Mechanism study on pressure fluctuation of pump-turbine runner with large blade lean angle

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\textbf{Abstract.} Excessive pressure fluctuations in the vaneless space can cause mechanical vibration and even mechanical failures in pump-turbine operation. Mechanism studies on the pressure fluctuations and optimization design of blade geometry to reduce the pressure fluctuations have important significance in industrial production. In the present paper, two pump-turbine runners with big positive and negative blade lean angle were designed by using a multiobjective design strategy. Model test showed that the runner with negative blade lean angle not only had better power performance, but also had lower pressure fluctuation than the runner with positive blade lean angle. In order to figure out the mechanism of pressure fluctuation reduction in the vaneless space, full passage model for both runners were built and transient CFD computations were conducted to simulate the flow states inside the channel. Detailed flow field analyses indicated that the difference of low-pressure area in the trailing edge of blade pressure side were the main causes of pressure fluctuation reduction in the vaneless space.

\section{1. Introduction}

As large-scale energy storage technology, pumped storage power station (PSPS) plays an important role in load regulation, frequency and phase modulation and black starts in power systems. With vigorous development of smart grid and extensive development of renewable energy, such as nuclear and wind power, many new PSPS are currently being designed and planed in China and around the world \cite{1-3}. As key component of mechanical part of a PSPS, reversible pump-turbine plays the role of hydro energy storage under low demand of grid and electricity generation under high demand of grid. High efficiency, no cavitation and good stability are important standards to evaluate the performance of a pump turbine unit. In real operations, efficiency under pump and turbine modes are usually set as design objectives and hydraulic stability, such as pressure fluctuations within the unit, are difficult to be concerned for its unstable characteristics \cite{4,5}. But the vibration problems caused by excessive pressure fluctuations do exist in PSPS, especially in the vaneless space, may induce mechanical vibrations and even premature mechanical failures \cite{6,7}. Studies to find out the

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mechanism on excessive pressure fluctuations and to bring down the pressure fluctuations to an acceptable extent have great meanings in pump-turbine development.

It is known that rotor-stator interactions (RSI) are the primary causes for the pressure fluctuations in the vaneless space [8]. And potential flow interaction and wake interaction are closely related to the RSI phenomenon, thus influencing the vibration modes in vaneless space [9]. Experimental and numerical researches on pressure fluctuations in both model and prototype pump-turbines were carried out [10,11]. Under optimum conditions, the amplitudes of pressure fluctuations were at the minimum and the dominant frequencies were blade passing frequency (BPF). Under off-design conditions, amplitudes of the pressure fluctuations increased and low frequency components were detected because of the occurrence of rotating stall cell. Factors influencing the amplitude and frequency of pressure fluctuations at different locations in the flow passages were also studied [12,13]. Smaller vaneless gap can cause higher pressure fluctuations in the vaneless space under pump mode and lower pressure fluctuations under turbine operation. Thickness of guide vane has little influence on the pressure fluctuation in the vaneless space, but height of the guide vanes can bring down the pressure fluctuations in the vaneless space under turbine operation. So far as is known to the author, the researches mainly focused on the pressure fluctuations of developed pump-turbines, seldom researches were found to bring down the pressure fluctuations in the vaneless space at design stage of pump-turbine runner.

In present paper, pressure fluctuation characteristics in the vaneless space under turbine operation for two runners with big positive and negative blade lean angle were analyzed in detail. First, the development of two model pump-turbine runners were briefly introduced. Thereafter, the tested pressure fluctuation characteristics of two runners were presented. Finally, transient flow field analysis was conducted to figure out the mechanism of pressure fluctuation difference, which aims at finding out beneficial guidance for reduction of pressure fluctuation in the development stage.

2. Design of pump-turbine runner

The pump-turbine runner designed in this paper was a middle high head with rated head $H_r = 259$ m under turbine operation. The maximum and minimum head were $H_{\text{max}} = 298$ m and $H_{\text{min}} = 239$ m under pump operation, respectively. Compared with other PSPS with close rated head in China, shown in table 1, the head variation range for Liyang PSPS is relatively high, which brings great challenge for hydraulic design of pump-turbine runner. According to the technical condition of model pump-turbine for Liyang PSPS, the pressure fluctuation amplitude in the draft tube, defined as $\Delta H/H$, should be lower than 6% under turbine operation and 2% under pump operation. The pressure fluctuation amplitude in the vaneless space should be lower than 12% under turbine operation and 8% under pump operation.

