CFD research on runaway transient of pumped storage power station caused by pumping power failure

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Abstract. To study runaway transient of pumped storage power station caused by pumping power failure, three dimensional unsteady numerical simulations were executed on geometrical model of the whole flow system. Through numerical calculation, the changeable flow configuration and variation law of some parameters such as unit rotate speed, flow rate and static pressure of measurement points were obtained and compared with experimental data. Numerical results show that runaway speed agrees well with experimental data and its error was 3.7%. The unit undergoes pump condition, brake condition, turbine condition and runaway condition with flow characteristic changing violently. In runaway condition, static pressure in passage pulses very strongly which frequency is related to runaway speed.

1. Introduction
Pumped storage power stations play important roles in the power network, such as peaking load shifting, frequency & phase modulation and emergency reserve, so we must take some necessary researches and measures to ensure its safety. There is one traditional numerical method called MOC (Method of characteristics) to calculate transient process of hydropower units\cite{1}, however, this numerical method can’t predict variation regularity of inner flow field and dynamic instability of pump-turbine unit. At present, three dimensional CFD (Computational fluid dynamics) simulation, as a fine numerical method containing large amount of information, has been applied widely to predict hydraulic performance of hydraulic machinery under normal condition\cite{2} and transient process\cite{3,4}.

In this paper, three dimensional unsteady CFD numerical method is established to investigate dynamic characteristics of pumped storage power station during the transient process that caused by pumping power failure and speed controller being invalid. The changing regularity of some transient dynamic parameters derived from CFD simulation will be verified with experimental data, and the inner flow field in the passage that is difficult to attain through physical model experiment can be visualized for further analysis.

Pumped storage power station’s whole flow system geometric model including diversion tunnel, surge chamber, penstock, pump turbine unit and tailrace tunnel has been built, as shown in Figure 1. The specific speed of pump-turbine unit $n_s = 182$ m$^3$\textbf{•}kW and its runner diameter $D = 3.57$m. Some important parameters of initial condition are as follows: water head $H_0 = 205$m, unit flow rate $Q_0 = 139$m$^3$/s, the runner rotating speed $n_0 = 250$rev/min, guide vane opening $\gamma = 23.75$°and total unit moment of inertia $J = 4825000$ kg$\cdot$m$^2$. 
2. Numerical method

2.1. Governing equations
To simulate the power-off runaway transient, Arbitrary Lagrangian Eulerian method is applied and continuity equation of water liquid is written as follows:

\[ \frac{\partial}{\partial x_j}(u_j - \hat{u}_j) = 0 \]  

(1)

Where \( u_j \) is absolute velocity, and \( \hat{u}_j \) is computational grid velocity. Momentum equation of water liquid is given below:

\[ \frac{\partial \hat{u}_j}{\partial t} + (u_j - \hat{u}_j) \frac{\partial u_j}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_j} + \nu \frac{\partial^2 u_j}{\partial x_i \partial x_j} \]  

(2)

Where \( f_i \) is unit body force, and \( p, \rho \) and \( \nu \) are pressure, water density and kinematic viscosity coefficient respectively. Rotating speed of turbine runner keeps varying during load rejection transient, which is decided by the following equation:

\[ M = J \frac{D\omega}{dt} \]  

(3)

Where \( M \) is resultant torque of the rotational system, \( J \) is total unit moment of inertia, \( \omega \) is angular velocity vector. Then, the angular velocity of every next time step is calculated by

\[ \omega_{i+1} = \omega_i + \frac{M}{J} \times \Delta t \]  

(4)

Where \( \Delta t \) is time step size.

2.2. Turbulent model
The VOF multiphase flow model is adopted in the paper based on the Realizable \( k - \epsilon \) model, which is an improvement on the standard \( k - \epsilon \) model, has been extensively validated for a wide range of flows, such as rotating homogeneous shear flows, free flows including jets and mixed layers, pipe flow and separation flows.

