Cavitation pressure fluctuation characteristics of a prototype pump-turbine analysed by using CFD

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Abstract. Cavitation in water turbine can induce blade erosion, efficiency decrease and unit vibration, and in some extreme conditions the reverse water hammer caused by draft-tube cavity collapse may lead to the unit-lifting accident. The purpose of this work was to analyse the influences of cavitation on pressure pulsation characteristics of a prototype pump-turbine. We conducted 3D CFD simulations by giving different cavitation coefficients that induce different cavity volumes at the draft-tube inlet. In one of severe cavitation conditions, the propagation characteristics of cavitation pressures across the whole flow channel was studied, which was considered as the leading pulsating source. The correlation between pressure impulse and vapour fraction is successfully confirmed by observing the formation, development and collapse of the cavity in flow fields. The results indicate that the cavity, originating from the runner cone, evolves with various shapes, varying volumes and random periods, causing the wide spectrum band of frequencies of pressure pulsations. These results may lay the foundation for further studying extreme transient processes with cavity collapse.

1. Introduction

In hydroelectric system, cavitation has significant influences on energy efficiency, pressure pulsation and structural vibration characteristics of the unit [1]. Meanwhile, cavitation may cause erosion damage to turbine, threatening safety and stability operation of the power station. Hence, cavitation characteristics need to be studied and restraining measures should be proposed.

The previous studies, mainly paid attention to the conventional water turbines, had made many achievements on cavitation influences. Xu et al. [2] implemented model tests and found that with the decrease of the cavitation coefficient, cavitation pressure pulsations first increase and then decrease. Liu et al. [3] adopted CFD method with Mixture two-phase flow model to study the cavitation characteristics of a Francis turbine, and obtained results agreeing well with model tests on location and form of the cavity. After that, CFD method had been widely applied to the study of cavitation vortex rope and frequency-amplitude characteristics of cavitation pressure pulsations [4-6].

In terms of cavitation characteristics of pump-turbines, Chen et al. [7] provided several suggestions about selecting cavitation parameters for mid or low-head pump-turbines by analysing cavitation performance of pump-turbines that are in operation. Liu et al. [8] found that cavitation region and pressure fluctuations reduce as guide vane opening decreases. Li et al. [9] studied cavitation
characteristics at part load conditions, and found that the occurrence and development of cavitation can lead to sharp reduction in hydraulic efficiency and significant increase in axial force. The effect of cavitation on energy characteristics of pump-turbine was studied by Hao et al. [10] by using shear stress transport (SST) $k-\omega$ turbulence model, which pointed out that cavitation occurs mainly at the exit of runner blade suction side near the band.

The changing of vertex rope in cavitation is one of the main excitation sources for the dynamic instability of hydraulic system. Doerfler P [11] observed the shapes of vertex rope in the draft-tube of a Francis turbine by both model and prototype tests, finding the helical vertex rope at part load and the torch-shaped vertex rope at full load, which were simulated and further analysed by Alligné S [12] and Landry C [13]. But for pump turbine, there is little experimental research due to limited conditions.

In some extreme cavitation conditions, reverse water-hammer may occur. Pejovic et al. [14] noticed that when operating point goes through the S-shaped region, liquid column separation developed from cavitation in pump-turbine would provoke large counter pressure and even lead to unit-lifting accidents. This phenomenon in runaway process was successfully simulated and analysed by Zhang et al. [15] with two-phase CFD model. It was indicated that when the suction height of draft-tube is large, local cavitation first appears below the runner cone, and then a large cavity forms, enlarges, collapses, and stimulates the large reverse water hammer impulse. It can be inferred that some strange and dangerous pressure pulsations are from cavitation, but little research on it has been made.

In this study, we directly simulated a prototype pump-turbine by 3D CFD method, based on different Thoma numbers, which are specially selected to obtain different cavitation behaviors. The frequency-amplitude characteristics of pressure pulsations the variation features of cavity volumes are analysed. The conclusions are meaningful for discussing instability of transient processes with reverse water hammer, providing important references for measures of reducing cavitation damages.

