Numerical study of the vortex breakdown and vortex reconnection in the flow path of high-pressure water turbine

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Abstract. The paper presents a study of the instability of the precessing vortex core in the model of the draft tube of a hydraulic turbine. The study was carried out using numerical modeling using various approaches: URANS, RSM, LES. The best agreement with the experimental data was shown by the RSM and LES methods with the modelling of the runner rotation by the sliding mesh method. In the regime under consideration, the precessing vortex rope is subject to instability, which leads to reconnection of its turns and the formation of an isolated vortex ring. Reconnection of the vortex core leads to aperiodic and intense pressure fluctuations recorded on the diffuser wall.

1. Introduction

Swirling flows are widely used in applications; therefore, the problem of the vortex flow stability is always payed attention. One of the phenomena that have a dramatic effect on the structure of the vortex flow is the vortex breakdown. It was experimentally determined that the condition for the onset of the breakdown is a longitudinal positive pressure gradient. Such a gradient occurs, in particular, when the channel expands (for example, a conical diffuser).

In particular, this effect is observed during the operation of high-pressure water power plants. One of the vortex breakdown modes is a precessing spiral vortex core. The vortex rope precession poses a serious danger to water turbine equipment due to intensive flow pulsations, which lead to strong vibrations of the water turbine structure and, in the case of the resonance, can lead to the equipment destruction.

The maximum pressure pulsations are observed in the modes of partial load on the hydraulic turbine (40-50\% of the nominal power). However, in some works \cite{1, 2}, it was determined some "shocks" as a result of the irregular and unstable shape of the vortex rope at modes close to optimal (70-80\% of the nominal power). In these works, a hypothesis was proposed that the reason for such "shocks" might be the formation of vortex rings as a result of reconnection of the precessing vortex rope and the impact of these rings on the turbine wall. Also in these works, an experiment was carried out on a simplified model of a hydraulic turbine (figure 1.).

2. Numerical model

The computational domain included an inlet channel, a stationary swirler, a rotor, a diffuser, and an outlet channel. The computational grid consisted of 9.5 million polyhedral cells. The mesh has been concentrated in the swirler, rotor and diffuser. The flow was determined by the rotor speed $N = 500$ rpm.
and the water flow rate at the inlet $Q = 80 \text{ m}^3/\text{h}$. The diameter of the throat of the diffuser $D = 0.1 \text{ m}$. Unsteady calculations were carried out with a time step of 0.0001 s, which corresponds to Courant number less than 2 in the diffuser. The rotation was modeled in the “frozen rotor” approximation and using the sliding mesh method. The LES and RSM methods were used to calculate turbulence.

![Figure 1. Scheme of the experimental setup.](image)

3. The simulation results

A comparison of the numerical results with experimental data on the components of the average velocity (figure 2) and velocity pulsations (figure 3) in the diffuser was made to validate the computational model. As seen from figure 2, both the LES and RSM models show close agreement with the experimental data when simulating rotor rotation using the sliding mesh method. The results of calculations with the “frozen rotor” approach are in noticeably worse agreement with the experimental data, underestimating the length of the recirculation zone. The plot of the swirl velocity component shows the area of solid-body rotation of the vortex both in the experiment and in the calculation results with the sliding mesh approach, but the “frozen rotor” approach does not reproduce this phenomena. The pulsations of the axial and swirl velocity components qualitatively reproduce the experimental data, while being slightly lower in intensity. In the “frozen rotor” approach, the peak of the swirl velocity pulsations is displaced from the diffuser axis, which is inconsistent with the experimental results and calculations using the sliding mesh method.

Under these conditions, a spiral vortex core is formed in the diffuser of the experimental setup [2]. Occasionally, the vortex rope is disturbed: the turns of the spiral overlap and their reconnection forms an isolated vortex ring. The calculation shows the formation of the precessing vortex core behind the rotor (figure 4), which induces pressure pulsations in the diffuser at the frequency of about 10 Hz (figure 5), which corresponds to the Strouhal number $St = \pi D^3 / (4Q) = 0.3$. The intensity of the low-frequency pulsations is about several kPa, which qualitative agrees with the experimental data. As can be seen from the signal plot, periodic pulsations corresponding to the rotation of the spiral vortex core are distorted. From time to time, much more intense pressure pulsations are occurred (see figure 6, 7).
Figure 2. Axial (a) and swirl (b) mean velocity components (crossection 40 mm under the throat).

Figure 3. Rms pulsations of the axial (a) and swirl (b) velocity components (crossection 40 mm under the throat).

Figure 4. Velocity components in the central vertical crossection.
Figure 5. Pressure pulsations on the diffusor wall (≈65 mm under the throat) (a); pressure pulsations spectrum (RSM, slide mesh) (b).

Figure 6. Pressure pulsations on the diffusor wall (≈105 mm under the throat).
Figure 7. An example of the “shock”: pressure pulsations on the diffusor wall (≈65 mm under the throat).

Analysis of the unsteady vortex flow pattern shows that different sections of the spiral vortex rope move down with different speed. Eventually, the spiral turns get closer and intersects with each other. As a result of such reconnection, a separate vortex ring is formed, and the vortex rope loses the symmetry (Fig. 8). Reconnection occurs in different sections of the vortex rope, both near the rotor and at the end of the diffuser. A similar phenomenon is observed in experimental studies in this mode [1, 2]. A similar phenomenon is also observed in experiments on stands close to real hydraulic units [4, 5].

Figure 8. Precessing vortex rope: a) experiment [3], b) simulation, visualization by mean of the Q-criteria iso-surface.

4. Conclusion

Thus, the calculations showed a good agreement with the experimental data on the mean velocity and fluctuations of the velocity components. In addition, the model reproduces the loss of stability of the precessing vortex core with reconnection of its turns and the formation of an isolated vortex ring.
Distortion of the vortex flow as a result of reconnection leads to disruption of the periodic pressure variation on the walls of the diffuser and the appearing of the strong aperiodic pressure “shocks”.

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**References**
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