Pressure Pulsation Characteristics of a Model Pump-turbine Operating in the S-shaped Region: CFD Simulations

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Abstract

The most detrimental pressure pulsations in high-head pump-turbines is caused by the rotor–stator interaction (RSI) between the guide vanes and runner blades. When the pump-turbine operates in the S-shaped region of the characteristic curves, the deteriorative flow structures may significantly strengthen RSI, causing larger pressure pulsations and stronger vibration with an increased risk of mechanical failure. CFD simulations were carried out to analyze the impacts of flow evolution on the pressure pulsations in the S-shaped region of a model pump-turbine. The results show that the reverse flow vortex structures (RFVS) at the runner inlet have regular development and transition patterns when discharge reduces from the best efficiency point (BEP). The RFVS first occur at the hub side, and then shift to the mid-span near the no-load point, which cause the strongest pressure pulsations. The locally distributed RFVS at hub side enhance the local RSI and makes the pressure fluctuations at the corresponding sections stronger than those at the rest sections along the spanwise direction. Under the condition of RFVS at the mid-span, the smaller flow rate makes the smaller difference of pressure pulsation amplitudes in the spanwise direction. Moreover, the rotating stall, rotating at 35.7%-62.5% of the runner rotational frequency, make the low frequency components of pressure pulsations distribute unevenly along the circumference in the vaneless space. However, it have little influence on the distributions of high components.

Keywords: Rotor–stator interaction, Pressure pulsations, rotating stall, Pump-turbine, S-shaped characteristics

1. Introduction

The pump-turbines are frequently switched between the pump and generate mode with prolonged operation under off-design conditions, far from the BEP, which may lead to large pressure pulsations and strong vibration with an increased risk of mechanical failure [1-3]. In high-head pump-turbines, the observations in engineering field and model tests both show that the most detrimental pressure pulsation is in the vaneless space [4, 5]. The pressure pulsations in vaneless space are primarily induced by the interaction between runner blades and guide vanes, namely RSI [6, 7]. In S-shaped region, the flow structures in the vaneless space are complicated, and the pressure pulsations are severe. The effect mechanism of different type vortices on pressure pulsations under the RSI is no clear.

Large amount of experimental measurements and numerical simulations have been carried out to investigate the pressure pulsations within the vaneless space. Zobeiri et al. [8] thought the viscous make the velocity field non-uniform in guide vanes, which increases the complexity of RSI. Roth S et al. presented the pressure fluctuations amplitude in the rotor-stator vaneless gap increase linearly with the operating specific energy, subjecting the pump-turbines components to high stresses at high head operations. Trivedi et al. [10] investigate the pressure pulsations of a high head turbine by experiment and numerical simulation, and found that the RSI causes torque oscillation over a particular power generation range and the pressure pulsations propagate up to the trailing edge of the blades. Sun et al. [11] and Xia et al. [12] reported that the highest pressure fluctuations along the circumferential direction occur at positions closing to the volute tongue. Hasmatuchi et al. [13] and Widmer et al. [14] performed model measurements and numerical simulation of the unstable pressure pulsations of a low specific speed pump-turbine at runaway and turbine brake conditions, respectively. The results show the rotating stall with a frequency of propagation about 60% -70% of the impeller speed arises in the vaneless space, which result a substantial increase of the pressure pulsations. Botero et al.
[15] investigated the flow filed at turbine brake mode in a model pump-turbine by wall pressure measurement and structure-borne noise monitoring, and found that the vibration increases slower than pressure pulsations and the vibrations are more severe during the rotating stall inception, while the pressure pulsation are more important when the stall is fully developed. Although the pressure pulsation characteristics within the vaneless space of pump turbines are studied by many researchers, the evolvement laws of pressure pulsations and flow structures within the vaneless space, and correlation between them are still unclear.

In this paper, 3D unsteady simulations were carried out to investigate the pressure pulsation characteristics of a model pump-turbine in S-shaped region. By investigating the evolvement law of vortex structures at the runner inlet and pressure pulsations in vaneless space at many operating points, the effects of different type vortex structures on the distribution and amplitude of pressure pulsations were clarified.