2. Numerical models and methods

2.1. Numerical models and mesh

A prototype pump-turbine of a pumped-storage power station was adopted in this study. The computational domain is consisted of 20 stay vanes, 20 guide vanes and 9 runner blades. The rated runner rotational speed is $n=500$ rpm, the rated water head is $H_r=510$m, the runner inlet diameter is $D_1=1.92$m. The whole domain is discretized by hybrid grids, with tetrahedral grid for the spiral case, wedge grid for the vanes, and hexahedral grid for the runner and draft-tube. To choose a proper mesh number, grid independence analysis with 5 grid sizes were conducted (Figure 1). The results show that when the total mesh number is more than $4.45\times10^6$, the changes of simulated working head can be nearly neglected. Considering the precision of simulation, the model with 5.09 million grids was adopted (Figure 2). The mesh numbers and $y^+$ values for each part are shown in Table 1.

| Mesh number (million) | Case | Vanes | Runner | Draft-tube |
|-----------------------|------|-------|--------|------------|
| 0.51                  | 1.22 | 2.31  | 1.05   |
| Average $y^+$         | 736.87 | 613.36 | 257.58 | 57.03 |

*Figure 1. Simulated working heads with different meshes.*

*Figure 2. Computational domain and mesh.*
2.2. Simulation settings
According to the water levels of upper and lower reservoirs, the pressure inlet and outlet boundary conditions were given to the inlet of spiral case and outlet of draft-tube, respectively. Since the inlet diameter of spiral case is large, the pressure was not assigned by default uniform distribution, but by linear gravity distribution implemented by UDF. The Sliding Mesh model was adopted to make the runner zone rotate, and the rotational speed was set to the rated speed. Three pairs of interfaces were set between the spiral case outlet and vane zone inlet, the vane zone outlet and runner inlet, and the runner outlet and draft-tube inlet. The non-slip boundary was used for wall surfaces.

The numerical simulations were done by the 16 cores commercial software ANSYS Fluent 15.0 on the supercomputing system in the Supercomputing Center of Wuhan University. The SST k-ω turbulence model was used to simulate the complex shear flow and rotating flow in the runner and draft-tube. The Schnerr and Sauer cavitation model combined with Mixture two-phase model was adopted, which has good numerical convergence and stability in simulations [16]. Furthermore, in order to model water hammer propagation, a compressible fluid model was adopted by defining pressure-dependent density [17]. The speed of sound in vapour phase was defined as 340m/s, and that in liquid phase was initially defines as 1200m/s, which varies with density in simulations. The timestep was set at 0.0008s, and the runner rotates 2.4° in one timestep. The residual errors of all parameters were set as 1.0e-4. The maximum iteration number of each timestep was 40, and it was found that the convergence of results could reach within no more than 35 iterations in every timestep.

2.3. Cavitation conditions and monitoring points
Six different cavitation conditions under different cavitation coefficients were simulated (Table 2). The cavitation coefficient is defined as follows:

\[
\sigma = \frac{p_a / \gamma - p_k / \gamma - H_s}{H_p}
\]

where \(p_a\) is the water surface pressure of downstream reservoir; \(p_k\) is the lowest pressure of the easiest cavitation point, which was taken from the pressure at the middle of runner blade back; \(H_s\) is the draught-height of draft-tube; \(H_p\) is the rated water head. In this research, the change of cavitation coefficient was realized by changing the water levels of upper and lower reservoirs.

In order to analyse the propagation characteristics of pressure pulsations in the whole flow channel, 16 monitoring points (Figure 3) were arranged in the turbine, among which P07 to P11 were sequentially distributed along the middle line of a blade. Beside, 6 monitoring sections were set from runner to the taper pipe of draft-tube (Figure 4) to analyse evolution behaviors of cavity collapse.

| Conditions | \(\sigma_1\) | \(\sigma_2\) | \(\sigma_3\) | \(\sigma_4\) | \(\sigma_5\) | \(\sigma_6\) |
|------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \(\sigma\) value | 0.083 | 0.074 | 0.064 | 0.056 | 0.035 | 0.021 |

**Table 2.** Simulated conditions of different Thoma numbers.

[Figure 3. Monitoring points.]

