On random pressure pulses in the turbine draft tube

P A Kuibin, S I Shtork, S G Skripkin, M A Tsoy
Kutateladze Institute of Thermophysics SB RAS, 1 Lavrentyev ave., Novosibirsk, 630090, Russia
E-mail: kuibin@itp.nsc.ru

Abstract. The flow in the conical part of the hydroturbine draft tube undergoes various instabilities due to deceleration and flow swirling at off-design operation points. In particular, the precessing vortex rope develops at part-load regimes in the draft tube. This rope induces periodical low-frequency pressure oscillations in the draft tube. Interaction of rotational (asynchronous) mode of disturbances with the elbow can bring to strong oscillations in the whole hydrodynamical system. Recent researches on flow structure in the discharge cone in a regime of free runner had revealed that helical-like vortex rope can be unstable itself. Some coils of helix close to each other and reconnection appears with generation of a vortex ring. The vortex ring moves toward the draft tube wall and downstream. The present research is focused on interaction of vortex ring with wall and generation of pressure pulses.

1. Introduction
The hydro power stations often play role of regulating instruments in electric grids. Moreover, the levels of head water as well as tail water undergo considerable variations due to seasons changes or meteorological conditions etc. Thus, the hydraulic machines need to operate under wide range of technological parameters. Most of the operating points lying away from the best efficiency point are subjected to instability or cavitation developments inducing undesirable unsteady phenomena. In a most extent this refers to the turbines of Francis type. The state of the art in area of different aspects of the hydrodynamic instabilities can be found in recent reviews [1, 2]. In particular, one type of instability, vortex breakdown, leads to generation of helix-like vortex rope. Our recent research [3] on the flow structure behind model of the runner had demonstrated that the helical vortex rope can be unstable itself. During recording with high speed camera we observed that sometimes the neighboring coils of the helix close to each other and process of reconnection starts with further generation of a vortex ring. The vortex ring after the reconnection moves apart from the main vortex rope toward the wall and downstream generating pressure pulses on the wall (some details on interaction of a vortex ring with the wall can be found in [4]). Such event belongs to random (or aperiodical) pulsations which present a particular interest, due to the fact that their nature is much more complex in comparison with precessional pulsations or blade pulsations [5].

The goal of this paper is to make a better understanding of the random pressure pulses phenomenon. We will perform synchronous registration of the vortex ring propagation via high speed camera together with recording the pressure signal from the probe mounted on the wall.

2. Experimental setup
The studies were performed using a closed hydrodynamic loop with a maximum flow rate (Q) of up to 0.067 m³/s. For simulating the cavitation regime in the test section, the set-up was equipped with a vacuum pump that provided additional evacuation up to 96 kPa. The working section (Figure 1)
analogous to one developed at Politehnical University of Timisoara [5], allowed for an optical access for the LDA system and high-speed visualization video camera. The working section presents a model of the draft tube cone with throat diameter \(D = 0.1\) m. Another details on the experimental setup see in [6]. In the present research the velocity distributions at the cone inlet cross-section was qualitatively similar to the flow regime observed during part-load operation of Francis turbine [7]. The flow swirl parameter \(s = 2 M/KD = 0.47\) was found through the angular momentum \(M\) and momentum \(K\). The second parameter characterizing the flow is Reynolds number, \(\text{Re} = 4Q/\pi D v\). Here \(v\) is the kinematic viscosity. The maximal Reynolds number in experiments was about \(5 \times 10^5\).

The vortex structures were visualized by the vapor bubbles formed due to cavitation in the zones of low pressure, i.e., at the vortex axis. Visualization was performed using high speed Photron video camera with a maximum resolution of 1 megapixel and frame rate of up to 20,000 fps. To measure pressure pulsations on the draft tube wall, the turbine model was equipped with a piezo resistive pressure transmitter Keller PA-4LC. The pressure fluctuations were measured at 64 mm downstream of the draft tube inlet (figure 1). Standard backscattering two-component LDV system LAD-06i was used for measuring the average velocity profiles (see details in [6]). The measured velocity profiles were used for evaluating the swirl parameter as well as parameters of the helical-like vortex. In particular, intensity of vortex, \(\Gamma = 0.13\) m\(^2\)/s was found [6].

3. Flow visualization

We used the modern visualization technique which allows investigating in detail the main stages of the vortex reconnection and vortex ring formation. The structure of the basic flow realized in a conical section of the hydraulic model of the turbine is shown in figure 2. Due to vortex breakdown phenomenon the vortex core takes form of a left-handed helix. Localization of the vorticity near the central axis of the vortex leads to the formation of cavitation rope, which is filled with water vapor. Conditions of vortex breakdown is associated with the formation of counter flow along the geometrical axis of the channel. At the same time, the direct downward flow occurs along the working section walls. It should be noted that such a topology corresponds to the velocity field generated by a left-handed precessing vortex structure.

