^2 dr d\theta}{\int_0^R \int_0^{\sqrt{2}} U^2 rdr d\theta}
\]

where \( V \) - mean tangential velocity, \( U \) – mean axial velocity, \( R \) is the radius of the cross-sectional area. High-speed visualization complements of velocity profiles that gives complete flow pattern.

3. Experimental results
Vortex rope patterns at different runner rotational speed are shown on figure 1. At \( N =800 \) rpm (swirl number \( S \sim 1.5 \)) PVC represents a close interweaving of smaller vortices rotating as a unit. At \( N =480 \) rpm PVC has pronounced spiral pattern and shorter spatial wavelength. On figure 1 one can see separated vortex ring marked dashed line which moves toward draft tube wall.
Figure 1. Visualization of vortex structure, $N = 480$ rpm (left), $N = 800$ rpm (right), dashed line marks separated vortex ring near wall, solid line indicates cross section for LDA measurements.

Pressure signal at $N = 480$ rpm and $N = 800$ rpm are presented on figure 2 (a, b). With runner rotational speed increasing i.e. at higher swirl number PVC radius is increased and peak-to-peak amplitude of wall pressure pulsation is increased too. Nevertheless, pressure spikes of the same order like at $N = 800$ are also observed in a regime near optimal when swirl of flow is low. It one can see at time 0.5 s on figure 2 (a). This pressure spike is caused by vortex ring and slightly differs from pressure drops related to vortex rope precession, the width in time of pressure drop detected by pressure transmitter in 3-5 times longer than pressure spikes.

Figure 2. Dynamic pressure pulsations, zero on vertical axis correspond static pressure in measured cross section, $N = 480$ rpm (a), 800 rpm (b).
Upper and low boundaries in terms of runner rotational speed i.e. of swirl number are defined using high-speed visualization technique. As the speed of rotation of the runner decreases relative to the low boundary, the stagnation point is displaced downstream and the spiraling vortex structure ceases to exist, with an increase in the rotational speed above the upper boundary, the vortex spiral becomes stable and separation of the vortex rings is not observed.

Axial and tangential velocity distributions shown on figure 3 are measured in a throat part of draft tube conical diffuser marked solid line on figure 1 in boundaries regimes. One may see that the axial velocity distributions at upper and low boundary are the same, but recirculation zone is absent at a low boundary when column like vortex is formed. Dimensionless tangential distribution has a local minimum at \( r = 0.3R \) and in average in 1.8 times less than at upper boundary.

The dependence of integral swirl number on runner rotational speed is shown on the figure 4 at fixed flow rate \( Q = 70 \, \text{m}^3/\text{h} \). As expected quicker runner rotation leads to increasing tangential velocity component and increasing swirl parameter. One can see that the dependence is well approximated by a linear function. Negative values of the swirl parameter correspond to the rotation of the flow counterclockwise twisted over the stationary guide vanes, in terms of hydraulic turbines this mode corresponds to overload. Dashed lines on figure 4 limits the unstable zone in which vortex ring formation is observed.

![Figure 3](image-url)  
**Figure 3.** Dimensionless axial (left) and tangential (right) velocity measured at low and upper boundaries.

![Figure 4](image-url)  
**Figure 4.** Dependence of swirl number on runner rotational speed.
Low threshold corresponds \( S = 0.3 \). Axisymmetric vortex column with breakdown point downstream is formed on the draft tube axis. With a slight increase in the runner rotational speed the breakdown point shifts upstream until it places on the tip of the cowl. Inside the unstable regime with increasing of swirl number the spatial period of the vortex rope and precession radius start to increase, which together leads to an increase in the local radius of curvature, and starting from \( S = 0.6 \) the vortex spiral becomes stable.

4. Conclusion

Study of the precessing vortex rope at low swirl parameter in the simplified draft tube model provides some new information regarding the vortex instabilities. Varying the rotation speed of runner at constant flow rate various flow patterns corresponding different swirl numbers are obtained. High-speed visualisation, LDA and pressure measurements provides insight into the physical understanding of phenomenon related to aperiodic pressure pulsations in hydraulic turbines. The boundaries of unstable regime accompanied by vortex ring formation are defined.

The most important is that near the optimal regime with a small swirl parameter \( S \sim 0.5 \), pressure shock caused by the vortex rings have the same amplitude with pulsations at the swirl parameter \( S \sim 1.5 \), which corresponds to a significant part load. The vortex ring formation in such complex system is very interesting from a practical and fundamental point of view, that requires further detailed investigations and explanations of principle leading to instability and vortex reconnection.

Acknowledgments

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