Numerical investigation of the behaviour of the cavitation rope in a Francis turbine with an optimized runner cone

An Yu¹, Daqing Zhou¹*, Huixiang Chen²

¹ College of Energy and Electrical Engineering, Hohai University, Nanjing, China
² College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China

*Corresponding author email: zhoudaqing@hhu.edu.cn

Abstract. In case of the hydro turbine operated departing from the optimum condition, vortex ropes usually occur in the draft tube, and consequently generate pressure oscillations. In most conditions, cavitation occurred in the center of the rope and turned it to be a multiphase cavitating rope. This kind of unsteady flow phenomenon is believed to be harmful for hydropower stations. This paper designs a kind of vortex-control grooves and make a numerical simulation in a Francis hydro turbine using the partially averaged Navier-Stokes method. The behavior of the cavitation rope and the induced pressure oscillations under several operation conditions with and without the grooves will be analyzed based on the calculation results.

1. Introduction

The increasing desire for environmental protection has resulted in the electric power industry receiving more and more criticism. Coal-fired power is still the main source of electric power in China. Some people criticized this since burning the fossil fuels pollutes the environment. Thus, the electric power industry is focusing on renewable non-polluting energy sources. Although wind, solar and nuclear energy systems have bright futures, hydropower is currently the most available clean energy and has already been widely used over a century. Also, hydropower can provide easy storage and flexible power generation which make hydropower an irreplaceable power source that can provide power-frequency control in the electrical grid. Thus, hydroturbines are frequently operated under a wide range of conditions. When operated at off-design conditions, the turbines have various types of problems. Among these, cavitation is the most common problem occurring where vapor bubbles form in low pressure regions. Kumar [1] summarized investigations of different kinds of cavitation in hydro turbines, described the effects of cavitation and identified gaps for future studies. The main effect of cavitation is damage to the metallic surfaces of turbine parts, cavitation erosion, which is caused by the collapse of the cavitation bubbles. Gohil [2] reviewed studies of cavitation and silt erosion in hydro turbines. They found the combined effect of cavitation and silt erosion to be more pronounced than their individual effects. The slit promotes cavitation formation and cavitation intensifies the pitting of the metallic surfaces.

System instabilities are another problem in hydraulic power plants, especially at off-design conditions. The hydraulic effects are the most common reason for these instabilities. The internal flow in a hydro turbine becomes rather complex at part-load conditions, and the swirling flow in the turbine draft tube is harmful to the steady operation of the hydropower station. The swirling flow starting from
the runner exit ultimately results in the development of a helical vortex called a “vortex rope”. The vortex rope is usually associated with large pressure fluctuations and can generate severe resonance. This can harm stable operation of a Francis turbine, especially at part load conditions and often causes structural troubles [3]. The vortex rope phenomenon has attracted an intensively attention with many investigations of the pressure pulsations presented in the 1990’s [4-5]. Hocevar et al.[6] successfully predicted the cavitation vortex dynamics using radial basis neural networks. Anup et al.[7] used a transient numerical analysis of the rotor-stator interactions in a Francis turbine at optimum load and part load conditions to show the velocity and pressure characteristics at the rotor-stator interfaces and captured the vortex rope at part load conditions. Experiment tests are very expensive and cannot show the detailed internal flow characteristics, so numerical simulations are used to better understand the flow mechanisms inside the turbines. Thus, computation methods for capturing the vortex rope have been studied for a long time [8-12]. Some attempts using Large Eddy Simulations (LES) and Reynolds Stress Models (RSM) have been carried out [8-11]. Unsteady statistical turbulence models have also been used to investigate the swirling flow with some good results [13]. Three turbulent models were compared for vortex simulation in Reference [14]. These studies have shown that numerical simulations can be used to study the flow mechanisms, especially the vortex rope. Choi et al.[15] used CFD models to improve the performance of a Francis turbine by optimizing the Francis turbine runner. Ciocan et al. [16-17] presented experimental studies of the draft tube rotating vortex with unsteady wall pressure measurements, 2D laser Doppler velocimetry, and 3D particle image velocimetry to investigate the pressure and velocity fields in the draft tube and the vortex dynamics. Then they both used CFD models with the standard $k$- turbulence model to predict the global vortex quantities, the pressure pulsation amplitudes and the vortex frequency with a relatively allowable error. Guo et al.[10] investigated the cavitating flow in a draft tube and captured the cavitation rope using the large eddy simulation method. Others have focused on the multiphase effects and internal flow analyses and have shown that CFD methods can be very accurate in FLINDT (flow investigations in draft tube) investigations [17-19].

