

Influence of double-row guide vane cascade on performance of a Francis turbine

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Abstract. In the case of small load condition, the water flowing impact angle is very large that the secondary flow and the backflow are generated between the flow passage of runner, resulting in flow separation in runner and producing inter-blade vortex when cavitation is serious. In order to improve the stability of the Francis turbine in the small load conditions, this paper presents a controlling method of double-row guide vane cascade, and its numerical simulation is carried out. In this paper, it is found that there are obvious inter-blade vortices in the runner and the vibrations in the tube are violent under the small load conditions on the original model turbine. Secondly, the relationship between the opening method of double guide vane cascade and the flow separation condition in the runner is studied, the suitable opening combination is obtained and the difference in the performance of the original turbine under the small flow condition is analysed. The results show that: Through adjusting the opening combination of outer guide vanes and inner guide vanes, it can effectively control the outflow angle of the guide vane and the runner, thus the influences of the vortex in the draft tube and the inter-blade vortex can be obviously reduced. At the same time, double-row guide vanes can effectively reduce the pressure fluctuation amplitude of the draft tube. It has provided a certain theoretical basis for improving the stability of Francis hydraulic turbine.

1. Introduction

The inter-blade vortex is a typical unstable flow condition on the Francis turbine and often causes vibration and noise problems, which seriously harms the safe and stable operation of the turbine. The earliest record on the hazards of inter-blade vortex is Pakistan's Tarbela hydropower station [1]. The earliest domestic report about the harm of inter-blade vortex is the Gongzui hydropower station of Leshan [2]. These studies [3-5] have found that inter-blade vortex is the main cause of vibration and noise of the runner, and gradually aroused people's attention to the harm of inter-blade vortex.

Distributor in Francis hydraulic turbine is an important flow passage component of the turbine, which is composed of guide vanes, stay vanes and transmission parts. The main effect is to regulate the flow rate, and to form and change the circulation of the runner [6]. It is very important to study the characteristics of the flow field between the guide vane and the stay guide vane and enhance its flowing capacity and regulating ability to optimize the inlet condition and improve the overall performance of the turbine.

The results obtained by applying the tandem cascade in the impeller mechanical rotor [7-11] can be used to determine the potential of the tandem cascade to have a higher potential for further improvement in aerodynamic or hydraulic performance compared to single cascades, And tandem cascade have a wider range of adjustment. Compared with the traditional single-guide vane, the



double-row guide vane can provide a reference for the optimized design of stable operation of Francis turbine.

2. Calculation model of Francis turbine with double-row guide vane

In this study, it is shown in the figure 1 three-dimensional full-passage model of a Francis turbine model in a domestic hydropower station is build up. Then the guide vane geometry model is used as the initial value. The double-row guide vanes are composed of two rows of guide vane, the front and rear. In order to distinguish the two rows of guide vanes, the concepts of the outer guide vane and inner guide vane are introduced, the outer guide vane is close to the stay vane and the inner guide vane is close to the runner. The number of the outer and inner guide vane is 24, and the number of stay vane is 12, the diameter of the runner is 0.34 m and the number of runner blades is 13

