Pressure oscillation suppression by air admission in a Francis turbine draft tube

X Luo1, A Yu2, W Yu3, L Wang1 and H Xu1
1State Key Laboratory of Hydroscience and Engineering, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China
2College of Energy and Electrical Engineering, Hohai University, Nanjing 210098, China
3School of Mechanical Engineering, Taizhou University, Taizhou 318000, China

luoxw@tsinghua.edu.cn

Abstract. When Francis turbine operated at part-load conditions, there is strong vortex rope in the draft tube, which may induce violent pressure oscillation, mechanical vibration and noise. This paper treats the pressure oscillations at a part-load operation by analyzing the unsteady multiphase flow in a Francis turbine. Air admission is used to alleviate pressure oscillation under different cavitation number. In order to improve the numerical accuracy, a modified method including the Level-set based method and FBDCM model is applied in the calculation. The simulation results indicate that the modified method can reasonably predict the pressure oscillations in turbine with good agreement with experimental data. The method can reflect more detailed flow characteristics and capture a clearer phase interface compared to the conventional method. It is noted that air admission with suitable ventilation rate does suppress the pressure oscillation in the turbine. The pressure oscillation in the vaneless area due to rotor-stator interaction cannot be depressed completely. Further, the mechanism on the pressure oscillation suppression in the draft tube is due to the spiral motion depression of vortex rope by air admission. As the increase of air admission, the pressure and its gradient distributions become much homogeneous. The homogeneous distribution of pressure in the draft tube would be favourable for the suppression of pressure oscillation

1. Introduction
When a hydro turbine is operated at off-design conditions, its internal flow becomes rather complex and a swirling flow is usually originated from the runner exit. The swirling flow has a major influence on the flow in a draft tube. At part load operation, the swirling flow develops and forms a processing spiral vortex in the draft tube. The spiral vortex produces self-induced flow instabilities leading to pressure fluctuations and ultimately to draft tube cavitation surge [1], and can harm stable operation of a Francis turbine, such as violent pressure oscillation, noise with large amplitude, etc.

The phenomenon of the spiral vortex in a draft tube has attracted an intensively attention with many investigations of the pressure oscillations in the past [2-3]. Döerfler [4] presented a theory to describe those oscillations in terms of a linear mathematical model with time-independent parameters and did the experimental verification. Kubin et al.[5] validated his mathematical models for predicting the swirling flow and the vortex rope in a Francis turbine operated at partial discharge. Ciocan et al. [6-7] carried out experiments for unsteady wall pressure measurements and the flow field in ae draft tube. Besides, numerical studies for pressure oscillations have also been conducted. Choi et
al.\[8\] used RANS method with the standard $k$-$\varepsilon$ turbulence model to predict the global vortex quantities, the pressure oscillation amplitudes and the vortex frequency with a relatively allowable error. Guo et al.\[9\] investigated the cavitating flow in a draft tube using large eddy simulation. However, the effects of the incondensable gas are not suitably considered.

Though there are several effective ways to alleviate the pressure oscillation caused by the vortex rope, such as the geometrical optimizing of turbine runner \[10\], water injection \[11\], aeration, etc., air admission is the most effective and convenient way. Numerical investigations \[12-13\] have shown some correlation of pressure oscillations with different aeration volumes. Unfortunately, little attention has been paid on the internal flow characteristics to depict the aeration mechanism.

The present paper aims to investigate the effect of air admission on pressure oscillation as well as the vortex behaviour in the whole passage of a model Francis turbine. For numerical simulation, a new multiphase model \[14\] and FBDCM (filter-based density corrected model) turbulence model \[15\] are applied to better capture the flow characteristics of the air-vapor-water two phase swirling flow in the turbine. Based on the results, the suppression of pressure oscillation is discussed for different air admission in the draft tube.

2. Francis turbine geometry and numerical methods
The geometry of a model Francis turbine is briefly introduced. Since the advanced models are applied for the present flow analysis, the numerical methods are described in detail as follows.

2.1. Francis turbine
Figure 1 shows the computation domain, where the full flow passage of Francis turbine is included. There are 17 blades for the runner. For air admission, an aeration hole is set along the runner shaft. Note that the domain inlet is the inlet plane of volute casing, and the domain outlet is the outlet plane of draft tube. The runner diameter $D_1$ is 420 mm. Other parameters for the turbine are introduced in our previous study \[16\]. Model tests have been conducted on a test rig at the Harbin Electric Company Ltd., China so as to achieve the hydraulic performance and pressure vibrations at typical stations of the turbine.

A structured mesh is generated for the full flow passage including the volute casing, stay vanes, guide vanes, runner, and draft tube. The mesh is refined close to the solid walls. The computation domain has around 1,900,000 nodes and 1,730,000 elements based on the verification of the grid independence and the balance between the prediction accuracy and computational capability.

