Experimental Investigation on Hump Characteristics of a Pump Turbine

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Abstract. With the upgrading of the world energy resources structure, the proportion of clean energy has gradually increased, and investment in the construction of Pumped Storage Power Station has increased around the world. As the core component of energy conversion, studying the operational stability of pump-turbine is of great significance. This study focuses on the hump region of reversible pump-turbine in pump mode, using experimental testing methods, energy experiments are conducted with different guide vane openings and flow rate coefficient. Besides, the hump coefficient is defined to quantitatively analyze the hump characteristics. Combining quantitative and qualitative analysis, research has shown that the hump coefficient is relatively high under small guide vane opening and small flow rate, indicating that the hump phenomenon is more obvious, and unstable operation has occurred under this operating condition. At the same time, this study also provides a reference for relevant research in terms of analytical and research methods.

Keywords: Reversible Pump-Turbine, Hump Region, Experimental Test, Operational Stability.

1 Introduction

With human evolution and emergence of populations, human society has developed, and human inevitably need to use energy for production and life [1]. Developing and utilizing renewable and clean energy is an inevitable trend in the history of human energy evolution for the sustainable development of human society.

Throughout the current stage of human development and utilization of solar energy, hydraulic energy, tidal power, biomass energy and other clean energy, hydraulic energy has been widely used in the field of power generation due to its energy conversion rate, conversion stability, and excellent peak shaving and frequency regulation capabilities [2]. With the upgrading of the global energy structure to the direction of continuous renewable, clean and pollution-free, the number of Pumped Storage Power Station (PSPP) has steadily increased around the world. As the core of energy conversion of PSPP, the operation stability, reliability and efficiency of reversible pump-turbine are of great significance to the economic benefit, safety and stability of the whole power

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station. Pumped Storage Power Station plays the role of peak load regulation and valley filling in the power grid [3]. Among them, the reversible pump-turbine enters into turbine mode to generate electrical energy during peak power consumption in the power grid, while the electricity consumption in the power grid is low, the unit enters into pump mode for energy storage [4].

The hump characteristic of pump-turbine refers to the presence of a hump region on the head characteristic curve. The pipeline characteristic curve and head characteristic curve may generate multiple intersections, and the operating conditions may repeat between multiple operating conditions, causing significant energy fluctuations in pump-turbine and posing a threat to the safe and stable operation of the unit [5]. Especially when operating under high head and low flow rate conditions, the hump region cannot be avoided. Li et al [6]. conducted a study on the hump characteristics of low specific speed pump-turbine and found that the instability of the hump is the result of the combined action of Euler momentum and hydraulic losses. Different Euler momentum and hydraulic losses in the two processes lead to the hysteresis phenomenon in hump region. Guo et al [7]. found that guided wave blades with biomimetic leading-edge protrusions can effectively improve the hump characteristics of pump-turbine. However, a small amount of experimental data will lead to the problem of insufficient hump characteristics and limited comparison between multiple working conditions.

This study carried out analysis based on experimental measurements of head characteristics under different guide vane openings on a pump-turbine model. Under the same guide vane opening, experiments are conducted on different flow rate conditions by adjusting the valve. The hump characteristic of multiple guide vane openings in pump mode are obtained. In addition, the quantitative analysis of energy fluctuation in the hump region is provided by defining the hump coefficient, which also provided reference for the study of hump characteristics of reversible pump-turbine.

2 Experimental setup

The experimental test of this study is aiming at a reversible pump-turbine unit, and the meridional view of runner and guide vane is shown in Fig. 1(a), and the photo of whole pump-turbine unit is shown in Fig. 1(b). The main flow passage components of the unit include: volute, stay guide vane, guide vane, runner and draft tube. In pump mode, the fluid flows into the unit from the water tank connected to draft tube component to the water tank connected to the volute component.

By adjusting the guide vane openings, explore the hump characteristics on its head performance curve. The guide vane opening (α) studied in this study ranges from 8 degrees to 26 degrees. The geometric size ratio between the real unit model and the test model is 10:1.

The photo of test rig is shown in Fig. 2. The entire model test rig consists of fluid circulation line and data transmission line. This test rig for hydraulic machinery can be used for energy testing of reversible pump-turbine. This study mainly focuses on hump characteristic tests in pump mode. All test parameters of the test rig, such as model size and Reynolds number, all meet the relevant provisions of the test rig standards. All test signals are collected by sensors and wirelessly transmitted to computer terminal.