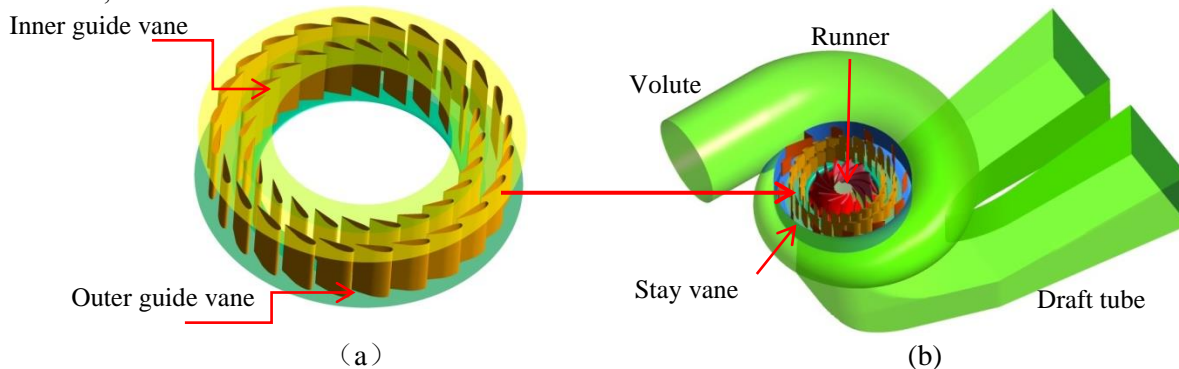


Figure 1. Double guide vane cascade and calculation domain of Francis turbine

Selecting the pressure-pulse monitoring point is very important to correctly predict the maximum and minimum values of the pressure pulsation and grasp the characteristics of the pressure pulsation. The monitoring points in figure 2 are mainly arranged according to the position of the pressure pulsation of the model test. In order to more accurately measure the vibration of the draft tube under the condition, the monitoring points are arranged on the upstream and downstream sides of the inlet section, the cone pipe section and the elbow section of draft tube respectively.

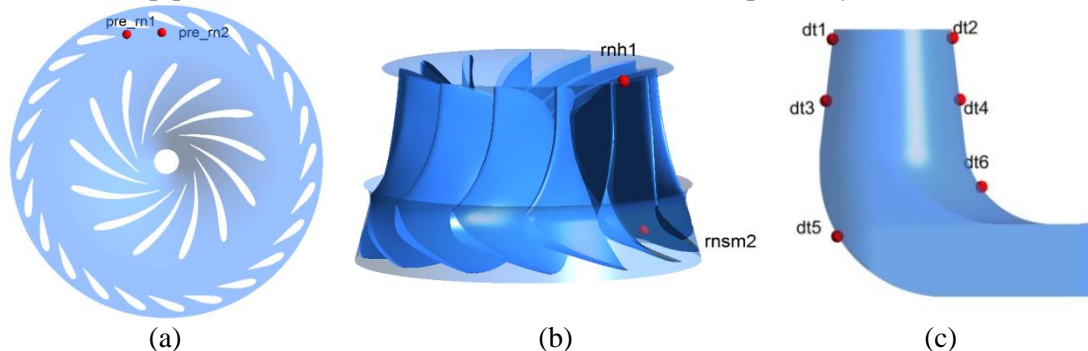


Figure 2. The arrangement of monitoring points

3. Numerical calculation method

The entire calculation model is divided into five parts, volute, stay vanes, double guide vanes, runner and draft tube. In order to improve the computational accuracy, the structured grid is used to discretize the flowing passage, and the guide vane and the runner blade wall corresponding to the encryption process. Through verification of grid independence, the final determination of the mesh is shown in the following table 1.

Table 1. The mesh statistics of each part of entire calculation model

Parts of turbine	Volute	Stay vane	Outer guide vane	Inner guide vane	Runner	Draft tube	Total
The number of mesh/ million	0.39	0.58	1.43	4.8	3.0	0.79	10.99

The finite volume method is used to discretize the control equations. In the difference scheme, the convective term is in the high order difference scheme. The rotor-stator interaction in Francis turbine refers to the interaction between the guide vane and the runner, and between the runner and draft tube. The Transient Rotor Stator mixed model can realize the transmission between the rotor-stator interference surfaces, and it can also calculate the influence of the upstream guide vanes on the downstream flow field. The calculation time step is 0.00172431s.

For boundary conditions, mass flow rate and the flow direction are specified at the inlet, and the average pressure p_0 is given at outlet, the non-slip boundary condition is used in the wall, and the standard wall function is used in the near wall. Firstly, it is used to calculate the whole flow passage in three dimensions, and then the steady result is used as the initial flow field of unsteady calculation.

