Numerical simulation and analysis of the internal flow in a Francis turbine with air admission

A Yu¹, X W Luo¹, ² and B Ji¹, ³
¹State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China
²Beijing Key Laboratory of CO₂ Utilization and Reduction Technology, Tsinghua University, Beijing 100084, China
Email: jibin@mail.tsinghua.edu.cn

Abstract. In case of hydro turbines operated at part-load condition, vortex ropes usually occur in the draft tube, and consequently generate violent pressure fluctuation. This unsteady flow phenomenon is believed harmful to hydropower stations. This paper mainly treats the internal flow simulation in the draft tube of a Francis turbine. In order to alleviate the pressure fluctuation induced by the vortex rope, air admission from the main shaft center is applied, and the water-air two phase flow in the entire flow passage of a model turbine is simulated based on a homogeneous flow assumption and SST k-ω turbulence model. It is noted that the numerical simulation reasonably predicts the pressure fluctuations in the draft tube, which agrees fairly well with experimental data. The analysis based on the vorticity transport equation shows that the vortex dilation plays a major role in the vortex evolution with air admission in the turbine draft tube, and there is large value of vortex dilation along the vortex rope. The results show that the aeration with suitable air volume fraction can depress the vortical flow, and alleviate the pressure fluctuation in the draft tube.

1. Introduction
To meet the variable demands of power system and take the task of power-frequency control in an electrical grid, hydro turbines are often operated under a wide range of loads. Thus it is necessary for a hydro turbine to be frequently operated under off-design conditions, especially part load conditions. People have acknowledged that the internal flow in a hydro turbine becomes rather complex at part load operations, and a kind of special swirling flow in the turbine draft tube is very vital for the safe operation of a hydropower station. This swirling flow started from the runner exit results in the development of a processing helical vortex called “vortex rope”. The vortex rope is usually associated with large pressure fluctuations in the draft tube and can be rather harmful for the stable operation of a Francis turbine, especially at part load condition and often causes structural troubles. The vortex rope phenomenon has attracted a widespread attention and the intensive investigations on draft tube pressure pulsation on various specific speed turbines were performed in 1990’s [1-3]. Due to the high costs of experiment investigation, and experiments can hardly reflect the detailed characteristics of the internal flow and sometimes the results of model test are not valid for the prototype, numerical simulations are needed for better understanding of the flow mechanism of the vortex rope. Computation methods for capturing the vortex rope have been studied for a long time, and some
achievements have been published [4-9]. Turbulent model plays an extremely important role during the simulation for the rather complex unsteady flow in a draft tube. Studies show that Reynolds Stress Models (RSM) and Large Eddy Simulation (LES) have a more accurate result than $k-\varepsilon$ models [4-7]. Three turbulent models for vortex simulation have been compared in Reference [10].

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. To aerate nature air into the draft tube is one of the most efficient way to depress the pressure fluctuations. Koichi Nakanishi and Tsuneo Ueda [11] made a systematic study by model tests. They point out the measurement of the most reasonable amount of air flow and the determination of the position of the air pipe installation. When air admission is considered, the flow in a turbine becomes a two-phase turbulent flow. This makes the simulation hard to get convergence. Qian [12] and Liao [13] 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. These researches focus on aeration’s effectiveness of fluctuation alleviating, and little attention have been spend on internal flow characteristic and the interaction between air admission and vortex movement.

In this paper, three-dimensional unsteady turbulent flow in the whole passage of a model Francis turbine is simulated based on the homogeneous flow assumption. The pressure fluctuation caused bay vortex rope is analyzed via Fast Fourier Transform (FFT) and compared to the experiment. The relationship of air admission and pressure fluctuation in the turbine draft tube is discussed based on the internal flow analysis and vorticity transport equation.

### 2. Model turbine geometry and numerical methods

This paper focuses on the aeration influence on the internal flow in a model Francis turbine, whose structure is showed in figure 1. The Francis turbine consists of a spiral casing, stay vanes and guide vanes, a runner, and a draft tube. An aeration hole is made along the turbine shaft center. The parameters of the model turbine are as follows: runner diameter i.e. $D_1=420$ mm, runner blade number $Z_b=17$, relatively height of the guide vane $b_0=0.18257$. The turbine operates at the head $H=30.07$ m, rotation speed $907.407$ r/min, and guide vane opening $\alpha_0 = 12.175^\circ$.

For the purpose of achieving better convergence and accurate results, structured mesh is generated for the computation domain. The localized refinement is applied in region close to the vane leading and trailing edges. The whole domain consists of 1,600,000 nodes and 1,490,000 elements.

![Figure 1. Computation domain for the turbine.](image1)

![Figure 2. Monitoring points in computation domain.](image2)

In the simulation, the RANS equations as well as SST $k-\omega$ turbulence model are used. Total pressure and static pressure are assigned for inlet and outlet conditions respectively. For the case of aeration condition, the flow in the turbine is assumed as a kind of homogeneous mixture.

