Investigation on pressure fluctuation in a Francis turbine with improvement measures

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Abstract. For a prototype turbine operating under part load conditions, the turbine output power is fluctuating strongly. The test for the prototype turbine at site shows that the main reason is the resonance between the draft tube vortex frequency and the generator natural frequency. In order to reduce the fluctuation of power output, different measures are investigated with using CFD methods. To keep the turbine unchanged, four kinds of draft tubes are examined, including the original draft, the draft tube with extending runner cone, the draft tube with damping gates and the draft tube with flow deflectors. The results are analyzed and compared in order to examine the effects on pressure fluctuation and formation of vortex rope of draft tube. It is found that adding flow deflector is the most effective to change the frequency of the draft tube vortex rope and reduce the amplitude of pressure fluctuation.

1. Introduction

With the vigorous development of hydropower utilities, Francis turbine has been increasingly used in hydropower development projects due to its own superiority and the characteristics of large-capacity; high specific speed and high efficiency tend to become more obvious. However, the stability of unit operation has become increasingly prominent, where the water pressure fluctuations generated by the draft tube vortex has always been one of the focus that people pay attention to. When a turbine operates out of the optimal mode, the flow in the draft tube is more complex, water entrained cavitation bubbles formed the draft tube vortex which is processed together with water under the effect of centrifugal force, and the eccentric motion occurs under the influence of periodic unbalanced factors. If pressure pulsating frequency evoked close to the natural frequency of the generator unit, a strong resonance will be caused, which will threaten the safe operation of the unit.

In the past few decades, domestic and foreign scholars have been studying the draft tube pressure fluctuation and some progress has been made. On the one hand, some scholars adopt the method of combining numerical simulation and experimental research to analyze the changing rule of pressure fluctuation in draft tube, which provides some references for improving the draft tube design. On the other hand, in order to abate low-frequency pressure fluctuation caused by the draft tube vortex, the effects of the shape of the runner cone on the draft tube vortex and pressure fluctuation have been studied by scholars, including adopting runner cones of different length [6], different bottom diameter [7], as well as different type [8-9] and so on. In addition, pressure fluctuation caused by the draft tube
vortex can be improved to some extent through the method of air supply and installing the disturbed flow device in the draft tube, thus improving operational stability of the unit.

During the automatic generation control test in a power station, it is found that the output power of the unit fluctuated violently when the unit operates within a power load range. According to the prototype turbine test results, the main reason turns out to be that the frequency of power system electric vibration and draft tube pressure fluctuation are particularly close, which causes the electric power resonance oscillation, leading to sharp fluctuations in power. In this paper, we take the power station's Francis turbine as an example and use CFD method to simulate the internal unsteady flow of it under four schemes: prototype runner cone, lengthened runner cone, damping gate or flow deflector installing in draft tube, compare and analyze the various measures' impact on the draft tube flow and pressure fluctuation and then the pressure fluctuation signal of each measuring point are compared and analyzed in detail with the Fast Fourier Transform (FFT).

2. Numerical Simulations

The geometry model of the turbine is shown in Fig.1 (a). Turbine parameters are as follows: the runner blade number \( z = 13 \), runner diameter \( D_1 = 3.3 \text{ m} \), rotational speed \( n = 214.3 \text{ r/min} \), rotation frequency is \( f = 3.57 \text{ Hz} \), the number of stay vane is \( Z_c = 24 \), the number of guide vane is \( Z_g = 24 \), rated head is \( H_r = 72 \text{ m} \), rated output is \( P = 66.7 \text{ MW} \). High quality hexahedral structured grid was used in calculation shown in Fig.2, and the grid number is about seven million. In order to analyze the hydraulic draft tube pressure fluctuation systematically, six pressure fluctuation monitor points were set up in the draft tube as shown in Fig.1 (b).

