Study on the Influence of Compressibility on Pressure Fluctuation Characteristics of Pump Turbine

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Abstract. In order to study the characteristics of pressure distribution and the influence of compressibility factors on pressure fluctuation of pump turbine under the condition of turbine. Based on RNG k-ε model, aiming at a pump turbine model, this paper uses UG NX10.0 software to build a three-dimensional model, and uses ICEM-CFD software to divide the mesh. Using ANSYS-CFX software, the unsteady simulation calculation of the whole flow passage under the opening of 10 mm movable guide vane is carried out, and the frequency spectrum of pressure fluctuation is obtained by using the fast Fourier transform. After analysis, the dynamic and static interference between the movable guide vane and the runner, as well as between the runner and the draft tube, has an impact on the pressure fluctuation in the front of the runner behind the guide vane and in the draft tube. There is a secondary peak at 9fn. Considering the compressibility, the amplitude of the fluctuation decreases, but the flow is more complex and the pressure fluctuation is more chaotic.

1. Introduction

Compared with other energy storage methods, pumped hydro storage is the most mature and economical large-scale energy storage in the world today. As a special form of power supply, pumped storage power station can adjust the peak and fill the valley, optimize the working position of all kinds of power sources in the system, undertake the dynamic functions of emergency standby, frequency modulation and equal adjustment, so as to improve the quality of power supply, ensure the safety of power supply, reduce pollution and other functions. Today, there are many pumped storage power stations in western developed countries, with the total installed capacity of 3% - 10%, and only about 2% in China [1, 2]. Pump turbine is the core equipment of pumped storage unit, which has the characteristics of strong applicability and high cost performance. As a two-way operation hydraulic unit, the forward and reverse operation of the runner respectively carries out the pump condition and the turbine condition. Its future development direction is high head, large capacity and high speed, but it is accompanied by instability, pressure and flow pulsation, cavitation and other serious problems, so it needs to be properly analyzed and solved [3]. The compressibility of a fluid is the property that the volume or density of a fluid particle can be changed under a certain pressure or temperature difference. Compressibility of fluid means that the fluid is compressed, the volume is reduced, the density is increased, and it can be restored to its original state after removing external force. Compressibility is actually the elasticity of the fluid. Under normal pressure or temperature, the compressibility of liquid is very small. For example, when water is at 100 atmospheric pressure (1 atmospheric pressure = 101
325 PA), the volume is reduced by 0.5%; when the temperature changes from 20 °C to 100 °C, the volume is reduced by 4%. But in some special problems, the liquid must be regarded as compressible.

As the core of pumped storage power station, the stable operation of pump turbine is directly related to the life of the unit and the safety of the power station. The hydraulic vibration caused by the unstable flow inside the unit is the main factor and internal cause of the unstable operation of the unit. Hydraulic vibration is mainly manifested by pressure pulsation. When the unit operates in non design conditions, such as pump hump area, s area of turbine condition, braking condition and return pump condition, it is particularly important to analyze and master the pressure pulsation of pump turbine. In this paper, the compressibility of the fluid as the starting point, through the simulation calculation of the flow inside the pump turbine, we expect to get a more complete result of pressure fluctuation, and analyze the result, understand the impact of compressibility on pressure fluctuation, and provide a broader idea for solving the problem of pressure fluctuation.

2. Calculation Model and Method

Computational fluid dynamics (CFD) is a new subject formed by the intersection of hydrodynamics, mathematics and computer science. It uses computer and discrete numerical methods to simulate and analyze the hydrodynamics problems [4]. CFD technology can be used to solve fluid flow, heat transfer and other related transfer phenomena. Through this numerical simulation, the distribution of physical parameters in the basin can be obtained. Thanks to the emergence of CFD technology, it is possible to simulate the turbulent flow inside the pump turbine.

2.1. Basic Equations of Fluid Control

The flow law of incompressible turbulent motion of viscous fluid can be described by the following two basic equations.

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j} + f_i \tag{2}$$

Where, \( u(i=1,2,3) \) is the fluid velocity, m/s; \( p \) is pressure, Pa.

