Vibration analysis of large centrifugal pump rotors

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Abstract: Through the critical speed of centrifugal pumps, internal flow field and the force of the impeller, we analyze centrifugal pump vibration. Using finite element analysis software ANSYS to calculate the natural frequency of the rotor system and the critical speed; with the help of the Fluent software to simulate pump internal flow field, we conclude that speed increase will not cause intense vibration of the fluid in the pump. Using unsteady numerical simulation we discovered that in an impeller suffering transient radial force cyclical change periodically, as well as the frequency size determined by the product of the impeller speed and number of blades, resonance phenomena should make impeller to transient radial force frequency. If wanting to avoid pump resonance when it is running away, the transient radial force frequency should avoid the frequency range which can cause resonance.

1. Introduction

Centrifugal pump as a kind of rotary hydraulic machinery, the run time will produce vibration due to a variety of reasons, because of its special structure. Rotor system as the core component of centrifugal pump, the run security problem that cannot allow to ignore. Nonlinear vibration analysis of a centrifugal pump belongs to the category of rotor dynamics. In recent years, the study on the rotor dynamics in China with the support of state funds is also booming [1-3]. But about large pump rotor system vibration and stability in our country's researches also greatly lag behind the foreign countries.

Large double suction centrifugal pump with good performance and operating stability, so it’s widely used in irrigation, water supply and drainage, etc. But it also often appears some problems in the running [4-5]. Along with the popularization and application in the field of frequency control of the motor speed regulation in the water supply and drainage, variable speed operation of large centrifugal pump technology is more and more mature, but improving the rotational speed of centrifugal pump, after improving it also has higher requirements to its safety stability. As a result, In this paper, with a large double suction centrifugal pump as the research object, this pump is designed based on a certain pumping station in Gansu province water conservancy requirements, working condition for its
design (Q = 3.0 m³/s, H = 56 m, n = 600 r/min), this pump in the pump station smoothed in running time state, various performance indexes meet the design requirements. After installing the pump running on a certain pumping station in Ningxia and increasing the pump speed to 750 r/min, by calculation it can meet the requirements, the head can reach 70 m as well as the required flow rate of the pump station, but the pump appears strong vibration at run time, lead to not normally operate. Redesigning the impeller after analyzing of the reasons for this phenomenon, the blade number from 6 pieces reduced to 5 pieces, so as to solve the problem.

This article from the following three aspects: large centrifugal pump rotor system critical speed, the internal flow field in pump and impeller rotor radial force analyzed the vibration condition of large centrifugal pump while improving the speed running, at the same time, made the analysis on the reasons for this phenomenon.

2. Impeller rotor by finite element analysis based on ANSYS Workbench
Using ANSYS Workbench to the pump impeller rotor is preliminary made modal analysis, obtaining on the draw the design speed of each order natural frequencies and critical speed. For determined the rotor of the centrifugal pump system, because of the natural frequencies of the rotor system with speed changes gently, it is thought that centrifugal pump impeller rotor natural frequency in constant, does not change with speed.

With finite element method for three-dimensional (3D) entity rotor system dynamics analysis, the need to solve the differential equation of movement of the system can be represented as:

\[ M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \]

M for a system of n * n order mass matrix; C as a system of n * n order damping matrix; K n * n order stiffness matrix for the system;
\( \ddot{u}(t) \), \( \dot{u}(t) \), \( u(t) \) respectively for the acceleration, velocity and displacement response of the system order n column; F(t) is a column vector n order dynamic load.

2.1. Impeller rotor model
Setting up model is composed of pump impeller and shaft of rotor in Pro/E, directly connecting to ANSYS Workbench and setting analysis module, selecting cast iron as impeller material, axis for 45# steel, other parameters are shown in table 1:

| Material Parameters of the impeller rotor |
|-----------------------------------------|
| Modulus of elasticity (E(N/m²)) | Poisson's ratio (\( \lambda \)) | Density (\( \rho (kg/m³) \)) |
|-----------------|-----------------|-----------------|
| Impeller        | 1.5×10¹¹        | 0.3             | 7500                     |
| Axis            | 2.0×10¹¹        | 0.3             | 7750                     |

According to structure of the impeller rotor, 2.4 m of the shaft span, 135 mm diameter of axle, setting bearing outer side and along the X axis, Y axis direction of the displacement is zero, along
the Z axis direction of the displacement with one end of the positioning bearing is zero, there is no limit on the other end, setting speed is 600 rpm, environment variables are set as showing in figure 1. System is automatic to meshing model for rotor, Modal extraction use subspace method and by setting the solving control options to control the subspace iteration process.