![Computational domains](image1.png)

(a) Computational domains

![Layout of monitor points](image2.png)

(b) Layout of monitor points

Fig.1 Turbine geometry model and the layout of monitor point

![Spiral case](image3.png)

(a) Spiral case

![Stay vane and guide vane](image4.png)

(b) Stay vane and guide vane

2
An unsteady three-dimensional turbulent flow simulation has been conducted on the basis of the commercial code CFX 14.0 for a full flow passage Francis turbine model from the inlet of spiral case to outlet of draft tube. The numerical information between the stator and rotor components is transmitted through the slip-mesh method. The two order central difference scheme is applied in the diffusion and convection terms while the term of time utilizes the two order implicit Euler algorithm. The boundary condition of inlet is set as mass flow rate while the boundary condition of outlet is set as average static pressure. The turbulence is simulated by $k-\omega$ based shear stress transport (SST) turbulence model together with automatic near wall treatments. In the calculation, the interface between the rotating parts and stator parts is defined as the "Transient Rotor Stator”, in which the relative position between rotating and stationary flow component are updated each time step.

3. Results and Discussion

3.1. Pressure fluctuation and vertex rope of the turbine

In order to verify the reliability of the mathematical model, in this paper we compared the calculation results with test data. The comparison of pressure fluctuation frequency and amplitude of draft tube monitor point B1 (shown in Fig.1(b)) with prototype test in part load operations ($H = 82$ m, $P = 55$ mw) and simulation results are shown in Table 1, among which amplitude $\Delta H/H$ represents the pressure fluctuation amplitude as well as the percentage of the pressure head. As can be seen from the table, for each point, the numerical simulation results of the pressure fluctuation frequency and the real machine test results are in good agreement. The pressure fluctuation spectrum diagram is shown in Fig.3.

![Fig.2 Mesh view of the hydraulic turbine](image)

![Fig.3 Comparison between test and simulation results](image)
| Monitor point | Frequency (Hz) | Amplitude ΔH/H(%) | Frequency (Hz) | Amplitude ΔH/H(%) |
|---------------|----------------|-------------------|----------------|-------------------|
| Monitor point B1 | 1.0 | 3.5 | 1.088 | 3.87 |
| Monitor point B2 | 1.0 | 3.5 | 1.088 | 3.92 |

The low-frequency pressure fluctuation caused by the draft tube vortex is one of the main factors affecting the stable operation of turbine [12]. The CFD results show that under partial load condition (H=82m, P=55MW), there exists an obvious spiral vortex zone in the draft tube of the turbine (see Fig.4). Its Direction of rotation is the same with the runner and under the calculation condition; the pressure pulsating frequency is 1.088Hz, which is 0.3 times of the runner that belongs to the low frequency pressure fluctuation.

![Draft tube vortex at different times](image)

Usually, when the units operate under the optimal condition, the outflow of runner is in the axial direction, consequently the circulation of runner outlet is very small, close to zero. While operating with part load, due to the reduce of flow quantity in the turbine, the flow at the runner outlet generates a circumferential component rotating in the running direction, which leads to the positive circulation in the runner outlet increasing, shown in Fig.5. With the circulation increasing, an eccentric vortex generates in draft tube center rotating consistent with rotation direction.

![Flow field at runner outlet: Cur (left) and meridional velocity (right)](image)

The prototype test results show that the output power is in strong fluctuation under this condition, the frequency is 1.15Hz. The plant cannot be connected to the grid because of the vibration. The frequency of draft tube fluctuation vortex is 1.088Hz which is close to real power fluctuation frequency. This low frequency is due to pressure fluctuation caused by the draft tube vortex. It is found from calculation that at this time, the system natural frequency of vibration constituted by generator set and electrical transmission lines is close to the draft tube pressure fluctuation frequency, causing...
electric power resonance and thus resulting in significant fluctuations in power. So in this paper, the research emphasis is: reduce or eliminate the draft tube vortex, change pressure fluctuation frequency in the draft tube and reduce the pressure fluctuation amplitude.

