Transient response and critical speed analysis of large vertical volute pump

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Abstract. The analytical investigation of the rotor dynamics system in large vertical volute pump is presented in this paper. The radial force imposed on impeller is a time-independent value which is extracted from the numerical simulation results. A three-dimensional finite element analysis of the pump rotor was performed to investigate the critical speed and mode shape. The transient response of the rotor dynamics is studied by analysing radial excitation force at variable flow conditions. In addition, the stiffness and damping of the bearings are calculated by Software ARMD. The result shows that the resonance of pump will not occur under design condition. The radial displacement of monitoring point at impeller presents periodic variation when the time-independent radial force is imposed on impeller.

1. Introduction

Large vertical volute pump is widely applied in pumping stations. The violent vibration which appears in the high-head and high-power vertical volute pump affects the pump operation stability and durability. The significant factors which cause pump vibration include unstable rotor system, fluctuating pressure in the pump and so on. Some studies have been carried to investigate the rotordynamic response of systems: Okabe et al. [1] investigated the influence of tilting pad bearing on the dynamic behavior of the rotor, and found pad preload, number of segments, radial clearance, pad position, and pad pivoting angle affects the rotor dynamic behavior obviously. Lund et al [2] found the radial force of hydrodynamic bearings is proportional to displacements of the shaft. White et al.[3] studied the rotordynamic behaviour of a vertical twelve stage multiphase pump.He compared linear and non-linear methods to calculate the force of shaft.The results showed that the bearing clearance was the dominating parameter to controlling the dynamic behavior. Zhang et al [4] investigated the two-dimensional dynamic stability of a high-spinning liquid-filled rotor. Their results shown that the external damping is a destabilizing factor and the internal damping had certain stabilizing effect. Shi et al. [5] studied the bearing forces in the nonlinear dynamic model of a vertical rotor-bearing system through numerical analysis, and found the stability of vertical rotorbearing system increased with the increasing rotor mass unbalance and bearing length. To our knowledge, few works have been conducted to study the critical speed analysis and transient response of large vertical volute pump.

The analytical investigation of the rotor dynamics system in large vertical volute pump is presented in this paper. The results provide a basis for rotor dynamics optimization design of this kind pump.

2. Model and Method

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The large vertical volute pump is studied in this paper. The design parameters of the pump are as follow: the flow rate (Q) is 11.25m^3/s, the head of the pump (H) is 53.5m, and the rotating speed (n) is 300rpm. The material of pump shaft is dual phase steel with density of 7800 kg/m^3. The modulus of elasticity is 210 GPa and the ratio of Poisson is 0.31. The material of impeller is ZG230-250 with density of 7850kg/m^3. The modulus of elasticity and the ratio of Poisson is 209GPa and 0.26 respectively. The model of impeller and pump shaft are shown in figure1.

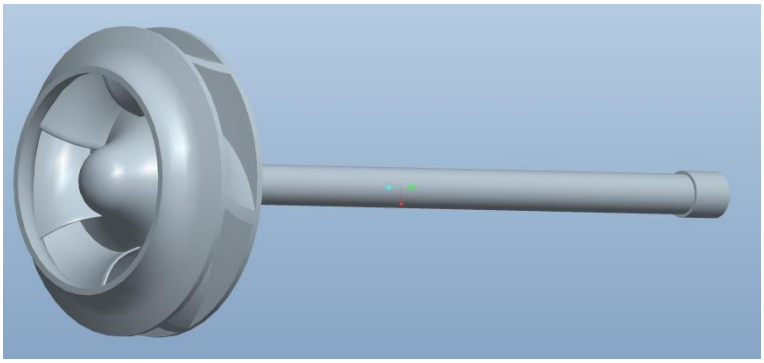


Figure 1. The model of impeller and pump shaft

The radial force imposed on impeller is a time-independent value, which is extracted from the numerical simulation results. The stiffness and damping of bearing are calculated by software ARMD. A three-dimensional finite element analysis of the pump rotor is performed to investigate the critical speeds and mode shape. The analysis module is Critical Speed & Stability when calculating critical speeds. The initial frequency and end frequency is 0Hz and 200Hz respectively. The algorithm of critical speeds is Pseudo-Modal.When considering transient response of system, the radial force extracted from unsteady flow field is imposed on the rotor as external excitation.