[Figure 4. Monitoring planes.]
2.4. Numerical validation

The macro-parameters in the steady rated operating condition (Condition 1) were simulated first. The whole computational time is 1.5s, during which the data of 12.5 rotation of runner is obtained. The resulting unit flow rate is 0.195m$^3$/s and the unit torque is 27.70N\*m. The error is -0.86% and +1.65% respectively, compared with those from model tests. Therefore, it can be considered that the grid independence and reliability of the numerical model are satisfied.

3. Pressure pulsation characteristics for different cavitation coefficients

3.1. Pressure pulsations

The pressure pulsations of P12 point in different cavitation conditions are presented in Figure 4 and Figure 5. It is shown that the pressure is smooth with no fluctuations in Conditions $\sigma_1$ and $\sigma_2$, which demonstrates little cavitation. The pressure pulsations appear in Condition $\sigma_3$ (Figure 5), in which the maximum value is almost 270m head ($0.53mH_p$). With further decrease of cavitation coefficient, the impulse amplitude increases and reaches the maximum value in Condition $\sigma_5$ (Figure 6), in which the maximum amplitude is about 1300m ($2.55H_p$). And then, the pressure pulsations decrease under Condition $\sigma_6$, indicating that the cavitation is suppressed compared to other conditions. Therefore, it can be summarized that the cavitation coefficient has a modulation effect on the cavitation formation, but not the only influencing factor.

![Figure 5. P12 pressure pulsations in Condition $\sigma_1$, $\sigma_2$, $\sigma_3$.](image)

![Figure 6. P12 pressure pulsations in Condition $\sigma_4$, $\sigma_5$, $\sigma_6$.](image)

The negative pressure of the severest cavitation condition can be obviously seen in Figure 7. After the minimum pressure reached critical condition of vaporization, vapor-filled cavities form, in which tensile stress is superimposed on the ambient pressure. After cavity collapse, a corresponding huge pressure impulse will suddenly rise up to a peak value at $t=0.557s$ (Figure 6). The process occurs repeatedly in flow field and apparently, such swift and violent variation of flow patterns severely deteriorates the stability of hydraulic system.

![Figure 7. P12 pressure pulsations in Condition $\sigma_5$.](image)
3.2. Vapor fraction
The area percentage occupied by vapor phase on a section is defined as the vapor fraction \( V_f \), which can be quantified as equation (2)

\[
V_f = \frac{S_{\text{vap}}}{S_{\text{vap}} + S_{\text{liq}}} \quad (2)
\]

where \( S_{\text{vap}} \) is the area of vapor phase, \( S_{\text{liq}} \) is the area of liquid phase. The fraction can reflect the volume of the cavity to a certain degree. And on each section the data shows diverse variations. Figures 8 and Figure 9 show various distribution and evolution behaviors under the 6 conditions. In Conditions \( \sigma_1 \) and \( \sigma_2 \), the vapor fractions on Section 2# and 3# are nearly 0, indicating that there is almost no cavitation. While in Condition \( \sigma_3 \), the average fraction on Section 2# is about 0.2% although that on Section 3# is still 0, which is because cavities begin to appear in water turbine. Besides, since the Section 2# is very close to the runner cone, it can be definitely considered as a source of cavitation. But the cavitation range is very small, which exists only in a short region that even doesn’t extend to Section 3#. And the cavities are too small that they collapse quickly. When the cavitation coefficient is further reduced, the vapor fraction gets much larger in Conditions \( \sigma_4 \), \( \sigma_5 \) and \( \sigma_6 \) and the time durations are longer. Similarly to pressure pulsations, the fraction arrives to the maximum in Condition \( \sigma_5 \) likewise. The whole cavitation zone has extended below the Section 3#. Therefore, it can be assumed that the primary cavitation coefficient of the prototype pump-turbine is 0.064, while the severe cavitation coefficient is 0.035, which can give a reference to the turbine manufactures. In addition, there are correlations between vapor fraction and pressure pulsations, which will be discussed later in the paper.

