Influence of cavitation on hump characteristics in a pump-turbine model

D Y Li, S Lin, H J Wang, W W Fu, J X Chen, X Z Wei, D Q Qin

1 School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China;
2 State Key Laboratory of Hydro-Power Equipment, Harbin Institute of Large Electrical Machinery, Harbin 150040, China

Email: lideyou@hit.edu.cn, wanghongjie@hit.edu.cn

Abstract. The hump characteristic in pump mode is one of unique instabilities in pump-turbines. Recently, it is found that the cavitation has a large influence on hump characteristic. Hence, in this paper, a specific speed \( n_q = 36.1 \) pump-turbine model was investigated experimentally in pump mode under different guide vane openings to verify the influence of cavitation on hump characteristic. Firstly, performance characteristic experiments were carried out to obtain the hump characteristics under three cavitation coefficients. Then, observation of cavitation at the runner inlet was conducted using the high speed camera. The cavitation at the runner inlet was presented. Finally, pressure fluctuation experiments were performed to analyse the characteristic frequencies and their variation with the cavitation coefficient. Through the analysis of pressure fluctuations, the hump characteristic is related to the low frequency pressure fluctuations, Analysis reveals that the strength of cavitation at the runner inlet has an obvious influence on low frequency pressure fluctuations, which leads to the change of the hump characteristic.

1. Introduction

Pump-turbine, as the key part of the pumped storage power plant, trend to higher specific speed, higher head and larger capacity. As a consequence, the instabilities becomes more crucial [1, 2]. The hump characteristic at the discharge-head curve is a unique instability of pump-turbine in pump mode. The hump instability has been investigated by lots of researchers. A great mount of achievements have been obtained. The experimental and numerical studies show that the hump characteristic are caused by prorotation and recirculation at the runner inlet [3, 4], rotating stall in the vaneless space and in the stay vanes [5, 6], cavitation at suction surface[7], as well as vortex motion in the stay/guide vanes [8, 9]. Additionally, hysteresis phenomena could be observed in the hump region [10, 11]. Li et al. [1, 12] performed numerical simulations to investigate the generation mechanism of hysteresis phenomena, and concluded that the hysteresis phenomena are caused by the decrease in the work of the runner and the increase in hydraulic loss, which are induced from vortices in the guide/stay vanes and backflow near the shroud at the runner inlet.

Recently, some researchers have found that the cavitation has obvious influence on the hump characteristics. Lu et al. [13] carried out the experimental study to validate that the cavitation has a large influence on the hump characteristic. Liu et al.[7] performed the numerical simulation to predict
the pump characteristic, and found that the numerical results through the improved cavitation model has a better agreement with the experiments compared with those without considering cavitation. Liu et al. [14] validated the hump characteristic was affected by the cavitation number through experimental investigation. Combining with numerical simulations, they concluded that the hump region will become weak until vanish with the decreasing of the cavitation number.

In a sum, the hump characteristics have been studied by lot of researchers through experimental and numerical methods, which could give a deep understanding on the generation mechanism of hump characteristics. However, the influence cavitation on the hump characteristics is not clearly. In this study, experimental studies were carried out to investigate the influence on the hump characteristics under different guide vane openings (GVOs), in a high head pump-turbine model through high speed camera and pressure fluctuations experiments. Firstly, the detail of experimental set-up was introduced. Secondly, performance characteristics experiments under three cavitation coefficients were carried out to validate the influence of cavitation on hump characteristics. Thirdly, flow pattern observation experiments at the runner inlet in pump mode was performed to show the cavitation conditions. Finally, pressure fluctuation experiments were conducted to study the the influence of cavitation condition on characteristic frequencies and their amplitudes.

2. Experimental set-up

2.1. Pump-turbine model specification

Under investigation pump-turbine model is scaled down (1:9.24) from a real pumped storage power plant in China. It is a single stage, vertical shaft, low specific speed ($n_q=36.1$), Francis pump-turbine as show in Figure 2. The pump-turbine consists of a runner with 9 blades, 20 guide vanes, 20 stay vanes including a special one, a draft tube and a spiral casing. The detailed information about main parameters is listed in Table 1.

![Figure 1. The pump-turbine model.](image)

Table 1. Main parameters of the pump-turbine model.

| Parameter                  | Symbol | Value  | Description       |
|----------------------------|--------|--------|-------------------|
| Specific speed             | $n_q$  | 36.1   | pump mode         |
| Runner inlet diameter      | $D_1$  | 0.250m | pump mode         |
| Runner outlet diameter     | $D_2$  | 0.450m | pump mode         |
| Guide vane height          | $B_0$  | 0.04373m |                 |
| Guide vane distribution    | $D_0$  | 0.54117m |                 |
| diameter                  |        |        |                   |
| Optimum GVO                | $GVO_{BEP}$ | 25mm | pump mode         |
| Investigated GVOs          |        | 19mm, 22mm, 25mm, and 28mm |
2.2. Test rig

The measurements in this research were carried out in Harbin Institute of Large Electrical Machinery (HILEM), in which six test rigs are available for turbine, pump-turbine and pump performance assessment in a closed loop (maximum head=80m, maximum discharge=0.8m$^3$/s) with an accuracy of 0.2%. The sketch of the test rig is shown in Figure 2. In pump mode, the water from the basement was pumped through an addition water supply pump to inlet pipe connected with draft tube, and then passed through the runner, guide vanes, stay vanes, and the spiral casing, finally through the downstream tank back to the basement. Measurement system was programed by LabVIEW 2014, and NI PXI platform with a PXI-8336 controller and a PXI-1042Q chassis was chosen. Digital, current and pressure signals could be measured with a high sampling rate. Detailed information for the measurement system was described in the reference [15].