2.3. Grid technology
As a result of tradeoff between grids sensitivity and PC computing capability, computational grids subdivision scheme for each part of flow passage is shown in table 1. Meanwhile, the varying speed sliding mesh technology is used to transfer flow field parameters between runner zone and adjacent part passages. Mesh rotating is resolved by dynamic mesh technology.
Table 1. Mesh subdivision scheme of flow passage.

| Passage            | Mesh elements type | Mesh cells size |
|--------------------|--------------------|-----------------|
| Diversion system   | Hex/Wedge          | 480516          |
| Surge tank         | Hex/Wedge          | 382608          |
| Casing             | Tet/Hybrid         | 435415          |
| Stay/guide vane    | Tet/Hybrid         | 833499          |
| Runner             | Tet/Hybrid         | 714785          |
| Draft tube         | Tet/Hybrid         | 560718          |
| Tailrace system    | Hex/Wedge          | 410845          |

2.4. Equations discretization and boundary condition
The governing equations are discrete with finite volume method: first-order implicit format for time item, PRESTO format for source and diffusion item, second-order upwind format for convection item, and PISO method for velocity-pressure coupling solution.
Diversion system inlet and tailrace system outlet pressures were given according to the actual water submergence depth, and we kept surge tank inlet full of air, which relative pressure was equal to zero. We presented roughness values of different passage walls: 2.55mm at surge tank, diversion system and tailrace system; 0.06mm in the casing; 0.0016mm at runner blades and vanes. In addition, turbulent kinematic energy and dissipation rate values were presented at inlet and outlet boundaries.

3. Results and discussions

3.1. Comparison between numerical value and test results
In order to monitor variable regularities of static pressure, three measuring points are set in the turbine passage, shown in the figure 2. Point 1 is at the inlet section center of spiral case, point 2 is at the half height and trailing edge of guide vane, and point 3 is at the center of draft tube inlet. Runaway speed information of numerical and test conversion results is sketched in figure 3, the numerical value point is near the test curve apparently. By comparison, the numerical runaway speed is larger than static state test one, which error is 3.7%, probably due to dynamic effects and omitting the mechanical friction resistance and wind resistance. Hence, the simulation result of power-off runaway transient could be valid and credible.

![Figure 2. Measuring points of static pressure in the passage.](image1)

![Figure 3. Curve of numerical and test runaway results.](image2)

3.2. Dynamic parameters analyses
For further study on power-off runaway transient, few dynamic parameters such as unit rotate speed, unit flow rate, surge tank flow rate, torque, axial thrust and static pressure are divided by corresponding parameters of initial condition so that normalized parameters are attained, and plotted in
the Figure 4. In addition to the initial condition parameters mentioned above, the initial torque $M_0 = 11.7 \times 10^6 \text{N}\cdot\text{m}$, initial axial thrust $F_0 = -6.82 \times 10^6 \text{N}$, initial flow rate of surge tank $Q_{c0} = 0 \text{m}^3/\text{s}$.

Originally, unit flow rate, unit speed, unit lift, torque and axial thrust declined quickly after power failed, as well as surge tank supplied water to the main pipe so that its water level also decreased. As time arrived at 6s, unit flow rate was equal to zero, which meant the end of pump condition. And then, brake condition had been lasted 10s until runner speed went down to zero. During this period, resistance torque and unit lift had been increasing tortuously, and there were turning points on curves of axial thrust and surge tank flow rate. After $t=16s$, pump-turbine unit entered into turbine condition, reversed speed increased more and more slowly since resistance torque become smaller and smaller. Reversed flow rate got the maximum $Q=137.5 \text{m}^3/\text{s}$ at $t=25s$, meanwhile, axial thrust reached one extreme value. After $t=50s$, unit speed was 339 rev/min and almost no longer changed, which was treated as a mark of runaway condition. Unit lift, torque and axial thrust were constant generally, but fluctuant locally.

![Figure 4](image)

**Figure 4.** Normalized value of dynamic parameters variations with time.

The static pressure curves of three measuring points were plotted in figure 5, as well as, unit flow rate curve and unit speed curve were also drawn in the same figure for correlation analysis. Seen from it, the static pressure of point 1 and point 2 declined continuously due to runner energy reduction, on the contrary, that of point 3 increased and reached extremum value near $t=6s$, the end of pump condition. Once entering brake condition, curves of static pressure became complicated and irregular, meaning that the flow regime was instability. However, they became regular and presented strong pulsation in runaway condition. Therefore, frequency domain information of static pressure was calculated and plotted in figure 6, we could draw a conclusion that pressure pulsation between runner and guide vanes is the most strongest, which dominant frequency is 9 times of runaway speed frequency, and that is 1 time near the casing inlet, 1/3 times in the draft tube.