Since the N-S equation is a second-order nonlinear partial differential equation, it is difficult to solve in the case of high Reynolds number and can only be solved by CFD. At present, most of the calculations are based on the Reynolds turbulence average motion theory, and the time mean and wave value are used to replace the transient value in the equation. After averaging the N-S equations, the above equations are transformed into the following equations.

Mass conservation:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{3}$$

Momentum conservation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_i \partial x_j} + f_i + \frac{1}{\rho} \frac{\partial (-\rho u_i u_j)}{\partial x_j} \tag{4}$$
Where, $u_i$ is the average velocity term, $P$ is the average pressure term. Because of the introduced Reynolds stress, the equations are no longer closed, but a relatively reasonable method to solve the complex turbulence problem is established, so it is widely used in engineering\cite{5}. Because there is no compressible water in ANSYS-CFX, it is necessary to define the compressible water in cfx-pre. After introducing compressible factor and other items, the relationship between density and pressure is as follows

$$\rho = \rho_0 + \frac{(P - P_0) \rho_0}{K - (P - P_0)}$$

(5)

$K$ is coefficient of water compressibility, $P$ is real time pressure, $P_0$ is atmospheric pressure, $\rho$ is density, $\rho_0$ is density at atmospheric pressure.

2.2. RNG $k-\varepsilon$ Model

Yakhot summarized the analysis method of turbulent flow field, used RNG method to analyze the pattern flow field, obtained the RNG $k-\varepsilon$ model. The momentum equations are renormalized, replaced correction factor $C_{\varepsilon,RNG}$ with $C_{\varepsilon}$. After correction, the turbulent kinetic energy dissipation equation goes as

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla (\rho U \varepsilon) = \nabla \left( \mu + \frac{\mu_t}{\sigma_{\varepsilon,RNG}} \right) \nabla \varepsilon + \frac{\varepsilon}{k} \left( C_{\varepsilon,RNG} P_k + C_{\varepsilon,RNG} \rho \varepsilon \right)$$

(6)

$$C_{\varepsilon,RNG} = 1.42 - f_{\eta}$$

(7)

$$f_{\eta} = \frac{\eta \left( 1 - \frac{\eta}{4.38} \right)}{(1 + \beta_{RNG} \eta^3)}$$

(8)

$$\eta = \frac{P_k}{\rho C_{\mu,RNG} \varepsilon}$$

(9)

In the RNG $k-\varepsilon$ model, a unique setting is adopted for the vortex flow, which improves the accuracy in the simulation of turbulent flow. On this basis, Prandtl number in the analytical formula provided by RNG theory is more widely used, also the model with higher accuracy and reliability. \cite{19}

2.3. Geometric Model and Mesh

In this paper, a pump turbine model is used, and CFD technology is used to simulate the working condition of the pump turbine in full flow channel mode. According to the flow direction, the water passing parts are volute, guide vane, runner blade and draft tube in turn. Using CAXA software to pick up the two-dimensional drawing lines, using UG NX 11.0 software to build the three-dimensional model and the full channel model.
Use ICEM to divide the whole flow passage of the pump turbine with 10mm guide vane opening into unstructured grids and add boundary layer on the boundary surface. The mesh shows as the follows.

3. **Unsteady Calculation Results and Analysis**

In order to obtain the influence of compressibility on the pressure fluctuation of pump turbine, in this paper, pressure monitoring points at symmetrical positions are set up in front of the runner behind the guide vane and in the draft tube on the same flow cross-section. Through unsteady calculation, the pressure values of each monitoring point are obtained. The dynamic pressure signal of each monitoring point is transformed from time domain to frequency domain by FFT (fast Fourier transform). At the same time, the frequency is converted between the frequency and the main frequency, and the frequency is dimensionless for analysis. Finally, the spectrum diagram of the relationship between the pressure fluctuation amplitude and the main frequency is obtained, which describes the frequency structure of the signal and the relationship between the frequency and the signal amplitude.
3.1. Characteristics of Pressure Fluctuation in Front of Runner Behind Guide Vane