4. Results

4.1. Analysis of internal flow field

In order to calculate accurately the effect of double-row guide vane on improving the vibrations of vane and draft tube of Francis turbine, a part load condition at which the inter-blade vortex has been occurred in turbine model test is used as calculation point of simulation. According to the turbine model test, the inter-blade vortex has been in the developed state, while a rotating vortex band has been produced in the draft tube.

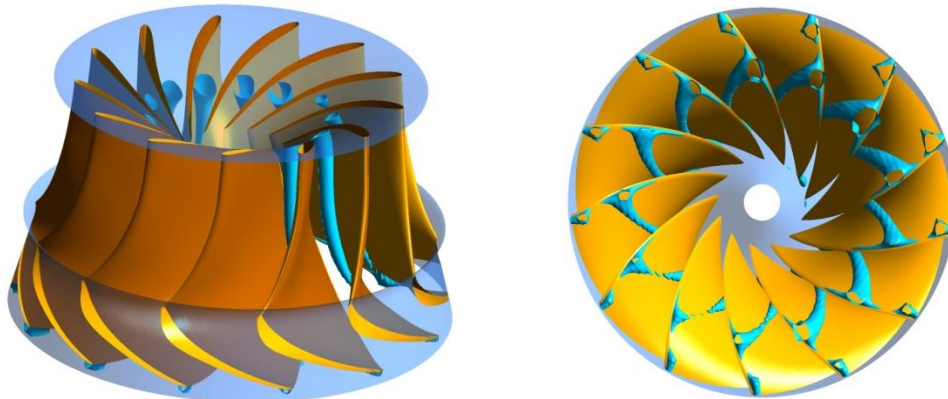


Figure 3. Numerical simulation of the shape of inter-blade vortices

The figure 3 shows the shape of the inter-blade vortices in the runner region, which is calculated by the numerical simulation of the whole flow passage. Under this condition, the pressure in the passage of runner is lower than the vapor pressure, and it has formed a cavity and gradually has developed into a vortex. The inter-blade vortices begin to flow straight from the crown of the blade to the outlet of suction surface.