![Model of the rotor and setting of restrictions and loading](image)

**Figure 1.** Model of the rotor and setting of restrictions and loading

Large centrifugal pump impeller rotor is calculating in each order modal frequency (Hz) is showing in table 2:

| Order | Frequency (Hz) |
|-------|----------------|
| 1     | 75.222         |
| 2     | 81.325         |
| 3     | 86.774         |
| 4     | 215.336        |

2.2. Critical speed
The first-order natural frequency of the impeller rotor is 75.222 Hz and the corresponding of critical speed is:

\[ n_c = 60 \times 75.222 = 4513.3 \text{ r/min} \]

2.3. Vibration Analysis
The centrifugal pump operating speed is low from traditional pump vibration analysis method, the design speed is 600 r/min, after raising speed reaches 750 r/min, due to the critical speed is higher, and more than the above two running speed, the pump in the above two speed run time should not vibrate, but vibrating obviously at 750 r/min.

3. Analysis of the internal flow field in pump based on Fluent
Hydraulic vibration is one of reason for the vibration of the centrifugal pump, unsteady flow inside the pump, such as impeller with pressurized water chamber, such as dynamic and noise interference, eddy current and back flow, these can cause pressure pulsation, stimulating the pump body vibration in turn[6]. This article respectively numerically calculates the internal flow field of pump under 1.0 n, 1.1 n and 1.2 n and 1.3 n (n is the design speed of 600 r/min), comparing and analyzing the internal flow of pump under different rotation speed.
3.1. Steady numerical simulation for Centrifugal pump
The large centrifugal pump inner flow area of the three-dimensional entity model is establishing by using Pro/E software, importing the ICEM mesh and grid optimization. Through the ICEM software carries on the grid and smooth and quality inspection, grid as shown in figure 2. The rotor to the total number of grid 3666076, meshing is thinner, mesh quality is good.

![Figure 2. Model of the Impeller rotor meshing](image)

Using the numerical simulation model of Fluent. The momentum, energy, turbulent kinetic energy and dissipation rate uses second-order windward scheme, when calculation carried out for conveying water, the pressure and velocity coupling would use SIMPLEC algorithm, choosing the standard model and the MRF model. Boundary condition definition: inlet conditions with uniform velocity-inlet, outlet conditions choosing outflow, the solid wall with no slip conditions, near the wall using the wall function method to correct.

3.2. Analysis of flow field and the simulation results
By Fluent software to carries on the numerical simulation results of the proposed model is as follows. As shown in figure 3: the pressurized water chamber of the pressure distribution can be seen, after the fluid into the pressurized water chamber in the pressurized water chamber spiral flow passage along the radial diffusion, pressure distribution more uniform and similar under different speed, no local high and low pressure in the whole flow phenomenon in line with the general law of the flow of the pump distribution.

![Figure 3. Pressure distribution](image)
Figure 3. Pressure-distribution of spiral casing at different speed

Figure 4 for velocity distribution under different speed, with the increase of rotational speed, pressure water indoor speed increases gradually, and four under the rotating speed of the velocity distribution is relatively uniform, speed is gradually increasing from the first section to export, relatively similar, no obvious speed, high, which means that there is no swirl or backflow phenomenon, also conforms to the general law of the flow of the pump.

Figure 4. Velocity-distribution of spiral casing at different speed
From pressure distribution and velocity profile in pressure water indoor can be seen that after the fluid into the pressurized water chamber in the spiral flow passage of pressurized water chamber diffuse along the radial direction, speed is reducing, along the spiral flow channel into the diffusion tube, speed is further reduced in the diffusion tube, fluid kinetic energy into pressure energy, and the diffusion tube into the pipeline. It can be seen that both pressure distribution and velocity distribution are both highly similar, conforming to the similarity law of vane pump form by contrasting four speed under similar conditions of the pressurized water chamber pressure distribution and velocity distribution; the three conditions under speed increasing of indoor water does not appear obvious vortex, reflux, flow field distribution is highly similar with the case of design speed, there is no unsteady flow. Therefore, speed increase will not cause fierce vibration among the fluid within the pump.

