Hydraulic torque on the guide vane within the slight opening of pump turbine in turbine operating mode

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Abstract: In a pumped storage power station, the units produce vibration and noise at times when the guide vanes rotate into the slight opening region during the turbine operating mode. According to this phenomenon, the simulation of transient flow in the units during the motion of the guide vane is carried out to investigate the variation of flow state in the process of startup and shutdown in turbine mode. The changing rate of hydraulic torque on a single guide vane is introduced to quantitatively represent the varying acuteness of the flow in the guide vanes and the possibility of the noise induced by the instable flow. The correlation between the frequency of noise and water head is summarized. The research indicates that the repeating reversal of fluid after load rejection is the hydraulic phenomenon which is the cause of the distributor vibration and noises within the slight opening, which is in accordance with the data recorded during the operation of the station. The effect of guide vanes closing law on the flow state in guide vanes and hydraulic torque on a single guide vane is analyzed.

1. Introduction

In Tianhuangping pumped storage power station, vibration and loud scrape produced by the units has occurred many times with friction assembly alarm of the guide vanes when the guide vanes rotate into the slight opening region (less than 20% of the maximum opening (33°)) in the process of shutdown in turbine operating mode since the power plant generated electricity, and the noise always lasts several seconds. Although the plant has taken many emergency measures, the vibration frequently occurred and the reason hasn’t been found. Figure 1 is the vibration monitoring of the guide vanes in turbine mode, which shows the shock response signal when the guide vanes are in slight opening in shutdown process in turbine mode but no obvious shock response signal when the units start up. In overhaul, cracks in the pin of gate operating ring and breaking of hold-down bolt of the friction assembly are found [1], but there is no abnormality in other flow passage components. So it can be guessed that noise appears in the guide vanes, vibration correlates closely with the flow state in guide vanes.

![Figure 1. Power generation process.](image-url)
Many numerical simulations of the hydraulic machine in steady operation have been carried out. The simulation for the transition such as startup and shutdown is still at developing stage, and some researchers have made preliminarily studies. Haifa [2] has made three dimension simulation of the transient performance in micro-pump when the screw is rotating, and the effect of screw threat, pitch, Reynolds number and pump load on dynamic flow property were studied. Wang [3] has made simulation of a two dimensional centrifugal pump with the Large Eddy Simulation (LES) during its starting period and obtained the velocity and pressure distribution in different time. Comparison between transient computation results and that of quasi-steady hypothesis indicates the transient effect of the flow during starting period. Wu [4] has made three dimensional simulation of the unsteady flow in a centrifugal pump with whole circulation pipeline during starting period. The unsteady flow evolution in the pump was analyzed and its transient hydraulic characteristics was predicted. The numerical results qualitatively agreed with the test results. Using RNG k-ε turbulence model, Zhou [5] obtained the variation of the model unit’s moment, axial hydro-thrust, rotational speed, and mass flow rate by simulation of the load-rejection transient of the Kaplan turbine under the rated head and the largest head condition with rated output, the runaway speed computation result and the test one error was less than 2%. Li [6] analyzed the unsteady flow and pressure fluctuation by a 3D unsteady turbulent simulation of the load-rejection transient of the Francis turbine with RNG k-ε turbulence model, the computation result of runner speed and pressure in the inlet of draft tube agrees with the test one, but the calculated pressure in the inlet of spiral casing was different with the test one without the consideration of water hammer in the penstock. Kolsek [7] has made three dimensional simulation of unsteady flow during shut-down process of an axial water turbine. Rotation speed, axial force and pressure at the point which located between distributor and runner were analyzed, and the results agree with the prototype measurement data. Benigni [8] obtained the velocity distribution around the runner for different operating points and found the separation zones near the wall of the draft tube by transient simulation with SST-model of Menter.

In summary, the simulation of flow state in guide vanes when they are rotating into slight opening is not deep. Unsteady numerical study of dynamic process is still in its infancy. The reason why the units produce abnormal vibration and make noise is not clear and doesn’t reach a consensus. Therefore to ensure the safety and stability of the units’ long-term operation, it is necessary to study the units’ stability in slight opening deeply, reveal the cause of vibration and put forward effective control schemes to avoid the vibration.

In order to reveal the hydraulic reason inducing the vibration of distributor, this paper studied the dynamic flow characteristic in guide vanes with numerical simulation method. The correlation between noise frequency and water level of upper reservoir and down reservoir is analyzed, and the simulation results and the plant operation statistics are compared.