On the other hand, researchers and engineers have presented many methods to alleviate the pressure fluctuation in a draft tube theoretically and technically, such as geometrical optimization, water injection and aeration. Jet control is one of the efficient ways to depress the pressure fluctuations. Koichi Nakanishi and Tsuneo Ueda [12] made a systematic study by model tests with air admission. Qian [13] and Liao [14] simulated the pressure fluctuations with different ventilation volume based on a water-air two phase flow model, and analyzed the relationship between pressure pulsation in the whole passage and air admission. R Susan-Resiga [15] and Al Bosioc [16] investigated the influence of water injection. The Conventional investigations about the flow instabilities in the Francis turbine is mainly focus on the cavity vortex rope behavior and self-induced pressure fluctuations with and without an optimized runner cone. This paper used the homogeneous flow assumption to investigate the cavitation rope behavior and pressure fluctuation of a model Francis turbine. The pressure fluctuations caused by the vortex cavitation rope are analysed using Fast Fourier Transform (FFT) with comparison to experiments. Attention is focused on vortex cavitation rope evolution and the connection with flow instabilities.

2. Model turbine geometry

This paper focuses on the vortex cavitation rope evolution and its control in the draft tube of a model Francis turbine, and an optimized runner was used, whose structure was showing in Figure 1. The parameters of the model turbine are showing in Table 1. A typical part-load was selected to have an all-sided investigation.

For the purpose of achieving better convergence and accurate results, structured mesh is generated for the computation domain. The localized refinement is applied in the region close to the vane leading and trailing edges. The whole domain consists of 2,900,000 nodes and 2,510,000 elements with a compromise of veracity and computing capability.

In the simulation, the modified partially averaged Navier-Stokes method and Zwart cavitation model were used. Total pressure and static pressure are assigned for inlet and outlet conditions respectively.
The time step is set as 0.001102s at first, corresponding to a rotating angle of 6 degree per time step. Then 1 degree per time step is adopted for the subsequent simulation.

| Table 1 Model structure |
|-------------------------|
| Name                    | Value     |
| runner diameter $D_1$   | 420mm     |
| runner blade number $Z_b$| 17        |
| stay vane number        | 23        |
| movable guide vane number| 24        |
| height of the guide vane $b_0$ | 0.18257 |
| guide vane opening $\alpha_0$ | 11.5mm |

3. Results and analysis
For the convenience of the analysis, one monitoring section was set in the draft tube and has a distance of 0.23m to the draft tube inlet. In order to investigate the effect of pressure fluctuations, two monitoring points i.e. p1 and p2 are set in the draft tube wall, as shown in Figure 2. Note that two monitoring points are located on the monitoring section, and at the opposite position. In order to display the effect of grooves clearly, both the cases with and without optimized runner cone were simulated for a comparison.

3.1. Pressure Oscillation under part load condition
The unsteady flows in the model turbine with the original and optimized runner cones were calculated under a typical part-load condition. To verify the effectiveness of the simulation results, the pressure fluctuation with original runner cone at the monitoring point was measured by experiment (The experimental test of the model Francis turbine was conducted on the test rig at Harbin Electric Company Ltd, China). The CFD and experiment data have a very close result in low-frequency component (3.12Hz
of CFD and 3.09Hz of experiment), which was proved to be induced by the Periodic rotation of vortex rope.

The effects of vortex-control grooves on a single phase vortex rope was investigated in our present research [25]. It is indicated that the vortex-control grooves can alleviate the pressure fluctuations effectively by increasing the vortex corn pressure and shorting the vortex diameter. Since the pressure fluctuations in the draft tube has a strong connection with the cavitation, the flow instabilities with a low cavitation number which turns the single phase vortex rope to a cavity vortex rope was investigated.

Figure 3 shows the pressure fluctuations measured in monitor point P1 at different cavitation numbers with conventional runner cone. Fast Fourier Transform (FFT) is applied to obtain the pressure fluctuation frequency and amplitude. It is indicated that the single phase vortex rope induces one low frequency pressure fluctuation $f_1$ and its harmonic wave $f_1'$. While when cavitation occurred and the rope turned to be a cavity rope, a lower frequency pressure fluctuation $f_2$ and its harmonic wave $f_2'$ appear. Also, with the decrease of the cavitation number, the frequency of $f_1$ increased while the frequency of $f_2$ decreased.

