A novel scenario of aperiodical impacts appearance in the turbine draft tube

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Abstract. The swirling flow in the discharge cone of hydroturbine is characterized by various self-induced instabilities and associated low frequency phenomena when the turbine is operated far from the best efficiency point. In particular, the precessing vortex rope develops at part-load regimes in the draft tube. This rope can serve a reason of the periodical low-frequency pressure oscillations in the whole hydrodynamical system. During the experimental research of flow structure in the discharge cone in a regime of free runner new interesting phenomenon was discovered. Due to instability some coils of helical vortex close to each other and reconnection appears with generation of a vortex ring. The experiments were fulfilled at the cavitation conditions when a cavity arises in the vortex core. So the phenomenon was registered with help of visualization by the high speed video recording. The vortex ring after the reconnection moves apart from the main vortex rope toward the wall and downstream. When it reaches the area with high pressure the cavity collapses with generation of pressure impact. The mechanism of cavitational vortex rings generation and their further collapse can serve as a prototype of the aperiodical pressure impacts inside the turbine draft tube.

1. Introduction

The swirling flow in the discharge cone of hydroturbine is characterized by various self-induced instabilities and associated low frequency phenomena when the turbine is operated far from the best efficiency point. The residual swirl in the draft tube conical diffuser leads to vortex breakdown known as precessing vortex core. This phenomenon appearing in the draft tube of hydraulic turbine operating at part or over load conditions has being investigated for a long time. Efforts of many researchers are focused on different aspects of the hydrodynamic instabilities (see reviews in [1, 2]). Nonetheless, there are some features of vortex rope interaction with itself and draft tube which requires deeper investigations.

Vortex rope can serve a reason of the periodical low-frequency pressure oscillations in the whole hydrodynamical system. Another source of periodical pulsations of the pressure and flow rate appears when the cavitational bubble arises inside the core of vortex rope. Random (or aperiodical) pulsations in the flow in draft tubes of hydraulic turbine present a particular interest, due to the fact that their source is much more complex [3]. In the same time the nature of aperiodical pressure impacts in the draft tube remains an enigma till now.
The goal of this paper is to make a better understanding of aperiodical pressure pulsation phenomenon. During the experimental research devoted to possibility for modeling velocity distribution behind the runner with use of simpler device consisting of axisymmetric channel with blade swirler and model of runner we obtained very interesting phenomenon. In such regime with low residual swirl vortex rope loses its stability in non-traditional manner. Some coils of helix close to each other and reconnection appears with generation of a vortex ring. The experiments were fulfilled at the cavitation conditions when a cavity arises in the vortex core. So the phenomenon was registered using high speed visualization technique. The vortex ring after the reconnection moves apart from the main vortex rope toward the wall and downstream. When it reaches the area with high pressure the cavity collapses with generation of pressure impact. The process of the vortex rings generation is aperiodical with the average frequency about three times less than the helix precession frequency. Thus we consider the phenomenon of cavitation vortex rings generation and their further collapse as a prototype of the aperiodical pressure impacts inside the turbine draft tube.

2. Experimental setup

The studies are performed using a closed hydrodynamic loop. Adjustable centrifugal pump with a maximum flow rate of up to 0.067 m$^3$/s is used as a feed pump. The flow rate is controlled by a feedback system that includes an electromagnetic flow meter and a frequency converter. For simulating the cavitation regime in the test section, the hydrodynamic loop is equipped with a vacuum pump that creates additional evacuation up to 96 kPa. Thus it was possible to achieve cavitation limit inside the vortex core, even for relatively weak vortices.

The working section presents a model of the draft tube cone with throat diameter $D = 0.1$ m. It consists of a swirl generator followed by a straight vertical diffuser made of transparent plexiglass with the polished walls. To reduce optical distortion, the outer walls of test section were made in the shape of a tetrahedral prism, Figure 1.

The main task of the swirler is to reproduce the conditions for the formation of the flow similar to one under the turbine runner. This is achieved by forming the appropriate profiles of the axial and tangential velocity components under the swirl generator, which correspond reasonably well to the situation in a real hydroturbine. The working section is analogous to the swirl generator developed at Politechnical University of Timisoara [4] which uses a runner at runaway speed to generate the total pressure imbalance from hub to shroud. The swirl generator consists of two swirlers, the first with fixed vanes followed by the second which is a freely rotating runner. This combination of swirlers provides the distribution of the axial and tangential velocity component closest to the distribution under the runners of real turbines. Thus obtained flow regime is qualitatively similar to the flow regime observed during operation of hydraulic turbine between 90% and 100% BEP [5].

The flow swirl parameter $s$ was calculated by direct integration of the velocity profiles measured with the Laser Doppler Anemometer.

![Figure 1. Simplified hydro turbine model](image)
Here, $M$ is the axial component of angular momentum, $K$ is the axial component of momentum, and $D$ is the diameter of the diffuser mouth.

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.

During the experiments visualization of flow structure were performed using high speed Photron video camera with a maximum resolution of 1 megapixel and speed of up to 20,000 fps and 20 megapixel SLR camera. Illumination of the flow was made with LED lamp with a luminous flux of 10,000 lumens. Standard backscattering two-component LDV system LAD-06i was used for measuring the average velocity profiles. LDV optical unit was mounted on automated coordinate table providing the accuracy of the positioning of the measuring volume up to 30 microns. 20-micron polystyrene spheres with neutral buoyancy were used as flow tracers. LDV measurements parameters were chosen in order to provide at least 1% accuracy. Generally the vortex flow regimes could be characterized by a swirl parameter and Reynolds number.

$$Re = \frac{4Q}{\pi D \nu}$$

Here $Q$ is the discharge, $\nu$ is the kinematic viscosity, $D$ is the throat diameter.