The time step is set as 0.001102 s at first, corresponding to a rotating angle of 6 degree per time step. Then 3 degree per time step is adopted for the subsequent simulation.

### 3. Results and analysis

For the convenience of the analysis, one monitoring section near the inlet of the draft tube is chosen. 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.

3.1. Pressure fluctuation without air admission
To verify the effectiveness of the numerical methods, the pressure fluctuation without air admission at the monitoring point p1 was measured by experiment (The experimental test of the model Francis turbine was conducted on the test rig at Harbin Electric Company Ltd, China). Fast Fourier Transform (FFT) is applied to process both calculation and experiment data to obtain the pressure fluctuation frequency and the corresponding amplitude.

![Comparison between calculated and measured pressure fluctuation.](image)

Figure 3. Comparison between calculated and measured pressure fluctuation.

Figure 3 shows the comparison between the experiment and CFD result for dimensionless pressure fluctuation. The CFD curve meets the experiments well both in frequency and amplitude. The dominant frequency and the secondary frequency predicted by CFD are 3.11 Hz with the amplitude of 0.57, and 6.19 Hz with the amplitude of 0.11, while that recorded by the experiments are 3.09 Hz with the amplitude of 0.59, and 6.09 Hz with the amplitude of 0.14. It is clear that the pressure fluctuation frequency is smaller than the runner rotation frequency of 15.12 Hz, and the pressure fluctuation is induced by the vortex rope in the draft tube shown in figure 4, where iso-pressure surface is used to illustrate the rope.

The shapes of vortex rope at several instants are shown in figure 4. The rope rotates in the draft tube and the frequency corresponds to the dominant frequency observed at monitoring point p1.

![Vortex rope shapes in one cycle.](image)

Figure 4. Vortex rope shapes in one cycle.

3.2. Aeration effect on pressure fluctuation
In order to alleviate the pressure fluctuation, the air is admitted into the draft tube from the aeration hole. The size of the hole is decided using the same way as Reference [13].

According to Li [14], the amplitude of pressure fluctuation may increase when the volume of the air admission is small. Only when the supplied air volume is large enough to change the eccentric
distance of vortex rope obviously, the pressure fluctuation will be alleviated. In this paper, the air volume is simulated in a wide range from $Q_{air}=0.5\%$ to $Q_{air}=4\%$ of water flow-rate at the inlet plane. Simulation results with various air admissions are shown in figure 5.

![Figure 5. Pressure fluctuation sat monitoring point p1 at different $Q_{air}$.](image_url)

It is noted that the pressure fluctuation characteristics predicted by the simulation agree well with the phenomena mentioned in Reference [14]. When $Q_{air}$ is very small e.g. $Q_{air}=0.5\%$, the pressure fluctuation amplitude increases a little and the frequency changes little. According to Li [14], the pressure fluctuation occurs because of the uneven distribution of static pressure. Figure 6 shows the static pressure distribution on the monitoring section at an instant, and the eccentric vortex rope makes an inhomogeneous pressure distribution. With the rotation of the rope, pressure transducer at p1 can measure a pulsation. The larger the eccentric distance and rope diameter are, the larger the amplitude could be. For small amount of air admission, the rope diameter increases, and the pressure fluctuation amplitude increases a little.

![Figure 6. Pressure distribution at an instant on the monitoring section.](image_url)

When $Q_{air}$ increase from 1\% to 3\%, the pressure fluctuation amplitude decreases a little, and the effects of the vortex rope are alleviated. Figure 5 also indicates that the pressure fluctuation frequency increases with the air admission. When $Q_{air}$ increases to 4\%, the amplitude decreases substantially. There seems no dominant component in this operation condition. Based on figure 7 where the static pressure distribution are shown, the low pressure core on the monitoring section becomes smaller with
the increase of air admission and the pressure distribution for $Q_{air}=4\%$ seems much more homogeneous than that without air admission.

![Figure 7. Pressure distributions with different air admission: (a) $Q_{air}=0$, (b) $Q_{air}=0.5\%$, (c) $Q_{air}=1\%$, (d) $Q_{air}=2\%$, (e) $Q_{air}=3\%$, (f) $Q_{air}=4\%$.](image)

Figure 8 shows the iso-surface with the air volume fraction of 10% with different air admission. It is noted that the rope diameter increases, but the orbit of the rope has a larger eccentric with the increase of the air admission.

![Figure 8. Iso-surface shaving 10% air volume fraction with different air admissions](image)

### 3.3. Vorticity Distributions

The vorticity transport equation is employed to better understand the vortex-air interactions. The equation is shown as

$$
\frac{D \omega}{Dt} = (\omega \cdot \nabla)V - \omega (\nabla \cdot V) + \frac{\nabla \rho_m \times \nabla p}{\rho_m^2} + \frac{1}{Re} (\nabla^2 \omega)
$$

(1)

where $\omega$: vorticity, $V$: velocity, $\rho_m$: mixed density, $Re$: Reynolds number.