3.2. Measures to reduce pressure fluctuations

Three measures were applied in this paper including extending runner cone, installing damping gate and flow deflector in the draft tube (see Fig.6), and at the same time unsteady three-dimensional turbulent flow simulation was conducted and compared with the prototype turbine calculation results. Starting from these aspects mentioned above, weaken the vortex amplitude, changing the pressure fluctuation frequency and reducing the vorticity of the vortex center in draft tube so as to achieve the purpose of vibration reduction of the entire turbine unit.

![Runner cone](image1)
![With damping gate](image2)
![With flow deflector](image3)

Fig.6 Structure of three measures

![Pressure distribution on monitoring Surface 1](image4)

(a) Original runner cone  (b) Lengthened runner cone  (c) Adding damping gate  (d) Adding flow deflector

Fig.7 Pressure distribution on monitoring Surface 1

![Pressure distribution on monitoring Surface 2](image5)

(a) Original runner cone  (b) Lengthened runner cone  (c) Adding damping gate  (d) Adding flow deflector

Fig.8 Pressure distribution on monitoring Surface 2
The pressure distributions on monitoring surfaces under partial load condition \((H = 82 \text{ m}, P = 55 \text{ MW})\) for the four different measures are shown in Fig.7 and Fig.8. The comparison of vortex rope in different time is shown in Fig. 9. Obviously, the original turbine draft tube has an obvious eccentric negative pressure zone on monitoring \textit{Surface 1} and \textit{Surface 2}, creating a vacuum in the region and the position of negative pressure zone on the two monitoring surfaces are different, while vortex presents a spiral downstream development. After using lengthened runner cone, the lowest pressure of the monitoring surface is increased and the negative pressure zone is reduced, but there is no significant change in vortex eccentricity. Also draft tube vortex rope doesn't change obviously compared with the original one. After adding damping gate in draft tube, the circumferential velocity of flow entered into draft tube inlet from the runner outlet is reduced, the negative pressure zone of monitoring surface is disappeared, and also, vortex has a very significant improvement compared with the prototype. The flow deflector added inside the draft tube reduces the eccentric vortex distance and vortex energy, no vortex rope is formed in draft tube, and therefore the reduction effect is most obvious.

Through the unsteady calculation of each measure mentioned above, the data of pressure changing over time on the monitoring surface of draft tube could be got and then we used FFT transform to analyze the pressure fluctuation signal of different monitoring points in the draft tube. Table 2 shows the comparison of pressure fluctuation frequency and amplitude in different measures. The frequency-domain plot and time-domain plot of the pressure fluctuation about B1 point under different measures are shown in Fig.10 and Fig.11.

| Measure                        | Monitor point B1 | Monitor point C1 | Monitor point D1 |
|-------------------------------|------------------|------------------|------------------|
|                               | Frequency (Hz)   | Amplitude \(\Delta H/H(\%)\) | Frequency (Hz)   | Amplitude \(\Delta H/H(\%)\) | Frequency (Hz)   | Amplitude \(\Delta H/H(\%)\) |
| Original runner cone          | 1.088            | 3.87             | 1.088            | 2.57             | 1.088            | 2.66             |
| Lengthened runner cone        | 1.088            | 3.36             | 1.2              | 2.08             | 1.0              | 2.53             |
| Adding damping gate           | 1.34             | 3.4              | 1.34             | 2.4              | 1.34             | 2.55             |
| Adding flow deflector         | 1.5              | 2.72             | 1.5              | 2.5              | 1.5              | 2.3              |
As can be seen from the comparison of the result, the pressure fluctuation frequencies of the draft tube under different measures are low frequency, and with respect to the turbine with original draft tube, the pressure fluctuation frequency has undergone some changes. From the frequency of pressure fluctuation on points B1, C1, D1, the impact on pressure fluctuation frequency is consistent, namely, the pressure fluctuation frequency of the monitoring points on each monitoring surface under the same measure is equal. Meanwhile, all three measures can reduce the pressure fluctuation amplitude. From the reduction effect, adding flow deflector is better than adding damping gate and prolonging runner cone.

