Modal Analysis on Impeller Rotor of the Axial Flow Pump based on Fluid-structure Interaction

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Abstract. It is important to study the vibration characteristics of the impeller rotor of an axial flow pump for avoiding resonance and ensuring the safe and stable operation of the pump. Based on the fluid-structure coupling method and considering the compressibility of fluid, the coupling equation of fluid and solid is solved by inserting APDL command flow into ANSYS Workbench platform. The natural frequencies of the runner of horizontal axial flow pump in water and the reduction coefficients of each order of frequencies are obtained, and the distribution of each order of modes is analyzed. Additional mass theory is used to analyze the reasons for the reduction of natural frequencies. The results show that the natural frequency of the impeller of an axial flow pump decreases due to the water medium. The increase of the vibration quality of the whole system caused by the water body vibration is the fundamental reason for the reduction of the natural frequency of the impeller. The damp dissipation of the water body will lead to the decrease of the amplitude of the impeller in water.

1. Introduction
The impeller rotor of an axial flow pump works in water. Besides gravity and motor torque, it is also subjected to external exciting forces such as hydraulic force. The force distribution is complex. When the frequency of these forces is the same or close to the natural frequency of the impeller, the impeller will resonate and the blade will produce resonance cracks or even breaks. Therefore, it is necessary to align the shaft. The natural vibration characteristics of impeller rotor of flow pump are studied. Zhang Xiheng et al. used ANSYS Workbench software and two methods of acoustic-solid coupling and fluid-solid coupling to carry out modal analysis of the valve pipeline system. Comparing the two wet modal frequencies, it was found that the calculation value deviation of the lower two methods was small, and there were some differences between the higher ones [1]. Zhang Bing et al. established an underwater fluid-solid coupling model of the motor, analyzed the frequency and modal characteristics of the first-order wet mode of the Lanwenjie oscillator, and compared it with the first-order mode in vacuum, verified its feasibility as an underwater driving oscillator, and laid a solid foundation for further research of the underwater actuator [2]. Gao Haisi et al. analyzed the dry and wet modal characteristics of impeller components; studied the influence of prestressing on the natural frequencies and modes of impeller components according to whether or not prestressing was applied to impeller components; and considered the material properties of impeller components, analyzed the influence characteristics of Young's modulus of metal materials on the natural frequencies of impeller components.
components [3]. Zhang Xin et al. used finite element software ANSYS Workbench, combined with fluid-solid coupling method, analyzed the mode of a horizontal axial flow pump in a pumping station, calculated the natural frequencies and vibration modes of the impeller rotor in air and water, and analyzed the variation law of the natural frequencies of the impeller and its causes [4]. Zhao Wenlu et al. analyzed the dry-wet modal of HL160 turbine runner by ANSYS software, and obtained the vibration characteristics of the runner in air and water, such as natural frequency and mode shape. It is necessary to analyze the wet modal of the runner. The wet modal analysis can more truly investigate the actual vibration mode of the runner under water [5].

Based on the fluid-structure coupling method and considering the compressibility of fluid, the coupling equation of fluid and solid is solved by inserting APDL command flow into ANSYS Workbench platform. The natural frequencies of the runner of horizontal axial flow pump in water and the reduction coefficients of each order of frequencies are obtained, and the distribution of vibration modes of each order is analyzed. The reason for the decrease of natural frequency is analyzed by the theory of added mass.

2. Establishment of Finite Element Model for Fluid-solid Coupled Modal Analysis

In order to solve the mode of impeller of axial flow pump in water, a circle of cylindrical water is wrapped around the impeller. The diameter of the cylinder is 2.5m and the height is 4.7m. The grid nodes of impeller structure and water body interface are set one to one, and the grid of impeller and water body is divided according to the method of free partition. After grid independence verification, the number of grid elements is 542868 and the number of grid nodes is 747973. The material attributes and constraints of impeller are the same as above; the material attributes of fluid domain need to be set by inserting APDL command stream into ANSYS Workbench. Fluid220 and Fluid221 units are used in fluid domain to obtain higher solution accuracy. The density of water body is set at 1000kg/m3, and the sound velocity in water body and impeller is set at 1483 m/s. The interface is a fluid-solid coupling surface and the external boundary pressure is set to 0 Pa.

2.1. "Dry" Modal Analysis

In the "dry" mode, the structure of the pump section is shown in Figure 1. Cylindrical constraints are set respectively. This section mainly connects the position of the leading bearing and the rear bearing. The GRid-INdependent validation of the "dry" mode of the axially extended tubular pump is carried out, and the results are calculated at the same time.

![Fig. 1 Structural diagram of pump section for "dry" modal analysis](image)

Ten-order modal analysis is made for the extended tubular pump under the "dry" mode. The natural frequencies of the extended tubular pump are shown in Table 1.

| Order number | f1, f2 | f3 | f4 | f5, f6 | f7 | f8, f9 | f10 |
|--------------|-------|----|----|-------|----|-------|-----|
| Frequency value | 62.97 | 85.18 | 98.90 | 100.94 | 128.51 | 179.42 | 211.72 |
Most of the natural frequencies of blades in the air appear in pairs, which is due to the periodic symmetry of the runner part of the axially extended tubular pump, which results in the same amplitude of the impeller's natural frequencies, but different phases. This can also prove that the symmetric model has two different modes with the same frequency and the phase is orthogonal.

