Frequency spectrum analysis for hump characteristic in a pump turbine

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FREQUENCY SPECTRUM ANALYSIS FOR HUMP CHARACTERISTIC IN A PUMP TURBINE

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Abstract

In order to analyze the instabilities during the hump region, three dimensional unsteady incompressible simulations are carried out using SST k-ω turbulence model for a scaled model pump turbine at the 18 mm guide vanes opening in pump mode. And 12 monitoring points are set on the whole pump turbine model passage. Then, pressure fluctuation for different operation conditions is analyzed compared with the best efficiency point. Finally this research states the cause of dominant frequency and the principle of spectrum varying with discharge. The results show that blade passing frequency occurs mainly at the best efficiency point, and for all the monitoring points excluding guide vane inlet point, the value of 0.25 - 1 time rotation frequency feathers obviously higher than the blade passing frequency one with discharge declining, especially in the hump region.

1 Introduction

The current trend of increasing the power output in large hydraulic machinery has led to a rise in the pressure fluctuation, especially for off-design operation conditions. As a consequence, the pressure fluctuation levels have increased and the fatigue problems have become common. It is extremely important to identify the principle of frequency distribution and how to avoid them.

Generally, in large pump turbines, the higher levels vibration usually are originated from the rotor stator interaction (RSI), so a great deal of research has been carried out to analyse the mechanism of RSI. Shi [1], Qin [2], Zhang and Tsukamoto [3] predicted the RSI pressure pulsation with a reasonable accuracy using CFD. Rodriguez [4] carried out a theoretical analysis to predict and explain frequencies and amplitudes in the rotor stator interaction (RSI). Most research about pressure fluctuation concerns about rotor stator interaction. Little research has been done to analyse the pressure fluctuation during the hump region. Wang et al [5] and Yi et al. [6] studied the pressure fluctuations during the small discharge region in a pump turbine in pump mode and the results suggested that low frequency fluctuations are remarkable and the pressure signal in the stay vanes is not affected by the runner while that in guide vanes is influenced obviously. But their research did not concern about the hump characteristics. And the cause of high vibration during the hump region is still unknown.

In this paper, three dimensional unsteady simulations are carried out using SST k-ω turbulence model to investigate pressure fluctuations during the hump region under 18mm guide vanes opening of a pump turbine model in pump mode. 12 pressure fluctuation monitoring points are set in the whole flow passage, including three points in spiral casing, six points in tandem cascade and the three points in draft cone. Detailed analysis is carried out for different components though FFT analysis during the hump region. Based on this analysis, hump characteristics mechanism can be continued. It is valuable for designer and condition analysts in a pump turbine.

2 Numerical Modeling and Computational Details

2.1 Computational Domain

The simulation model includes draft tube (inlet), runner, guide vanes, stay vanes and spiral casing (outlet) as shown in Figure 1. Geometry configuration is established using the UG NX 6.0 commercial software. The parameters of the reduced scale pump turbine are listed in Table 1. 18mm guide vanes opening operation conditions are chosen for simulations.

2.2 Grid Generation

Structured hexahedral grids are generated for each part employed ANSYS ICEM. In order to capture the flow

Figure 1. Computational domain.
Table 1. Parameters of the pump turbine (pump mode).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter of runner at inlet (mm)</td>
<td>274</td>
</tr>
<tr>
<td>Nominal diameter of runner at outlet (mm)</td>
<td>524</td>
</tr>
<tr>
<td>Number of runner blades</td>
<td>9</td>
</tr>
<tr>
<td>Number of stay vanes</td>
<td>20</td>
</tr>
<tr>
<td>Number of guide vanes</td>
<td>20</td>
</tr>
<tr>
<td>The height of guide vane (mm)</td>
<td>45.77</td>
</tr>
</tbody>
</table>

separation of guide vanes, stay vanes as well as runner using SST \( k-\omega \) turbulence model, the mesh layers are more than 10 and \( y^+ \) at the wall layer is less than 11. The total nodes of the grid are 4.5 million and the grids for different parts are shown in Figure 2.