In this equation, the vorticity production of a fluid includes four parts: the first term on the right-hand-side i.e. $(\omega \cdot \nabla)V$ represents the vortex stretching; the second term i.e. $\omega (\nabla \cdot V)$ means the vortex dilation caused by volumetric expansion/contraction; the third term i.e. $(\nabla \rho_m \times \nabla p)/\rho_m^2$ is called the baroclinic torque, which is nonzero only at the area with the air, and is caused by the misaligned
pressure and density gradients; and the last term named as viscous diffusion, can be ignored as its effect on the vorticity transport is much smaller than the other terms. Thus, only vortex dilation and baroclinic torque terms are analyzed.

Figure 9 shows the typical instantaneous distributions of the vortex-dilatation and baroclinic torque terms in vortex transport equation projected on the monitoring section. The result shows that there are vorticity variations near the vortex rope, and the vortex dilation term plays a major role in the vertical flow in the draft tube. At the case of small air admission and without air admission, a clear vortex pair appears along the vortex rope. This indicates that the vertical flow is strong at those operation conditions. With $Q_{air} = 2\%$ and $3\%$, there are two vortex pairs with less intensity. This phenomenon is visible from both the vortex dilation and baroclinic torque terms. At the case of $Q_{air} = 4\%$, the effect of the baroclinic torque term almost disappears, and that of vortex dilation becomes much depressed. These results can explain that the vertical flow is still strong at small air admission, and the pressure fluctuation is not alleviated yet. Consequently, a suitable air admission e.g. $Q_{air} = 4\%$ for this work is necessary to depress the vortex movement and alleviate the pressure fluctuation. Thus, the analysis of the vortical flow evolution is helpful to understand the pressure fluctuation behavior in the turbine draft tube.

![Figure 9. Contours of vortex dilation and baroclinic torque terms at the monitoring section:](image)

(a) $Q_{air}=0$, (b) $Q_{air}=0.5\%$, (c) $Q_{air}=1\%$, (d) $Q_{air}=2\%$, (e) $Q_{air}=3\%$, (f) $Q_{air}=4\%$

### 3. Conclusions

The internal flow in a model Francis turbine is studied with particular emphasis on the interaction between the flow field and the vortices. Based on the present study, the following conclusions can be drawn:

1. The numerical simulation reasonably predicts the pressure fluctuations in the draft tube, which agrees fairly well with experimental data.
2. The analysis based on the vorticity transport equation shows that the vortex dilation term plays a major role in the vortex evolution with air admission in the turbine draft tube. There is large value of vortex dilation along the vortex rope.
3. The aeration with suitable air volume fraction can depress the vortical flow, and alleviate the pressure fluctuation in the turbine draft tube.

### Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (Project Nos. 51179091, 51376100, and 51206087) and the National Key Technology Research and Development Program (Grant No. 2011BAF03B01).
Reference

[1] Kercan V, Bajd M, Djelić V, Lipej A and Jošt D 1994 Work group on the behavior of hydraulic machinery under steady oscillatory conditions Proc. of the 17th IAHR symposium on hydraulic machinery and cavitation (Beijing, China, 15-19 Sept 1994) A6

[2] Kercan V, Bajd M, Djelić V, Lipej A and Jošt D 1996 Proc. of the 18th IAHR symposium on hydraulic machinery and cavitation vol II (Valencia, Spain, 16-19 Sept 1996) pp 994-1003

[3] Kercan V 2001 Ph.D thesis (Rijeka Croatia: University in Rijeka)

[4] Ji B, Luo X W, Arndt R and Wu Y 2014 Ocean Eng. 87 64-77

[5] Ji B, Luo X W, Arndt R Peng X and Wu Y 2015 Int. J. Multiphase Flow 68 121-134

[6] Luo X W, Ji B, Peng X, Xu H and Nishi M 2012 J. Fluid Eng. 134(4) 041202

[7] Ji B, Luo X W, Wu Y, Peng X and Duan Y 2013 Int. J. Multiphase Flow 51 33-43.

[8] Miyagawa K, Tsuji K, Yahara J and Nomura Y 2002 Proc. of the 21st IAHR symposium on hydraulic machinery and systems (Lausanne, Switzerland, 9-12 Sept 2002)

[9] Zhou L J, Wang Z W and Tian Y 2006 23rd IAHR symposium on hydraulic machinery and systems (Yokohama, Japan, 18-21 Oct 2006)

[10] Jošt D and Lipej A 2011 J. Mech. Eng. 57 (6) 445-456

[11] Nukunishi K and Uedo T 1964 Air supply into draft tube of Francis turbine

[12] Qian Z, Yang J and Huai W 2007 J Hydrodyn. 19 (4) 467-472

[13] Liao W L, Ji J T, Lu P and Luo X Q 2008 J. Hydraulic Eng. 8 18

[14] Li Q 1981 Waterpower 5 8