Numerical study of a case of the free discharge of water through the turbine with a braked runner

D V Platonov¹,², A V Minakov¹,², A V Sentyabov¹,²

¹ Institute of Thermophysics SB RAS, 1 Acad. Lavrentiev pr., Novosibirsk, 630090, Russia
² Siberian Federal University, 79 Svobodny pr., Krasnoyarsk, 660041, Russia

E-mail: platonov-08@yandex.ru

Abstract. The paper presents a numerical study of the free discharge of water through the turbine with a braked runner. The simulation was carried out for a unit of a full-scale Francis turbine. The finite volume method was employed for unstructured meshes using the DES method. The simulation results show the flow structures, integral characteristics, and pressure pulsations in the flow path. The analysis of the applicability of this approach to real conditions is carried out.

1. Introduction

Hydroelectric power plants have a unique feature, the ability to smoothly regulate the generation of electricity depending on the consumption peaks. At the same time, they belong to the category of fairly conservative machines. The key point is extending the ranges of safe and efficient operation of the station and reducing the forbidden zones in which the hydraulic unit is experiencing colossal loads on all components and mechanisms [1-2].

One of the options for the operation of the hydroelectric unit in the maximum load mode is free water discharge.

The free water discharge through the turbine unit is used in the construction of a hydroelectric power station or in the event of an emergency discharge of water and is a complex technological process.

In any variant of the free water discharge, the flow around the main structural elements of the flow path will occur in an off-design mode and, therefore, be accompanied by a significant increase in non-stationary processes and cavitation, which leads to additional deterioration and a reduction in the service life of the unit. Therefore, studying and optimizing the free water discharge is quite an interesting task.

When discussing free water discharge options through a hydraulic unit with a Francis turbine, the following options should be considered the most realistic:

1. Free discharge of water with an unloaded runner. In this option, the unit is disconnected from the electrical network. The hydrodynamic moment on the runner is equal to zero. In this case, the runner rotates freely with the accelerating rotational speed.

2. Free discharge of water through the turbine with a braked runner. In this option of discharge, the runner is braked and kept from rotating in any way. In this case, the guide vanes are open, and the torque on the runner increases 1.5 ... 2 times in comparison with the rotating runner. As an option to reduce the moment on the turbine shaft, the guide vanes should be set to a certain negative angle from...
the optimal opening, then the vanes of the device will take on part of the swirl of the flow, while they will experience enormous loads.

3. Free discharge of water through the unit with the runner removed. In this case, the runner is removed from the flow path, whose resistance decreases and the flow rate increases.

In this work, a numerical study of one option for a free discharge through a hydraulic unit was carried out, namely, an option with a braked runner.

2. Numerical model
The authors have accumulated quite a lot of experience in simulating three-dimensional unsteady flows with complex geometry, as applied to high-pressure hydroelectric power plants. To describe this kind of flows, a system of Reynolds-averaged Navier-Stokes (RANS) equations was used. In particular, the work used two parametric turbulence models and the Detach Eddy Simulation (DES) method. More details on the numerical technique can be found in [6-7].

The DES method used in this work [3-5] combines the RANS and LES approaches. In this paper, DES was based on Menter's k-ω SST model.

3. The simulation results
For the numerical study, a hydroelectric unit of the Francis turbine RO-230/833-B-677 was taken (figure 1). These types of turbines are currently used for operating high-pressure hydroelectric power plants. The main parameters of the hydroelectric unit are presented in table 1.

![Figure 1. Geometry for the numerical simulation](image)

**Table.1 Main parameters of the investigated hydraulic unit**

| Parameter               | Value       |
|-------------------------|-------------|
| Turbine type            | Radial-axial (Francis) |
| Runner type             | RA-230/833-B-677 |
| Maximum head            | 220 m       |
| Maximum power           | 640 MW      |
| Rated speed             | 142.8 rpm   |
An unstructured computational grid was built for the given geometry of the hydraulic unit. The grid consisted of about 10 million nodes. The mesh was thickened in the area of the runner blades and guide vanes, as well as in the inlet diffuser of the draft tube. Preliminary validation showed that such a detailing of the computational grid is sufficient to obtain results that are acceptable in terms of accuracy.

In this option, it is assumed that the runner is braked and kept from rotating in some way. The free discharge was simulated for the full-scale geometry of the flow path. Investigations were carried out for three openings of the guide vane $A_0 = 206; 353; 500.5$ mm. All calculations were carried out for a head value equal to $H = 210.5$ m. The integral characteristics of the flow were determined from the calculations: the flow rate of water through the hydraulic unit, the torque on the runner, as well as the pulsation characteristics and the flow structure.