2. Numerical setup

2.1 Computational domain and grid

The computational domains include the whole turbine flow passages, from the spiral case inlet to the draft-tube outlet (Fig.1 (a)). The draft-tube outlet is extended to smooth the swirl flow. The detailed specifications of the model pump-turbine is listed in Table 1, where $D_1$ and $D_2$ stand for the inlet and outlet diameters of the runner, respectively; $z_{in}$, $n_{sw}$, and $n_{gv}$ are the numbers of runner blades, stay vanes and guide vanes, respectively; $n$ is the rotation speed of the runner; $\alpha$ is the guide vane opening (GVO) degree.

<table>
<thead>
<tr>
<th>$n_s$ (m·Kw)</th>
<th>$D_1$ (m)</th>
<th>$D_2$ (m)</th>
<th>$z_{in}$</th>
<th>$n_{sw}$</th>
<th>$n_{gv}$</th>
<th>$\omega$ (rpm)</th>
<th>$\alpha$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.17</td>
<td>0.280</td>
<td>0.1409</td>
<td>9</td>
<td>20</td>
<td>20</td>
<td>1000</td>
<td>15</td>
</tr>
</tbody>
</table>

Hybrid grids were generated for different domains by software ANSYS ICEM. The tetrahedral grids were used in the spiral case; the wedge grids were used in the vane diffuser; the structured hexahedral grids were applied in the runner and draft-tube (Fig.1 (b)). Special refinements were applied in the runner and in the guide vanes domains to match the requirement of $y^+<5$. The total element numbers of the turbine model are set as 7.04 million, according to the grid independence verification.

2.2 Turbulence model and boundary conditions

The unsteady simulations are performed using ANSYS FLUENT. Based on a comparative analysis, the SAS-SST model was applied, which introducing the von Karman length-scale into the turbulence scale equation. The information provided by the von Karman length-scale allows SAS-SST models to dynamically adjust to the resolved structures in the unsteady Reynolds Averaged Navier-Stokes (URANS) simulation, which results in a LES-like behavior in unsteady regions of the flow field. At the same time, the model provides standard RANS capabilities in stable flow regions [16].

The boundary conditions were defined as follows: total pressure was defined at the spiral case inlet, and velocity boundary was applied at the outlet of the draft-tube. The remaining boundary conditions are imposed by the no-slip walls.

2.3 Time step and numerical scheme

During the numerical simulation setup, the results of steady RANS were used as the initial flow field. For the URANS, the time-step was chosen as 0.00025s, corresponding to 240 time steps per revolution. The convergence criteria of the residuals at each time-step were set to 1.0E-5, and the maximum number of iterations per time-step was set to 40. The simulations were conducted in a 16-cores dual-processors Xeon (2.4Hz) workstation. Simulating one revolution consumed about 18-25h, and 6-10 revolutions were needed for the simulation of every operating point.

For both steady and unsteady simulations, the SIMPLEC algorithm was chosen to achieve the coupling solution for the velocity and pressure equations. Second order discretization schemes in time and in space were used.

2.4 Schematic diagram of monitor points

In order to analyze the distribution and propagation of the pressure pulsations within the vaneless space, twenty monitoring points with equal angular intervals (18°) on three sections at different heights were set (see Fig.2 (a)). Three sections locate at hub
side, the mid span, and the shroud side, respectively. As shown in Fig. 2(b), the monitoring points on three different heights were named as nsi (hub side), nzi (mid span) and ndi (shroud side), respectively.

![monitoring points](image)

Fig. 2 Positions of monitoring points within vaneless space

3. Results and Analysis

The internal flow field of the pump turbine is complex in S-shaped region and could not be easily observed through experiments. Therefore, in order to identify the correlation between the pressure pulsation characteristics with the evolution laws of vortex structures at the runner inlet, 21 operating points covering from turbine mode to reverse pump mode at GVO 15° were simulated by URANS. The experiments were carried out on the test rig of the Harbin Institute of Large Electric Machinery. A water head losses control system was adopted to stabilize the machine operation that can enable the testing facilities to get the entire S-shaped characteristic curves. As shown in Figs. 3, the good agreement between the numerical and experimental results demonstrate the reliability of the adopted CFD simulation method.