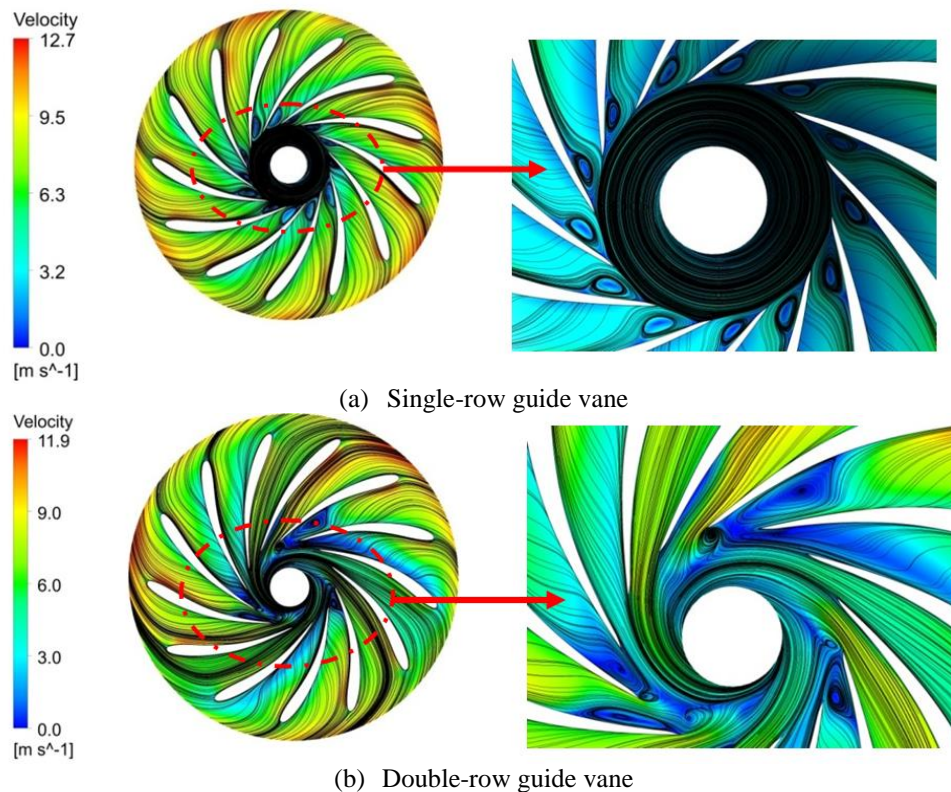


Figure 4. CFD result of the streamline in the runner crown for Single row guide vane and Double-row guide vane.

The operating condition is located in the design flow of 67%, in turbine with single-row guide vane at 14° , flow separation can be seen clearly in figure 4 in the suction surface of blade, and each blade has vortex. In the Francis turbine with double-row guide vane, the number of vortices is reduced to three. It is shown that the adjustment of the double-row guide vanes has played a significant role in improving the flow separation, and the inter-blade vortices have improved distinctly with the increase of the opening of inner guide vane.

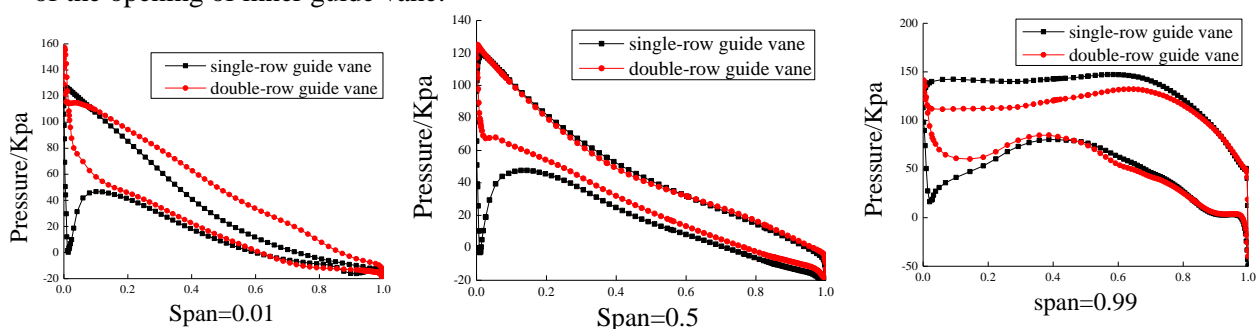


Figure 5. Comparison of pressure distribution of different section of runner blade for single-row guide vane and double-row guide vane.

From the above figure 5 we can see the pressure distribution of blade surface on turbine with double-row guide vane and turbine with single-row guide vane. Compared with the turbine with double-row and the turbine with single-row guide vane, the pressure changes in the blade surface are basically the same, and the pressure in the pressure surface is larger than in the suction surface. From the inlet of runner to the outlet side, the pressure gradually reduced. The pressure in surface of blade in turbine with double-row guide vane is higher than the single-row guide vane, near to the runner crown the change is obvious. In the pressure surface at 0.5 position, the pressure change is not obvious, but in

the 0.99 position, turbine with double-row guide vane is lower than the turbine with single-row guide vane. It has a significant effect to improve the pressure distribution of suction surface and avoid the cavitation phenomenon.