Low-frequency pressure fluctuations generated in the draft tube will be spread throughout the turbine; therefore it will also cause pressure fluctuations in the spiral case. To investigate pressure fluctuations in the spiral case, two monitoring points are placed in the inlet of the volute.

| Monitor point A1  | Frequency (Hz) | Amplitude ΔH/H(%) | Monitor point A2  | Frequency (Hz) | Amplitude ΔH/H(%) |
|-------------------|----------------|--------------------|-------------------|----------------|--------------------|
| Original runner cone | 0.669 | 1.53% | 0.669 | 1.61% |
| Lengthened runner cone | 1.0 | 0.97% | 1.0 | 0.97% |
| Adding damping gate | 0.335 | 1.96% | 0.335 | 1.96% |
| Adding flow deflector | 0.5 | 1.31% | 0.5 | 1.32% |

Table 3 shows the comparison of pressure fluctuation frequency and amplitude in different measures. It shows that the frequencies of pressure fluctuation in the spiral case under different measures are also low, and with respect to the prototype, pressure fluctuation frequency also undergoes some changes. Meanwhile, from the table we can see that extending runner cone and adding flow deflector can reduce the pressure fluctuation amplitude, and with regard to an additional damping gate, pressure fluctuation amplitude rises to some extent. In summary, the measure of adding the flow deflector is better for the stability of power plant units.

In order to confirm the feasibility of the schemes, the condition of $H = 82$ m and $P = 45$ MW was checked, the conclusion is shown in Table 4. From the table about the change of frequency and amplitude of pressure fluctuation, it can be found that adding flow deflector in draft tube can effectively improve pressure fluctuation caused by vortex. At the same time, compared with other schemes, the scheme has more advantages under this condition.
Table 4 Pressure fluctuation for operation condition H = 82 m and P = 45 MW

| Monitor point B1 | Monitor point C1 | Monitor point D1 |
|------------------|------------------|------------------|
| Frequency (Hz)   | Frequency (Hz)   | Frequency (Hz)   |
| Amplitude        | Amplitude        | Amplitude        |
| ΔH/H(%)          | ΔH/H(%)          | ΔH/H(%)          |

Original runner cone 1.76 4.57 1.76 4.33 1.76 2.5
Lengthened runner cone 1.76 4.32 1.76 4.17 1.76 2.0
Adding damping gate 1.88 4.14 1.88 3.98 1.88 1.6
Adding flow deflector 2.0 3.92 2.0 3.5 2.0 1.3

4. Conclusions
In order to solve the problem of power fluctuations under part load condition of a power plant, CFD has been adopted to simulate the unsteady flow in turbine under four cases, including the original draft, the draft tube with extending runner cone, the draft tube with damping gates and the draft tube with flow deflectors. The results show that the pressure fluctuations caused by draft tube vortex is low-frequency fluctuation, which is one of the main factors affecting the stable operation of the turbine. The principal effect of prolonged runner cone affects the vortex rope shape and to some extent, reduces the pressure fluctuation amplitude, while it does not change the pressure fluctuation frequencies effectively. Adding damping gate in draft tube can reduce the circumferential velocity of flow while adding flow deflector in the draft tube can reduce the vortex eccentricity. Both measures will eliminate draft tube vortex rope to some extent, thereby changing the pressure fluctuation frequency.

Compared to the other measure, adding flow deflector can be more effective to change the draft tube pressure fluctuation frequency and amplitude, in order to deviate the frequency of pressure fluctuation caused by vortex rope in the draft tube from the units' natural frequency so as to avoid resonance and improve the operational stability of the unit. Therefore, adding flow deflector to the draft tube will be chosen to solve the problem of high fluctuation of output power of the power plant, and will be tested by experiment at site.

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