3. Numerical results and discussions

In this paper, the rotor dynamics system is numerically simulated by Samcef Rotor. The Samcef Rotor calculating accuracy is validated by comparing with the result of Bansal and Zhao [6, 7]. Reproducing the geometric model from Bansal, the whirling speed is calculated by applying our numerical method. The shaft diameter (D) of the model was fixed to 12.7mm, the elastic modulus (E) and the shear modulus (G) of the material was 204.8e9N/m^2 and 81e9N/m^2 respectively. According to Poisson ratio calculation formula: v=(E/2G-1)=0.2642.The rotor dynamics parameters are: K_{1xx}=K_{1yy}=1803.8N/mm, K_{2xx}=K_{2yy}= 1961·4 N/mm,C_{1xx}=C_{1yy}=0.876N·S/mm,C_{2xx}=C_{2yy}=0.876N·S/mm.

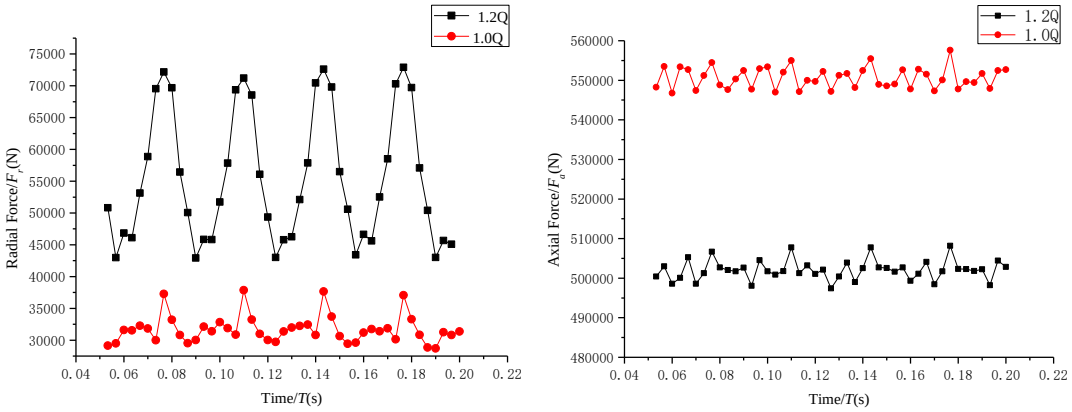
The results are shown in Table 1. Compared with the results of Bansal and Zhao, it can be found that the maximum error appeared in the second order reverse whirling which was about 9.34%.The study of Zhao showed that the result obtained by the better algorithm is closer to the actual results. The error between the results extracted by Samcef and the results of Zhao is 0.463%. Therefore, the numerical simulation result obtained by Samcef is accurate and reliable.

Table 1. Comparison of results

	Bansal	Zhao	Samcef	Maximum Error (%)
First order reverse whirling speed （rpm）	1408	1410	1403.82	0.618
Second order reverse whirling speed(rpm）	3338	3067	3052.85	9.34

Third order reverse whirling speed （rpm）	6495	6568.6	6551.82	0.883
Forth order reverse whirling speed （rpm）	-	6917.4	6903.3	0.204

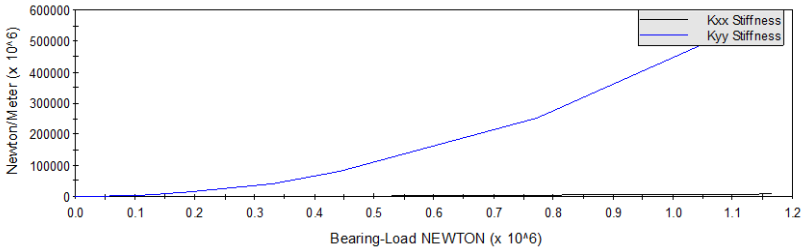
The commercial software CFX was applied to calculate the axial and radial force at design flow rate condition (1.0*Q*) and larger flow rate condition (1.2*Q*). It can be seen that the axial and radial force periodically changed in figure 2. As increasing flow rate, the radial force increases obviously, and the axial force decreases a little.