![characteristic curves](image)

Fig. 3 Characteristic curves of the pump-turbine for GVO 15°

![average flow rate distributions](image)

Fig. 4 Average flow rate distributions along the spanwise at the runner inlet

The evolution laws of the flow patterns at the runner inlet in the S-shaped region were obtained by analyzing the distributions of average flow rate along the spanwise of the circumference surface at the runner inlet, as shown in Fig.4. When the operating condition get away from the BEP, there are two type reverse flow vortex structures (RFVS) at the runner inlet. The RFVS first incept at the hub side of the runner inlet, and the locations translate from the hub to the mid-span near the runaway points. Different RFVS have different effect on the RSI of the runner and guide vanes; thereby the pressure pulsation characteristics corresponding to different RFVS may be different.

3.1 Pressure pulsation amplitudes and reverse flow vortices

The average pressure pulsation amplitudes of aforementioned 20 monitoring points on three different spanwise sections were
provided by supposing on the $n_{11}-Q_{11}$ characteristic curves, as shown in Fig.5. The diameters of the circles are proportional to the respective amplitude. With decreasing the flow rate from the BEP to turbine brake region, the pressure pulsation amplitudes first increase and get highest around the turning point of S-shaped curve. Then, the values decrease gradually with reduced flow rate. In the reverse pump mode, the pressure pulsations are increased with increasing the reverse flow rate. Fig.6 also demonstrates that the pressure pulsations in the vaneless space have significant difference between the three sections when the RFVS occur at the runner inlet. The RFVS not only have influence on the distribution of the pressure pulsations along the spanwise direction, but also in the circumferential direction (Fig.7).

In order identify the spatial distribution characteristics of pressure pulsations, the average pressure pulsation amplitudes of 20 monitoring points at three spanwise sections and their stand deviations are shown in Fig.7. As shown in Fig. 7 (a), when the pump-turbine operates without RFVS occurring at the runner inlet, the amplitude differences between spanwise are little; when the RFVS emerge at the hub side of the runner inlet with decreasing flow rate ($Q_{11}=0.444-0.096\text{m}^3/\text{s}$), the pressure pulsations at the hub side are distinctively stronger than that at the shroud side. At the onset point of the RFVS near the hub side of the runner inlet, the amplitudes differences are largest, and then are reduced with lower flow rate. For each spanwise section, the pressure pulsations amplitudes reach the maxima at the turning point ($Q_{11}=0.044\text{m}^3/\text{s}$) of reverse flow locations translating from the hub side to the mid-span, and get minima when the $Q_{11}$ is -0.021m$^3$/s in the reverse pump mode.

The pressure pulsations amplitude differences along the spanwise and circumference within the vaneless space demonstrate that the RFVS at the hub side lead to more significant differences of the pressure pulsations amplitudes than the vortex structures at the mid-span. Both the pressure pulsations maximum amplitudes for different spanwise and deviations in the circumferential direction occur at the turning point of reverse flow locations translating from the hub side to the mid-span; whereas the maximum amplitudes differences of pressure pulsations for different spanwise occur at the onset point of the RFVS at the hub side of the runner inlet.

$$A_d = \sqrt{(1/20) \sum_{i=1}^{20} (A_i - \bar{A})^2}$$

(1)
Fig. 6 Amplitudes of pressure pulsations at different spanwise within vaneless space

Fig. 7 Characteristics of pressure pulsation amplitudes within vaneless space
3.2 Correlation between pressure pulsations and velocity variations

Further analysis is carried out for ware carried out for the relations between the inverse flow and pressure pulsations. The radial and tangential velocity variations of three monitoring points on the three different spanwise sections are shown in Fig.8. With reduced flow rate, the velocity variations between three monitoring points have significant differences in spatial and time.