![Figure 8. Vapor fraction on Section 2#](image1)

![Figure 9. Vapor fraction on Section 3#](image2)

4. Pressure pulsations and vapor fraction in severe cavitation conditions

4.1. Correlation between pressure pulsations and vapor fraction
By analysing the severe cavitation condition \( \sigma_5 \), the correlation between pressure pulsations and the vapor fraction is given in Figure 10. It is worth noting that in the overall distribution, the peak values of pressure pulsations and vapor fraction appear alternatively, but they are not positive related. A small fraction may corresponds to a larger impulse. At the time of 0.56s, the cavity volume is the largest and the pressure pulsation is the maximum after it collapses. However, the cavity volume 0.0086 formed at 1.136s arouses a larger pressure pulsation 772.9m than the pressure pulsation 351.5m aroused by cavity volume 0.02 at 0.65s. Hence, it can be inferred that the volume of cavity has an effect on the cavitation instability of hydraulic turbine, but is not the only influencing factor, which may relate to the evolution behaviors of cavity.
4.2. Distribution and evolution behaviors of cavities

The variations of vapor fraction on different monitoring sections in Condition σ5 are presented in Figure 11. It is obvious that the fraction on Sections 1# and 6# are almost 0, but that on Section 3# and 4# are much larger, whose maximum values are 0.065 and 0.085, respectively. It reveals that the cavitation region is mainly limited between the runner cone and the taper pipe of the draft-tube.

By recognizing the volume vapor fraction larger than 0.05, the cavity patterns are displayed in Figure 12. Apparently, the cavity volumes and corresponding pressure pulsations in the flow fields vary with time. At Moment A, the pressure at P12 point reaches at cavitation pressure, causing the liquid phase converts into vapor phase and forming a torch-shaped cavity beneath the runner cone, which corresponds to the vortex rope at full load of Francis turbine [11]. Meanwhile, there are also a few sheet cavities at the inlet and exit of runner blades. Although their volumes are very small, it doesn’t mean the effects on pressure pulsations are negligible. At Moment B, cavities sharply collapse to a tiny one, generating a large pressure impulse. Then the remaining small cavity collapses completely, forming a new pressure impulse at Moment C, but with a smaller value. Such pressure pulsations are caused by rapid filling of cavity space by water after cavity collapse. And such collapse is not a one-time process that the shrinking rate of cavity is non-uniform, which may relate to the effect of surrounding water pressure. At the next two moments of D and E, the pressure in draft-tube is reduced to cavitation pressure again, forming a helical torch-shaped vortex rope. As it rotates and expands, the cavity collapses again, arousing huge pressure pulsation near Moment F. After Moment G, the remaining smaller cavity forms a smaller impulse again. At Moment H, a swirl vortex rope is formed beneath the cone. Accordingly, new pressure pulsation will be triggered in flow fields. Such similar process occurs repeatedly but doesn’t show regularity even the macro-parameters are steady.

Figure 10. Cavitation pressure pulsations at P12 and vapor fraction on Section 3#.

Figure 11. Variations of vapor fraction on the 6 sections in Condition σ5.

In the evolution process of cavity, the vapor fraction of each section increases and decreases synchronously. And pressure pulsation is inevitably generated after it collapses. However, the moment of maximum pulsation is not always after cavity completely collapses. In fact, according to the results, it mainly hinges on the rate of volume shrinking. The large cavity collapse may produce small cavity. And after it fully collapses, new large one will be generated, which means the rate of collapse varies.
In addition, the cavity is very rich in shape, including the inverted conical cavity beneath the cone (A), the narrow helical cavity (E, H), and the sheet cavities at exit of blades (A).

![Image](image1.png)

**Figure 12.** Changing behaviour of cavities in Condition σ5.

5. Distribution and propagation characteristics of cavitation pressure pulsations in flow channel

5.1. Influence of cavitation on pressure pulsations

To clarify the influence of cavitation on pressure pulsations in the whole water channel, the variations of pressure pulsations in Condition σ5 are displayed in Figure 13. Evidently, there is similarity among the pulsations at all measuring points, and the only difference is in the amplitudes. It reveals that the pressure pulsations caused by cavitation significantly spread and influence pulsation in the overall flow channel.

