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Original Paper

Numerical Investigation of Pressure Fluctuation Reducing in Draft Tube of Francis Turbines

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Abstract

For a prototype turbine operating under part load conditions, the turbine output is fluctuating strongly, leading to the power station incapable of connecting to the grid. The field test of the prototype turbine shows that the main reason is the resonance between the draft tube vortex frequency and the generator natural vibration frequency. In order to reduce the fluctuation of power output, different measures including the air admission, water admission and adding flow deflectors in the draft tube are put forward. CFD method is adopted to simulate the three-dimensional unsteady flow in the Francis turbine, to calculate pressure fluctuations in draft tube under three schemes and to compare with the field test result of the prototype turbine. Calculation results show that all the three measures can reduce the pressure pulsation amplitude in the draft tube. The method of water supply and adding flow deflector both can effectively change the frequency and avoid resonance, thus solving the output fluctuation problem. However, the method of air admission could not change the pressure fluctuation frequency.

Key words: Francis turbine; draft tube vortex; air supply; water supply; flow deflector

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 [1-5]. On the other hand, the effects of the shape of the runner cone on the draft tube vortex and pressure fluctuation have been studied by scholars[6-8], including adopting runner cones of different length different bottom diameter, as well as different types and so on[9-10]. In addition, pressure fluctuation caused by the draft tube vortex can be improved to some extent through the method of air admission [11], water admission and installing a disturbed flow device in the draft tube[12], 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 fluctuates strongly when the unit is under operation within a power load range. According to the prototype turbine field test results, the main reason turns out to be that the frequency of power system electric vibration and draft tube pressure fluctuation are very close, which causes the electric power resonance oscillation, leading to strong fluctuations in output power.

This paper focuses on solving the problem of high fluctuating output of the turbine caused by the resonance, three schemes have been put forward through numerical simulations, including air admission to the draft tube, water injection to the draft tube and adding a flow deflector in the draft tube. The results from different schemes have been compared and discussed in detail.

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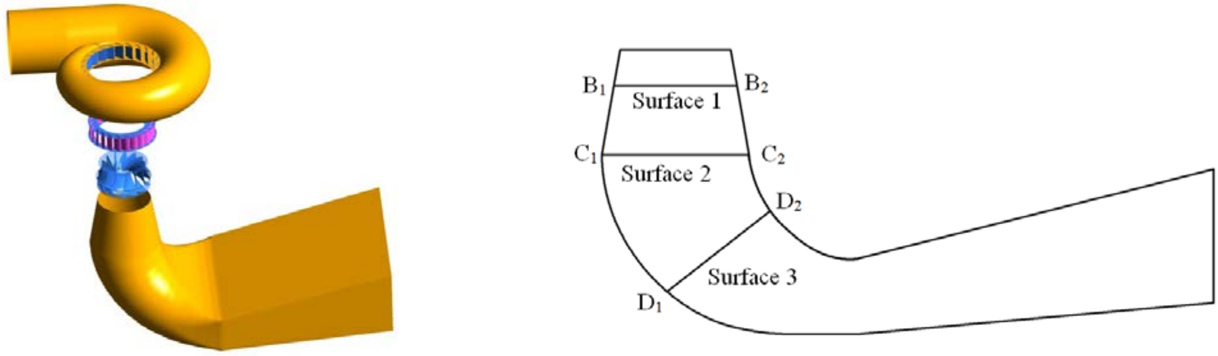
2. Numerical Simulations

The computational model of the prototype turbine is shown in Fig.1 (a). Turbine parameters are given as follows: the runner blade number z=13, runner diameter D_1=3.3 m, rotational speed n=214.3 r/min, rotation frequency f = 3.57 Hz, the number of stay vane Zc = 24, the number of guide vanes Zg=24, rated head Hr=72 m, rated output P= 66.7MW. High quality hexahedral structured grid is applied 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).