Considering diffuser throat cross-section maximal Reynolds number $5 \times 10^5$ could be obtained, based on the feeding pump flowrate range, with corresponding mean axial flow velocity 5 m/s.

Investigated regimes of vortex flow in the test section correspond to the conditions of a highly turbulent flow with swirl parameter exceeding the critical value, at which vortex breakdown occurs in form of precessing vortex rope. Such flows can occur behind the hydraulic turbine runner operating at part load.

3. Flow visualization

Modern visualization technique 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. The vortex core rolls-up into the left-handed helix. Localization of the vorticity near the central axis of the vortex leads to the formation of cavitation bubble, 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 is shown in Figure 3. The left-handed spiral vortex tube rotates together with the swirl flow to the right. Due to the unstable state of the vortex system in the expanded channel, at some moment, one of the spiral coils starts moving upward, in particular, due to the 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 spiral tube and moves downstream the cone. Thereafter vortex ring enters the high pressure area and collapses (similar to usual cavitational bubble) generating aperiodic pressure pulsation.

The reconnection process with the formation of an isolated ring is observed regularly. In addition, it can be concluded that in terms of phase $\theta$ of a spiral as a geometric figure, the ring is formed at approximately $\Delta \theta = \pi$, thereby determining the size of the ring. Also, the size of the vortex ring depends upon the separation space. The upstream reconnection occurs the smaller the original size of the vortex ring. Similar processes of reconnection is investigated numerically [6], but papers on the reconnection in the swirling flow especially in hydro turbine was not found in the literature.
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, $Q = 116 \text{ m}^3/\text{h}$
By using high-speed visualization technique it was observed different scenarios of vortex ring reconnection. In contrast to the case of reconnection with the formation of an isolated ring (figure), when closing occurs at the spiral part with \( \Delta \theta \approx \pi \), here, \( \Delta \theta \approx 2\pi \). Therefore, the size of the linked ring is two or more times larger (taking into account the apparent stretching of the vortex) than the isolated ring. The described process exhibits good repeatability, but the frequency of linked rings formation is an order of magnitude less than that for the isolated rings. Figure 4 presents photos comparing the two mechanisms when the formation of an isolated and linked vortex rings on the precessing vortex core.

**Figure 4.** The view of formation of isolated vortex ring (left) and linked vortex ring (right), 
\( Q = 116 \text{ m}^3/\text{h} \), the exposure time is 125 \( \mu \text{s} \)

Based on analysis of video data (statistics up to 1000 revolution of vortex rope precession) we obtained the probability distribution histogram of the separations of vortex rings depending on the separation frequency. Figure 5 shows the dependence of the probability of the frequency of rings separation \( (F_n) \) normalized to the precession frequency. The averaged period of vortex rings separations accounted for about 3 of the vortex precession period, i.e. one separation every three revolutions. From the histogram it can be seen that the reconnection with vortex ring formation can take place almost one by one but the probability of such an event is quite small.

**Figure 5.** Histogram of probability of the vortex rings separation, \( Q = 116 \text{ m}^3/\text{h} \).
4. LDV

Velocity measurements were carried out in draft tube cone using LDV technique. LDV system was installed on automatic coordinate table allowing measuring volume automatic movement. Information about the flow velocity in a measuring volume is obtained by measuring the Doppler frequency shift of the laser light scattered on the special particles seeded in a flow. Polyamide spherical particles for an average diameter of 20 µm and density close to the water were employed as seeding particles. Transparent walls of conical part of the draft tube provided full optical access to the flow downstream the runner. The measurements were averaged basing on 1000 bursts at every measuring point with 2 mm step. To evaluate parameters of the helical-like vortex we compare the experimental profiles of axial and circumferential velocities averaged over time with the corresponding distributions for the model of ideal infinitely long helical vortex with circular cross-section and uniform distribution of axial component of vorticity [7, 8] (figure 6). This theoretical models provides analytical dependencies of the averaged velocities induced by the helical vortex on the vortex parameters. Thus choosing parameters which give best fitting of measured profiles with analytical curves we estimate the helix pitch, vortex intensity as well as other parameters. Outside the zone $r < 15$ mm in the experiment there is significant vorticity slowly decreasing towards the periphery. It looks like a concentrated vortex core (with helical shape) inside the distributed axisymmetric vortex.

![Figure 6](image)

**Figure 6.** Profiles of axial, $V_z$, and circumferential, $V_\phi$, velocities in the experiment (symbols) and in the theoretical model [6] (line) with parameters of helical vortex: intensity $\Gamma = 0.13$ m$^2$/s, pitch $h = 0.037$ m, precession radius $a = 0.007$ m, radius of the vortex core $\epsilon = 0.007$ m, velocity at the tube center $u_0 = – 0.4$ m/s.

5. Conclusion

A phenomenon of vortex ring formation on the precessing vortex core have been investigated experimentally in the simplified laboratory model of hydro turbine. Thus, in this experimental work for the first time the presence of the vortex reconnection processes in the helical-like vortex tube is demonstrated. Vortex rope is formed in a swirling flow in a conical diffuser with sufficiently large values of the swirl parameter. The result of reconnection can be either the formation of an isolated vortex ring or the formation of a vortex ring linked with the main vortex. After displacement into the high-pressure area the vortex ring is collapsed. It should be noted that this mode is accompanied by a
sharp biting noise obviously related to the collapse of cavity in the core of vortex rings. The separation and collapse of the vortex rings generates aperiodic pressure pulsations at an average rate of 0.3 frequency of the vortex rope precession. We suggest that a similar phenomenon can take place in a real hydraulic turbines.

Further studies will be focused on obtaining quantitative information in the area of vortex of reconnection. It is also planned to explore a range of conditions in which separation of the vortex ring is possible.

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