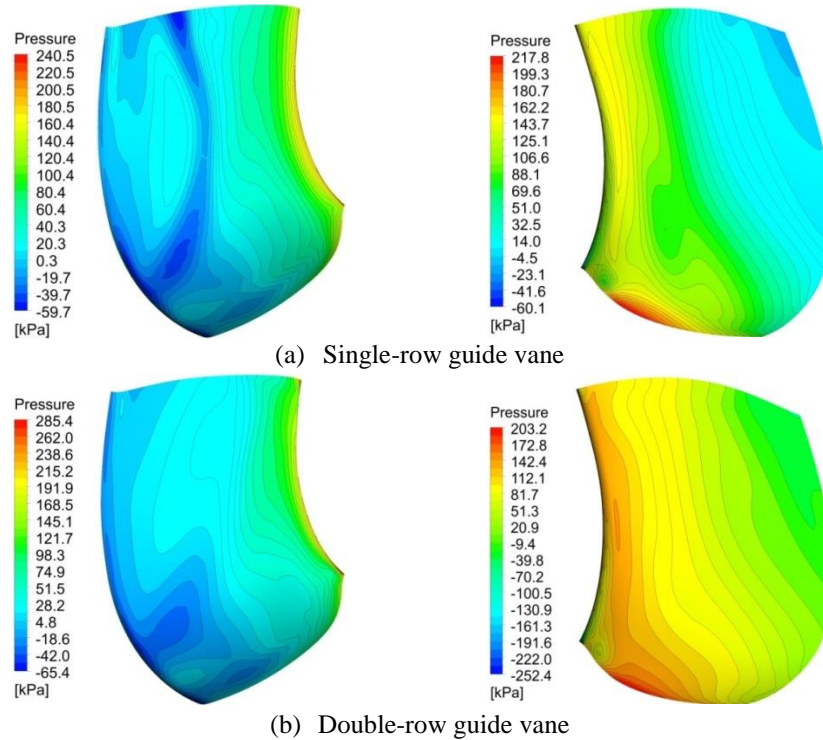


Figure 6. Pressure contours on runner blade surface.

In the case of a single-row guide vane, the development state of apparent inter-blade vortex can be seen in figure 6, from the suction side of the crown position to the suction surface of blade near to outlet of the water. It can be seen from the pressure cloud of single-row guide vane, the lowest point of pressure appears in the crown and the middle of the blade, which are located in the strongest position of the inter-blade vortex, while the pressure surface in the crown near the water outlet there is a negative pressure area.

Compared with the pressure cloud of double-row guide vane, pressure distribution of blade surface has been significantly improved, in the suction surface, the low pressure area has disappeared near the crown, the overall pressure distribution is more uniform than the original.

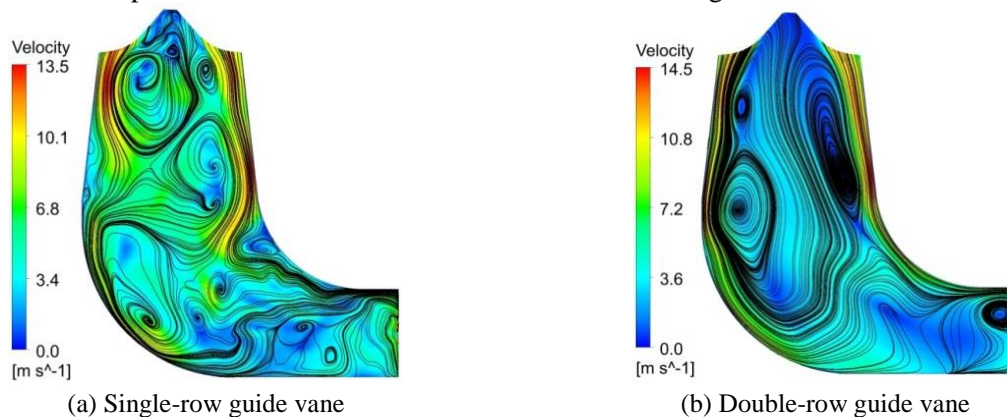


Figure 7. The streamline in the draft tube for Single row guide vane and Double-row guide vane.

As can be seen from the figure 7, from the inlet of draft tube to the elbow section of draft tube, there is a lot of backflow in the draft tube on Francis turbine with single-row guide vane, which seriously hinder the flow of water. In Francis turbine with double-row guide vane, the backflow in the draft tube inlet has relatively reduced.