According to the previous research, the gas components in water has a significant effect on the speed of sound [18]. And the more the gas is, the less the speed is. However in this research, the pressure pulsations are almost at the same time in the flow channel, not showing propagation differences. It may be because that the previous wave speed formula in vapor-liquid mixture applies to uniform mixing condition, while in cavitation condition, the vapor phase is mainly concentrated on the inlet of draft-tube. And the maximum volume vapor fraction in the whole flow field is 0.0002 appearing at 0.512s, which is too little to cause much decrease of wave speed. Besides, since the size of model is short, the difference can not be monitored. In addition, the amplitude of pressure pulsations is so large that almost covers the influence of other pulsating sources, becoming the main source. Meanwhile, the amplitude decreases progressively with propagation distance. Hence, the pressure pulsations in the draft-tube inlet are the most intense. It can be explained that the pulsation is a kind of signal source that uses water as medium to deliver frequency signal to other regions, whose energy is gradually dissipated with distance due to the vortex structure, water viscosity and other disturbances in the flow fields.
It’s also noticeable that the frequency domain distribution of pressure pulsations has a rich spectrum band as shown in Figures 14. The highest frequency approaches to 60fn (500Hz), but the largest amplitude is less than 12m (2.3%Hrp). Moreover, there is no prominent basic frequency except for P03 (vaneless zone), which shows an apparent frequency of 9fn caused by rotor-stator interaction. Its amplitude is nearly 20m, but other frequency components of P03 are still wide and weak. Such unusual frequency distribution is quite different from that in ordinary condition, but is proved to be reasonable analysed in the next section.

5.2. Influence of cavitation on frequency pressure pulsations
For further investigation, the frequency components of three typical locations in Conditions σ1, σ3 and σ5 were obtained by data statistics (Figure 15). It is observed that the high and low frequency signals all multiply with the aggravation of cavitation, which is related to the intensification of random and irregular cavity formation and collapse. Hence, it explains why the frequency distribution is unusual in severe cavitation conditions, when cavitation is the main pulsating source and the amplitude is shared by a variety of frequency signals.

It is remarkable that the original frequency with small amplitude may be assigned or swallowed by other similar frequencies of cavitation. From the results of this research, the energies of 18fn, 20fn and 27fn are too small that gradually disappear in severe cavitation conditions, fostering new frequencies instead, such as 21.4fn in Condition σ3, 26.8fn in Condition σ5. However, the frequency of 9fn in rotor-stator interaction zone (Figure 15(b)) has high power that is not much affected by cavitation.

6. Conclusions
In this paper, six cavitation conditions of a prototype pump-turbine were simulated by applying Schnerr and Sauer cavitation model. The pressure pulsations and vapor fraction in different locations of the turbine were obtained, whose distribution and propagation characteristics are analysed, and the correlation between them is clarified.

The amplitude of cavitation pressure pulsations of the pump-turbine increases first and then decreases with cavitation coefficient reducing. In this research, the primary cavitation coefficient is 0.064. And severe cavitation coefficient is 0.035, when the maximum pressure pulsation and vapor fraction appear, about 1300m (2.55Hrp) and 0.085, respectively. And in severe cavitation condition, the cavity originating from the runner cone evolves irregularly and has no fixed shape. The recurrence
process of cavity formation, development and collapse greatly destroy the flow field stability. However, it is mainly concentrated on the inlet of draft-tube. Huge pressure pulsations are inevitably generated after cavities collapse, whose peak values are mainly determined by the rate of collapse.

The pressure pulsations caused by cavities collapse spread and influence pulsation in the whole flow channel. And the amplitude of pulsations decreases progressively with propagation distance. When cavitation in turbine is getting severe, the pulsations become the leading pulsating sources, which almost overshadow the effects of other sources. Besides, the frequency signal will display a wider spectral band with cavitation getting severer, which relates to the random evolution of cavities. The energy of pulsations is apportioned by every order of frequencies, which have small amplitudes.

7. Acknowledgement
This work was supported by the National Natural Science Foundation of China (Grant No. 51579187), Science and Technology Program of State Grid Corporation of China (Grant No. SGBXSJJS1700007) and Natural Science Foundation of Hubei Province (Grant No. 2018CFA010).

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