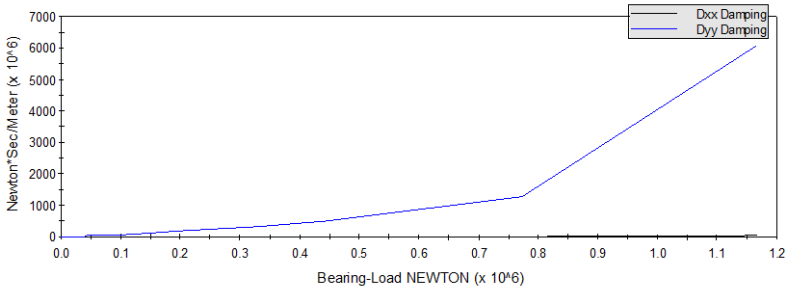
(a)The radial force (b) The axial force

Figure 2. The radial and axial force of the pump

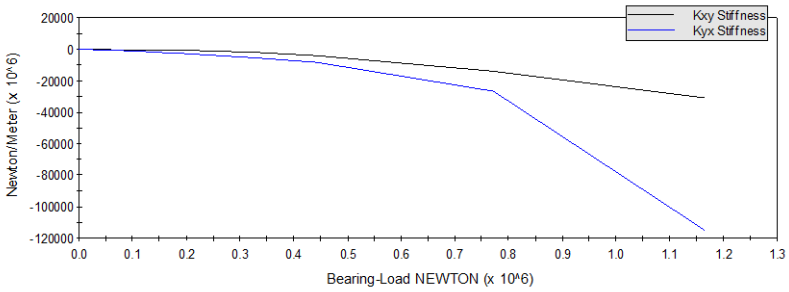
The stiffness and damping of thrust bearing and journal bearing is calculated by ARMD. With increasing the load, the stiffness and damping changed obviously. According to the radial and axial force calculated by CFX, the stiffness and damping can be found in figure 3 and figure 4.