4.2. Analysis of pressure fluctuation

Unsteady calculation results are shown in the following table 2, in which the pressure of the different monitoring points in the monitoring part in turbine fluctuating over time was recorded and the peak to peak value of pressure fluctuation was obtained. To facilitate the comparative analysis, the ratio of the peak to peak value and water head is used as the amplitude of the pressure pulse. The change of frequency and amplitude of each monitoring point is obtained by fast Fourier transform.

Table 2. The comparison of the amplitude and frequency of the pressure pulsation in the monitoring points on the turbine with double-row guide vane and turbine with single-row guide vanes

Location of monitoring point	The inlet of volute	Before the runner		The inlet of draft tube		Cone section of draft tube		Elbow section of draft tube	
Monitoring point	sp1	pre_rn1	pre_rn2	dt1	dt2	dt3	dt4	dt5	dt6
$\Delta H / H^a$ /%	2.97	3.22	7.96	9.13	9.96	14.67	11.08	4.12	15.14
$\Delta H / H^b$ /%	3.18	24.35	19.12	5.44	5.78	5.66	7.73	6.06	12.80
f^a /Hz	7.25	7.25	265.81	7.25	4.83	7.25	24.16	7.25	16.92
f^b /Hz	7.25	26.58	26.58	265.81	265.81	14.50	14.50	12.08	14.50

ΔH The peak to peak value of pressure fluctuation

H The calculated water head

f The frequency of pressure fluctuation

^a Single-row guide vanes

^b Double-row guide vanes

The amplitude of pressure fluctuation at three different sections of the draft tube is analyzed in the Table 2. It shows that pressure-pulse amplitude of different monitoring points located in upstream and downstream side is not the same, while the difference of pulsing frequency is relatively large. However, the inlet of the draft tube is the strongest place for rotor-stator interference, but the point with the largest amplitude of the pulsation appears in the elbow section. The pressure pulsation in the draft tube is dominated by low frequency pressure fluctuation, which is 7.25Hz about 0.3 times of rotating frequency of runner, at the same time, the secondary pressure fluctuation of one time of rotating frequency of runner (24.16Hz), and 11 times of frequency of runner (265.81Hz) is existed. This low-frequency pressure pulsation will propagate throughout the whole turbine, and the pressure pulsation of the draft tube is the main pulsation source of the turbine pulsation.

Behind the guide vane and before the runner, pressure pulsation is mainly caused by the rotor-stator interference of runner and guide vane, but also caused by the pressure pulsation of draft tube, which has 7.25Hz and 265.81Hz. Pressure pulsating frequency in the inlet section of volute is mainly dominated by low-frequency (7.25Hz) pressure pulsation of the draft tube.

After applying the double-row guide vane, the amplitude of pressure fluctuation in the draft tube has been significantly reduced in the table 2, and the most noticeable location appears where the vortex is the largest.

In figure 8 and figure 9, pressure-pulse data in the two positions at which the pressure pulsation of

inter-blade vortex is most strongly has been analyzed, at the same time, the changes of pressure pulsation in the area of inter-blade vortex on turbine with double-row guide vane and turbine with single-row guide vane are contrasted and analyzed. In the analysis of the figure 8 and figure 9, the pressure-pulse amplitude of the double-row guide vane is significantly lower than the pressure-pulse amplitude of the single-row guide vane at the same monitoring point. In the point of rnh1, the main frequency of single-row guide vane and double-row guide vane is 7.25Hz and 142.57Hz respectively. And in the point of rnsn2, the main frequency of single -row guide vane and double-row guide vane is 7.25Hz and 142.57Hz respectively, while it is existed secondary frequency on single -row guide vane, which is 21.75Hz. Although the frequency increases, the pressure-pulse amplitude has been significantly reduced.