4. Radial force of the impeller is calculated based on Fluent
The structure of double suction pump is symmetry, the axial force can be self balancing, forces acting on the impeller is mainly the radial force, rotational speed increased then the flow rate increased and the radial force of impeller increased[7]. Because of the asymmetric structure of the single volute pump body, the influence of impeller and volute tongue gap, the insulation impeller by radial load is insulating circumferential distribution, it will produce radial fluid exciting force on the impeller[8], and then lead to pump for vibration, especially in the large centrifugal pump. Impeller radial force can be divided into steady state transient radial force and radial force, steady state reaction is the cause of impeller appears eccentric, and transient force is the cause of the centrifugal pump with rotor vibration [9]. This article does not consider the situation about the impeller to the eccentricity of the rotor; we only calculate transient radial force what could cause severe vibration of the impeller. Below using the Fluent software to unsteady numerically simulate centrifugal pump impeller unsteady radial force calculation and find its change rule, for further analysis of the vibration.

4.1. Unsteady numerical simulation of centrifugal pump
Using the Fluent software and applying the theory of sliding grid, using the method of unsteady numerical simulation to centrifugal pump, other settings is the same as the steady-state numerical simulation model.

4.2. Transient radial force calculation of impeller
Directly numerically integrating to the pressure and viscous force of fluid flow that effecting on the impeller in Fluent software, then getting the radial force and its components, namely the direct integral method.

The time steps from second time step after are convergences. In order to study the stable operation of the radial force for centrifugal pump, research scope is 240th steps length to 300th steps, and 0.4 s to 0.4 s as the study area. In Fluent software, respectively applying transient radial force calculation of the direct integral method of the research area within each time step , calculating each transient radial force and its components, as shown in figure 5, 6;
4.3. Pattern analysis
The transient radial force F and its F_y, F_z of the centrifugal pump impeller components are time t cycle function, and the period of 0.0167 s from figure 4, 5. Speed is 600 r/min, the impeller rotating period T = 0.1 s, the impeller rotating in a cycle, F_y, F_z both changed for 6 cycles, the impeller blade number is 6. Impeller rotation cycle and the ratio of leaf number for T/N = 0.1/6 = 0.0167 s, diagram of transient radial force of the impeller cycle also is 0.0167 s.

Therefore, when the number of impeller blades is N, the impeller transient radial force is equal to the change of the frequency of the impeller rotating speed N times:

\[ f = N \cdot n \]

f - Impeller transient radial force frequency (Hz); n- Impeller speed (r/s);
Namely the pump impeller transient radial force is equal to the blade by frequency change frequency, this is similar with studies at home and abroad such as literatures [10-11] and leaves through the frequency of the basic consistent conclusions.

4.4. Analysis of vibration
The pump impeller blade is 6 pieces and the first-order natural frequency of impeller rotor system is 75.222 Hz, which is the reason of resonance frequency in the range of \((1 + 8\%) \times 75 = 69 \sim 81\) Hz\(^{[12]}\).

The impeller transient radial force frequency is 6 * 10 = 60 Hz, less than that can cause resonance frequency, when running on a certain pumping station in Gansu, and the pump in this pump station run smoothly. In the pump installation a pumping station with operation for the first time in Ningxia, the impeller rotating speed is 750 r/min, the impeller transient radial force frequency is 6 x 12.5 = 75 Hz, the frequency which can cause resonance frequency is locating in right range, so the runtime appeared strong vibration phenomenon. After reducing number of impeller blades for 5 pieces, the pump impeller at the 750 r/min instantaneous frequency of the radial force is 5 * 12.5 = 12.5 Hz, not in which the range can cause resonance frequency, so does not cause resonance. Improved the pump in the pump station running smoothly is also borne out the correctness of the analysis.

5. Conclusions
When analysis vibration of the large centrifugal pump which the traditional pump design method, and considering its design speed far less than the critical speed, thus improving the rotate speed does not reach the critical speed and resonance of judgment method is not enough tight.

When changing the rotate speed of pump, it will not cause vibration between the fluid.

Analyzing stress of the impeller rotor from the Angle, using Fluent software to finish unsteady numerical simulation, calculating the transient radial force of the pump impeller change frequency is
equal to the number of impeller blades and rotating speed of the product: \( f = N \cdot n \). If the impeller pump in running time, the transient radial force frequency closes to the rotor natural frequency, it will cause resonate; it also can influence the safe and stable operation of pump. In order to avoid resonance phenomenon in pump running time, it should make impeller transient radial force frequency avoid range that can cause resonance frequency.

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