2.2. Modified simulation method
In the present study, the proposed method is based on a homogeneous assumption, where the mixture of water, air and vapor is the flowing fluid with spatially and timely dependent density and viscosity. The basic governing equations for the flow are listed as the following:

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{Computation domain.}
\end{figure}
\[
\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0
\]

where \(\rho\), \(\mathbf{u}\), \(p\) represent the fluid density, velocity, and pressure, respectively. The subscript \(m\), \(v\), \(a\) mean the mixture, vapor, and air, respectively. \(\mu_m\), \(\mu_t\) are the molecular and turbulent viscosity.

Note that the last term of equation (2) is the surface tension force acting on the interface with \(\sigma\), representing the surface tension coefficient, \(\kappa\) representing the surface curvature, and \(n\) representing the interface normal vector pointing from the primary fluid to the second fluid (calculated using the volume fraction gradient). To capture the interfaces of air-liquid and vapor-liquid, a Level-set function i.e. \(\phi\) is adopted. Further, the Level-set function is also applied to calculate the term of surface tension force, and to modify the density and viscosity for the mixture of liquid, vapor and air [14].

For better simulation accuracy, a modified \(k-c\) turbulence model named as FBDCM model is used. The turbulent eddy viscosity \(\mu_t\) in this model is described as follows:

\[
\mu_t = \frac{C_\mu \rho_m k^2}{\varepsilon} \left[ \varphi \cdot \min(1, \frac{\lambda \cdot \varepsilon}{k^{1.5}}) + (1 - \varphi) \frac{(\rho_v + (1 - \alpha_v) \rho_a)}{(\rho_v + (1 - \alpha_v) \rho_a)} \right]
\]

\[
\varphi = 0.5 + \tanh \left[ \frac{C_1 (0.6 \rho_m / \rho_v - C_2)}{0.2 (1 - 2 C_2) + C_2} \right] \left[ a \tanh(C_1) \right]
\]

where \(C_1\) and \(C_2\) are set as 4 and 0.2, respectively. This can help to limit the overproduction of the turbulent eddy viscosity both near the foil wall and in the wake.

For cavitation modelling, the mass transfer due to evaporation \(\dot{m}^+\) and condensation \(\dot{m}^-\) is considered as the source term for mass conservation equation. The injected non-condensable air is considered, in which the source terms due to vaporization and condensation is presented as equations (5) and (6).

\[
\dot{m}^+ = C_e \frac{3 \rho_v (1 - \alpha_v - \alpha_g) \max(\alpha_g, \alpha_{\text{nuc}})}{R_b} \frac{2 \max(p_v - p, 0)}{\rho_l} \sqrt{3}
\]

\[
\dot{m}^- = C_e \frac{3 \rho_a \alpha_v}{R_b} \frac{\sqrt{2 \max(p - p_v, 0)}}{\rho_l}
\]

where \(C_e\), \(C_i\) are the empirical parameters and calibrated by the experiment data. The subscript nuc means non-condensable gas nucleation. \(R_b = 5 \times 10^{-3} \text{ m}\) is the bubble radius at initial condition. \(\alpha\) is the volume fraction.

The simulations have been conducted using the commercial CFD code ANSYS CFX. The time-dependent governing equations are discretized both in space and time. For simulation, the time step is set as 0.001102s (corresponding to a runner rotating angle of 6 degree per time step) till stable convergence. Then, the time step is changed to 0.0001837s (1 degree per time step) for the subsequent simulation. The interactions between the rotating runner and the stationary flow parts are calculated using a slipping mesh for the unsteady calculation.

2.3. Operation and boundary conditions

The turbine is operated at a part-load condition with the guide vane opening of \(a_0 = 11.5\text{mm}\) (note that the opening of \(a_0 = 16.3\text{mm}\) is at the best efficiency point). The other operation parameters are listed as table 1. Note that two conditions with different cavitation number, whose definition is shown at equation (7), are involved, including the cavitation case with \(\sigma = 0.04\) and the non-cavitation case with
\( \sigma = 0.12 \). In order to observe the effect of aeration, 4 ventilation rates, i.e. \( Q^* \) defined as equation (8) are considered.

\[
\sigma = \frac{(p_a - p_v - \rho g H_s)}{\rho g H} 
\]

where \( p_a \) and \( p_v \) are the atmosphere pressure and saturated vapor pressure. \( H_s \) is the suction head, and \( H \) is the turbine head. \( g \) is the gravitational acceleration.

\[
Q^* = \frac{Q_{\text{air}}}{Q_{\text{out}}} \quad (8)
\]

where \( Q_{\text{air}} \) and \( Q_{\text{out}} \) are the flow rate for air injection and that at domain outlet.

