Hydrodynamic and Structural Stability Analysis for Shaft Tubular Pump Unit

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Abstract. Hydrodynamic and structural stability directly affect the efficiency and safety of pump units operation. In this paper, we simulated inner flow field of a shaft tubular pump unit through Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) for exploring the blade pressure and dynamic stress characteristics, where first part focus on the hydrodynamic pressure fluctuation on inlet and outlet of impeller and second part focus on dynamic stress distribution in time and frequency domain on pump impeller. Monitoring points are set at the inlet and outlet of impeller to obtain the dynamic pressure, then mapping the time domain data to frequency domain through Fast Fourier Transform (FFT) method. The results show that the pressure fluctuation has strong periodicity, and the fundamental frequency of the pressure fluctuation on the inlet and outlet surfaces is the blade passing frequency and the blade passing frequency respectively, which means the rotation of impeller and rotor stator interaction (RSI) phenomenon between impeller blades and guide vanes are the origin of hydrodynamic pressure fluctuation. Hydrodynamic pressure on impeller blade is applied to the impeller structure to obtain structural responses, results show that maximum dynamic stress appears in the root of impeller blade, the dynamic stress fluctuate in the nearby of static stress concentration and maximum dynamic stress appear in the permissible stress range. In frequency domain, the basic frequency and secondary basic frequency are impeller blade passing frequency and guide vane passing frequency, which indicated that the major reason of impeller dynamic stress fluctuation is water excitation pressure.

1. Introduction
China's water resources have the characteristics of uneven distribution in time and space. In recent decades, the development of social economy has driven the demand of water resources regulation in all walks of life. As a typical type of pumping station with low construction difficulty and large discharge, the shaft tubular pump station plays an important role in various water resources dispatching projects. The hydraulic and structural stability of the core device of the pump station directly affects the safe operation of the pump station.

The phenomenon of dynamic and static interference in water pump is a common cause of flow induced vibration. The dynamic static interaction refers to the periodic large hydraulic exciting force pulsation produced when the impeller passes through the wake of guide vane. The high frequency exciting force will make the impeller suffer fatigue load and accelerate the damage of the impeller. When the frequency of the exciting force is close to the natural frequency of the impeller, 70-300
some impeller types, the dynamic stress caused by static and dynamic interference accounts for more than 80% of the total stress of the impeller. Therefore, the research on the hydraulic vibration pressure fluctuation in the pump is the basis of analyzing the stability of the pump. With the development of computer technology, CFD is used to simulate the characteristics of pressure fluctuation and fluid structure coupling in the pump become the main way to analyze the stability of the pump. Zheng Yuan [1] tested the inlet and outlet of the impeller of the pump model device, and studied the change of the internal pressure pulsation of the pump when a variety of parameters changed; Xie Lu [2] analyzed the flow characteristics near the inlet and outlet parts of the pump through CFD calculation, and studied its influence on the pump performance. Kan [3] studied the flow characteristics in the pump under the condition of stall and load rejection, and analyzed the pressure fluctuation distribution in the pump under various flow conditions. Tang Fangping [4] analyzed the pressure fluctuation distribution caused by dynamic and static interference in axial-flow pump, and found that the pressure pulsation was large under non optimal conditions. Zhang [5] used numerical simulation and experiment to study the distribution of turbulence and pressure fluctuation in the pump. Previous studies on the pump mainly focus on the distribution characteristics of pressure pulsation, but the relationship between pressure fluctuation and dynamic stress is less understood.

2. Formatting the title, authors and affiliations

2.1. Governing equations of fluid and structure calculation
If the fluid in the pump can be approximately regarded as a continuous and incompressible homogeneous fluid, the governing equation is a viscous incompressible hydrodynamic motion equation with constant viscosity coefficient $\mu$ and density $\rho$, i.e., N-S equation. Its differential form is shown in (1).

$$\rho \frac{dv}{dt} = \rho F - \nabla p + \mu \Delta v$$  \hspace{1cm} (1)

Where $\rho$ is the density, $\mu$ is the viscosity coefficient, $v$ is the fluid velocity, $P$ is the surface force on the liquid, and $F$ is the mass force on the fluid element. The Reynolds number $Re$ of the flow inside the pump is generally very high, which indicates that the flow belongs to the highly developed turbulent flow. In this paper, the SST $k-\varepsilon$ turbulence model is used to simulate the transport and dissipation of turbulent kinetic energy, so that the Reynolds path is closed. Compared with the traditional $k-\varepsilon$ model, SST $k-\varepsilon$ mode is more efficient than the traditional $k-\varepsilon$ model $k-\omega$ model and $k-\varepsilon$ model, and has more accurate effect in numerical simulation of internal turbulence in rotating machinery.

The governing equation for stress calculation of single blade of shaft tubular pump is shown in equation (2)

$$Ku = Fs + Ft \quad \sigma = DBu$$  \hspace{1cm} (2)

Where $K$ is the stiffness matrix of the structure, $u$ is the displacement matrix of the node, $Fs$ is the water pressure generated by the water flow on the fluid solid coupling interface of the blade surface, $Ft$ is the resultant force of the centrifugal force generated by the rotation of the blade itself and its own gravity; $\sigma$ is the stress value; $D$ is the elastic matrix; $B$ is the stress matrix.