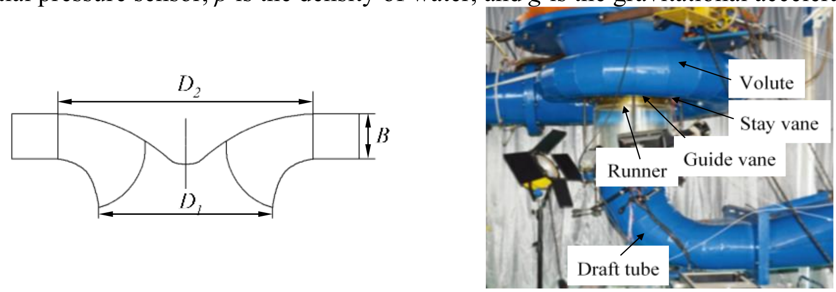
During the hump characteristic test, the main task is to determine the relationship between head (H) and flow rate (Q) under pump mode. This test changes the resistance in the system by changing the regulating valve in the pipe system on the high-pressure side at a constant speed, so as to regulate the flow rate of the unit and test different working conditions. Under the same guide vane opening, experiments are conducted on different flow rate conditions by adjusting the valve.

Throughout the entire test process, the speed was measured by E6B2-CWZ1X speed encoder which is connected to the generator shaft. The IFC090 electromagnetic flowmeter is used to measure the flow rate under various working conditions. The instrument error does not exceed ± 0.2%. The head under pump mode is measured using ROSEMENT3051 differential pressure sensor installed at the inlet and outlet of the model, the instrument error does not exceed ± 0.05%.

The head value is calculated by Eq. (1).

$$H = \Delta P / \rho g \tag{1}$$

Among them, $\triangle P$ is the inlet and outlet pressure difference measured by the differential pressure sensor, ρ is the density of water, and g is the gravitational acceleration.



(a) Meridional view of runner and guide vane

(b) Photo of whole pump-turbine unit

Fig. 1. Model of objective pump-turbine.

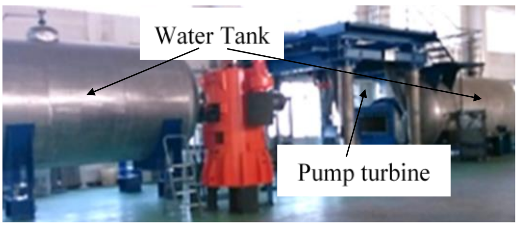


Fig. 2. Photo of test rig.

When studying the hump characteristics in pump mode, this study adopts the dimensionless parameters ψ (head coefficient) and φ (flow rate coefficient) to characterize, the expressions of which are as follows:

$$\psi = 2gH / u_2^2 \tag{2}$$

$$\varphi = Q / \pi\omega r_2^3 \tag{3}$$

Where u_2 is the tangential velocity of runner.

3 Hump characteristics

Due to the bidirectional operation of reversible pump-turbine, it cannot be guaranteed that both operating conditions are within the optimal performance range of their respective operating modes. Therefore, in the design process, it is necessary to focus on one operating mode and comprehensively consider the other. For the pump mode and turbine mode, the working conditions of the pump mode are relatively difficult, belonging to decelerated and pressurized flow, and are prone to flow separation and cavitation during operation. Therefore, in the design process of reversible pump-turbine, it is often ensured that the pump mode operates within the optimal range, and the corresponding turbine mode is verified. This design method often ensures that the majority of working conditions operate in efficient and stable areas. However, there is an unstable region on the head characteristic curve with high head and low flow rate in pump mode. The intersection of positive and negative slopes will appear on the operating curve, often referred to as the hump region. This study is an experimental study on the hump characteristics under different guide vane openings.

4 Experimental Results

Through the above test rig and method, the hump characteristic curves under different guide vane openings are shown in Fig. 3. From the figure, it can be seen that at each guide vane opening, as the flow rate coefficient increases, the head coefficient shows a downward trend, but it is accompanied by a hump region generated by the intersection of positive and negative slopes. The energy fluctuation of the unit in this area is large, which can cause unstable operation of the unit and cause vibration and other problems.