(a) Computational domains (b) Location of monitor points

Fig.1 Turbine geometry model and layout of monitor points

Three-dimensional turbulent flow filed inside the turbine is simulated by using a commercial CFD code ANSYS CFX-14.0. A constant total pressure was specified at the inlet of the computational domain, with flow direction normal to the inlet surface. At the outlet, mass flow rate is given. Smooth and no-slip condition is imposed on walls. Since the runner is defined in rotating frame of reference, and the rest are defined in stationary frame of reference, multiple frames of reference are involved. The sliding mesh technology is utilized for data transfer through interfaces. For the discretization method, the second order backward Euler scheme is chosen for the time domain, and second order format is used in space and other terms. The interfaces between the rotating runner and the stationary components are defined as “transient rotor-stator”, in which the relative position between the rotor and stator is updated during each time step. The time step Δt for unsteady calculations is set to 0.0031s. The turbulence is simulated by k-ω based on shear stress transport (SST) turbulence model together with automatic near wall treatments[13].

3. Results and Discussion

3.1 Pressure fluctuation and vortex rope of the turbine

To validate the CFD method of predicting pressure fluctuations in Francis turbines, an unsteady numerical simulation on the prototype turbine under the part load condition (H=82m, P=55MW) is conducted, and the dominant frequency and amplitude of pressure fluctuation in the draft tube are compared with those obtained from the field test of the prototype turbine. The comparison of the result is listed in Table 1, in which the amplitude ΔH/H represents the pressure fluctuation amplitude. The pressure pulsation spectrum diagram is shown in Fig 2. As can be seen from Table 1 and Fig 2, the dominant frequency and amplitude obtained from the numerical simulation agrees well with the prototype test result, indicating that mathematical model calculation method adopted is reliable and capable of calculating pressure fluctuations in the draft tube of Francis turbines.

Table 1 Comparison between test and calculation results

Monitor point	Experiment		Calculation	
	Frequency (Hz)	Amplitude Δ H/H(%)	Frequency (Hz)	Amplitude Δ H/H(%)
B_1	1.0	4.5	1.09	4.37
B_2	1.0	4.5	1.09	4.32

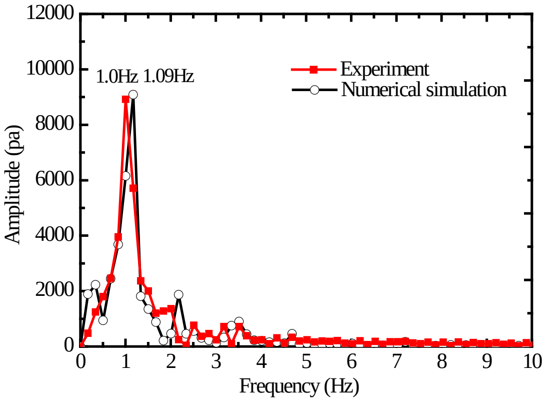


Fig.2 Comparison of frequency

Fig.3 Vortex rope in draft tube

The low-frequency pressure fluctuation caused by the draft tube vortex is one of the main factors affecting the stable operation of turbine [14]. The CFD results show that under partial load condition (H=82m, P=55MW), there exists an obvious spiral vortex rope in the draft tube of the turbine (see Fig.3), whose direction of rotation is the same with the runner. At this operation condition, the pressure pulsating frequency caused by the vortex rope is 1.09Hz, which is 0.3 times of the rotation frequency of the turbine.

Meanwhile, the field test result of the prototype turbine shows that under this operation condition, the vortex rope in draft tube causes a strong fluctuation to the output power generated by the turbine. The active power exhibits an obvious cyclical fluctuation with a frequency of 1.15Hz. The output power cannot be connected to the grid because of the vibration. The frequency of pressure fluctuation (1.0Hz) caused by the draft tube vortex rope is very close to the system natural vibration frequency (1.067Hz) which is constituted by the generator set and electrical transmission lines, causing electric power resonance and thus resulting in significant fluctuations in the output power. Therefore, main focus of this paper has been put on the measures to reduce or eliminate the draft tube vortex rope, to change pressure fluctuation frequency in the draft tube, and to reduce the pressure fluctuation amplitude.