2. Numerical simulation method
RNG k-ε two equation model [9][10] is selected to simulate the flow in the pump turbine in the paper, because it can simulate the flow separation and vortex, and is more accurate in the near wall areas. Equation (1) and equation (2) are the equations of RNG k-ε model:
\[ \frac{\partial}{\partial t} (\rho u) + \frac{\partial}{\partial x_i} (\rho u u_i) = \frac{\partial}{\partial x_j} (\alpha_g \mu_{ref} \frac{\partial u}{\partial x_j}) + G_i + G_b - \rho \varepsilon - Y_k \]  

(1)

\[ \frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} (\alpha_g \mu_{ref} \frac{\partial \varepsilon}{\partial x_j}) + G_i \varepsilon k + C_{\varepsilon} G_k - C_{\varepsilon} \rho \frac{\varepsilon^2}{k} - R_i \]  

(2)

Where, i and j are direction of axis, x is axis, u is absolute velocity, t is time, \( \rho \) is density, \( G_i \) is the generation of turbulence kinetic energy due to the mean velocity gradients, \( G_b \) is the generation of turbulence kinetic energy due to buoyancy, \( Y_k \) is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, the quantities \( \alpha_g \) and \( \alpha_k \) are the inverse effective Prandtl numbers for \( \varepsilon \) and \( k \), respectively.

### 3. Computational domain

In pump turbine, the distributor height is small, and the flow is 2 dimensional and periodic. The influence of finite number of guide vanes can be neglected. A two dimensional model is set up in order to rational use the limited computation resource. The domain is shown in Figure 2 includes a guide vane and a channel between two stay vanes, which extends to upstream and downstream.

![Computation domain](image1)

![Boundary conditions](image2)

![Mesh between the guide vanes](image3)

In turbine mode, it flows from fix vanes to guide vanes, so a velocity is imposed on the boundary near the fix vane. According to the fundamental equation of the hydraulic machine, the radial component of the velocity in the inlet of the computation domain can be calculated by equation (3), where flux \( Q(t) \) can be calculated by the transient simulation of the power station.

\[ V_r(t) = \frac{Q(t)}{A} \]  

(3)

The tangential component can be set by the condition that there is no shock in the inlet of stay vane. A constant static pressure is set on the side near the guide vane because the relative pressure amplitude is small. Guide vane and stay vane is set as no slip wall. Periodic boundary conditions are used at both sides of the single periodic channel. Boundary condition can be shown in Figure 3.

It is necessary to open or close guide vanes according to some law in the transient process of pump turbine, such as startup, shutdown and operation switch. In the transient simulation of the flow in the pump turbine, meshes around the vanes should be adjusted with the movement of the guide vanes. Considering that the guide vanes are set as the moving boundary, Spring-based smoothing and local remeshing [11] are used to realize the adjustment of the meshes around the guide vanes in the transient process.

In the slight opening, the gap is much less than the characteristic length of the passage, such as vane length. Boundary-fitted quadrilateral mesh is used around the guide vane and triangle mesh is used in
other area, which is shown in Figure 4.

The steady numerical simulation is performed in different guide vane opening angles. The number of elements is compared ranging from 5000 to 300,000. Figure 5 indicates that the hydraulic torque in a guide vane is independent of element number when it is larger than 50000. In this paper, the domain involving single channel is meshed with 50000 elements.

Startup and shutdown process in pumping mode is simulated in different time steps ranging from 0.01s to 0.00025s. the hydraulic torque amplitude varies to time step is shown in Figure 6, which indicates that the hydraulic torque amplitude is independent of time step when it is less than 0.001s. The time step of the transient simulation in guide vanes is set as 0.001s.

![Figure 5. Different mesh numbers.](image)

![Figure 6. Different time steps.](image)

4. Results and analysis

4.1. Startup process simulation in turbine mode

Figure 7 shows the flux of the unit in different heads when the guide vanes are opening, which is calculated by the transient simulation of the power plant. Figure 8 shows the hydraulic torque of the guide vane which is opening with the 25s slope. The figures show that hydraulic torque changes gently and no sudden change happened when guide vanes rotate into the slight opening.

![Figure 7. Discharge of the unit.](image)

![Figure 8. Hydraulic torque on the guide vane.](image)

Figure 9 shows the streamlines and the pressure distribution in different opening angles when the guide vanes are opening in the turbine mode and the head is 610m. In the process of opening, flow in guide vanes maintain the same flow pattern and static pressure changes gently, which is not easy to induce the vibration of the distributor. The result is consistent with the fact that there is no noise in the startup process of turbine mode in the power plant.
4.2. Shutdown process simulation in turbine mode

When the units shut down, the runner speeds up in the direction of turbine mode with the closing of guide vanes. As shown in Figure 10, closing law (2) has a different inflection point with law (1) while the second segment of law (2) has the same slope with law (1).

Figure 11 shows the flux of the unit in different heads when the guide vanes are closing, which is calculated by the transient simulation of the power plant. Adopting closing law (1), the discharge of unit fluctuates near 0 in slight opening of guide vanes when the head is less than 570m, which means that the direction of the flow changes frequently, and while the head is above 570m, it keeps negative. The flux of units adopting closing law (2) fluctuates near 0 within the whole operating head.
Figure 12 shows the hydraulic torque in a guide vane which is closing. As shown in Figure 13, the time from the maximum hydraulic torque to the minimum is defined as the transition time, the max change of the torque of the guide vane is defined as the torque amplitude, and the ratio of the torque amplitude to transition time is defined as the torque change rate, which indicates the average change of the torque. Figure 14 shows the correlation between hydraulic torque changing rate and head. The changing rate of torque is large in low head by using closing law (1), which indicate that flow pattern in guide vanes changes intensely. By using closing law (2) the maximum value of torque change rate appears when the head is about 550m. When the head is above 550m, torque change rate of the units adopting law (2) is significantly greater than the units adopting closing law (1).