![Figure 5](image)

**Figure 5.** Static pressure curves of measuring points.
3.3. Analyses of transient flow field in the passage

Generally, the flow field in the turbine passage will take on different feature during power-off runaway transient, which is intrinsic factor leading to variations of external characteristic parameters. In the following contents, the transient flow fields in different parts of turbine passage at critical moments are visualized for analysis and plotted in the figure 7 to figure 10.

In the figure 7, we could see that static pressure changed with flow rate. As t=0s, the initial condition had a perfect performance with water flowing upstream smoothly. Flow rate was half of that initial condition at t=4s. When t=6s, unit flow rate was equal to zero approximately, hence water flowed slowly and disorderly, besides static pressure became minimum because of the weakest pump function. While t=25s, the reversed flow rate was about equal to that at t=0s, but static pressure was smaller because the opposite flow direction generated different hydraulic loss.

![Figure 7](image.png)

**Figure 7.** Flow field in spiral case and between guide vanes at different moments.

Figure 8 displayed transient flow field information including relative velocity and static pressure in the runner. From figure 8(a), there was no turbulence at the process beginning. Once power failure happened, unit rotating speed declined quickly, as a result, flow configuration in runner underwent very complex and unsteady change: when t=10s, there were high speed jets toward blades leading to high local static pressure and reversed flow went to downstream mainly along pressure surface, which could be typical characteristics at brake condition. At t=15s, static pressure in the central region of blade pressure was small and might be less than vaporization pressure, so there would be cavitation at the end of brake condition. In the runaway condition, runner rotated so fast that moment was no different on the both sides of runner blade, seen from figure 8(d).

![Figure 8](image.png)

**Figure 8.** Flow field in runner at different moments.
Draft tube is an important part of pumped storage power station, which not only effects energy utilization efficiency, but also influences unit stability. As shown in figure 9(a), water flowed harmoniously in pump mode. At the critical state of pump condition and brake condition, \( t=5 \) s, unit flow rate became small, but wall static pressure was still large. At \( t=10 \) s and \( t=50 \) s, the flow field became very disorder and dangerous. In addition, the rotational direction of vortex rope at \( t=10 \) s was contrary to that at \( t=50 \) s.

![Figure 9. Flow field in runner at different time.](image)

During power-off runaway transient, surge tank supplied water to main pipe from \( t=0 \) s to \( t=48 \) s, and then, water regurgitated into it. At \( t=50 \) s, there was surge due to backflow was big enough. We could see the height variation of water level at different moments from figure 10.

![Figure 10. Flow field in surge tank at different time.](image)

4. Conclusions
Through three dimensions unsteady CFD simulation, not only external characteristic, but also internal flow configuration were obtained and analyzed during power-off runaway transient. By comparison with experimental date, the simulation results are accurate and valid. In the transient process, flow configuration undergoes very complex and unsteady changes, and pulses strongly in runaway condition.

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References
[1] Zhang J, Lu W H, Fan B Q and Hu J Y 2008 J. Hydrol. Eng. 27 158
[2] Zhou D Q, Zhang L G and Zhang C H 2013 J. SCU. (Eng. Sci. Ed.) 45 63
[3] Li J W, Liu S H, Zhou D Q and Wu Y L 2008 J. Hydrol. Eng. 27 148
[4] Huang W D, Fan H G and Chen N X 2012 Transient simulation of hydropower station with consideration of three-dimensional unsteady flow in turbine Proc. of 26th IAHR Symp. on Hydraulic Machinery and Systems (Beijing, China, 19-23 August 2012)
[5] Nicolle J, Morissette J F and Giroux A M 2012 Transient CFD simulation of a Francis turbine startup Proc. of 26th IAHR Symp. on Hydraulic Machinery and Systems (Beijing, China, 19-23-August 2012)