2.3 Boundary Conditions

Total pressure inlet is used at the draft tube (pump mode). The turbulence parameters are specified in terms of turbulence intensity and hydraulic diameter of the inlet. And the mass flow at spiral casing is used for the inlet boundary condition. In addition, smooth no-slip wall condition is imposed for the rest of solid surfaces. Boundary function is adjusted to the low Reynolds number wall function. Moreover all the cases are investigated for the energy characteristic without considering the cavitation. The time step is 1/300 rotating period.

2.4 Numerical Scheme

The software ANSYS CFX is employed for the numerical simulations. And incompressible unsteady Reynolds-Averaged Naiver-stokes equations and mass conservation equations are solved using finite volume method. Two-equation turbulence model is chosen for closing equation. Therefore, SST \( k-\omega \) turbulence model is employed for the simulation. In addition, high resolution scheme is used for the advection term and 1st order upwind scheme is chosen for other terms. The time step is 1/300 rotating period.

3 Detailed Analysis

In this research, four operation conditions points are chosen to analyse comparing with the best efficiency point shown in Figure 3. Figure 3 shows the difference between simulation and the experimental data. The simulation results have a same trend with the experimental data. And fundamental frequency \( f_n \) is rotation frequency about 16.687Hz. Since sample points number and sample time is 1800 and 0.0002s respectively, the frequency resolution is 2.78 Hz.

3.1 Pressure Fluctuation Analysis in Spiral Casing

In order to get the pressure fluctuation in spiral casing, three monitoring points are set in spiral casing outlet. All of the three points are in symmetry plane, which is shown in Figure 4.
Amplitude spectrum of these five operation conditions points are given in Figure 5. Main frequency distribution of sp-1 monitoring point under different operation conditions is listed in Table 2. It can be known that amplitude spectrum of three monitoring points is almost same. The amplitude spectrum under the best efficiency point is simpler than others, which mainly has 0.25 time rotation frequency, 9 times rotation frequency (namely the blade passing frequency) and 18 time rotation frequency. As for 0.94Q_{BEF} operation condition, the second main frequency changes to low time frequency. At the same time, the amplitude of different main frequency increases. When the discharge is reduced to 0.9Q_{BEF} and 0.87Q_{BEF}, the first main frequency changes to 0.5 and 0.75 time rotation frequency respectively and the amplitude has a certain decrease. It can also be obtained that the amplitude between 1 to 3 times rotation frequencies for 0.87Q_{BEF} is half of the ones for 0.9Q_{BEF}. However the amplitude near the 4 times rotation frequency increases. As for 0.8Q_{BEF} point, the first main frequency change to 0.25 time rotation frequency again, and the pressure fluctuation amplitude between 1 and 6 times rotation frequencies increases. Based on unsteady analysis, during this hump region, there appear rotating stall groups with synchronous speed of runner which lead this low time rotation frequencies.

### Table 2. Main frequency distribution for different operation conditions points (sp-1).

<table>
<thead>
<tr>
<th>Points</th>
<th>1st main frequency (f/τ)</th>
<th>Amplitude of 1st (MPa)</th>
<th>2nd main frequency (f/τ)</th>
<th>Amplitude of 2nd (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_{BEF}</td>
<td>0.25</td>
<td>7.139 x 10^{-4}</td>
<td>9</td>
<td>4.525 x 10^{-4}</td>
</tr>
<tr>
<td>0.94Q_{BEF}</td>
<td>0.25</td>
<td>3.298 x 10^{-3}</td>
<td>1.5</td>
<td>1.641 x 10^{-3}</td>
</tr>
<tr>
<td>0.9Q_{BEF}</td>
<td>0.5</td>
<td>2.628 x 10^{-3}</td>
<td>1.25</td>
<td>2.054 x 10^{-3}</td>
</tr>
<tr>
<td>0.87Q_{BEF}</td>
<td>0.75</td>
<td>1.725 x 10^{-3}</td>
<td>9</td>
<td>1.518 x 10^{-3}</td>
</tr>
<tr>
<td>0.8Q_{BEF}</td>
<td>0.25</td>
<td>3.275 x 10^{-3}</td>
<td>3</td>
<td>2.116 x 10^{-3}</td>
</tr>
</tbody>
</table>

3.2 Pressure Fluctuation Analysis in Tandem Cascade

The internal flow in tandem cascade is complex, and the loss in tandem accounts for most. Rotating stall and vortex usually appear from the special guide vane. So, in this research, six monitoring points are set in special stay vane passage and guide vane passage, which are shown in Figure 6.

