Numerical study of pressure fluctuations transfer law in different flow rate of turbine mode in a prototype pump turbine

Y K Sun¹, Z G Zuo¹, S H Liu¹, Y L Wu¹, J T Liu², D Q Qin³ and X Z Wei³

¹ State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, 100084, China
² Beijing Institute of Control Engineering, Beijing, 100090, China
³ State key laboratory of hydro-power equipment, Harbin, 150040, China

E-mail: syk11@mails.tsinghua.edu.cn

Abstract. Numerical simulation using SST k-w turbulence model was carried out, to predict pressure fluctuation transfer law in turbine mode. Three operating points with different mass flow rates are simulated. The results of numerical simulation show that, the amplitude and frequency of pressure fluctuations in different positions are very different. The transfer law of amplitude and frequency of pressure fluctuations change with different position and different mass flow rate. Blade passing frequency (BPF) is the first dominant frequency in vaneless space, while component in this frequency got smaller in the upstream and downstream of vaneless space when the mass flow is set. Furthermore triple blade passing frequency (3BPF) component obtained a different transfer law through the whole flow passage. The amplitude and frequency of pressure fluctuations is also different in different circumference position of vaneless space. When the mass flow is different, the distribution of pressure fluctuations in circumference is different. The frequency component of pressure fluctuations in all the positions is different too.

1. Introduction

The pump storage power stations (PSPs) get rapidly developed in recent years. There are many technical problems in pump turbine, which is the most important hydraulic part of PSPs. Hydraulic instability of pump turbine is found as one of the most influence problems, which is mainly caused by strong pressure fluctuations. The start difficulties cause by hydraulic instability has happened in Guangzhou PSPs, Shisanling PSPs, Yixing PSPs, Tianhuangping PSPs and many other PSPs [1-3]. It is very important to study the pressure fluctuations and find the way to reduce the pressure fluctuations.

Many researches have been done to indicate that the pressure fluctuations in vaneless space of the pump turbine are stronger than the other position, which are mainly caused by rotor stator interaction (RSI). The main frequencies of pressure fluctuations in vaneless space are blade passing frequency (BPF) and its multiple frequencies. But little research has focus on the transfer law of pressure fluctuations in different frequencies in circumference direction and vertical direction. In this article, the numerical simulation was done to study the pressure fluctuations in different positions and different flow rate, further to study the transfer law of pressure fluctuations in turbine mode of prototype pump turbine.

2. Numerical method

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2.1. Geometry and operating parameters
The prototype pump turbine of one certain pump storage station is used as simulation geometry in this article. Figure 1 shows hydraulic domain of the pump turbine, which includes spiral casing, stayvanes, guidevanes, runner and draft tube. Table 1 shows the geometry parameter and operating parameter of the prototype pump turbine.

| Table 1. Geometry and operating paremeter |
|-------------------------------------------|
| Geometry parameter                        |
| No. of runner blade | No. of stay& guide vanes | Height of vanes /mm | D1 /mm | D2 /mm |
| 7 | 20 | 595 | 4802 | 3152 |
| Operating parameter (Design in turbine mode) |
| Head/mm | Rotating speed/rpm | Flow rate /m3/s | Specific speed |
| 285 | 300 | 119.9 | 140 |

Figure 1. Hydraulic model

2.2. Mesh generation
The mesh was generated by software ICEM to finish the numerical simulation. Unstructured mesh was used in spiral casing; while structural mesh was used in the other parts of hydraulic model include stayvanes, guide vanes, runner and draft tube. The boundary layers of stayvanes, guide vanes and runner blades are refined to match the requirement of Y+. The total elements number of the whole mesh is set to be 17.3 million according to the mesh independence results. Figure 2 shows the mesh of several parts. Table 2 shows the mesh details in different parts of the model.

| Table 2. Mesh details of different parts |
|-----------------------------------------|
| Type | Inlet | Spiral casing | Guide vanes | Runner | Draft tube | Whole |
| Element number (million) | Structural | Unstructured | Structural | Structural | Structural | 17.3 |
| 0.3 | 7.8 | 1.8 | 5.7 | 1.6 |

Figure 2. Mesh in spiral casing, guide vanes and runner

2.3. Pressure sensors
The pressure sensors were set along two directions in the pump turbine. There are 20 equally distributed sensors along the circumferential direction in the vaneless space (HVS1-20). There are another several pressure sensors along the flow path. They are HC (in the spiral casing), HST2 & HST1 (in the stay vanes), HG (in the guide vanes), HF (at the incircle of guide vanes), HVS (in the vaneless space) and HD (in the draft tube). The pressure sensors are shown in figure 3 and figure 4.

Figure 3. Pressure sensors (top view)  
Figure 4. Pressure sensors (side view)
2.4. Boundary conditions
The boundary condition of numerical simulation is velocity inlet and pressure outlet in the turbine mode. SIMPLEC was used as coupling of velocity and pressure. The discretization scheme of simulation is second order upwind. Time step of unsteady simulation is time of 1/360 rotational circle, which is 5.56E-4 seconds.

3. Accuracy of simulation results
The steady and unsteady simulation results were compared to the experimental results to check accuracy of numerical simulation.