3.2 Air admission to the draft tube

Air admission to draft tubes is one of the common measures to reduce the vortex rope in the draft tube of Francis turbines. This measure has been applied to the turbine for the operation condition H=82m and P=55MW, with the air admission amount of 0.1% Q, 0.5% Q, and 1%Q (Q is the flow rate of the turbine). The air is added to the draft tube through the hole on the bottom of the runner cone, shown in Fig.4

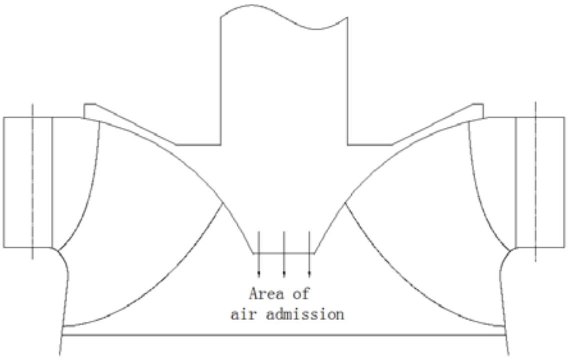


Fig.4 Structure of air admission

The vortex rope in the draft tube for the air admission of 0.5%Q and 1%Q are shown in Fig.5. It can be found that under air supply condition an obvious spiral vortex rope still exists, denoting that air admission under this condition doesn't have any effect on reducing the vortex rope.

(a) Air admission of 0.5%Q (b) Air admission of 1%Q

Fig.5 Vortex rope in the draft rope for different amount air admission

Table 2 shows the comparison of dominant frequency and amplitude of pressure fluctuation in the draft tube among different amounts of air admission. In addition, the fluctuating component of the unsteady pressure at monitor point B_1 is plotted in Fig. 6 as a function of time, as well as the frequency spectrums of the pressure fluctuation.

Table 2 Influence of pressure fluctuation amplitude with different amounts of air admission

Air admission	Monitor point B_1		Monitor point C_1		Monitor point D_1	
	Amplitude $\Delta H/H(\%)$	Frequency(Hz)	Amplitude $\Delta H/H(\%)$	Frequency(Hz)	Amplitude $\Delta H/H(\%)$	Frequency(Hz)
0	4.37	1.09	3.6	1.09	2.75	1.09
0.1%Q	8.38	1.09	6.89	1.09	7.0	1.09
0.5%Q	2.55	1.09	3.97	1.09	3.24	1.09
1%Q	3.46	1.09	4.51	1.09	3.20	1.09

It can be seen from Table 2 that the amount of air admission has a strong influence on the amplitude of pressure fluctuation. When the air admission is 0.1%Q, the amplitudes of pressure fluctuation at all three monitor points B_1, C_1 and D_1(see Fig1(b)) are much higher than those for the case without air admission to the draft tube, indicating that the small amount of air admission amplifies the pressure fluctuation in the draft tube. For the case with air admission of 0.5%Q, the amplitude of pressure fluctuation at point B_1 is reduced by approximately 50%, while the ones at point C_1 and D_1 have been slightly increased. With the further increase of air admission to 1%Q, the amplitudes of pressure fluctuation at all three monitor points tend to amplify. Furthermore, air admission to the draft tube does not change the dominant frequency of the vortex rope, which can be observed from the table. Therefore, air admission to the draft tube cannot fundamentally solve the problem of output fluctuation caused by the resonance.