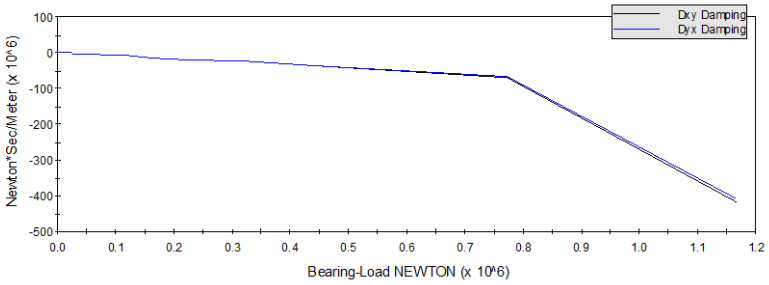
(a) The main stiffness coefficient



(b) The main damping coefficient

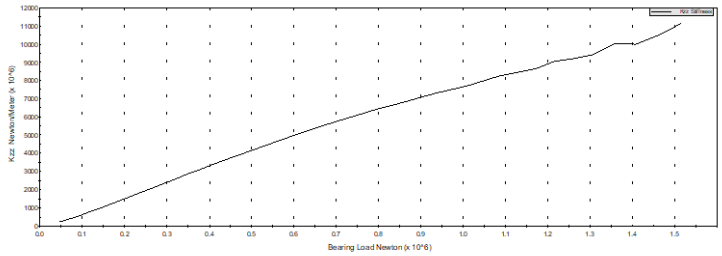


(c) The cross stiffness coefficient

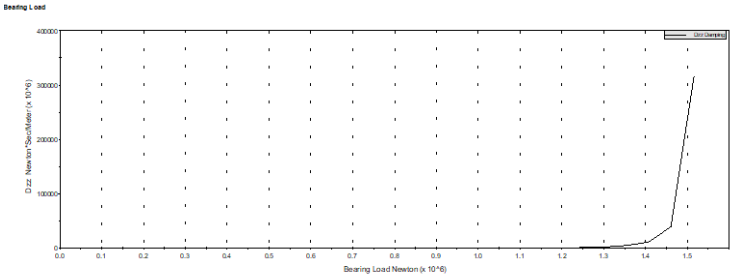


(d) The cross damping coefficient

Figure 3. The stiffness and damping of journal bearing



(a) The stiffness coefficient



(b) The damping coefficient

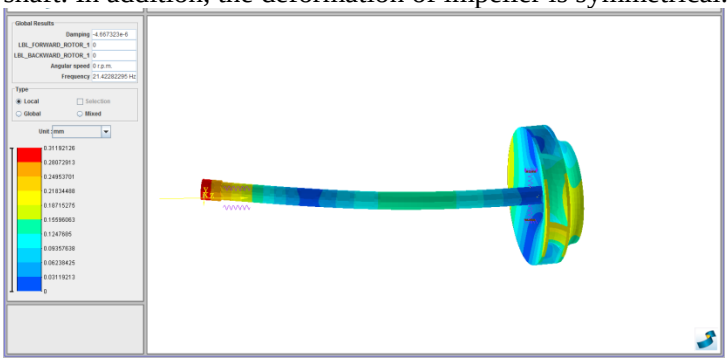
Figure 4. The stiffness and damping of the thrust bearing

In general, the centroid of the rotor is generally not on the axis because of manufacturing and installation deviation. When the rotor is rotating, the unbalance caused by eccentricity will lead to the rotor lateral vibration. When the rotor speed is near some critical speeds, the rotor will vibrate strongly. Under general circumstances, the rotating speed of pump rotor is low, so the first four whirling frequency were extracted in table 2.

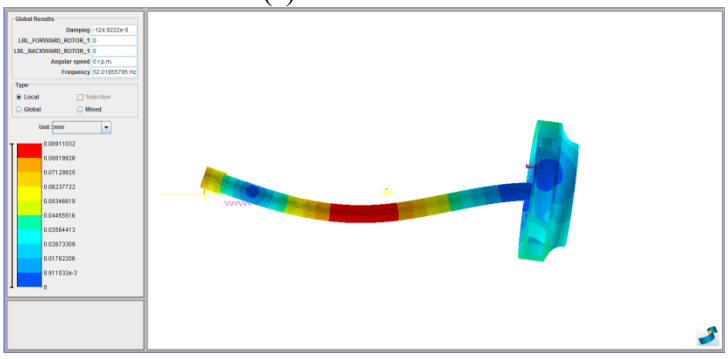
Table 2. The reverse whirling frequency

The order	The reverse whirling frequency （Hz）
1	21.4228
2	52.0196
3	112.889
4	152.837