The total pressure is assigned at the domain inlet, and the static pressure is assigned at the domain outlet. The mass flow rate is assigned according to the ventilation rate at the air inlet, i.e. aeration hole shown at figure 1. All solid walls have nonslip boundary conditions.

### Table 1. Operating condition.

| Parameter                        | Value               |
|----------------------------------|---------------------|
| Guide vane opening, \( \alpha \)/mm | 11.5                |
| Head, \( H \)/m                  | 30.07               |
| Unit flow rate, \( q_{11} \)/l/s  | 254.51              |
| Unit speed, \( n_{11} \)/r/min   | 69.5                |
| Cavitation number, \( \sigma \)   | 0.04 (cavitation), 0.12 (non-cavitation) |
| Ventilation rate, \( Q^* \)       | 0, 0.01, 0.02, 0.04 |

### 3. Results and considerations

In this text, the modified methods are validated, and the effects of air admission on pressure oscillation and vortex flow are discussed. For convenience, the monitoring sections and points are shown in figure 2. At the vaneless area between the runner exit and the guide vane leading edge, 2 monitoring points are defined as “Psv1” and “Psv2”. Five reference sections marked with “S1-1”, “S1-2”, “S1-3”, “S1-4” and “S2” are set in the draft tube. Monitoring section S1-1 is the draft tube inlet, and S1-2, S1-3, S1-4 are 0.23m, 0.46m and 1m from the draft tube inlet. Section “S2” namely meridian plane, is perpendicular to section “S1-1”. Five monitoring points are selected on section “S2”, and marked as “P1”, “P2”, etc.

![Figure 2](image-url)
3.1. Comparisons of different simulation method

For comparison, apart from the modified simulation method, a conventional method with the k-ω SST turbulence model and Zwart cavitation model is employed to analyze the same question.

Table 2 shows the hydraulic performance and pressure oscillations obtained by experimental test and numerical simulations. Compared with the experimental data, the frequency of pressure oscillation measured at the monitoring point Psv1 in the turbine is well predicted by both numerical methods. The turbine performance parameters such as flow rate, averaged efficiency, pressure oscillation amplitude, etc. are better predicted by the modified method than the conventional method.

| Parameter                  | Experimental data | Prediction by modified method | Prediction by conventional method |
|----------------------------|-------------------|-------------------------------|----------------------------------|
| Flow rate, Q/(l/s)         | 249.18            | 256.32                        | 261.73                           |
| Average efficiency, η(%)   | 91.22             | 92.85                         | 93.92                            |
| Frequency of pressure oscillation, f/f_n | 0.231          | 0.232                         | 0.233                            |
| Amplitude of pressure oscillation, ΔH/H | 0.661          | 0.641                         | 0.580                            |

Further, the vortex rope structures formed by Q criterion are shown in figure 3. Though the major vortex rope is well predicted by both methods, the modified method can capture the vortex breakdown. In figure 4, the air volume fraction distributed on monitoring section S1-1 is shown. Note that the modified method can predict the clear interface between gas and liquid, while a vague boundary between two phases is predicted by the conventional method. Thus, the modified method is used for the numerical analysis in this study.

3.2. Pressure oscillations without air admission

Figure 5 shows the pressure oscillations at two monitoring points in the vaneless area and draft tube. Without air admission, there are two dominant components at Psv1: a low frequency (0.23f_n) component and a high frequency (17f_n) component. It is obvious that the oscillation component of 17f_n named as f_17 in the following text is due to the rotor-stator interaction. At the monitoring point P1, the dominant component has almost the same low frequency of 0.22f_n. According to the literature [17], this oscillation component marked as f_1 in figure 5(a) is due to the vortex rope in the draft tube when Francis turbine is operated at part-load condition.

![Figure 3. Vortex rope structure (Q*=0). Left: the conventional method; Right: the modified method.](image)

![Figure 4. Air volume fraction distributed on monitoring section S1-1 (Q*=0.02). Left: the conventional method; Right: the modified method.](image)
There are other components found in the draft tube as shown in figure 5(b): the $f_2$ component with the frequency of $0.43f_n$, and the $f_3$ component with the frequency of $0.073f_n$. Obviously, the $f_2$ component with the frequency of $0.43f_n$ is a harmonic component of the dominant component $f_1$. On the other hand, the $f_3$ component is resulted from cavitation in the draft tube.

Thus, there are dominant components of $f_1$ and $f_3$ in the turbine for the part-load operation. For the $f_1$ component, the pressure oscillation at the inlet of draft tube has larger amplitude compared with that at the vaneless area. Besides, cavitation will induce the very low frequency component $f_3$ in the draft tube.