2.2. Modeling and meshing generating
According to the geometric parameters of the shaft tubular pump, the whole flow channel model is established. The basic parameters of the pump are shown in the table below
The pump model mainly includes inlet passage, impeller, guide vane and outlet passage. The model is shown in Figure 1. The pump section includes impeller and guide vane and other parts, and the structure is relatively complex. Considering the calculation accuracy, the mesh of the pump section, especially the blade part, is encrypted. The grid density will have a great impact on the calculation results, too sparse grid cannot obtain enough flow details in the flow field, which leads to poor calculation accuracy and thus does not meet the requirements. However, the grid independence verification can approximately determine the minimum number of grids to obtain sufficient details. It is found that the difference between the calculation results of 4.2 million grid and 4.8 million grid is less than 1%. On the premise of ensuring the calculation speed and accuracy, the final grid number is 4.2 million.

3. Pressure fluctuation characteristics

3.1 Pressure fluctuation monitor points

In order to obtain the pressure pulsation information of the shaft tubular pump during operation, several monitoring points are set at the inlet of pump impeller F1, internal section F2 of runner and outlet surface F3 of impeller, as shown in Fig. 2. At the inlet of impeller, guide vane and outlet section, three groups of monitoring points are evenly set from the rim to the hub, which are A1-A3, b1-b3 and C1-C3. Since a1-c1 points are close to the hub and a3-c3 points are close to the wall, in order to obtain more accurate flow information inside the pump section, the data of A2 and C2 monitoring points are taken for analysis.

At the same time, in order to make the unsteady calculation results more accurate and stable, in the calculation process, the time required for each blade rotation of 3° is taken as a time step, and four rotation cycles after calculation stability are selected as the sampling time. Take the dimensionless pressure fluctuation coefficient CP, and the expression is shown in formula (3)

\[ Cp = \frac{p_i - p_{ave}}{p_{ave}} \]  

(3)

Where CP is the dimensionless pressure coefficient; \( p_i \) is the pressure value of the monitoring point at a certain time; and \( p_{ave} \) is the average value of pressure in one rotation cycle.

| Parameters     | Value |
|----------------|-------|
| Impeller diameter | 4.3 m |
| Rate head         | 3.2 m |
| Maximum head      | 3.8 m |
| Rate speed        | 86 rpm|
Figure 3 (a) (b) shows the pressure distribution at the inlet and outlet of the blade at a certain time in the rotating cycle, and the pressure at the impeller inlet can be seen from Figure 3 (a) The pressure distribution is uneven, and with the blade rotating, the pressure surface of the blade will have periodic high-pressure pulsation, and the spatial distribution characteristics of the pressure fluctuation are obvious. The high pressure is mainly distributed on the pressure surface of the inlet side of the impeller blade, and the low pressure is mainly distributed on the suction surface. The water inlet edge of the blade is the obvious boundary between the low-pressure area and the high-pressure area. This shows that the flow is affected by the rotating impeller before entering the impeller from the front shaft. However, the amplitude of pressure fluctuation at the impeller outlet is large and stable, which indicates the flow at the impeller outlet.

It can be seen that the impeller rotation will cause local high-pressure pulsation at the impeller inlet. It can be seen from Figure 3 (b) that the pressure distribution at the impeller outlet is relatively uniform, and the pressure spatial distribution characteristics are clear. The high pressure is mainly between the pressure surface at the outlet side of the impeller blade and the pressure surface at the inlet side of the guide vane blade, while the low pressure is mainly distributed between the suction surface side of the impeller blade edge and the suction surface side of the guide vane edge, and the root area of the guide vane gap. It is obvious that the periodic local high pressure caused by the dynamic and static interference between the impeller and the guide vane forms the pressure fluctuation at the outlet of the impeller,
which indicates that the dynamic and static interference is the main reason for the pressure fluctuation at the outlet of the impeller. By analysing the time-frequency characteristics of pressure fluctuation, the relationship between dynamic and static interference and pressure fluctuation can be further verified.

![Fig.4 Hydrodynamic pressure characteristics](#)

### 4. Dynamic stress analysis of impeller

#### 4.1. Model and computing setup

The 3D model of impeller is established based on impeller parameters, as shown in Fig. 5. The impeller is mainly composed of main shaft, hub body and blade. Through grid independence verification, the optimal number of grids is 131882 under the premise of ensuring the calculation accuracy and accelerating the calculation speed. When the pump is running, the external forces include water pressure generated by water flow, gravity generated by impeller mass, and centripetal force generated by impeller rotation. The coupling module loads the blade water pressure load calculated by Fluent into the transient structure calculation module for structural calculation. Its essence is equivalent to the unidirectional fluid structure coupling calculation in each time step. Many scholars pointed out that the calculation results of unidirectional fluid structure coupling and bidirectional fluid structure coupling in hydraulic machinery with small deformation during the operation of pumps have little difference. The constraint conditions of structural calculation are shown in Fig. 6. In Fig. 6 (a), constraints A and C are cylindrical constraints imposed by guide bearing and thrust bearing, e is rotating speed of impeller, and interface d is fluid solid coupling interface of blade. The cloud chart of water pressure distribution loaded on the

![Fig.5 Model and mesh grid of pump turbine](#)
blade is shown in Fig. 6 (b). In this paper, two working conditions of rated speed 86 rpm and runaway speed 152.22 rpm are selected for dynamic stress analysis under the maximum head of 3.8 m.