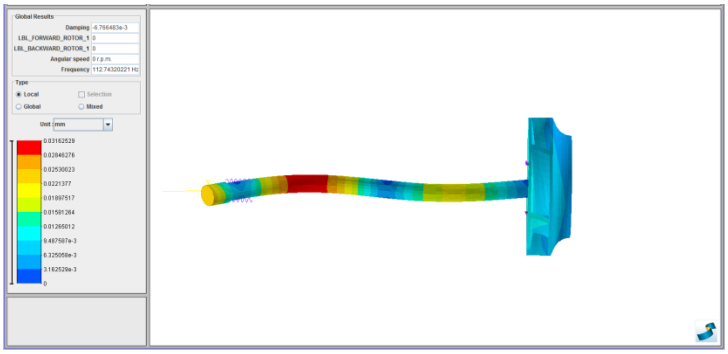
As can be seen from the above table, with the order increasing, the whirling frequency increases gradually. The first-order frequency is 21.4228Hz, which indicates the first order critical speed is 1285.014rpm. The critical speed is obviously larger than the rotating speed under design condition. Therefore, the rotor is a rigid rotor and the resonation will not appear under design condition. Compared with the high-order natural vibration mode, the low-order natural vibration mode has a greater effect on the vibration of the rotor system. Therefore, the low-order natural vibration mode has a decisive effect on the dynamic characteristics of the rotor system. The first four whirling frequency is analyzed. The mode of each model is shown in figure 5. It can be seen the bending deformation appears in the pump shaft. In addition, the deformation of impeller is symmetrical.



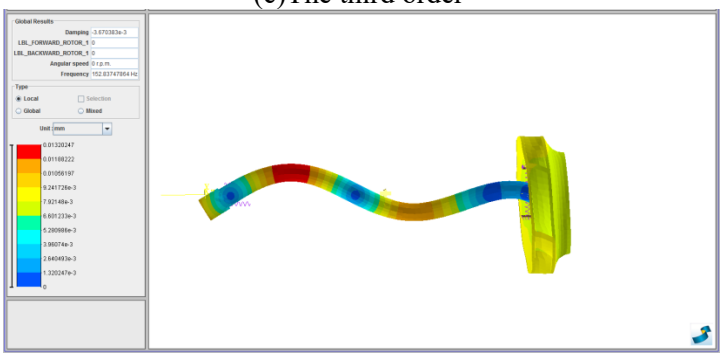
(a)The first order



(b)The second order



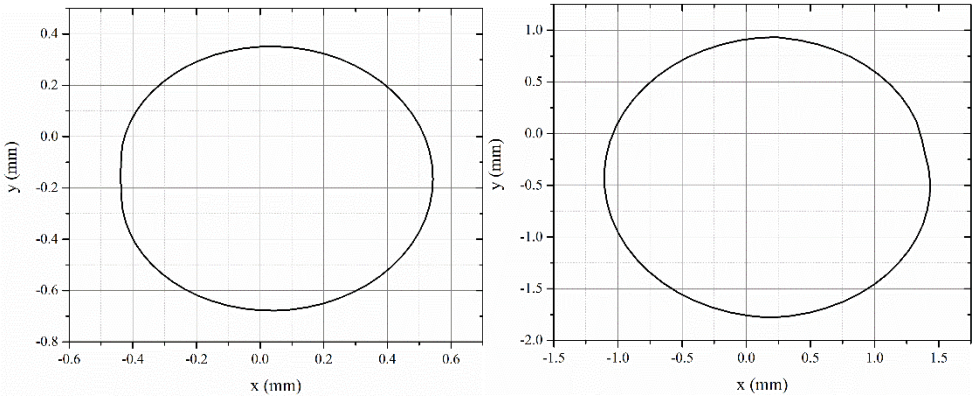
(c)The third order



(d)The forth order

Figure 5. The mode at different orders

The transient response of the rotor dynamic is analyzed in Transient Response module. The radial force is imposed on impeller to simulate the centroid movement of the axis center. The results were shown in Figure 6. It can be found that the flow rate increases, the displacement of the center enhances. What is more, the movement of the centroid is closed to third and fourth quadrant, which is caused by radial force under different conditions.



(a)1.0Q (b)1.2Q

Figure 6. The centroid movement

4. Conclusion

The periods of radial and axial forces are almost same. As flow rate increasing, the radial force increases obviously, and the axial force decreases a little.

The bending deformation appears in the pump shaft in the first four modes, and the deformation of impeller is symmetrical.

At larger flow rate condition, the displacement of the shaft center increases obviously. What is more, the movement of the centroid is closed to third and fourth quadrant, which is caused by radial force.

Acknowledgments
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