3-D Simulation of a prototype pump-turbine during starting period in turbine model

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Abstract. Three dimensional (3-D), unsteady flows in a prototype pump-turbine during a transient process of start-up at no load condition were studied using the computational fluid dynamics method. The fluid coupling and DM method were used to calculate the rotational speed for each time step. The dynamic mesh (DM) method and remeshing method were applied to simulate the rotation of guide vanes. Calculations were performed based on the $\bar{v} - f$ turbulence model, and the calculation results were compared and verified by experimental data. Transient explicit characteristics such as the flow-rate, head, torque of the runner etc., as well as the internal flow during the start-up were analyzed. The amplitude of pressure fluctuation was larger as the rotational speed of runner increased. The pump-turbine was more unstable with the decrease of the moment of inertia. The impact jet flow in the runner has a direct relationship with the increase of the torque of runner. No stall phenomenon in the runner when the pump-turbine runs close to no load opening condition. This calculation was based on a prototype of a pumped storage power station and the computational method could be used in the fault diagnosis of transient operation.

1. Introduction
Pumped water storage plants are mainly used to peak-shave variations in electrical energy demands. Load changes and frequent start-up/stop are major characteristics of the pump-turbine units. Lots of problems existed in transient process. During the unit’s transient process of start-up, due to the S-shape of pump-turbines at turbine mode, the instability is associated with head and flow rate fluctuates in the system. The fluctuations lead to the performance fluctuation in the starting period, even lead to a prolonged synchronization process [1].

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Normally the stability of a pump-turbine can be improved by misaligning a few guide vanes during the starting period at no load condition \cite{2-4}. However, the flow mechanism of the reason causing the instability is unclear. Studies on dynamic performances of transient processes, such as load rejection, start-up, etc. were carried out directly by experiments \cite{5-7}. Most of the experimental tests were performed by model test. Due to the scale effect, experiment results of models during transient processes weren’t similar to results of prototypes. Besides, it is hard to monitor and visualize the internal flow of the prototype pump-turbine, which further increases the difficulty of the research on transient processes in prototype.

At present, the most robust approach for investigation of transient behavior of pump-turbine is one dimensional (1-D) method of characteristics. 1-D methods of characteristics were widely used in the prediction of transient characteristics of pump-turbine \cite{8,9}, but it lacked the detailed internal 3-D flow field, so most of mechanisms of transient processes were unclear.

3-D simulations of transient processes of pump-turbine were the most efficiency methods to investigate the instability of a turbomachineries. Studies on dynamic performance of turbomachineries by 3-D simulations developed from a constant boundary condition \cite{10} to a variable value \cite{12}, and from the specified change rule \cite{13} to the control rule defined by fluid coupling method \cite{14}. These developments make it possible to study the starting period of a pump-turbine by 3-D simulation.

During the starting period of a pump-turbine at no load condition, the guide vanes gradually opened, and the pump turbine ran along the runaway line. In this paper, the $\gamma$-t model was used to simulate the transient process of starting period at no load condition. The rotational speed of the runner was calculated by fluid coupling method, and the change of opening of guide vanes were carried out based on the dynamic mesh (DM) method. External characteristics such as flow rate, head, rotational speed as well as torque were analyzed with the instantaneous flow fields.

2. Prototype pump-turbine
2.1 Geometry
The structure of the prototype pump-turbine is shown in Figure 1, which contains spiral casing, stay vanes, guide vanes, runner and draft tube. The relative opening ($\gamma$) of guide vanes was from 0 to no load opening (20%) during the starting period at no load condition.

2.2 Parameters
Parameters of the prototype pump-turbine are shown in Tab.1. $D$ denotes the runner outlet diameter in turbine mode; $Z$, $Z_S$ and $Z_G$ are the number of blades of runner, stay vanes and guide vanes, respectively; $H_d$ denotes the rated head; $Q_d$ denotes the rated discharge; $n$ denotes the rated rotational speed of the runner.

| Table 1. Parameters of the prototype pump-turbine |
|---|---|---|---|---|---|
| $D$(m) | $Z$ | $Z_S$ | $Z_G$ | $H_d$(m) | $Q_d$$(m^3/s)$ | $n$(r/min) |
| 1.92 | 9 | 20 | 20 | 503 | 69.7 | 500 |

Guide vanes were gradually opened during the starting period. 20 guide vanes rotated around their own centers of gravity at a speed of 1.04 r/min. The opening rule of relative opening of guide vanes ($\gamma$) was shown in Figure 2. In this paper, the period of 12-18.3 s was studied. This process of
starting period lasted about 6 seconds.