4.2. Analysis of dynamic stress characteristics of Shaft Tubular Pump Impeller

Fig.6 Boundary condition of structural analysis

Structural calculation shows that the maximum point of dynamic stress appears near the center of the interface between blade root and hub, as shown in Figure 7, and its position is the same as that of static stress. The maximum static stress of impeller at rated speed and runaway speed is 66.4 MPa and 103.1 MPa respectively. The fluctuation of the maximum value of the dynamic stress of the impeller shows obvious periodicity in the time domain and has a significant primary and secondary frequency in the frequency domain. The time domain and frequency domain characteristics of the dynamic stress of the impeller are shown in Fig. 8.

Fig.7 Maximum dynamic stress on impeller

As shown in Fig. 8 (a), the maximum value of dynamic stress has obvious periodicity in time domain distribution, and its amplitude fluctuates near the maximum value of static stress. Compared with the rated condition, the fluctuation amplitude of dynamic stress under runaway condition is larger, which indicates that the stress fluctuation of impeller under runaway condition is larger, and the calculation of dynamic stress can meet the actual requirement of actual structural strength check of impeller compared with static stress. In this paper, the material of impeller is ZG0Cr13Ni4Mo, and its yield strength is 550MPa. According to the design requirements and material mechanics knowledge, the safety factor $\sigma_y$ is taken as 3, and the allowable stress of impeller is taken as $[\sigma]$ value = $1 / 3 \times \sigma_y$ = 183mpa. It can be found that the maximum dynamic stress fluctuation peak value of the pump shaft under runaway condition is still less than the allowable stress, so it can be considered that the structural strength of the impeller can meet the requirements of operation safety under extreme conditions. The time-domain characteristics of dynamic stress of impeller show that the maximum value of dynamic stress fluctuates greatly under runaway condition, the peak valley value deviates from the static stress far, and the peak value may be close to the allowable stress. Therefore, the influence of dynamic stress fluctuation should be taken into account in the structural calculation.
Fig. 8 Dynamic stress characteristics

Fast Fourier transform (FFT) is used to transform the maximum value of dynamic stress from time domain to frequency domain, and figure 8 (b) is drawn. It can be seen from the figure that the main frequency of maximum dynamic stress fluctuation occurs at 4.3 Hz and the secondary frequency is 8.6 Hz. The main frequency of the maximum dynamic stress fluctuation at runaway speed occurs at 7.6 Hz and the secondary frequency appears at 15.2 Hz. Comparing with the frequency domain characteristics of pressure fluctuation at rated speed, it can be found that the primary and secondary frequencies are impeller blade frequency and guide vane passing frequency respectively.

There are two main factors causing the dynamic stress fluctuation of the impeller. The first is the flow induced pressure fluctuation caused by the rotation of the impeller itself, and the second is the hydraulic excitation pulsation caused by the dynamic and static interference between the impeller blade and the fixed guide vane.

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5. Conclusion

In this paper, through the numerical simulation of the flow and fluid structure coupling of a shaft tubular pump, the characteristics of pressure fluctuation and maximum dynamic stress distribution in the shaft tubular pump are explored, and the internal relationship between them is revealed.

1) The time-frequency characteristics of pressure pulsation at the inlet and outlet of the shaft tubular pump under different working conditions were analysed. It was found that the main frequency of the pressure fluctuation at the impeller inlet was the impeller blade rotation frequency, which indicated that the pressure pulsation was mainly caused by the rotation of the impeller, and its amplitude was smaller; the main frequency of the pressure pulsation at the impeller outlet was the guide vane passing frequency, and its amplitude was significantly increased compared with the impeller inlet, indicating that the pressure fluctuation in pump caused by two main reasons, first is the rotation of the impeller, the second is the rotator and stator interaction between the impeller and the guide vane, and the RSI has a greater and more significant impact on the former.

2) The results show that the maximum dynamic stress appears at the root of the blade, which is the same as the maximum static stress point, and its amplitude fluctuates up and down near the maximum value of static stress, and the fluctuation of load-rejection condition is large, which is in the structural check. At the same time, frequency domain analysis shows that the primary and secondary frequencies of dynamic stress are blade passing frequency and guide vane passing frequency respectively.

3) Compared with the calculation results of frequency domain and time domain of dynamic stress and pressure fluctuation, it is shown that the primary and secondary frequency of dynamic stress correspond to the main frequency of pressure fluctuation at the inlet and outlet section of the impeller.
respectively, which indicates that the dynamic stress fluctuation is mainly caused by the pressure fluctuation, and the main reasons are the rotation of the impeller and the dynamic and static interference between the impeller and the guide vane. Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure.

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