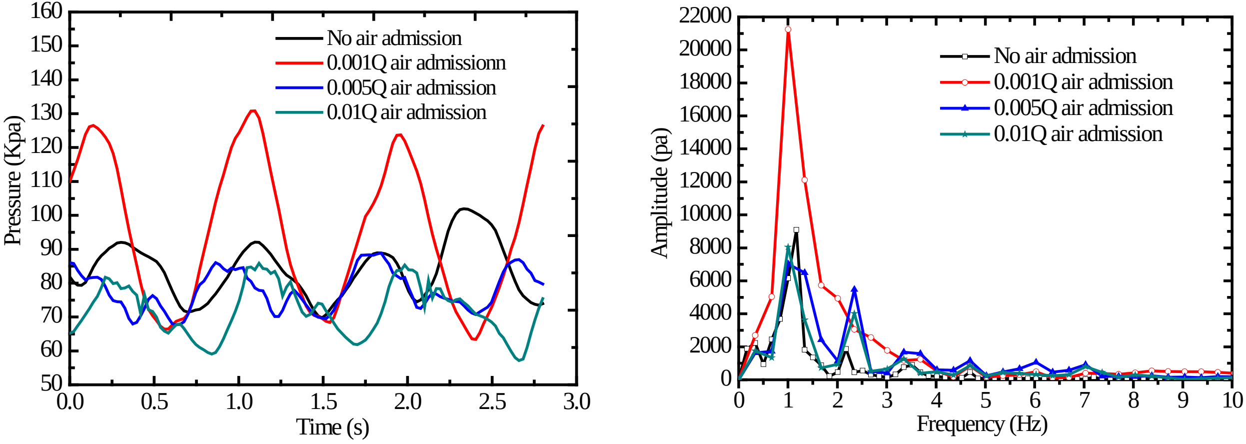
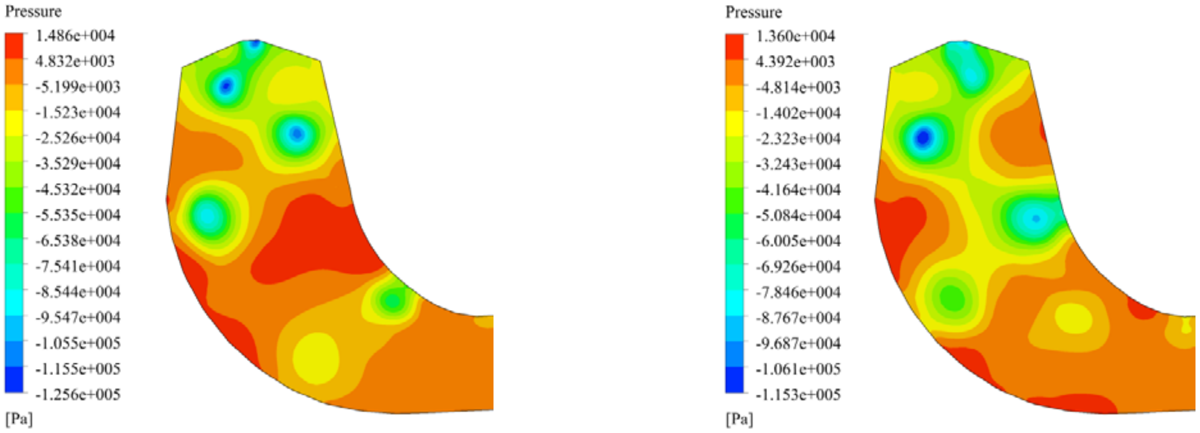


Fig.6 Pressure fluctuation at point B_1 with different amounts of air admission

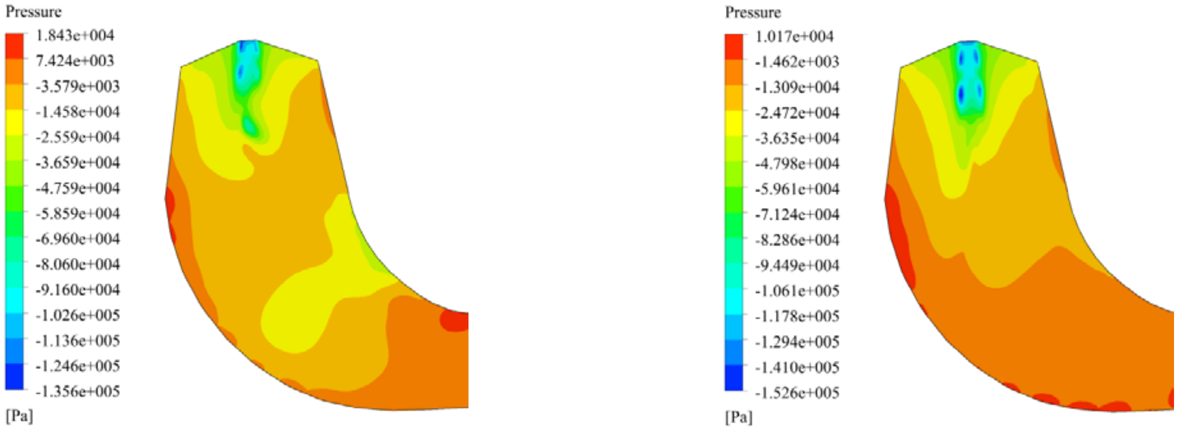
3.3 Water admission to the draft tube

Another measure of supplying water to the draft tube through the hole on the runner cone is taken into consideration, in order to reduce vortex intensity and to change pressure fluctuation frequency.

Figure 7 depicts the relative pressure contours for different amounts of water admission to the draft tube: from 0 to 5%Q. It can be seen that, the shape of the low pressure zone below the runner cone varies with the amount of water injection: from a spiral at 0 and 1%Q water injection to a cylinder at the amount of water injection of 3%Q and 5%Q.



