Predicting the Inception Cavitation of a Reversible Pump-Turbine in Pump Mode

Ran Tao¹, Ruofu Xiao¹, Di Zhu¹, Weichao Liu²

¹College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
²Dongfang Electric Machinery Co., LTD, Deyang, Sichuan Province 618000, China

E-mail: xrf@cau.edu.cn

Abstract. Inception cavitation is a crucial indicator for reversible pump-turbines especially in pump mode. In actual applications, it is difficult to use CFD for the inception cavitation character. In this study, CFD simulation is conducted to find a proper way to evaluate the inception cavitation, different levels of vapor volume fraction in the impeller is predicted based on the tested results. Results show that the prediction of the location and scale of cavitation is accurate. The predicted cavitation number also matches the experimental data well. The vapor volume fraction levels from 0.0001% to 0.001% are recommended as the criterion of inception cavitation.

1. Introduction

Cavitation is crucial for hydraulic turbo-machinery because it will cause noise, vibration and damage to the components. Conducting a specific study on the inception cavitation would be meaningful for the operation stability and security. For a reversible pump-turbine, cavitation is more serious when it works as a pump [1]. Compared with common pumps, it is necessary to use the inception cavitation standard in reversible pump-turbines due to the larger cavitation scale. In the pump mode, cavitation usually incepts on the leading edge when the fluid separates here with an abrupt pressure drop [2]. Thus, it is important to study the inception of leading edge cavitation of pump-turbine.

There are already a lot of researches on the cavitation in hydraulic turbo-machineries. Escaler et al [3] conducted an experimental investigation on the cavitation in hydraulic turbine. They provided a good guidance for researchers to detect the inception cavitation in different types of turbine in actual applications. Cencic et al [4] also conducted experiments to detect the leading edge cavitation in pump mode. It is helpful for researchers to investigate the inception cavitation in a pump-turbine. However, experimental studies are difficult to obtain all the flow details in the reversible pump-turbine. Thus, numerical simulation is used as an effective supplement for experiments. Based on the experiment, Anciger et al [5] predicted the rotating stall and cavitation inception in a pump-turbine in pump mode. Even the numerical simulation results were consistent with the experimental results, the criterion of inception cavitation are not clear. Jese et al [6] also gave an experimental-verified simulation for the inception cavitation in pump-turbine, they used the void ratio in the first cavitating cell as the criterion of inception cavitation. The numerical results also matched well with the experimental data, but there were only the simulations under off-design conditions. Liu et al [7] and Zhang et al [8] also conducted simulations for cavitation in pump-turbine in pump mode. These numerical simulations performed well...
in the prediction of the location of cavitation. It shows that the numerical simulation is applicable for the inception cavitation.

In our previous research, numerical simulation was already used for the optimization of a reversible pump-turbine [9]. In this study, a detailed study for the inception cavitation in pump-turbine in pump mode is conducted. Based on the former works, CFD simulation is used for the predicting of the inception cavitation. Different levels of vapor volume fraction is predicted. Both the design condition and off-design conditions are taken into consideration. On one hand, the locations of cavitation are indicated. On the other hand, the proper way of criterion of inception cavitation for reversible pump-turbine in pump-mode are discussed.

2. Research Object and Methods
The research object in this study is a Francis pump-turbine. It mainly consists of five components including the volute, stay-vane, guide-vane, impeller and draft tube. The flow domains for numerical simulation were modeled as shown in Fig. 1. In the pump mode, fluid flows into the draft tube first, then impeller, guide-vane,stay-vane and volute. In this study, both the design condition \( Q_{md} = 360 \text{ kg/s} \) and 4 off-design conditions \( 0.8Q_{md} \), \( 0.9Q_{md} \), \( 1.1Q_{md} \) and \( 1.2Q_{md} \) were discussed. The relationship between flow rate \( Q_m \) and guide-vane opening angle \( \alpha \) is shown in Fig. 2.

![Figure 1. The flow domain of the pump-turbine model](image1)

![Figure 2. The relationship between flow rate and guide-vane opening angle](image2)

In this study, RANS simulation was conducted by using commercial CFD code in ANSYS CFX. Before the simulation, the flow domains were meshed using ICEMCFD. Structural elements were used for draft tube, impeller, guide-vane and stay-vane. Unstructured elements were used for the volute. A proper mesh scheme was determined with an independence check. By making sure the variation of simulated pump head less than 1%, the mesh scheme was finalized with altogether 2’863’660 nodes.

In the RANS simulation for turbulent flow, the SST \( k-\omega \) model was used to close the averaged equations. The Zwart Model was used for cavitation. The multiple reference model was used with the impeller domain rotating in 1200 r/min and other domains keeping stationary. In the boundary condition setup, a mass flow inlet was given at the draft tube inflow and a pressure outlet was given at the volute outflow. All the solid walls were set as no-slip wall boundary. Transient sliding interfaces were set to connect the flow field of the domains. The environment pressure was set as 1 Atm.

3. Results and Discussions

3.1. Calculation of Vapor Volume Fraction
Vapor volume fraction in the impeller is used to evaluate the inception cavitation. By modifying the pressure on the outlet boundary, it is able to control the domain pressure and monitor the variation of vapor volume fraction in the impeller. Figure 3 shows the process of finding the vapor volume fraction \( f_v = 0.001\% \). For clearance, Fig. 3 shows only part of the data sets. The \( p_{out}/f_v \) curves drop abruptly then become flat. Looking conversely at the horizontal axis, when the pressure is high enough, cavitation would not happen. With the pressure decreasing, water turns into vapor in somewhere, usually on the...
blade leading edge, in the impeller. If the pressure continue decreasing, the vapor volume fraction grows up rapidly.