![Figure 2. Schematic diagram of the test rig.](image)

3. Performance Experiments and Analysis

Performance characteristics of the pump-turbine in pump mode were carried out under three cavitation conditions at 19mm, 22mm, 25mm and 28mm GVOs, namely in the experiments, the cavitation coefficient was changed through the changing the pressure at draft tube inlet. All the experiments were processed strictly following the standard of International Electrotechnical Commission (IEC)[16], and all the uncertainties are below 0.2%. Performance parameters are normalized according to following equations.

\[ E_{ao} = \frac{gH}{n^2D_i^2} \]  
\[ Q_{ao} = \frac{Q}{nD_i^\gamma} \]  
\[ T_{ao} = \frac{T}{\rho n^2 D_i^5} \]  

Figure 3 depicts the performance characteristics (energy, torque and efficiency) under three coefficients ($\sigma=0.14$, 0.18 and 0.22) at 19mm, 22mm, 25mm and 28mm GVOs. It could be found that the hump characteristics were obviously influenced by cavitation conditions. At small GVO (19mm), with the decreasing of the coefficient, from operating condition $\sigma=0.22$ to operating condition $\sigma=0.18$ the value of the wave peak (point A) drops obviously and the efficiency has a certain decrease. When the cavitation coefficient continually decreases, the value of performance at the point A has no change. Moreover, the performance characteristics including energy, torque and efficiency has no obvious change for the other operating points outside the hump region. At 22mm GVO, with the decrease of the cavitation coefficient, some small decreases in the energy characteristics and efficiency at wave trough point B in the hump region could be observed. At 25mm GVO, obvious decreases in the energy characteristics and efficiency at operating point C could be found when the cavitation coefficient
decreases from 0.22 to 0.18, while there are no changes when the coefficient is reduced from 0.18 to 0.14. The variation law is the same with that at 19mm GVO. At large GVO (28mm), only some small decreases in the energy characteristics and efficiency at point D could be observed when the cavitation coefficient decreases. The variation law is almost the same with that at 22mm GVO.

It could be concluded that, the hump characteristics were influenced by cavitation conditions. Moreover, under different GVOs, the degree of influence is different.

Figure 3. Performance characteristics under different cavitation condition, (a) 19mm GVO, (b) 22mm GVO, (c) 25mm GVO, (d) 28mm GVO.

4. Flow Patterns Observation Experiments and Analysis

When performance characteristics experiments were conducted, the flow patterns observation experiments at the runner inlet were performed simultaneously. Figure 4 gives the observation results at operating point A under three coefficients at 19mm GVO. Sheet cavitation at the leading edge of suction surfaces could be observed. As the cavitation coefficient is reduced, the area of sheet cavitation increases. Hence, the decrease in performance characteristics at 19mm GVO might be related to the sheet cavitation at leading edge of suction surfaces.

Figure 5 gives observation results at operating point B under three cavitation coefficients at 22mm GVO. When the cavitation coefficient σ=0.22, sheet cavitation at leading edge of suction surfaces could be found. As the cavitation coefficient is reduced to 0.18, sheet cavitation disappears, and cavitation due to secondary vortices at the runner inlet could be observed. As the cavitation coefficient continues to reduce to 0.14, sheet cavitation appears again, and cavitation due to secondary vortices becomes more severe. Hence, at 22mm GVO, the drop in energy characteristics might be related to the cavitation due to secondary vortices and sheet cavitation.

Figure 6 shows observation results at operating point C under three cavitation coefficients at 25mm GVO. It can be seen that, when the cavitation coefficient σ=0.22, sheet cavitation at leading edge of suction surfaces could be found. When the cavitation coefficient σ=0.18, cavitation due to secondary vortices appears. When the cavitation coefficient σ=0.14, sheet cavitation turns to cloud cavitation, and cavitation due to secondary vortices becomes more severe. At this point, the drop in performance characteristics is quite obvious when the cavitation coefficient is reduced to σ=0.18 from σ=0.22.

Figure 7 depicts observation results at operating point D under three cavitation coefficients at 28mm GVO. It can be found, as the increase of the GVO, the cavitation conditions turn well. Cavitation due to secondary vortices disappears for all three cavitation conditions. When the cavitation
coefficient $\sigma=0.22$, no cavitation could be observed. As the cavitation coefficient is reduced, the sheet cavitation appears, and the cavitation area at the leading edge of suction surfaces increases sharply.