A complete scenario of reconnection process with the formation of a vortex ring was described by Alekseenko et al. [6] and is shown in Figure 3. Due to the unstable state of the vortex system in the expanded cone, at some moment, one of the spiral coils starts moving upward, in particular, due to the

![Figure 1. Simplified hydro turbine model](image)
reverse flow in the near-axis zone of the channel. Subsequently, we observed an overlap of this coil, and further, the mechanism of convergence of the tube parts with the opposite vorticity vectors turns on (see Figure 3d). The tubes bend at the points of their connections and then the process of reconnection occurs. As a result of the reconnection, vortex ring separates from the spiral tube and moves downstream the cone. The duration of this process is approximately 10 ms from the start of convergence of the spiral parts and ending with full detachment of the ring. After reconnection process, the basic pattern of the vortex has being restored. The reconnection process with the formation of an isolated ring is observed regularly. The size of the vortex ring depends on the separation placement. The upstream reconnection occurs the smaller the vortex ring size. Similar processes of reconnection were investigated numerically [8], but papers on the reconnection in the swirling flow especially in hydro turbine was not found in the literature.

Two different scenarios of vortex ring reconnection were described in [6]: generation of separated vortex ring and generation of ring linked with main helical vortex. Here we are interested in first scenario only which leads to origin of pressure impacts. Based on analysis of video data (statistics up to 1000 revolution of vortex rope precession) we obtained the probability distribution histogram of the events of separations of vortex rings versus time delay between the events (figure 4). The averaged period of vortex rings separations $T_{\text{ring}}$ is about 3 times higher than the vortex precession period $T_{pr}$. 

Figure 2. Basic flow regime in a conical draft tube model, $Q = 116 \text{ m}^3/\text{h}$

Figure 3. Sequence of the video frames demonstrating formation of isolated vortex ring in a conical part of draft tube model, $Q = 116 \text{ m}^3/\text{h}$ [6]
4. Pressure measurements

The oscillograms (figure 5) show the variation in time of the pressure on the wall (figure 1) of the draft tube model. Zero on the ordinate axis corresponds to the normal atmospheric pressure. The amplitude of the draft tube wall pressure pulsation in this flow regime caused by precession of the vortex rope is small, approximately 5-7 kPa. In the same time, the pressure pulse caused by the vortex ring is approximately 35-40 kPa, which is 7 times higher than the level of main fluctuations. In some cases, experiments show that the pressure shock caused by the vortex ring may exceed the pulsation induced by PVC by 10 times. After formation of the vortex ring, full collapse of the PVC cavity may occur. Depending on the vortex ring trajectory relative the pressure sensor, the different patterns of pressure pulses can be seen in the oscillogram: pressure pulse (figure 5), pressure pulse with subsequent depressurization and vice versa.

5. Conclusion

A phenomenon of vortex ring formation on the precessing vortex rope and pressure pulses induced by vortex ring travelling near probe on the wall have been investigated experimentally in the simplified laboratory model of hydro turbine. Thus, in this experimental work for the first time high-speed visualization synchronized with the wall pressure measurement made it possible to associate random pressure pulses in draft tube with aperiodical process of vortex rings generation due to reconnection between the coils of helical vortex rope. After reconnection the vortex ring can move very close to the wall of the draft tube, causing a sharp local pressure drop. The average period of the vortex rings formation is about 3 times higher than the precession period. The recorded pressure signal depends on the vortex ring trajectory relative to the pressure sensor. Both the sharp rise and fall of the pressure were recorded. The trajectory of the vortex ring and its interaction with the wall of the draft tube are very complex. There are few factors influencing its motion: main swirling flow, PVC induced velocity, self-induced velocity, and velocity induced by interaction with the wall.

Acknowledgments

This work was supported by the Russian Science Foundation, grant No 16-19-00138.

References

[1] Nishi M and Liu S 2013 An outlook on the draft-tube-surge study Int. J. Fluid Mach. Syst. 6(1) 33-48
[2] Nicolet C, Zobeiri A, Maruzewski P and Avellan F 2011 Experimental Investigations on Upper Part Load Vortex Rope Pressure Fluctuations in Francis Turbine Draft Tube Int. J. Fluid Mach. Syst. 4(1) 179-190
Figure 5. Oscillograms of the pressure pulses associated with vortex rings passing near the sensor.

[3] Alekseenko S V, Kuibin P A, Shtork S I, Skripkin S G and Tsoy M A 2016 Vortex Reconnection in a Swirling Flow JETP Letters 103(7), 455–459
[4] Nicolet C 2007 Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems, Phd Thesis, Lausanne, EPFL, 314
[5] Susan-Resiga R F, Muntean S, Tanasa C and Bosioc A 2008 Hydrodynamic design and analysis of a swirling flow generator. Proc. of the 4th German–Romanian Workshop on Turbomachinery Hydrodynamics (GRoWTH), June 12–15, 2008, Stuttgart, Germany http://acad-tim.tm.edu.ro/iSMART-flow/pdf/Resiga_4GRoWTH1.pdf
[6] Alekseenko S V, Kuibin P A, Shtork S I, Skripkin S G, Sonin V I, Tsoy M A and Ustimenko A S 2016 A novel scenario of aperiodical impacts appearance in the turbine draft tube IOP Conf. Series: Earth and Environmental Science 49, 082025
[7] Hosein Foroutan and Savas Yavuzkurt 2014 Flow in the Simplified Draft Tube of a Francis Turbine Operating at Partial Load – Part I: Simulation of the Vortex Rope J. Appl. Mech 81(6), 061010
[8] Hussain F and Duraisamy K 2011 Mechanics of viscous vortex reconnection Phys. Fluids 23(2), 021701
[9] Naguib A, Koochesfahani M 2004 On wall-pressure sources associated with the unsteady separation in a vortex-ring / wall interaction Phys. Fluids 16(7) 2613-2622