Figure 15 shows the streamlines and the pressure distribution in different opening angles of unit adopting closing law (1) when the guide vanes are closed in the turbine mode and the head is 526m. The flow pattern in the guide vanes changes noticeably because of the repeating reversal flow. The streamlines and the pressure distribution in different opening angles of unit adopting closing law (1) when the guide vanes are closing in the turbine mode and the head is 610m are shown in Figure 16. The direction of flow in guide vanes keeps negative and the flow pattern changes smoothly. Therefore the torque change rate is smaller than it at low head.

The simulation results indicate that the repeating reversal flow is the main performance of the change of flow state in guide vanes after load rejection. Although the absolute value and change rate is tiny, relative change rate of flux is large when the guide vanes are in slight opening. The flux of units adopting closing law (1), for example, fluctuates around 0 at low water head and keeps negative at high head. At low head, the relative change rate of flux is much greater than at high head resulting that the torque change rate is greater.
Figure 15. Transient flow when the guide vane is closing with law (1) in head 526m.
Velocity (m/s)

| Velocity (m/s) |
|---------------|
| 80            |
| 60            |
| 40            |
| 20            |
| 0             |

Pressure (Pa)

| Pressure (Pa) |
|---------------|
| 7.0E+06       |
| 6.0E+06       |
| 5.0E+06       |
| 4.0E+06       |
| 3.0E+06       |
| 2.0E+06       |

(a) Guide vane opening is 5°. (b) Guide vane opening is 3.4°. (c) Guide vane opening is 1.8°.

Figure 16. Transient flow when the guide vane is closing with law (1) in head 610m.

The water levels of reservoirs recorded when the loud scrape occurs is converted into the operation head, which is called the noise head. Figure 17 shows the noise head distribution when the loud scrape occurs in the shutdown process using two guide vane closing laws, which indicate that noise head mainly concentrates at the head ranging from 530m to 550m. Comparison of simulation results and plant operation statistics is shown in Figure 18 and Figure 19. The calculation predict accurately that the possibility of making noise at low head is greater. At high head conditions units adopting closing law (2) are more likely to make noises, which coincides with the statistic data.

Figure 17. Scattered distribution of noise head.

4.3. Comparison of different guide vanes closing laws
Repeating reversal flow is the cause of the vibration in the sight opening guide vanes when the units
shut down. In order to restrain the flux fluctuation around 0, different closing laws are analyzed. Figure 20 shows the closing laws, which have different slope at second segment.

![Figure 20. Closing laws.](image)

![Figure 21. Discharge of the unit.](image)

Figure 20 shows the closing laws, which have different slope at second segment.

Figure 21 shows the flux of the unit using different closing laws, which is calculated by the transient simulation of the power plant. As can be seen, with the acceleration of second segment of the closing law, unit flux increases in reversal direction, moves away from 0 gradually.

Figure 22 shows the hydraulic torque of a guide vane varies with the closing law. Figure 23 shows the relation between change rate of torque and the slope of second segment of closing law, which indicates that accelerating the closing speed of second segment appropriately can reduce the change rate of torque of guide vane. However, with the acceleration of closing speed, the maximum pressure of spiral case inlet and minimum pressure of draft tube inlet are deteriorated, which have a negative influence to the safe operation of the diversion system, as shown in Figure 23 (the reference value is the pressure when the slope of second segment is 25s).

![Figure 22. Hydraulic torque of the guide vane.](image)

![Figure 23. Hydraulic torque changing rate of different closing speed.](image)

5. Conclusion

Simulation of the transient flow in the guide vanes indicates the repeating reversal of fluid occurs when the guide vanes rotate into the slight opening during the shutdown process in turbine mode, which results in the sudden change of the torque. When the torque made by the servomotor can’t adapt the abrupt change quickly, the vibration and loud scrape maybe occur. The larger torque change rate, the more possibility of the vibration and scrape. The calculation result is basically in agreement with the statistical data of the power station.

In the end, the effect of different closing laws is studied when guide vanes rotate in slight opening, which indicates that accelerating the closing speed appropriately can reduce the reversal flow in guide
vanes and improve the stability of flow state in guide vanes, but the maximum pressure of spiral case inlet and minimum pressure of draft tube inlet are deteriorated.

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Nomenclature

\[ V = \] absolute velocity
\[ r = \] radial coordinate
\[ \theta = \] tangential coordinate
\[ t = \] time
\[ Q = \] discharge
\[ p = \] static pressure
\[ \rho = \] density
\[ \nu = \] viscosity coefficient
\[ g = \] gravity acceleration
\[ A_r = \] area

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