![Fig.8 Velocity variations on different spanwise sections of 1st monitoring points](image)

At large flow rate \(Q_{11}=0.120\text{m/s}\) without RFVS occurring, the velocity variations within the vaneless space between runner and guide vanes are regular and small, and are dominated by high frequency. When the RFVS emerges at the runner inlet, the velocity variations become unstable and intense. At the primary stage \(Q_{11}=0.076-0.096\text{m/s}\) of the RFVS emerging at the hub side, the fluids enter the runner at the shroud side with positive radial velocity, while vortices block the rest cross section with negative radial velocity. The RSI between the runner and guides vanes make the tangential velocity at the hub side have more significant pulsations than the shroud side, thereby the pressure pulsations at the hub side are stronger than the shroud side. When the unit flow rate \(Q_{11}\) reduces to 0.032-0.076m/s, the radial velocity variations exhibit a remarkable periodicity with low frequency, which indicate that rotating stall occurs within the vaneless space. The rotating stall vortices block some flow passages and make the runner inflow non-uniform on the circumference, which intensify the local RSI effect. Consequently, the velocity and pressure pulsations in the circumferential direction increased with the occurring of rotating stall.

The features of radial velocity variations under rotating stall condition are different for different type RFVS at the runner inlet. When the RFVS are at the hub side with rotating stall occurring \(Q_{11}=0.055-0.076\text{m/s}\), the radial velocity variations at hub side and shroud side are unsynchronized and have a 180° phase offset, which means the rotating stall emerges alternately at hub side and shroud side of runner inlet. When the RFVS are at the mid span with rotating stall \(Q_{11}=0.032-0.055\text{m/s}\), the radial velocity variations at hub side and shroud side are synchronized, which means the rotating stall occurs simultaneously at hub side and shroud side of runner inlet. At the turning points of revere flow location, the combine actions of rotating stall vortices and RFVS at the hub side lead to the strongest velocity variations within the vaneless space, which resulting most severe pressure pulsations. When the unit flow rate is less than 0.032m/s, the rotating stall disappears.

The rotating stall vortices enhance the momentum exchange between the hub and shroud, which will reduce the amplitude differences of pressure pulsations along spanwise. Therefore, the maximum amplitude differences of pressure pulsations along spanwise occur at the primary stage of the RFVS emerging at the hub side without rotating stall.

3.3 Low frequency component of pressure pulsations

The rotating stall cells rotate with the runner at sub-synchronous frequency [17, 18]. The stall cells will block part flow passages, resulting in periodical fluctuations of flow rate in the runner channels (Fig.9 (a)) and pressure in the vaneless space (Fig.9 (b)). Table 2 shows the frequency of rotating stall and stall cells number. When the RFVS locate at the hub side, there two stall cells occur inside the runner passages (Fig.10), which emerges at hub side and shroud side of runner inlet, respectively. The sub-synchronous frequency of pressure pulsations caused by two stall cells varies from 0.714f_n -1.249f_n, which means that the rotating stall rotates at 35.7%-62.5% of the runner rotational frequency. When the RFVS locate at the mid span, there is only on stall cell inside the runner passages (Fig.11), and the sub-synchronous frequency of pressure pulsations caused by two stall cells varies from 0.499f_n -0.598f_n. The frequency of the rotating stalls decrease with reduced flow rate for two stall cells, while the
frequency increase for one stall cell. These is because the momentum exchanges in the vaneless space that at onset and demise stages of the rotating stall are smaller than that at the full developed stage, so the flow resistances in rotating direction are smaller.
In other words, the more intense of the RSI between runner blades and guide vanes caused by stages frequency increase for. The more exchange of momentum in the vane-space. As a consequence, the increased flow resistance in rotating direction leads to smaller rotational frequency of the stall cells and stronger pressure pulsations.