Figure 5. Frequency spectrum in spiral casing outlet.
From Figure 7, it can be seen that the first main frequency for special stay vane is 0.25 time rotation frequency, and the second main frequency is rotation frequency or blade passing frequency. Figure 7 also shows that the amplitude of different monitoring points under the same operation condition is similar. As for the four points during the hump region, the amplitude of the first and second main frequency gradually decreases along the flow direction. This may come from the effect of vortex motion with guide vanes passages. In addition, the amplitude of sv-3 has an increasing trend with the discharge reducing, but as for sv-1 and sv-2, there is no change. The amplitude spectrum under the best efficiency point still mainly has 0.25 time rotation frequency, 9 time rotation frequency (namely the blade passing frequency) and 18 time rotation frequency. In addition, there appears high amplitude frequency for all the monitoring points between 0 and 6 and during 9 to 10 times rotating frequency.

It can be observed in Figure 8, the gv-3 monitoring point near the rotor stator interaction (RSI) has high amplitudes of 9 and 18 times rotation frequency, and low amplitude for low frequency such as 0.25 time rotation frequency. The amplitudes of 9 and 18 times rotation frequency decrease along with the flow direction while the ones for low frequency increase. This may result of monitoring points far away from rotor stator interaction and the flow gradually becomes complex from guide vanes inlet to outlet. In addition, the main frequency amplitude of gv-2 monitoring point has an obvious rise as the discharge is reduced, while other points have no obvious change. There also appears high amplitude frequency for all the monitoring points between 0 and 6 and during 9 to 10 times rotating frequency as the discharge is reduced. The frequency amplitude of gv-2 is obviously higher that the other points, because separation and vortex usually begins from the centre of guide vanes passages.

3.3 Pressure Fluctuation Analysis in Draft Cone

Backflow usually will appear in the inlet of runner in the small discharge operation conditions. When the discharge continues to be reduced, this area will become large and enter to the draft cone, so three monitoring points are set in draft cone, which are shown in Figure 9.

It can be noticed in Figure 10, the frequency amplitude of dt-2 monitoring point is lowest than the others. As for the best efficiency point, the flow is simple and smooth, there are only 9 time rotation frequency (namely the blade passing frequency) and 18 time rotation frequency. The principle in draft cone is similar with other components. When the discharge is reduced, the main frequency changes from blade passing frequency to low frequency, and high frequencies such as blade passing frequency gradually disappear. During the hump region, the low frequency amplitudes have an obvious rise, while the amplitude of dt-3 monitoring points has no obvious change.

4 Conclusion

The article presents a systematic analysis for pressure
fluctuation during the hump region of a pump turbine model in pump mode under the 18mm guide vanes opening. 12 monitoring points are set in the whole flow passage, and the frequency spectrum is obtained through FFT analysis. The results show that, as for the best efficiency point, the flow is simple and smooth; there are mainly 9 times rotation frequency (namely the blade passing frequency) and 18 times rotation frequency. When the discharge is reduced, especially entering the hump region, the main frequencies change from high time frequencies to low frequencies (0.25 - 1 time rotation frequency) and their amplitudes have an obvious rise. This may result

Figure 8. Frequency spectrum in guide vane.

Figure 9. Monitoring points in draft cone.

Figure 10. Frequency spectrum in draft cone.
from rotating stall or vortex in the flow passages. Based on this research, we can continue to investigate the mechanism of hump characteristic.

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References