2.2. "Wet" Modal Analysis

In order to solve the mode of impeller in water, a circular cylinder with diameter of 2.5m and height of 4.7m is wrapped around the impeller, as shown in Figure 2. The fluid blade surface and the solid impeller surface are set as the fluid-solid coupling interface, and the impeller material is set. At the same time, the restriction conditions of solid runner are limited. The bottom surface of the restriction conditions is fixed, the circumferential surface is circumferential, and the circumferential can rotate.

![Fig. 2 Three-dimensional model of fluid and impeller](image)

3. Analysis of mode calculation results

3.1. Modal Characteristics of Impeller in Air

Cylindrical constraints are applied at the positions of the leading bearing and the rear bearing of the runner to restrict the degrees of freedom of the impeller in the tangential, axial and radial directions. The natural frequencies of impellers in air are calculated by ANSYS workbench finite element method, as shown in Table 2.

| Order number | f1, f2 | f3 | f4 | f5, f6 | f7 | f8, f9 | f10 |
|--------------|-------|----|----|--------|----|--------|-----|
| Frequency value | 62.45 | 85.05 | 98.90 | 100.92 | 128.26 | 176.32 | 211.72 |

Due to space limitation, only the mode diagrams corresponding to the first four natural frequencies are given below, as shown in Figure 3. The first and second natural frequencies are 62.45Hz. The vibration modes are that the blades oscillate up and down, the third natural frequencies are 85.05Hz, the vibration modes are that the blades vibrate around the rotating axis in a central torsional way, and the fourth natural frequencies are 98.90Hz. The vibration modes are that the blades oscillate back and forth, and the upper and lower and left blades oscillate symmetrically.

![Fig. 3 The first four modes in the air](image)
3.2. Modal in Water
The natural frequencies of impellers in water are calculated by inserting APDL command flow, and compared with those in the air of the upper section, as shown in Table 3. In order to analyze the effect of additional mass of water on the natural frequencies of runners, a frequency reduction factor \( \delta \) is introduced.

\[
\delta = \frac{f_a - f_w}{f_a}
\]  

(1-1)

The impeller \( f_a \) is natural frequency in air and the impeller \( f_w \) is natural frequency in water.

| Mode | In the air (Hz) | In the water (Hz) | \( \delta \) |
|------|----------------|------------------|-----------|
| 1    | 62.45          | 51.62            | 0.17      |
| 2    | 85.05          | 56.83            | 0.33      |
| 3    | 98.90          | 61.25            | 0.38      |
| 4    | 100.92         | 70.97            | 0.29      |
| 5    | 128.26         | 114.85           | 0.10      |
| 6    | 176.32         | 135.03           | 0.23      |
| 7    | 211.72         | 135.05           | 0.36      |

As can be seen from Table 3, the natural frequencies of runners at different stages have been reduced to varying degrees due to the presence of water medium. The frequency reduction coefficient is not a fixed value, but changes with the different modes. The frequency reduction coefficient ranges from 0.10 to 0.38. The reduction coefficients of each order depend on their modes, and there is no obvious law in numerical value. The first four modes of the impeller of an axial flow pump in water are shown in Fig. 4.

Fig. 4 The first four modes in water

Comparing with the vibration mode diagram of impeller in air in Fig. 3, it can be seen that the vibration mode of impeller in water is basically similar to that in air, but the amplitude is slightly different. It can be clearly seen from Fig. 3 and 4 that the vibration amplitude of impeller hub in water is smaller than that in air, which shows that the presence of water medium can reduce the vibration amplitude of impeller.

The above can be explained by the theory of added mass. According to the law of conservation of energy, the total energy of the vibration system is the same in different media, so the maximum kinetic energy of the vibration system is the same. When the impeller vibrates in water, the impeller needs to work on the water body to drive the vibration of the surrounding water body, which is equivalent to increasing the total vibration quality of the system. Since the total kinetic energy of the system is constant and the vibration of the water body has partial kinetic energy, the kinetic energy of the impeller itself will be reduced. Because the reduction of impeller's kinetic energy will inevitably lead to the reduction of impeller's vibration frequency and speed, so the natural frequencies of impeller in water will be reduced. Because the vibration of impeller at each stage is different and the work done for water body is also different, the reduction coefficients of natural frequencies of all walks of life are different. Because of the existence of water damp around the impeller, the energy of the whole vibration system will be dissipated, so the amplitude of the impeller vibration in water will be lower than that in air.
4. Conclusion
In this paper, the finite element software ANSYS Workbench and the fluid-solid coupling method are used to calculate and analyze the modal of a horizontal axial flow pump in a pumping station. The natural frequencies and vibration modes of the impeller rotor in air and water are calculated, and the variation law of the natural frequencies of the impeller and the reasons for the change are analyzed. The main results are as follows:

(1) By inserting APDL command stream into ANSYS Workbench, the modal solution of impeller of axial flow pump in water is realized.

(2) Water medium will reduce the natural frequency of impeller of axial flow pump. The reduction coefficient of the first ten order natural frequency of impeller ranges from 0.1 to 0.38. The reduction coefficient is related to the vibration modes of impeller, and there is no obvious regularity in numerical value.

(3) The increase of the vibration quality of the whole system caused by the water body vibration is the fundamental reason for the reduction of the natural frequency of the impeller. The damp dissipation of the water body will lead to the decrease of the amplitude of the impeller in water.

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