![Graphical representation](image)

**Fig.9** variations of flow rate and pressure pulsations under rotating stall condition ($Q_{11}=0.044m^3/s$)

**Table 2** Frequency of rotating stalls

<table>
<thead>
<tr>
<th>$Q_{11}/10^3m^3/s$</th>
<th>Location of RFVS</th>
<th>frequency /Hz</th>
<th>Stall cells number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.076</td>
<td>At hub side</td>
<td>20.812Hz (1.249$f_0$)</td>
<td>2</td>
</tr>
<tr>
<td>0.066</td>
<td>At hub side</td>
<td>16.649Hz (0.999$f_0$)</td>
<td>2</td>
</tr>
<tr>
<td>0.055</td>
<td>At hub side</td>
<td>11.897Hz (0.714$f_0$)</td>
<td>2</td>
</tr>
<tr>
<td>0.044</td>
<td>At mid span</td>
<td>9.975 Hz (0.499$f_0$)</td>
<td>1</td>
</tr>
<tr>
<td>0.032</td>
<td>At mid span</td>
<td>9.868Hz (0.592$f_0$)</td>
<td>1</td>
</tr>
<tr>
<td>0.021</td>
<td>At mid span</td>
<td>9.975 Hz (0.598$f_0$)</td>
<td>1</td>
</tr>
</tbody>
</table>

The low frequency components of the pressure pulsations are not uniform on the circumference, as show in Fig.12. At the onset stage with two stall cells in the runner, there are two regions with high amplitude of low frequency components in the vaneless space between the runner and guide vanes, which locate near the volute tongue and the opposite position (Fig12(a)). When there is only one stall cell in the runner, the region with high amplitude cover about the section between the monitoring points n11 to n19. The difference of low frequency components in the circumference should be caused by the spiral case asymmetrical shape, which loads to different pressure recovery abilities in the guide vane passages. The non-uniform pressure distribution make the runner bear large dynamic unstable radial force.

![Graphical representation](image)
4. Conclusions

3D-CFD simulations were performed to investigate the pressure pulsations characteristics and the effect of the vortices at the runner inlet on the pressure pulsations in S-shaped region. The conclusions are drawn as follows:

1. The reverse flow vortex structures at the runner inlet have regular transitions when the operating points get away from the best efficiency point to reverse pump mode in the S-shaped region. The reverse flow vortex structures first incept at the hub side, and the locations translate from the hub to the mid-span near the runaway points.

2. The reverse flow vortex structures at the runner inlet and rotating stall vortices both enhance the pressure pulsations within the vaneless space. However, they have different impacts on spatial distribution of the pressure pulsations. The former make the intensity of pressure pulsations in the vaneless space different along the spanwise direction, whereas the latter make the pressure pulsations distribute unevenly in the circumferential direction.

3. The location of the reverse flow vortex structures at the runner inlet determine the type of the rotating stalls. When the reverse flow vortex structures locate at the hub side of the runner inlet, there two stall cells inside the runner passages, whereas when the reverse flow vortex structures locate at the mid span, there only one stall cell inside the runner passages. The rotating stall vortices enhance the momentum exchange between the hub and shroud, which will reduce the amplitude differences of pressure pulsations along the spanwise direction.

Acknowledgments

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{11}$</td>
<td>Unit rotational speed [rpm]</td>
<td></td>
</tr>
<tr>
<td>$T_{11}$</td>
<td>Unit torque[N·m]</td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>Pressure pulsation amplitude[m]</td>
<td></td>
</tr>
<tr>
<td>$Q_{11}$</td>
<td>Unit flow rate [m³/s]</td>
<td></td>
</tr>
<tr>
<td>$f_n$</td>
<td>Rotating frequency[Hz]</td>
<td></td>
</tr>
<tr>
<td>RFVS</td>
<td>Reverse flow vortex structures</td>
<td></td>
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</tbody>
</table>
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Mechanical Systems and Signal Processing, 48(1), p.15
Francis turbine at several operating points
Cavitation and Dynamic Problems in Hydraulic Machinery and Systems (No. EPFL
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Pressure fluctuation in distributor channel
a centrifugal pump turbine
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