During the operation of pump turbine, the force on the runner directly affects the stable operation of the unit. The figure shows the pressure fluctuation characteristics of the guide vane in front of the rear runner at the opening of 10 mm. It can be seen from the figure that the pressure presents periodic pulsation. In a rotation cycle, nine peaks and troughs can be found, which are consistent with the number of blades. This shows that the periodic change of the pressure in this area is directly related to the number of blades, and the pulsation frequency is related to the frequency of the blade and the frequency doubling of the blade frequency. It shows that the dynamic and static interference in the boundary area between the runner and the fixed movable guide vane caused by the rotation of the blade affects the pressure pulsation in this area. The peak value appeared at $9f_n$, $18f_n$, and $27f_n$, but the amplitude of pulsation decreased gradually. When considering the compressibility factor, we can see that, compared with the incompressible condition, the pulsation amplitude is lower and more regular in the compressible condition, and the pulsation amplitude is higher in the compressible condition of $9f_n$, but lower in the compressible condition of $18f_n$. It can be almost ignored at $27f_n$, which is similar to the surrounding time domain, indicating that the compressibility does not change the main frequency characteristics, but for different main frequency, the pulsation amplitude is caused by the pulsation.

![Figure 4. 1st point of incompressible water](image1)

![Figure 5. 2nd point of incompressible water](image2)

![Figure 6. 1st point of compressible water](image3)

![Figure 7. 2nd point of compressible water](image4)
3.2. Pressure Fluctuation Characteristics of Draft Tube

The following figures shows the pressure fluctuation characteristics of draft tube. In the actual flow process, there will be a variety of bad flow conditions at the impeller outlet, and the bad flow area will expand the scope and spread to the draft tube. It can be seen from the 10mm opening that at $9 f_n$, the draft tube have higher pressure fluctuation amplitude, which shows that the dynamic and static interference between the runner and the draft tube has a great influence on the cone tube and the elbow tube of the draft tube. Compared with the same opening, considering the compressibility factor, the pressure fluctuation of the draft tube is lower.

Figure 8. 1st point of incompressible water

Figure 9. 2nd point of incompressible water

Figure 10. 1st point of compressible water

Figure 11. 2nd point of compressible water

3.3. Summary of this Chapter

In this chapter, the unsteady results are processed, and the pressure fluctuation spectrum of each monitoring point is obtained by FFT analysis. The results show that the amplitude of the first main frequency pressure pulsation at the inlet and outlet of the volute is high, and then there is no large pulsation; in the area in front of the runner behind the guide vane, there are peaks at $9 f_n$, $18 f_n$, $27 f_n$ and so on under the influence of dynamic and static interference, but the amplitude of the pulsation decreases gradually, and the pressure pulsation decreases when considering the compressibility, but does not change the main frequency characteristics; in the draft tube, Under the influence of the
dynamic and static interference between the runner outlet and the draft tube inlet, the pressure pulsation peak also appears at $9 f_n$ and $18 f_n$. Considering the compressibility, the pressure peak decreases, but does not change the main frequency characteristics.

### 4. Conclusion

In this paper, based on the N-S equation and RNG k- $\varepsilon$ model, the unsteady numerical simulation of a pump turbine is carried out with the help of ANSYS-CFX software under the opening of 10 mm movable guide vane, and the numerical simulation results are analyzed and processed with cfxpost, and the pressure distribution and pressure fluctuation diagram are obtained. The pressure distribution characteristics and pressure fluctuation characteristics of the internal flow field under the working condition of pump turbine are analyzed. The main conclusions are as follows: For the front part of the back runner of the guide vane, due to the influence of the static and dynamic interference in the boundary area between the runner and the fixed movable guide vane caused by the rotation of the blade, there are peaks at $9 f_n$, $18 f_n$, $27 f_n$, etc., but the pulsation amplitude decreases gradually; considering the compressibility, the pressure pulsation amplitude decreases slightly, but does not change the main frequency characteristics. For draft tube, due to the dynamic and static interference at the junction of runner and draft tube, the pressure fluctuation amplitude of cone tube and elbow tube is higher at $9 f_n$. When compressibility factor is introduced, the amplitude of pulsation is lower and more regular in compressible condition than in incompressible condition. When compressibility factor is introduced, the amplitude of pulsation is higher in $9 f_n$, but it is lower in $18 f_n$. The results show that the compressibility does not change the characteristics of the dominant frequency, but the amplitude of the pulsation decreases for different dominant frequencies.

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