![Figure 4](image_url)

**Figure 4.** Cavitation at runner inlet at point A under 19 mm GVO, (a) $\sigma=0.14$, (b) $\sigma=0.18$, (c) $\sigma=0.22$.

![Figure 5](image_url)

**Figure 5.** Cavitation at runner inlet at point B under 22 mm GVO, (a) $\sigma=0.14$, (b) $\sigma=0.18$, (c) $\sigma=0.22$.

![Figure 6](image_url)

**Figure 6.** Cavitation at runner inlet at point C under 25 mm GVO, (a) $\sigma=0.14$, (b) $\sigma=0.18$, (c) $\sigma=0.22$.

![Figure 7](image_url)

**Figure 7.** Cavitation at runner inlet at point D under 28 mm GVO, (a) $\sigma=0.14$, (b) $\sigma=0.18$, (c) $\sigma=0.22$.

5. **Pressure Fluctuation Experiments and Analysis**

To investigate the pressure fluctuation in the pump-turbine, 12 monitoring points are set in the experiments. As shown in Figure 8, 1 point in the spiral casing (SC1), 1 point in the stay vanes (SV1), 2 points in the vaneless space (RG1 and RG2), 2 points in the guide vanes (GV1 and GV2), 1 point at the top cover (TC1), 1 point at the bottom shroud (BS1), 2 points in the cone of the draft tube (CT1 and CT2), and 2 points in the elbow of the draft tube are mounted. Moreover, the phase difference between RG1 and RG2 is $90^\circ$ at the same circumference, which is the same for monitoring points GV1 and GV2.
All the data of pressure fluctuation are normalized according to the equation (4).

\[ C_n = \frac{p - \bar{p}}{\frac{1}{2} \rho U^2} \times 100\% \quad \text{(4)} \]

**Figure 8** Monitoring points of pressure fluctuations corresponding experiments, (a) front view, (b) overhead view.

The comparison of frequency spectrum among the three cavitation conditions at 12 monitoring points at 19mm GVO was shown in Figure 9. In the elbow of draft tube, the main frequency is 3.12\( f_n \), and low frequencies could be found. When the cavitation coefficient is reduced, the amplitudes of all characteristics show an increase trend. And the low frequency 0.078\( f_n \) increases to 0.096\( f_n \). This might come from two reasons. The first one is the due to change of the cavitation conditions. The second one might be the difference of the discharge. This needs to be investigated in future. In the cone of the draft tube, comparison results are the same with those in the elbow of the draft tube. However, the amplitudes of characteristic frequencies show a little higher than those in the elbow. In a sum, the cavitation has obvious influence on the pressure fluctuation in the draft tube, especially in the cone of the draft tube.

In the vaneless space, guide vanes, stay vanes, spiral casing, top cover and bottom shroud, no obvious differences could be found. Hence, at the current cavitation conditions, the cavitation has no obvious influence on pressure fluctuation of other operating points.
Figure 9. Frequency spectrum at point A under 19 mm GVO. (a) ET1, (b) ET2, (c) CT1, (d) CT2, (e) RG1, (f) RG2, (g) GV1, (h) GV2, (i) SV1, (j) SC1, (k) TC1, (l) BS1.
Figure 10 shows the comparison results under three cavitation coefficients at operating point B at 22mm GVO. It can be found that cavitation has an obvious influence on low frequencies ($f_n \sim 3f_n$) in the draft tube, while no obvious differences could be found for other monitoring points.

Figure 11 gives the comparison results under three cavitation coefficients at operating point C at 25mm GVO. The analysis results are the same with those at 22mm GVO.

Figure 12 depicts the comparison results under three cavitation coefficients at operating point D at 28mm GVO. Through the comparison, it can be concluded that the cavitation only has a small influence on low frequencies in the draft tube. No obvious influences on the characteristic frequencies for other monitoring points.

Figure 10. Frequency spectrum at point B under 22 mm GVO, (a) ET1, (b) CT1, (c) RG1, (d) GV1.

Figure 11. Frequency spectrum at point C under 25 mm GVO, (a) ET1, (b) CT1, (c) RG1, (d) GV1.
6. Conclusions

In this study, the performance characteristic, flow pattern observation and pressure fluctuation experiments were carried out to investigate the influence of cavitation on the hump characteristic in pump mode of a pump-turbine model. Based on this study, some achievements could be obtained as follows.

1) Hump characteristics in pump mode were influenced by cavitation. Under different GVOs, the degree of influence is different.

2) The drop in energy characteristics might be related to the sheet cavitation at leading edge of suction surface, and cavitation due to secondary vortices at the runner inlet.

3) When the cavitation coefficients is reduced from 0.24 to 0.14, cavitation has obvious influences on low frequencies in the draft tube. Due to existence of the cavitation at runner inlet, some low frequencies induced by cavitation could be found. As the cavitation coefficients is reduced, the frequencies and the amplitudes are influenced, which leads to the increase in hydraulic loss.

Based on present study, numerical simulation should be carried out in future to investigate deeply the influence mechanism of cavitation on hump characteristics.

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