![Figure 3 Pressure fluctuations at different cavitation numbers](image)

The vortex-control grooves was supposed to bring a reverse swirl flow to neutralize the positive vortex flow and was proved having a positive effect on alleviating the pressure fluctuations in single vortex rope. While figure 4 shows the pressure fluctuations measured in monitor point P1 with the optimized runner cone.

![Figure 4 Pressure fluctuations at $\sigma=0.03$ with conventional and optimized runner cone](image)

Figure 4 shows that with the optimized runner cone, both of the amplitude of $f_1$ and $f_2$ decreased. The amplitude of $f_1$ decrease from 812 to 511, while amplitude of $f_1$ decrease from 478 to 95. Also, the characteristic of the frequency changed towards the tendency of high cavitation number. This means
that the optimized runner cone can alleviate the low frequency pressure fluctuations and also suppresses the cavitation.

3.2. Cavitation vortex rope with optimized runner cone

Previous studies show that the characteristic of the pressure fluctuations has a strong connection with the behavior of the vortex rope. Also the research in this article shows the optimized runner cone can alleviate the cavitation and pressure fluctuations. Thus, the optimized runner cone may have a positive effect in alleviating the vortex rope behavior.

Figure 5 show the vortex rope structure by Q-criterion which reflect the vortex intensity. It is indicated that there is a strong swirling flow in the draft tube with a conventional runner cone. The vortex rope start from the runner exit to the elbow part of the draft tube. While with the optimized runner cone, the vortex rope became thinner and shorter. This means the optimized runner cone can reduce the swirling flow and alleviate the pressure fluctuation of $f_1$.

![Figure 5 Vortex rope structure by Q-criterion](image)

Pressure fluctuation of $f_1$ occurs along with the cavitation and may have a connection with it. Thus, in Figure 6, the cavitation rope is structured by iso-surface of vapor volume fraction. Since cavitation occurs in the center of the swirling flow and make the vortex rope visible. Figure 6 indicate that the optimized runner cone can reduce the cavitation phenomenon and alleviate the pressure fluctuation of $f_2$.

![Figure 6 Cavitation rope structure by iso-surface of vapour volume fraction](image)
4. Conclusion
The internal flow in a model Francis turbine with an optimized runner cone is studied with particular emphasis on the alleviation of the pressure fluctuation and vortex rope behaviour. Based on the present study, the following conclusions can be drawn:

1. When operated under part-load conditions, there is only one type of pressure fluctuation in the draft tube without cavitation. While when cavitation happened, a new lower pressure fluctuation occurs. Also, the frequency is changed with the cavitation number. The vortex-control grooves can alleviate the pressure fluctuations effectively by increasing the vortex cone pressure and shorting the vortex diameter.

2. The optimized runner cone can reduce the swirling flow and alleviate the pressure fluctuation of $f_1$.

3. The optimized runner cone can reduce the cavitation phenomenon and alleviate the pressure fluctuation of $f_2$.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (Project No. 51806058) and the Fundamental Research Funds for the Central Universities (Project No. 2017B07014).