| PSPS     | Capacity       | Rated head (m) | Variation range ratio |
|----------|----------------|----------------|-----------------------|
| Tongbai  | $4 \times 300$MW | 244           | 1.219                  |
| Liyang   | $6 \times 250$MW | 259           | 1.299                  |
| Heimifeng| $4 \times 300$MW | 295           | 1.228                  |

Based on a design strategy combining 3D inverse design, CFD, DoE, RSM, and multiobjective genetic algorithm (MOGA), the author developed two model pump-turbine runner for Liyang PSPS. The two developed scaled pump-turbine runners are shown in Figure 1, one with rather big positive blade lean angle and the other one with rather big negative blade lean angle. Comparing with conventional pump-turbine runner, the two runners discussed in this paper has rather large blade lean angle[14,15].
3. Test Results

In order to estimate the performances of the designed runners, model tests were conducted on a standard hydraulic machinery test rig in Harbin Institute of Large Electric Machinery in China, which has approximately ±0.2% of composite error for efficiency measurement (Fig. 2). Some important performances, including efficiency, pressure fluctuation and cavitation in pump mode and efficiency, pressure fluctuation and S-shaped characteristics in turbine mode, are tested.

In this paper, the pressure fluctuation characteristics were mainly studied, so only the pressure fluctuation characteristics of test results were presented here. Totally, there are ten monitor points placed in the channel to estimate the pressure fluctuation characteristics, one in the volute, three in the vaneless space, four in the draft cone, two in the draft tube, as is shown in Figure 3. The locations of monitor points in the pump operation are the same as the locations in the turbine operation.
Figure 3. Monitor point location in model tests

Figure 4 shows the pressure fluctuation amplitude in pump operation for two pump-turbine runners with big positive and negative blade lean angle. As is shown, the maximum fluctuation amplitude in the vaneless space is 7.1% and 6.0% for runner with positive and negative blade lean angle, respectively. The maximum fluctuation amplitude in the draft tube is 1.7% and 1.2% accordingly. The maximum fluctuation amplitude of both runners meet the requirement of technical condition, and the unit with a negative runner has better pressure fluctuation characteristics.

![Figure 4](image_url)

**Figure 4.** Pressure fluctuations under pump operation for: (a) runner with big positive blade lean angle; (b) runner with big negative blade lean angle.

Figure 5 shows the pressure fluctuation amplitude of monitor point Ch4 in vaneless space under turbine operation for two runners with big positive and negative blade lean angle. As the head decrease, the fluctuation amplitude will increase. Meanwhile, the fluctuation amplitude under optimum mass flow rate is minimum and begin to increase as discharge decrease. In the stable operation zone under turbine operation[22], the maximum fluctuation amplitude in vaneless space (Ch4) is 24.0% for runner with positive blade lean angle, while the maximum fluctuation amplitude is 12.0% in same location for runner with negative blade lean angle. By comparing the change of amplitude with discharge under minimum head, the runner with big negative blade lean angle has obviously better pressure fluctuation characteristics.
Figure 5. Pressure fluctuations in the vaneless space under turbine operation for: (a) runner with big positive blade lean angle; (b) runner with big negative blade lean angle.

Figure 6 shows the pressure fluctuation amplitude in the draft tube (Ch6) under turbine operation for two runners with big positive and negative blade lean angle. In the stable operation zone, the maximum fluctuation amplitude in draft tube is 9.0% for runner with positive blade lean angle, while the maximum fluctuation amplitude in draft tube is 6.0% for runner with negative blade lean angle. The change of fluctuation amplitude with discharge for runner with positive blade lean angle is also more obvious than the runner with negative blade lean angle.

Figure 6. Pressure fluctuations in the draft tube under turbine operation for: (a) runner with big positive blade lean angle; (b) runner with big negative blade lean angle.

Overall, the pressure fluctuation amplitude under turbine operation is much higher than it under turbine operation, which shows the importance of study on pressure fluctuation under turbine mode. In consideration of the change of amplitude with head and discharge, the operation point with minimum discharge under minimum head has maximum pressure fluctuation amplitude in the stable operation zone. Also, the pressure fluctuation amplitude in the vaneless space is obviously higher than other part, which will be deeply studied in the next part.

Mechanism studies on pressure fluctuation in the vaneless space

3.1. Numerical models
In order to estimate the pressure fluctuation characteristics more accurately, full passage model is built. Five parts are divided from the model for the convenience of meshing, which includes spiral casing, stay vane, guide vane, runner and draft tube, as is shown in Figure 7. Adapted mesh for the computational domain is obtained by commercial software ICEM and TurboGrid. Structured mesh is adopted for most part except the volute tongue for its complex structure. Detailed mesh information and mesh structure for full passage is shown in Table 2.