A qualitative picture of the flow with this option of discharge can be observed from figures 2-3. As can be seen from the presented figures, when flowing in a braked runner, its blades flow around in an off-design mode. Behind the leading edges of the blades, intense vortices are formed, which are clearly visible in the velocity fields in the central horizontal sections of the guide vanes (figure 2b). These vortices will serve as powerful sources of cavitation, as evidenced by the local pressure minimum in figure 2a. In this case, practically the entire surface of the runner will be in conditions dangerous for cavitation erosion.

![Figure 2. The pressure field and the velocity vector in the longitudinal section of the spiral case $A_0 = 206$ mm.](image-url)
An interesting flow structure is formed at the exit from the runner. As can be seen from figure 3, when the water is freely discharged through the turbine with a braked runner, a precessing structure of several concentrated vortices, which rotate along the surface of the fairing of the runner, is formed behind the trailing edges of the blades. The bases of these vortices are clearly visible in figure 3a in the form of distinct pressure minima on the walls of the runner. This vortex structure has the highest intensity at guide vanes opening $A_0 = 353$ mm.

The spectrum of pressure pulsations at a free discharge for opening the guide vane $A_0 = 206$ mm is shown in figure 4.

![Pressure field on the wall and vortex structure behind the runner $A_0=206$ mm.](image)

Figure 3. Pressure field on the wall and vortex structure behind the runner $A_0=206$ mm.

Analysis of the pressure pulsation spectra shows that the main frequency of pressure pulsations in the flow path during the free discharge through the unit with a braked runner when opening $A_0 = 206$ mm is within the region of $0.55$ Hz. With an increase in the opening of the guide vane, the pulsation frequency increases to $1$ Hz at $A_0 = 353$ mm and up to $1.5$ Hz at $A_0 = 505.5$ mm.

It should be noted that, unlike other openings, the pulsation spectrum at opening $A_0 = 206$ mm is very diffuse, which is explained by the fact that the blades of a stationary runner are streamlined at a very large angle of attack, and the flow around is accompanied by intense generation of vortices with different frequencies.
Figure 4. Pressure pulsation spectrum for $A_0 = 206$ mm.

The intensity of pressure pulsations is maximum in the diffuser of the draft tube (figure 4) and when opening $A_0 = 206$ mm is about 18% of the head, which is 65% higher than the same value at the nominal operating mode of the unit. At large openings, pressure pulsations reach a very large value of 44% of the head at $A_0 = 353$ mm, and 56% at $A_0 = 505.5$ mm. Implementing free discharge through a braked runner during such openings can be very dangerous.

The magnitude of the torque on the runner at the free discharge through the unit with a braked runner increases 2.83 times when opening $A_0 = 206$ mm, 2 times when opening $A_0 = 353$ mm, and 1.5 times when opening $A_0 = 505.5$ mm compared to the same value at the nominal operating mode of the unit. Even with the minimum opening $A_0 = 206$ mm, the moment on the runner is 36.8 MN $\times$ m, and the possibility of keeping the runner from rotating, in this case, is quite debatable in terms of constructive implementation (figure 5).

Figure 5. Torque ripple on the runner for $A_0 = 206$ mm.

4. Conclusion
It was found that discharge water through a hydraulic turbine with a braked runner causes significant pressure pulsations up to 56% of the head at maximum opening. Nevertheless, this type of discharge
can be possible with very small openings of the guide vanes, since when the opening is 206 mm, the level of pressure pulsations in the diffuser of the draft tube is about 18% of the head, which is comparable to 11% at the nominal operating mode of the turbine. In this case, the problem of keeping the runner from rotation arises, since, as calculations show, the torque on the shaft of the braked runner increases by 1.5-3 times.

Acknowledgments
The numerical methodical testing and verification were carried out under state contract with IT SB RAS.

References
[1] Doerfler P. System dynamics of the Francis turbine half-load surge. 1982, Proc. IAHR Symp. on Hydraulic Machinery and Systems, Amsterdam, Netherlands.
[2] Dekterev, A.A., Zakharov, A.V., Minakov, A.V., Platonov, D.V., Pylev, I.M. 2015 Fluid Dynamics 50 (5) 601-612.
[3] Weijia Yang, Jiandong Yang, Wencheng Guo, Wei Zeng, Chao Wang, Linn Saarinen and Per Norrlund 2015 Energies 8 10260-10275.
[4] Cherny S, Chirkov D, Bannikov D, Lapin V, Skorospelov V, Eshkunova I and Avdushenko A 2010 IOP Conf. Series: Earth and Environmental Science 12 012071
[5] Yanna Liu, Jiandong Yang, Jiebin Yang, Chao Wang and Wei Zeng 2016 2016 1504659, 13 pages.
[6] Minakov A V, Platonov D V, Dekterev A A, Sentyabov A V and Zakharov A V 2015 Computers and Fluids 111 197-205
[7] Minakov A V, Platonov D V, Dekterev A A, Sentyabov A V and Zakharov A V 2015 International Journal of Heat and Fluid Flow 53 183-194