(a) No water admission (b) Water admission of 1%Q



(c) Water admission of 3%Q (d) Water admission of 5%Q

Fig.7 Relative pressure contours at different amount of water admission

Table 3 Influence of pressure fluctuation amplitude with different water admission

Water admission	Monitor point B_1		Monitor point C_1		Monitor point D_1	
	Amplitude $\Delta H/H$(%)	Frequency(Hz)	Amplitude $\Delta H/H$(%)	Frequency(Hz)	Amplitude $\Delta H/H$(%)	Frequency(Hz)
0	4.37	1.09	3.6	1.09	2.75	1.09
0.01Q	4.59	1.0	3.59	1.0	3.21	1.0
0.03Q	0.85	0.5	1.02	0.5	2.09	0.5
0.05Q	0.29	3.5	0.55	3.5	0.045	3.5

The comparison of dominant frequency and amplitude of pressure fluctuation for different amount of water injection to the draft tube is listed in Table 3, and the unsteady pressure fluctuation and the frequency spectrums of the pressure fluctuation at monitor point B_1 are plotted in Fig.8. It can be observed that the pressure fluctuation amplitude of monitoring points depends on the amount of water admission. At water admission of 1%Q, the pressure fluctuation amplitude at all monitor points has been somewhat magnified, equipped with slightly reduced main frequency, compared with the case without water injection. At water admission of 3%Q, the pressure fluctuation amplitude has been greatly reduced, as well as the main frequency shrunk to 0.5Hz. When increasing further the water admission to 5%Q, the amplitude continues decreasing, but the main frequency of pressure fluctuation increases exceedingly to 3.5Hz. Therefore, both water admission of 3%Q and 5%Q can diminish the pressure fluctuation amplitude, and enable to deflect the main frequency of vortex rope from the generator natural vibration frequency to avoid successfully the resonance between them.