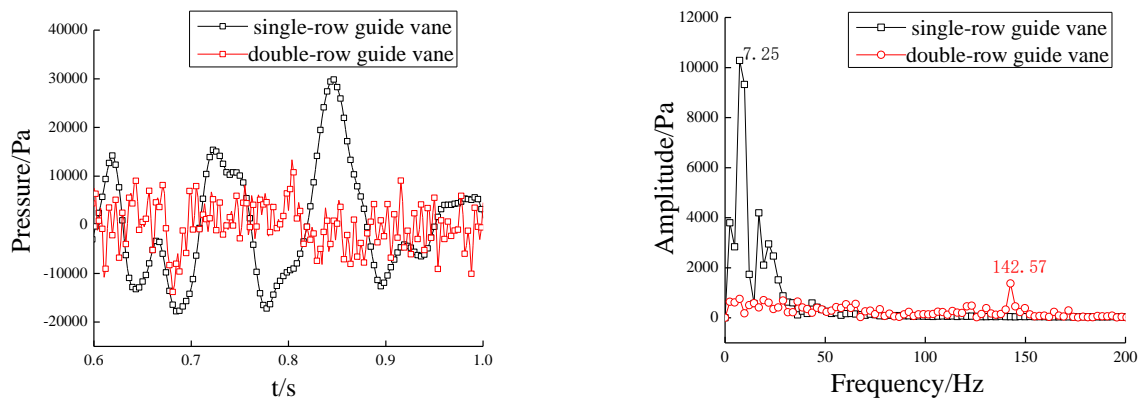


Figure 8. Pressure pulsation at the monitoring point rnh1 for turbine with single-row guide vane and turbine with double-row guide vane.

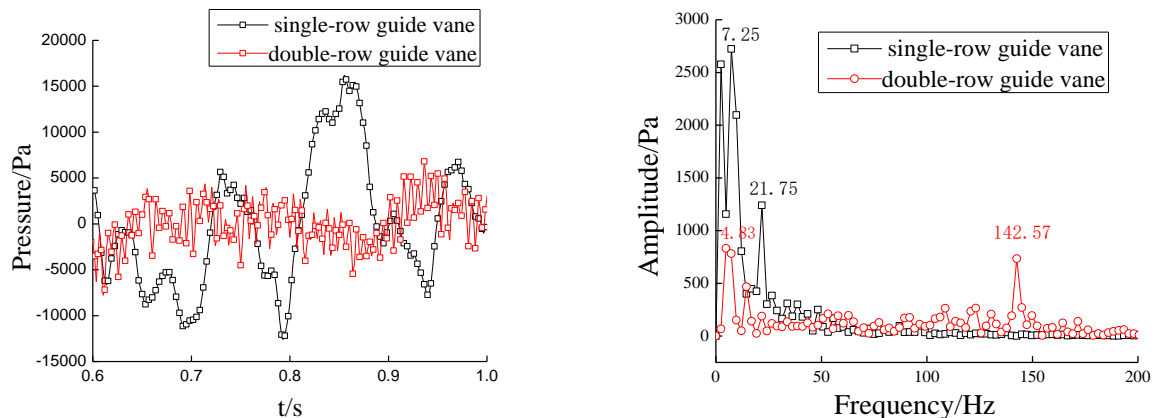


Figure 9. Pressure pulsation at the monitoring point rnsn2 for turbine with single-row guide vane and turbine with double-row guide vane.

5. Conclusion

The double-row guide vanes have higher ability of regulation than the single-row guide vanes, which can effectively improve the matching relationship between the guide vanes and the runners, and also can reduce the pressure-pulse amplitude of the draft tube.

In this research, a large number of vortices appear in the area of the crown and the development of blade vortices can be seen through the pressure cloud of blade on turbine with single-row guide vane.

Through the adjustment of the double-row guide vanes, it can be seen that the number of inter-blade vortices is reduced to three, and it is a significant improvement that inter-blade vortices are reduced from the developed state to the nascent state.

Through the unsteady numerical calculation, it is verified that the pressure fluctuation of the draft tube is the main vibration source of the pressure fluctuation of turbine. In the double-row guide vane, the pressure-pulse amplitude of the draft tube is obviously reduced, and the influence of rotor-stator interference between the guide vane and runner is weakened.

Acknowledgements

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