Figure 1. Profile of Pump-turbine

Figure 2. Opening of guide vanes during starting period

3. Numerical method

3.1 turbulence model

In order to consider the near-wall turbulence anisotropy and non-local pressure-strain effects, \( \overline{v} - f \) model [16] was used to simulate the starting period. \( \overline{v} \) and \( f \) equations are as follow:

\[
\frac{\partial \overline{v}^T}{\partial t} + U \frac{\partial \overline{v}^T}{\partial x_i} = \frac{k}{\sigma} \frac{\partial \overline{v}^T}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \frac{\mu}{\sigma} \frac{\partial \overline{v}^T}{\partial x_j} \right) \quad (1)
\]

\[
L^2 \overline{v}^T f - f = C_1 \left( \frac{\overline{v}^T}{T} \right)^{\frac{2}{3}} - C_2 \frac{p_L}{\epsilon} \quad (2)
\]

where \( \overline{v}^T \) is a velocity scale for evaluation of the eddy viscosity; \( f \) is an elliptic relaxation function; \( L \) is the turbulence length scale; \( T \) is the turbulence time scale; the coefficients are defined as \( C_{\mu} = 0.22, \sigma = 1, C_1 = 1.4, C_2 = 0.45 \). The turbulent viscosity is calculated by \( \mu_t = C_{\mu} \overline{v}^T T \).

\( \overline{v}^T - f \) model calculates the near wall region directly. In this paper, 12 layers of mesh were created near the wall in order to reduce the value of \( y^+ \). Mesh grids of the runner is shown in Figure 5. The model’s unstructured hexahedron and tetrahedron grids were created in ICEM.

Figure 3. Mesh grids of runner

3.2 Transient rotational speed

For the simulation of the starting period of a pump-turbine, boundary conditions are hardly to be specified due to the uncertain change of external characteristics, such as rotational speed of the runner, pressure at the casing inlet. To predict the change of rotational speed of the runner, fluid coupling and DM method were used in runner to simulate the change of rotational speed during the starting period. The angular velocity \( \omega \) of the runner was obtained by equation (3),

\[
I \frac{d\omega}{dt} = M_e - M_c \quad (3)
\]
where $I_z$ is the overall moment of inertia of prototype runner and generator. The additional moment of inertia caused by the water in the pump-turbine is less than 0.3\% of $I_z$, so it is ignored in the calculations. $M_R$ is the runner torque; $M_G$ is the payload torque; $t$ is the time.

In order to study the influence of overall moment of inertia to the transient performance of the starting period at no load condition, three kinds of moments of inertia were used to calculate the change of rotational speed. The calculation of rotational speed was realized by UDF (User Defined Function). The opening process of guide vanes was performed by DM method and remeshing technique.

3.3 Simulation methods

The relative opening of the guide vanes is 10\% at the beginning of the starting period. The computational range of the relative opening of guide vanes is 10-20\%, shown in Figure 2. The computational code used here was FLUENT, a commercial finite volume based CFD code. The pressure of the casing inlet was set according to experimental data. The initial pressure of the draft tube outlet was set to 0. Second order upwind scheme was used to discretize the convective terms. SIMPLEC algorithm was used for solving the pressure field. The total number of mesh was 5.1 million. The time length of 0.001 s was chosen as the time step. Maximum number of iterations for each time step was set to 100. Before the transient calculation, the beginning point must be calculated first. Then the transient calculation was performed with the converged result of the beginning point. The residual error of each time step was less than 0.0001.

4. Results

4.1 External characteristics during starting period

Three transient calculations were performed based on three kinds of moments of inertia, which are $I_z$, 0.8$I_z$ and 0.6$I_z$, respectively. $I_z$ is the real moment of inertia of the unit. The rotational speed of the runner during the transient process of starting period was shown in Figure 4. When the moment of inertia is $I_z$, calculation result agrees well with experimental result. The decrease of $I_z$ leads to the increase of the angular acceleration of the runner. When the moment of inertia is $I_z$, the pressure fluctuations at the casing inlet and draft tube outlet are shown in Figure 5. Pressure at the casing inlet gradually reduces, and the pressure fluctuation at the casing inlet is about 1\%. Pressure fluctuation at the draft tube outlet increases greatly when the pump-turbine run close to no load opening condition.

![Figure 4. Rotational speed of the runner](image1)

![Figure 5. Pressure at the inlet of casing and outlet of draft tube](image2)

The flow rate ($q$), torque of the runner ($M_z$) and rotational speed ($n$) during the process of starting period are shown in Figure 6 (a) and (b). The trend of $M_z$ curve is the same to the curve of $M_s$, and the fluctuation of $M_z$ gradually decreases. $M_z$ increases smoothly and it has a maximum value when $t=4$ s. The flow rate of the pump-turbine has a linear relationship with the relative opening of guide vanes.
Figure 6 (c) and (d) show forces of the runner in three directions of cartesian coordinates, the force in x coordinate \( f_x \), y coordinate \( f_y \) and z coordinate \( f_z \). The frequency of fluctuation of \( f_x \) and \( f_y \) increases when \( t > 3 \) s. \( f_z \) fluctuates with a high frequency during the total transient process. Fluctuations of axial force are large enough that they should be taken into account.