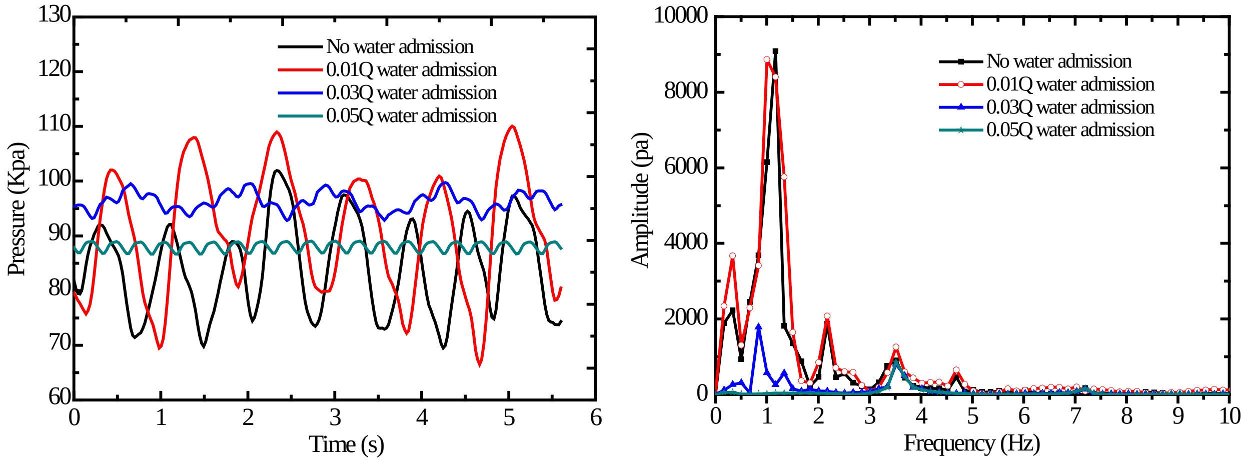


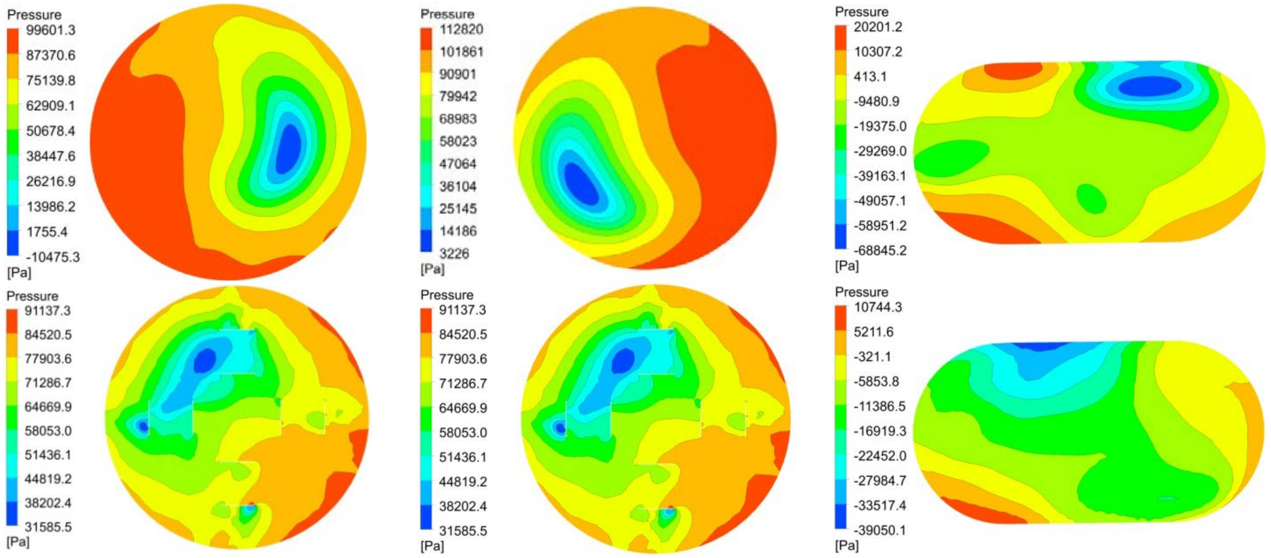
Fig.8 Pressure pulsation at point B_1 with different amounts of water admission

3.4 Flow deflector installing in the draft tube

Adding a flow deflector in the straight taper section of the draft tube is also applied to the Francis turbine, with the view given in Fig. 9

Fig.9 View of flow deflector

Fig.10 presents the comparison of relative pressure contour at three monitor surfaces defined in Fig. 1(b) between the prototype and adding flow deflector, for the partial load condition (H=82 m, P =55 MW). It can be seen that for the case of prototype, there exists an obvious eccentric low pressure zone on monitoring *Surface 1* and *Surface 2*, with the position of low pressure zone different on the two monitoring surfaces. After adding flow deflector in the draft tube, the circumferential velocity of the flow entering into the draft tube inlet from the runner outlet has been reduced, and the low pressure zone on monitoring surfaces has been reduced. In addition, the vortex rope has been broken into pieces by the flow deflector, resulting in a reduction in the energy of the vortex rope. At downstream on monitor *Surface 3*, the low pressure of adding flow deflector is observed higher than that of the prototype. The evolution of vortex rope for adding flow deflector is illustrated in Fig. 11 at three time instants.



(a) On Surface 1 (b) On Surface 2 (c) On Surface 3

Fig.10 Comparison of pressure contours between prototype (upper) and adding flow deflector (lower)