3.3. Pressure oscillations with air admission

To investigate the effects of air admission, the pressure oscillations at different $Q^*$ at the monitoring point P1 are shown in table 3, and that at the monitoring point P5 are shown in figure 6 for examples. The results indicate that air admission has the overwhelming effect on the pressure oscillations, the $f_1$ and $f_2$ component due to vortex rope occurring in the draft tube, as shown in table 3. However, there are no obvious effects of air admission on pressure oscillation due to rotor-stator interaction i.e. $f_{17}$, and that due to cavitation i.e. $f_3$. It is also seen that air admission increases the frequency of the $f_1$ component a little according to table 3. At the monitoring P5, the dominant pressure oscillation is the $f_3$ component, and it is suppressed at the large ventilation rate of $Q^*$=0.04.

| Ventilation rate $Q^*$ | Oscillation type | Frequency $f/f_n$ | Amplitude $\Delta H/H$ |
|-----------------------|-----------------|------------------|---------------------|
| 0                     | Type 1: $f_1$   | 0.2145           | 0.4312              |
|                       | Type 2: $f_2$   | 0.4290           | 0.0331              |
|                       | Type 3: $f_3$   | 0.0734           | 0.1344              |
|                       | Type 4: $f_{17}$| 17               | 0.3449              |
| 0.01                  | Type 1: $f_1$   | 0.2446           | 0.4258              |
|                       | Type 2: $f_2$   | 0.4892           | 0.0221              |
|                       | Type 3: $f_3$   | 0.0723           | 0.1593              |
|                       | Type 4: $f_{17}$| 17               | 0.3884              |
| 0.04                  | Type 1: $f_1$   | 0.2641           | 0.0312              |
|                       | Type 2: $f_2$   | 0.5282           | 0.0031              |
|                       | Type 3: $f_3$   | 0.0661           | 0.1152              |
|                       | Type 4: $f_{17}$| 17               | 0.2992              |

Figure 5. Pressure oscillations at different monitoring points ($Q^*$=0, $\sigma$=0.04): (a) Psv1; (b) P1.
The relations between pressure oscillation and ventilation at different monitoring point are shown in figure 7. The results depict that the pressure oscillation is the most violent at the monitoring points P2 and P3, and is small at the elbow of draft tube (at the monitoring point P5) without air admission. With the increase of air admission, the pressure oscillation is alleviated gradually, and almost suppressed at large ventilation rate. The pressure oscillation at the vaneless area i.e. Psv1 and Psv2 cannot be depressed completely due to the rotor-stator interaction. That means air admission only has remarkable effect to suppress the pressure oscillations due to vortex rope at part-load operation.

Figure 6. Pressure oscillations at different $Q^*$ at monitoring point P5.
3.4. Vortex structure

To discuss the mechanism of pressure oscillation suppression, the effect of air admission on the vortex structure is shown at figure 8. The vortex rope is shaped by $Q$ criterion in figure 8(a), and is shown by the iso-surface of air volume fraction in figure 8(b).

The vortex is long in the draft tube, and broken down at the downstream for the cases of $Q^*=0.01$ and 0.02. For the large ventilation rate, the vortex is depressed greatly and becomes very short. The air/vapor cavity has spiral shape, and becomes longer when the ventilation rate changes from 0.01 to 0.02. The cavity is a straight column at $Q^*=0.04$. For this condition, the vortex rope has small oscillation strength due to spiral movement even the cavity rope has large volume.

Pressure and pressure gradient distributions in the monitoring sections S1-1 and S2 are shown in figure 9. It is clear that there is a low pressure core and large jump of pressure gradient on both sections due to the vortex rope. The great variations of pressure and pressure gradient distribution results in the pressure oscillation in the draft tube. As the increase of air admission, the pressure distribution becomes much homogeneous. The homogeneous distribution of pressure in the flow field would be favourable for the suppression of pressure oscillation.
4. Conclusions

The unsteady cavitating turbulent flows in a model Francis turbine were simulated for a typical part-load operating condition with a guide vane opening of 11.5mm. The internal flow in the turbine was studied with particular emphasis on the effects of air admission on pressure oscillation. Based on the results, the following conclusions can be obtained:

(1) The modified method can reasonably predict the pressure oscillations in turbine with good agreement with experimental data. The method can reflect more detailed flow characteristics and capture a clearer phase interface compared to the conventional method.

(2) Air admission with suitable ventilation rate does suppress the pressure oscillation in the turbine. The pressure oscillation in the vaneless area due to rotor-stator interaction cannot be depressed completely.

(3) The mechanism on the pressure oscillation suppression in the draft tube is due to the spiral motion depression of vortex rope by air admission. As the increase of air admission, the pressure and its gradient distributions become much homogeneous. The homogeneous distribution of pressure in the draft tube would be favourable for the suppression of pressure oscillation.

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