Figure 6. External characteristics of load rejection when the moment of inertia is \( I_z \).

Figure 7 shows the relationship between the unit speed \( n_{11} \) and unit discharge \( Q_{11} \). The pump-turbine is easy to run at turbine braking mode with the decrease of \( I_z \), which may leads to failure synchronization with the power system. The increase of \( I_z \) is benefit for the stability of pump-turbine during the transient starting period.

Figure 7. \( n_{11}-Q_{11} \) curve of starting period

4.2 Pressure fluctuation in the pump-turbine
Pressure fluctuations at the inlet of stay vanes and guide vanes are shown in Figure 8. The average pressure at the two point decreases during the starting period. The amplitude of pressure fluctuation at the inlet of stay vanes is 2.1%, and it is 3.6% at the inlet of guide vanes. The amplitude of pressure fluctuation increases along the flow direction. Pressure fluctuation increases when the pump-turbine runs close to the no load opening condition.
4.3 Unsteady flows during load rejection

The flow field in the pump-turbine is the most convenient way to study the instability of the pump-turbine during starting period. Streamlines of blade to blade surface of four moments, which are $t=0$ s, $t=2$ s, $t=4$ s and $t=6$ s, are analyzed and shown in Figure 9. At the beginning of the starting period, due to the pump-turbine runs at small flow rate, large vortexes in each passage of the runner can be found in Figure 9(a). There has a water ring at the runner inlet, which blocks the water flow through the runner. The water ring is weaker as the relative opening of guide vanes increases, and it disappears when $t=4$ s. Due to the small opening of guide vane, the impact jet flow at the pressure side of runner inlet makes the runner rotate. The impact jet flow is strengthened by the increase of flow rate when $t<4$ s, it has a direct relationship with the increase of the torque of the runner. Streamlines on the blade to blade surface of the runner gradually gets better as the rotational speed increases. The rotating stall region decreases, and there has no stall passage when $t=6$ s.

![Figure 9](image)

5. Conclusions

Both external characteristics and internal flows of transient processes can be obtained by 3-D simulations. It can be used to obtain the internal flow and external characteristic during transient operations of a pumped power station. The use of $\overline{\nu_{ef}}$ model is proven suitable to predict characteristics of the transient process during starting period in a pump-turbine.

The amplitude of pressure fluctuation was larger as the rotational speed of runner increased. The amplitude of pressure fluctuation increases along the flow direction. The decrease of the moment of inertia will make the pump-turbine run in turbine braking mode, which may lead to instability of the pump-turbine. The impact jet flow in the runner maybe the reason for the increase of torque of the
runner. The stall phenomenon in the runner gradually disappears when the pump-turbine runs close to no load opening condition.

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Reference
[1] Mei Z Y Generation technology of pumped storage power station. Beijing: China machine press., 2000:200-221.
[2] Klemm D Voith Forschung Konstruktion, 1982(28)paper 2.
[3] Billdal J T, Wedmark A. Recent experiences with single stage reversible pump turbines in GE Energy’s hydro business, Hydro 2007, Granada, 2007, Paper 10.3.
[4] You G H, Kong L H, Liu D Y Journal of Hydroelectric Engineering, 2006,25(6):136-139.
[5] Tsukamoto H and Ohashi, H, ASME J. Fluids Eng., 1982,104(1): 6-13.
[6] Vladimir V. Synchronous and asynchronous generators frequency and harmonics behavior after a sudden load rejection. IEEE Transactions on Power Systems, 2003(18):730-736.
[7] Husmatuchi V and Farhat M, Experimental investigation of a pump-turbine at off-design operating conditions. 3rd IAHR International meeting of the workgroup on cavitation and dynamic problems in hydraulic machinery and systems. Brno, Czech Republic, 2009:339-347.
[8] Nicolet C, Unstable operation of Francis pump-turbine at runaway: rigid and elastic water column oscillation modes. IAHR. 24th Symposium on Hydraulic Machinery and Systems, FOZ DO IGUASSU, 2009.
[9] Pannatier ., Transient behavior of variable speed pump-turbine units. 24th Symposium on Hydraulic Machinery and Systems, FOZ DO IGUASSU, 2009.
[10] Wu Y L, Liu S H. Engineering with Computers, 2011(27): 235-250.
[11] Liu J T, Li Z F, and et al. Journal of Fluids Engineering 2011,133(11) 111101.1-111101.7.
[12] Li Z. and Wu D., Journal of Fluids Engineering 2010, 132(8)081102.1-081102.8.
[13] Liu J T, Liu S H and et al. Engineering with Computers 2012, DOI: 10.1007/s00366-012-0258-x,