NUMERICAL INVESTIGATION OF BLADE DYNAMIC CHARACTERISTICS IN AN AXIAL FLOW PUMP

by

Desheng ZHANG**, Dazhi PAN, Yan XU, Peipei SHAO, and Guotao WANG

Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang, China

Short paper
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The unsteady numerical simulation of fluid field and structural transient dynamic analysis of axial flow pump were carried out at three operating conditions based on fluid-structure interaction method. Numerical results show that the maximum equivalent stress of impeller occurs at the joint region of the impeller blade root and the hub, and the maximum deformation of impeller occurs at the tips of blade leading edges. The frequency-domain of the maximum equivalent stress and outlet pressure fluctuation of impeller are mainly affected by the impeller blade passing frequency.

Key words: *axial flow pump, fluid structure interaction, pressure fluctuation, equivalent stress*

Introduction

Axial flow pumps with large flow rate and low head have been widely applied to agricultural irrigation, municipal water supply and drainage system, large-scale water diversion project, and so on [1]. Rotor-Stator Interaction (RSI) is the consequence of the interaction between the rotating flow perturbations caused by the impeller blades and the guide vanes, which can cause strong vibration of the machine, noise, blade fatigue failure, bearing damage and other serious problems [2]. In the case of the forced vibration caused by RSI, the dynamic stress of the impeller and the vibration amplitude will significantly increase, which might cause damage events. Resonance occurs when the natural frequency of impeller is close to or equal to the hydraulic excitation, which is the most disadvantaged condition for the impeller safe operation [3]. Childs [4] carried out a series of experiments to investigate the fluid-structure interaction (FSI) method forces between the impeller and the shroud of a pump as well as the axial vibrations. Zhang [5] established a fully coupled model of flow and flow-induced structure vibration using a hydride generalized variational principle of fluid and solid dynamics. Yuan *et al.* [6] simulated the flow field of centrifugal pumps based on FSI method.

To investigate blade dynamic characteristics in an axial flow pump, a combined calculation for turbulent flow and vibrating structure was carried out using two-way coupling method to supply a theoretical basis for the steady operating of axial flow pump.

Fluid-structure interaction method

Fluid control and structural dynamic equations

The unsteady RANS equations for turbulent incompressible fluid flow are used in the simulation, and the SST k-ω turbulence model is applied. Motion equation of the integral

* Corresponding author; e-mail: zds@ujs.edu.cn

structure is established by Hamilton principle [6]. A two-way coupling of the flow calculation and the solid calculation is required to obtain the complete FSI phenomenon.

Pump model and meshing

An axial flow pump model is presented in fig. 1. Flow rate Q = 1188 m^3/h, head H = 4.2 m, rotation speed n = 1450 rpm, impeller diameter D_2 = 300 mm, impeller blade number is 3, and its guide vane number is 5. The wall grids of the fluid computational regions and the unstructured grids of impeller solid are shown in fig. 2.

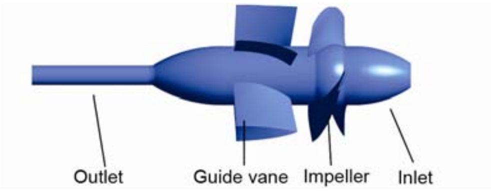


Figure 1. Pump model

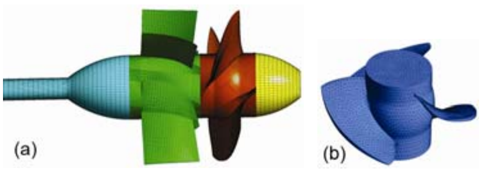


Figure 2. Grids of the fluid and structure regions

Boundary conditions

The full implicit coupled multi-grid linear solver is used for the unsteady solver of the flow field of axial flow pump based on ANSYS Workbench in which the fluid equations and structural dynamic equations are embedded. The inlet and outlet are set to be velocity inlet and outflow boundary conditions; and the interfaces between impeller inlet and outlet are set to be transient rotor-stator. Setting the date type that fluids pass to structure to be total forces, and the method that structures affect the fluid regions to be total mesh displacement. One time step corresponds to 3 degrees of the impeller rotation, and 120 time steps should be calculated in one cycle of impeller.

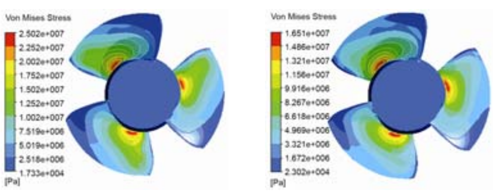
Numerical results and discussion

Material stress and deformation distributions

The distributions of equivalent stress of axial flow pump impellers under small flow rate (0.8 Q_{opt}) and design (1.0 Q_{opt}) conditions when t = 0.1655 s are shown in fig. 3.

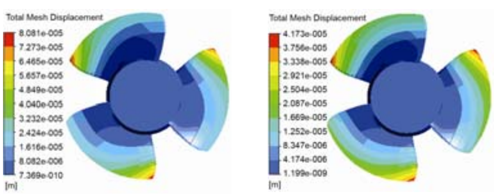
The maximum equivalent stress of impellers occurs to the joints of blade roots and hub close to the inlet, where there is also the place that is liable to crack and break. The stresses of the outlet and tips of impeller blades are relatively small. The high stress distribution in the entire impeller basically occurs at the outlets of impeller blades near the hub. The stress decreases from hub to tip in the circumferential direction of blades. At the small flow condition (0.8 Q_{opt}), the maximum stress is 1.52 times that at design condition (1.0 Q_{opt}).