3.1. Accuracy of steady results
Four operating points of total operating range were chosen to check the accuracy of steady results. T1 is the design point of turbine mode. T2, T3 and T4 are operating points with same head but different flow rate. The flow rate of these 4 operating points in the simulation is set as same as experimental data, so the head and efficiency results are compared to the experimental results. Table 3 and figure 5 showed the comparison results. The head and efficiency are almost the same as the experimental data, which proved accuracy of the simulation.

| No. | Head(m) | Efficiency(%) |
|-----|---------|---------------|
|     | Cal.    | Exp.          | Cal. | Exp.  |
| T1  | 280.08  | 285           | 92.9 | 93.5  |
| T2  | 233.68  | 230           | 83.8 | 85.8  |
| T3  | 232.78  | 230           | 90.2 | 91    |
| T4  | 232.27  | 230           | 64.1 | 66    |

Figure 5. (a)Head (b)Efficiency comparison of calculation and experiment results

3.2. Accuracy of pressure fluctuations
The simulation pressure fluctuations of T1 operating point are compared with experimental data to check the accuracy of unsteady results. Table 4 is the simulation and experimental amplitude of pressure fluctuations in HC, HVS and HD, while figure 6 shows the spectrum results. The comparison results show that unsteady results are acceptable.

|     | HC   | HVS  | HD   |
|-----|------|------|------|
| Exp. | 0.8% | 3.7% | 0.73%|
| Cal. | 0.5% | 4.7% | 0.93%|

Figure 6. Frequency comparison between experiment and simulation
4. Results and analysis

4.1. Generally analysis of pressure fluctuations

Figure 7. Amplitude and frequency in different positions of T3

Figure 7 shows amplitude and frequency in different positions in T3 operating points. Pressure fluctuations in vaneless space are much higher than that in the other positions. The frequency is different, too. The first main dominant frequency of pressure fluctuations in vaneless space is BPF. BPF component is very small in spiral casing and draft tube, while 3BPF got larger because the guide vanes’ number is 20 which is almost the same as triple runner blade number (7). Low frequency in draft tube got strong proportion. It is always known that the draft tube vortex caused the low frequency pressure fluctuations.

4.2. Pressure fluctuations in different circumference

Figure 8. Relative amplitude in different circumference in different operating points
The pressure fluctuations characteristic in different circumference positions in the vaneless space is analysed in this part. Figure 8 shows relative pressure fluctuations in different circumference. The position of HVS1-20 can be got from figure 3. Pressure fluctuations are different in vaneless space. When the mass flow rate is small (T2 operating point), the highest pressure fluctuations appear in HVS11. With the mass flow rate increasing, the highest pressure fluctuations positions moves from HVS11 to HVS 12 (T3 operating point) and further to HVS 14 (T4 operating point). The reason of this phenomenon is because when the mass flow rate increases, the velocity in vaneless space is larger. The total flow field moves to downstream, which caused the highest pressure fluctuations position moves to downstream, too.

Figure 9 is amplitude of frequency BPF, 2BPF and 3BPF. The relative pressure fluctuations in operating T3 and T4 showed in figure 8 is similar to the amplitude of BPF in figure 9. While in operating T2, the trend of relative pressure fluctuations in figure 8 is different with trend of amplitude of BPF in figure 9. Because when the flow rate is small, the proportion of BPF, 2BPF and 3BPF is smaller and the proportion of other low frequency is larger.

4.3. Spectral analysis in different position of flow path

The pressure fluctuations characteristic in different positions in the flow path from upstream to downstream is analysed in this part. The different positions mean HC, HST2, HST1, HG, HF, HVS and HD. Figure 10 shows the spectrum analysis of different positions in three operating points. Figure

(a) point T2 (b) point T3 (c) point T4

**Figure 9.** Amplitude of different frequency (BPF, 2BPF, 3BPF) in different circumference

Figure 10 is spectrum analysis of different position

(a) point T2 (b) point T3 (c) point T4

**Figure 10.** Spectrum analysis of different position

(a) point T2 (b) point T3 (c) point T4

**Figure 11.** Proportion ($A_{rel}/\triangle H$) of amplitude of different frequency in different position
11 shows the proportion of different frequencies (BPF, 2BPF, 3BPF and 4BPF) caused by RSI. The proportion is calculated by amplitude of frequency over relative total amplitude \( \left( \frac{A_{fr}}{\Delta H} \right) \). Figure 10 indicated that in the vaneless space (HVS), the BPF is the first main dominant frequency. The component of BPF decreases from vaneless space to upstream and downstream. The proportion of 3BPF in the vaneless space is much less than BPF, but its component almost keeps the same to the upstream and downstream. Figure 11 indicated that BPF mostly influences the vaneless space, while 3BPF influence almost all the flow path.

Figure 10 and 11 show that there are two different kind of RSI frequency in the pressure fluctuations. BPF is the most strong frequency in vaneless space, it influences just near the vaneless space and decrease rapidly to upstream and downstream. 3BPF has a lower amplitude but it influences almost all the flow path and almost keeps same to upstream and downstream.

4.4. Spectral analysis in different flow rate

Table 5 indicates the relative pressure fluctuations in different positions in three operating points. T3 is the highest efficiency point in 230 meter head. The pressure fluctuations are much lower than the other operating points in the same head. Figure 12 show the spectrum analysis of HVS in different operating points. The BPF and its multiple frequency is the dominant frequencies in vaneless space, but some low frequencies get higher in the low mass flow rate point and high mass flow rate point.

### Conclusions

From former analysis, the following conclusion can be get:

Firstly, when the mass flow rate is set, the pressure fluctuations in vaneless space is different in different circumference. Some zones get higher amplitude and others get lower amplitude.

Secondly, when the mass flow rate is set, the component of BPF gets smaller in the upstream and downstream of vaneless space. The component of 3BPF changes little from upstream to downstream.

Thirdly, when the mass flow rate is different, the distribution of pressure fluctuations in vaneless space is different. The zones with stronger pressure fluctuations moves when the mass flow rate get larger or smaller.

Finally, the component of frequency is different when the mass flow rate is different. The component of low frequency (below rotational frequency) gets larger no matter when the mass flow rate increase or decrease.
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