3.2. Predicting the Leading Edge Cavitation

In Fig. 3, we can find the point that the fraction curve rises up from flat, and define it as the “turning point”. Even the saturation pressure are the same for these conditions, the “turning point” are different due to the different flow rate. Under the design flow rate of $1.0 Q_{md} \text{ (450 kg/s)}$, the “turning point” occurs when the outlet pressure $p_{out}$ is about 500 kPa. Under the off-design condition of $0.9 Q_{md} \text{ (405 kg/s)}$ and $1.1 Q_{md} \text{ (495 kg/s)}$, it occurs when $p_{out}$ is about 550 kPa. Under the $0.8 Q_{md} \text{ (360 kg/s)}$ and $1.2 Q_{md} \text{ (540 kg/s)}$, it occurs when $p_{out}$ is about 650 kPa. It means that the condition departs further from the design point, the cavitation happens earlier. Figure 4 shows the reason of the inception of leading edge cavitation. When operation goes away from the design point, it will cause the leading edge separation. Pressure drops in the separation region and induces the leading edge cavitation.

CFD prediction is very useful to indicate the location of the inception cavitation on the leading edge. As shown in Fig. 5, under lower off-design flow rate ($0.8 Q_{md}$), leading edge cavitation occurs on the suction surface. On the contrary, leading edge cavitation is found on the pressure surface under higher off-design flow rate ($1.2 Q_{md}$).

3.3. Criterion of Inception Cavitation

Even the vapor volume fraction can indicate the cavitation, an exact criterion of volume fraction is still necessary for the inception cavitation. For this purpose, different vapor volume fraction levels were simulated and compared with experimental data. Figure 6 is the test rig and facilities. In the experiment, the first three bubbles were captured and defined as the inception cavitation. Figure 7 shows the cavitation coefficient $C_{\sigma}$ by both the experiment and the simulation, where $C_{\sigma}$ is defined as:

$$C_{\sigma} = \left( \frac{p_s}{\rho g} + \frac{V^2}{2g} - \frac{p_{out}}{\rho g} \right) / H$$

(1)
where $\rho$ is the density of water, $g$ is the acceleration of gravity, $p_i$ and $V_i$ is the pressure and velocity at the reference position (here is the draft tube inlet), $p_s$ is the saturation pressure, $H$ is the pump head.

The $C_\sigma$ value of the vapor volume fractions that $f_v = 0.0001\%$, $f_v = 0.0005\%$, $f_v = 0.001\%$ and $f_v = 0.002\%$ are simulated. Comparing with the experimental data, the $C_\sigma$ curve from $f_v = 0.0005\%$ matches the experimental curve best. However, the range from fraction 0.0001% to 0.001% is recommended as the criterion of inception cavitation for reversible pump-turbines.

4. Conclusions

CFD is available and effective for the prediction of inception cavitation in reversible pump-turbine. Firstly, it is effective for the calculation of vapor volume fraction which can be used as the criterion of inception cavitation. Secondly, CFD is available to visualize the location of the leading edge cavitation. By conducting CFD simulation and comparing it with experiment data, it is found that the vapor volume fraction level from 0.0001% to 0.001% is a proper criterion for inception cavitation. This rule can be applied to the engineering applications of reversible pump-turbines.

References

[1] Zhou Y W. Draft head options for pump turbine of pumped storage plant. Mechanical & Electrical Technique of Hydropower Station, 2006, 29, 12-15.
[2] Pan Z Y, Yuan S Q. Fundamentals of cavitation in pumps. Jiangsu University Press, Zhenjiang, China, 2013.
[3] Escaler X, Egusquiza E, Farhat M, et al. Detection of cavitation in hydraulic turbines. Mechanical Systems and Signal Processing, 2006, 20: 983-1007.
[4] Cencic T, Hočevar M, Širok B. Study of erosive cavitation detection in pump mode of pump-storage hydropower plant prototype. Journal of Fluids Engineering, 136(5): 051301.
[5] Anciger D, Jung A, Aschenbrenner T. Prediction of rotating stall and cavitation inception in pump turbines. 25th IAHR Symposium on Hydraulic Machinery and Systems, Timisoara, Romania, 2010.
[6] Jese U, Fortes-Patella R, Antheaume S. High head pump-turbine: Pump mode numerical simulations with a cavitation model for off-design conditions. 27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada, 2014.
[7] Liu J T, Wu Y L, Liu S H. Study of unsteady cavitation flow of a pump-turbine at pump mode. IOP Conference Series: Materials Science and Engineering, 2013, 52(6): 062021.
[8] Zhang L, Jing X, Wang Z, et al. Analysis of Francis pump-turbine runner cavitation flows in pump mode. ASME 2009 Fluids Engineering Division Summer Meeting, Colorado, USA, 2009.
[9] Tao R, Xiao R, Yang W, et al. Optimization for cavitation inception performance of pump-turbine in pump mode based on genetic Algorithm. Mathematical Problems in Engineering, 2014: 234615.