Figure 4 shows the deformation distributions of impeller blades at different conditions. The maximum deformation of blades occurs in the tips of blade leading edges due to the



0.8Q_{opt} 1.0 Q_{opt}

Figure 3. Stress distributions
(for color image see journal web site)



0.8 Q_{opt} 1.0 Q_{opt}

Figure 4. Deformation distributions
(for color image see journal web site)

inadequate thickness of leading edges of blades and the insufficient stiffness and strength. Deformation distribution at small flow rate conditions is consistent with the stress distribution, and it is 1.94 times that at design condition. The blades are unable to release stress by elastic deformation at the leading edges close to hub because of the sensitive blade leading edges, thus it causes the formation of stress concentration especially at small flow rate condition.

Pressure fluctuation and impeller dynamic stress

The pressure fluctuation at impeller outlet may produce hydraulic excitation which could make the stress of the impeller changing with the pressure fluctuation. Figures 5 and 6 show the time and frequency domains of pressure fluctuation of monitoring points at the impeller outlet. The four monitoring points are named p21~p24, and their radiuses are 80 mm, 100 mm, 120 mm and 140 mm respectively, which are located from hub to tip along the radius. It is obvious that pressure fluctuation occurs in each monitoring points of the impeller outlet sections. The fluctuating features are almost coincident with each other, and they all have three peaks and three troughs, which are same to the blade number. The amplitude of pressure fluctuation increases gradually from hub to tip, and the frequency of pressure fluctuation of each monitoring point is 3 times (24.1 Hz) that the rotation frequency of impellers (72.5 Hz), which is equal to the blade-passing frequency. Pressure fluctuation at impeller outlet of axial flow pump is mainly determined by the passing frequency of the impeller blades.

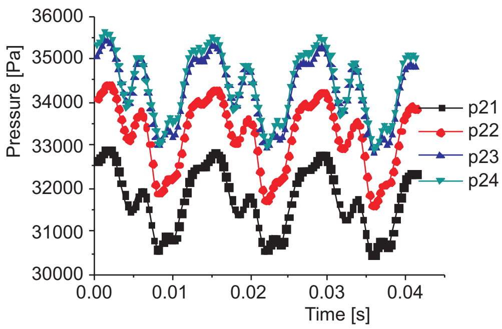


Figure 5. Time domains of pressure fluctuation *(for color image see journal web site)*

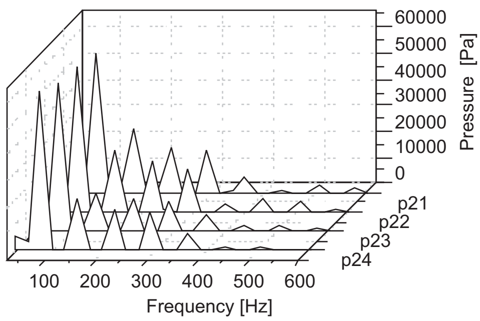
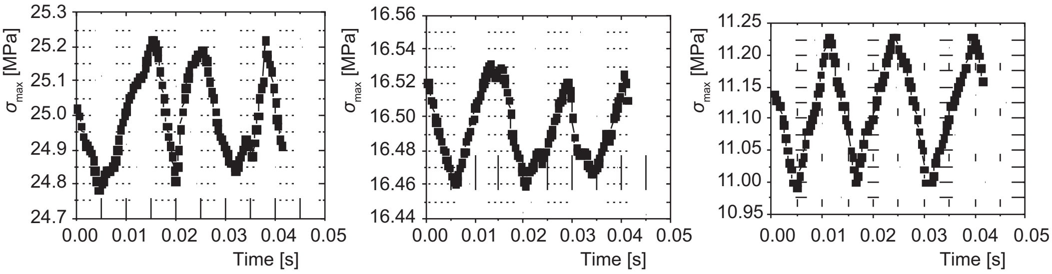


Figure 6. Frequency domains of pressure fluctuation

As we know, when the material deformation occurs, the reaction forces have the same size but opposite direction to resist the external forces, which is called stress. The external forces of some materials in the work process do not change over time. The magnitude of internal stress of the material is unchanged which is known as the static stress. While the external force presents cyclic variation over time, so this internal stress of material is known as the alternating stress. The material damage taking place under the alternating stress is called fatigue damage. The distribution of time-domain of maximum equivalent stresses of blades is presented in fig. 7.

As shown in fig. 7, the maximum equivalent stresses of impellers in a rotating period change periodically at various operating conditions. Three wave peaks and troughs agree with the number of impeller blades, which means that the periodic changes of the maximum equivalent stresses are mainly affected by the number of impeller blades. Although the maximum equivalent stresses of impellers are smaller than permissible stresses of materials, it is necessary to prevent the fatigue damage of impellers due to the periodic variations. The fre-



(a) 0.8 Q_{opt} (b) 1.0 Q_{opt} (c) 1.2 Q_{opt}

Figure 7. The distributions of time-domain a of maximum equivalent stresses of impellers

quencies of the maximum equivalent stresses of impellers and the passing frequencies are about 72.5 Hz, thus the frequencies of the maximum equivalent stresses of axial flow pump impellers are also mainly affected by pressure fluctuation frequency.

Conclusions

Numerical results based on the two-way coupling FSI method show that the maximum equivalent stress of impeller occurs at the blade root and the hub junction region, but the maximum deformation of impeller occurs at the tips of blade leading edges. The time-domain results show the maximum equivalent stress of blades distributes periodically with three wave peaks and troughs in a rotating period, which is identical to the number of impeller blades. The frequency-domain of the maximum equivalent stresses of impellers and the pressure fluctuation of impeller outlet are also about 72.5 Hz, which is equal to the blade passing frequency, so the rotor stator interaction plays an important role in the pressure fluctuation and periodical stress of axial flow pump impeller.

Acknowledgments

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