Figure. 4 shows an enlarged view of the hump characteristic curve under different guide vane openings. Cut the curve to a data point after the intersection of positive and negative slopes of the curve, and magnify the hump region which is the intersection of positive and negative slopes ender different guide vane openings. It can be seen that in the case of a small guide vane opening, the hump region on the curve is more obvious, and the intersection of positive and negative slopes appears at the position with smaller flow coefficient. As the guide vane opening increases, when the opening is 18 degrees and 22 degrees, there is no obvious intersection of positive and negative slopes. As the guide vane opening further increases, the hump region appears in areas with smaller flow rate coefficients under large opening conditions. This indicates that the hump phenomenon is more likely to occur in low flow rate conditions, where energy fluctuations are greater.

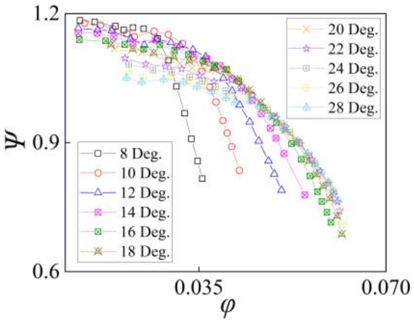


Fig. 3. Experimental results of hump characteristics.

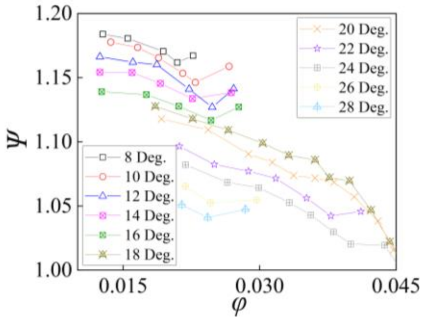


Fig. 4. Enlarged view of hump region under different guide vane openings.

On the premise of confirming the occurrence of a hump region with the intersection of positive and negative slopes, as shown in Fig. 5, the difference between head coefficient of the intersection point of positive and negative slopes and the mean head coefficient of adjacent two points is defined as the hump coefficient (τ)，which is used to represent the amplitude of energy decrease when the hump is generated, and its expression is Eq. (4). For working conditions without obvious hump region, assign a negative value to the hump coefficient.

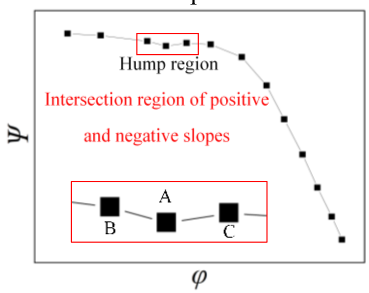


Fig. 5. Auxiliary diagram for defining hump coefficient.

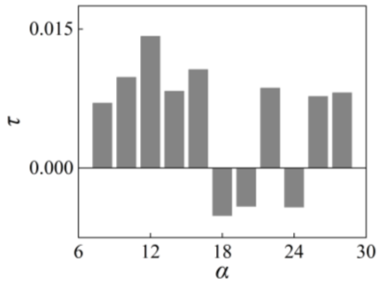


Fig. 6. Auxiliary diagram for defining hump coefficient.

$$\tau = (\psi_B + \psi_C)/2 - \psi_A \tag{4}$$

Among them, Ψ_A, Ψ_B, Ψ_C represents the head coefficient values of points A, B, and C.

Figure. 6 shows the values of hump coefficients at various openings. It can be seen that when the guide vane opening is less than 16 degrees, the value of τ is relatively large, and when the guide vane opening is 12 degrees, the value of τ reached maximum. This quantitatively indicates that under small opening conditions, the hump is more obvious, the energy fluctuation of the unit is large, and the unstable operation phenomenon is more obvious. As the guide vane opening increases, the value of τ becomes negative or significantly decreases, indicating that the hump is not the main factor affecting the unstable operation of the unit during large guide vane opening operation.

5 Conclusion

The hump characteristic in the pump mode of pump-turbine is one of the important reasons for unstable operation. To further explore the hump characteristics of pump-turbine, this study is based on energy tests conducted on different guide vane openings. From qualitative and quantitative angles, the experimental test results of hump characteristics under different guide vane openings are analyzed, and the following conclusions are obtained:

1. This study provides a detailed introduction to experimental method for the energy characteristics of hydraulic machinery, and hump characteristic curves under the different flow rate conditions and guide vane openings are obtained.
2. This study compares the hump characteristic curves of different guide vane openings and finds that under low opening and low flow rate conditions, the hump region is more obvious, indicating that the operating stability of this condition is worse and should be avoided as much as possible during operation.
3. This study proposes and defines the head coefficient to quantitatively analyze the head loss in hump region of pump turbine under different guide vane openings, it also provided a quantitative analysis reference for other studies.

Acknowledgments

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