ANSYS CFX 13.0 is used to conduct the unsteady computation for flow field analyses. Transient rotor-stator model and no-slip wall conditions are imposed for the interfaces between stationary and rotational components. All calculations are conducted in a cluster computer with eight CPUs of Intel 5645 2.4 GHz processor, 96 GB RAM, and 2 TB hard drive.

| Part           | Mesh type         | Number of nodes | $y^+_\text{mean}$ |
|----------------|-------------------|-----------------|-------------------|
| Spiral casing  | Structured & Unstructured | 990 000         | 185               |
| Stay vane      | Structured        | 1 160 000       | 74                |
| Guide vane     | Structured        | 1 050 000       | 57                |
| Runner         | Structured        | 1 450 000       | 51                |
| Draft tube     | Structured        | 1 100 000       | 66                |
| Full domain    |                   | 5 750 000       |                   |

3.2. Transient flow field analysis
Figure 8 shows six transient pressure states in the vaneless space in a period for runners with positive and negative blade lean angle. As is seen, the pressure distribution in the vaneless space is deeply influenced by the rotation of runner. When the edge of blade gets close to the monitor point in the vaneless space, the pressure will decrease. In the same way, as the edge of blade rotates away, the pressure of monitor point will increase. The difference between the minimum and maximum value of pressure directly determines the fluctuation amplitude of monitor point. In the figures, a low-pressure area around the leading edge on the pressure side of blade can also be seen, which affects the pressure of monitor point in the vaneless space with the rotation of runner. Comparing the low-pressure area of two different runners, the runner with positive blade lean angle has larger low-pressure area, thus influencing the pressure fluctuations in the vaneless space more strongly. In combination with the
relatively steady flow in guide vane, the higher pressure fluctuation amplitude of runner with positive blade lean angle can be ascribed to the stronger influence of low-pressure area around the leading edge on the pressure side of blade.

Figure 8. Comparison of pressure distribution in the vaneless space for pump-turbine runner with (a) positive blade lean angle; (b) negative blade lean angle.

Figure 9 shows the transient pressure distribution on pressure side of blade in a period. Under the influence of large blade lean angle, the three-dimensional flow state around high-pressure side of runner is greatly changed. Although the low-pressure area still exists for both runners with different blade lean angle, the locations are quite different. For runner with positive blade lean angle, the low-pressure area is close to hub. For runner with negative blade lean angle, the low-pressure area is close to shroud. Meanwhile, the low-pressure area for runner with positive blade lean angle is still larger.
than the low-pressure area for runner with negative blade lean angle, which agrees well with the two-dimensional analysis of pressure distribution in the vaneless space.

Figure 9. Comparison of pressure distribution in the vaneless space for pump-turbine runner with (a) positive blade lean angle; (b) negative blade lean angle.

Figure 10 shows the transient pressure distribution on suction side of blade in a period. Under the influence of large blade lean angle, the pressure distribution along high pressure side of runner becomes quite nonuniform. In the figures, a high-pressure area exists near hub for runner with positive blade lean angle, and it also exists near shroud for runner with negative blade lean angle, but is smaller. Considering the locations of low-pressure region and high-pressure region, the runner with positive blade lean angle has larger pressure fluctuation amplitude at the hub side and the runner with negative blade lean angle has larger pressure fluctuation amplitude at the shroud side. Considering the area of low-pressure region and high-pressure region, the pressure fluctuation amplitude for the runner with
positive blade lean angle is obviously larger than runner with negative blade lean angle, which validates that pressure fluctuation amplitude can be reduced by imposing suitable blade lean angle.

4. Conclusions
Based on model test results, transient flow field analysis were conducted for two developed pump-turbine runners with big positive and negative blade lean angle, which aims at figuring out the mechanism of pressure fluctuation characteristics in the vaneless space under minimum head and minimum discharge in the stable operation zone.

Under minimum discharge condition, a low-pressure area exists around the leading edge on the pressure side of blade, which affects the pressure fluctuation amplitude in the vaneless space with the rotation of runner. The low-pressure area for runner with positive blade lean angle is larger than the low-pressure area for runner with negative blade lean angle, thus the runner with negative blade lean angle has smaller pressure fluctuation amplitude.

The existence of blade lean angle influences the three-dimensional flow state around high-pressure side of runner greatly. Under different blade lean angle, not only the location of low-pressure area is
changed, but also the area is quite different. By imposing suitable negative blade lean angle at high-pressure side of runner, the pressure fluctuation amplitude in the pump-turbine can be effectively reduced.

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