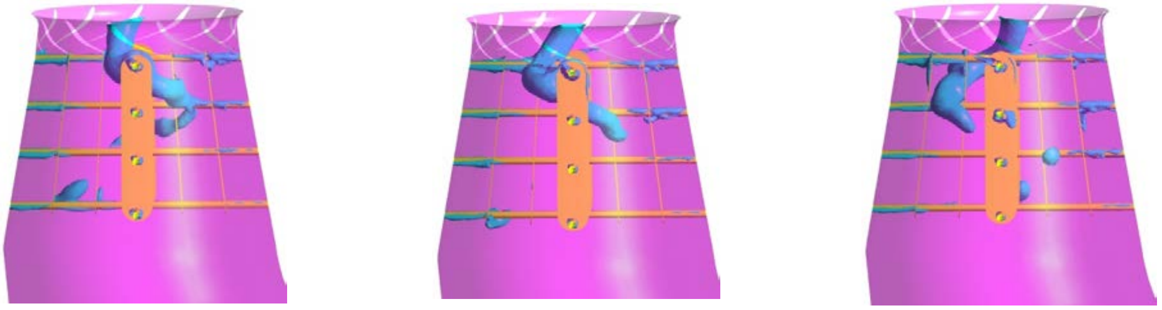
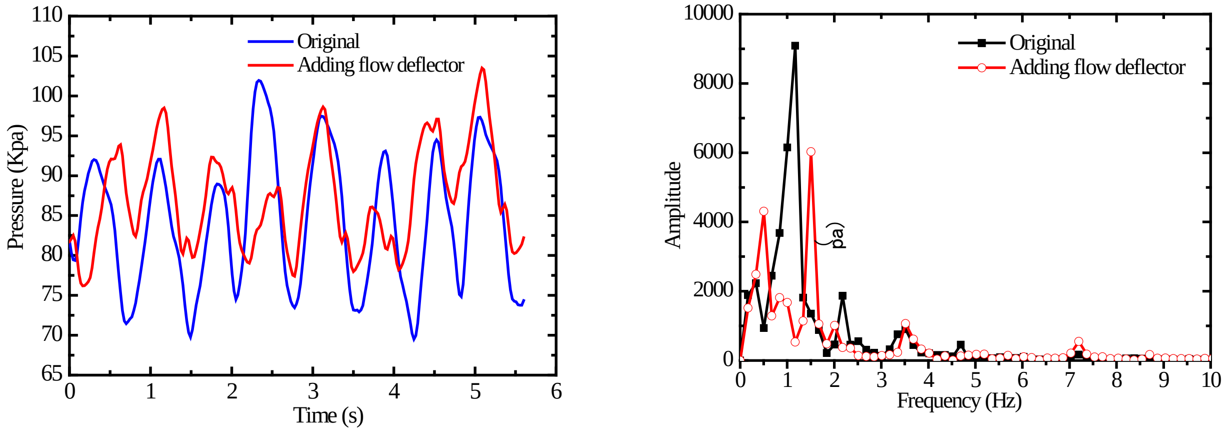


Fig.11 Evolution of vortex rope for adding flow deflector

Table 4 shows the comparison of dominant frequency and amplitude of pressure fluctuation for the mentioned two cases, together with unsteady pressure fluctuation and the frequency spectrums of the pressure fluctuation at monitor point B_1 plotted in Fig.12. It can be seen from the comparison that after adding flow deflector in the draft tube, the pressure fluctuation amplitude of monitoring points B_1, C_1, D_1 has been reduced, with the dominant frequency of 1.5Hz, denoting that adding flow deflector can change the frequency of the fluctuating pressure and avoid the frequency of power system electric vibration (1.067Hz). With the reduced pressure fluctuation and different frequency of the pressure fluctuation, the problem of output power fluctuation caused by the resonance can be assumed to be solved.

Table 4 Comparison of pressure fluctuation amplitude and frequency

Scheme	Monitor point B1		Monitor point C_1		Monitor point D_1	
	Amplitude Δ H/H(%)	Frequency(Hz)	Amplitude Δ H/H(%)	Frequency(Hz)	Amplitude Δ H/H(%)	Frequency(Hz)
Prototype	4.37	1.09	3.7	1.09	2.75	1.09
With flow deflector	3.2	1.5	3.04	1.5	2.35	1.5



(a) Pressure fluctuation (b) Frequency spectrums

Fig12. Comparison of pressure fluctuation at monitor point B_1

4. Conclusions

In order to solve the problem of high fluctuating output of the turbine caused by the resonance between the draft tube vortex frequency and the generator natural vibration frequency, three schemes have been put forward through numerical simulations, including air admission to the draft tube, water injection to the draft tube and adding a flow deflector in the draft tube. Based on the numerical and experimental results, it is concluded that the low-frequency pressure fluctuation caused by the vortex rope is the main reason to cause the unstable operation of the turbine. Some conclusions can be drawn as follows:

(a) Adding air to the draft tube can reduce the amplitude of pressure fluctuation caused by the vortex rope in the draft tube but cannot change the main frequency of the pressure fluctuation, failing in solving the problem of high fluctuation of output power of the turbine.

(b) Both the scheme of water injection through the runner cone to the draft tube and the scheme of adding a flow deflector in the draft tube can not only decrease the pressure fluctuation amplitude, but also deflect the main frequency of pressure frequency from the generator natural vibration frequency, therefore avoiding successfully the resonance between them. In addition, the effect on the reduction of pressure fluctuation from water injection is more evident than from adding a flow deflector.

Acknowledgments

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