References
[1] Kumar P and Saini RP. Study of Cavitation in Hydro Turbines—A Review. Renewable & Sustainable Energy Reviews 2010; 14 (1): 374-383.
[2] Gohil PP and Saini RP. Coalesced effect of cavitation and silt erosion in hydro turbines—A review. Renewable & Sustainable Energy Reviews 2014; 33: 280-289.
[3] Jacob T. Evaluation sur Modèle Réduit et Prédiction de la Stabilité de Fonctionnement des Turbines Francis. Ph.D thesis, École Polytechnique Fédér de Lausanne, Switzerland, 1993.
[4] Kercan V, Bajd M, Djelić V, et al. Model and prototype draft tube pressure pulsations. Hydraulic Machinery & Cavitation 1995; pp. 994-1003.
[5] Qian ZD, Zheng B, Huai WX. Analysis of pressure oscillations in a Francis hydraulic turbine with misaligned guide vanes. Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy 2010; 224 (A1), 139-152.
[6] Hocevar M, Sirok B and Blagojevic B. Prediction of cavitation vortex dynamics in the draft tube of a francis turbine using radial basis neural networks. Neural Computing & Applications 2005; 14 (3): 229-234.
[7] Anup KC, Thapa B and Lee YH. Transient numerical analysis of rotor–stator interaction in a Francis turbine. Renewable Energy 2014; 65: 227-235.
[8] Skotak A, Mikulašek J and Lhotakova L. Effect of the inflow conditions on the unsteady draft tube flow. In: Proceedings of the 21st IAHR Symposium on Hydraulic Machinery and Systems. EPFL/STI/LMH, Lausanne, Switzerland, 9-12 September 2002, pp. 284-291.
[9] Sick M, Doerfler P, Sallaberger M, et al. CFD simulation of the draft tube vortex. In: Proceedings 21st IAHR Symp on Hydraulic Machinery & Systems, EPFL/STI/LMH, Lausanne, Switzerland, 9-12 September 2002, pp. (32): 1-9.
[10] Guo Y, Kato C and Miyagawa K. Large-eddy simulation of non-cavitating and cavitating flows in an elbow draft tube. In: Proceedings 23rd IAHR Symposium on Hydraulic Machinery and Systems, Yokohama, Japan, October, 2006, pp. 17-21.
[11] Kurosawa S and Satou S. Turbulent flow simulation for the draft tube of a Kaplan turbine. In: Proceedings 23rd IAHR Symposium on Hydraulic Machinery and Systems, Yokohama, Japan, October, 2006.
[12] Miyagawa K, Tsuji K, Yahara J et al. Flow instability in an elbow draft tube for a Francis pump-turbine. In: Proceedings of the 21st IAHR Symposium on Hydraulic Machinery and Systems, EPFL/STI/LMH, Lausanne, Switzerland, 9-12 September 2002. pp. 277-286
[13] Paik J, Sotiropoulos F and Sale MJ. Numerical Simulation of Swirling Flow in Complex Hydroturbine Draft Tube Using Unsteady Statistical Turbulence Models. Journal of Hydraulic Engineering 2005; 131 (6): 441-456.
[14] Jošt D, Lipej A. Numerical prediction of non-cavitating and cavitating vortex rope in a Francis turbine draft tube. Journal of Mechanical Engineering 2011; 57(6): 445-456.
[15] Choi HJ, Zullah MA, Roh HW, et al. CFD validation of performance improvement of a 500 kW Francis turbine. Renewable Energy 2013; 54: 111-123.
[16] Ciocan GD, Iliescu MS, Vu TC, et al. Experimental Study and Numerical Simulation of the FLINDT Draft Tube Rotating Vortex. Journal of Fluids Engineering-Transactions of the ASME 2007; 129(2): 146-158.
[17] Iliescu MS, Ciocan GD and Avellan F. Analysis of the Cavitating Draft Tube Vortex in a Francis Turbine Using Particle Image Velocimetry Measurements in Two-Phase Flow. Journal of Fluids Engineering-Transactions of the ASME 2008; 130(2): 021105.
[18] Liu SH, Zhang L, Nishi M, et al. Cavitating Turbulent Flow Simulation in a Francis Turbine Based on Mixture Model. Journal of Fluids Engineering-Transactions of the ASME 2009; 131(5): 051302.
[19] Tridon S, Barre S, Ciocan GD, et al. Experimental Analysis of the Swirling Flow in a Francis Turbine Draft Tube: Focus on Radial Velocity Component Determination. European Journal of Mechanics B-Fluids 2010; 29(4): 321-335.
[20] Nukunishi K, Uedo T, Air supply into draft tube of Francis turbine. 1964.
[21] Qian ZD, Yang J, Huai W. Numerical simulation and analysis of pressure pulsation in Francis hydraulic turbine with air admission. Journal of Hydrodynamics, Ser. B, 2007, 19(4): 467-472.
[22] Liao WL, Ji JT, Lu P and Luo XQ. Effect of air admission through center hole of turbine shaft on the flow in draft tube. J. Hydraulic Engineering, 2008, 8: 018.
[23] Bosioc A I, Susan-Resiga R, Muntean S. Unsteady Pressure Analysis of a Swirling Flow With Vortex Rope and Axial Water Injection in a Discharge Cone. Journal of Fluids Engineering, 2012, 134(8): 081104.
[24] Susan-Resiga R, Vu TC, Muntean S. Jet control of the draft tube vortex rope in Francis turbines at partial discharge. Proceedings of the 23rd IAHR Symposium on Hydraulic Machinery and Systems. 2006, 17-21.
[25] Yu A, Luo XW, Ji B. Studies of the effect of vortex-control grooves on pressure oscillations in a Francis turbine draft tube. ASME/JSME/KSME 2015 Joint Fluids Engineering Conference. 2015.