**Influence of Bifurcation Pipe Position on Hydraulic Turbulence for Pumped Storage Power Station**

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**Abstract.** There must be hydraulic turbulence transient in the pumped storage power station with one pipe corresponding to several units. This paper established a simulation model by using the method of characteristics for a pumped storage power station to analyse how the change of upstream and downstream bifurcation pipe position and different arrangements of downstream surge tank affect the hydraulic turbulence. The results indicate that unit output’s amplitude of power mode is smaller than that of frequency mode. And the upstream and downstream bifurcated pipes far away from the units can reduce the hydraulic turbulence of normal operating unit while the upstream without bifurcation pipe is better than the downstream without bifurcation pipe to control the output swing. Sharing the downstream surge tank can effectively reduce the maximum relative over output of the unit, while the surge tank placed in the downstream branch pipe will worsen turbulence process.

**1. Introduction**

At present, most pumped storage power stations adopted the layout of one tunnel with multiple units because of economy. However, there must be hydraulic interference between the units sharing the bifurcated pipe and surge chamber.

Meifeng Sun et al. [1] established a simulation model of turbines parallel running in high head power station by MATLAB and analyzed the influence of main pipe length, operation conditions, surge chamber parameters, pipeline parameters and governor parameters on hydraulic interference. Jianxu Zhou et al. [2] compared and analyzed the hydraulic interference problem of tailrace surge chamber scheme and variable top tailrace tunnel scheme. Haiyan Bao et al. [3, 4] analyzed the influence of governor regulation mode on hydraulic interference transient process through numerical simulation and experimental study respectively. Xu Lai et al. [5] studied the influence of unit governor parameters on the hydraulic disturbance process, and optimized the governor parameters under the isolated network by using multi-objective particle swarm optimization algorithm. Haizhou Zhou et al. [6, 7] studied the influence of diversion channel layout and tailrace layout of water conveyance system on large fluctuation transition process. Xianyu Zhang et al. [8] analyzed the influence of bifurcation position on the transient process of load rejection by using two kinds of pipeline models and optimized the branch pipe position.
In order to analyze how the change of upstream and downstream bifurcation pipe position affect the hydraulic turbulence process, this paper established a simulation model for a pumped storage power station and calculated the disturbed unit output swing in different locations of upstream and downstream bifurcated pipes and analyzed the reasons for these differences.

2. Mathematical model

2.1. Characteristic compatibility equation

The basic equation of unsteady flow in pressure pipeline is [9]:

\[
\frac{\partial H}{\partial x} + \frac{V \partial V}{g \partial x} + \frac{1}{g} \frac{\partial V}{\partial t} + \frac{f}{2gD} \frac{V^2}{V} = 0
\]

(1)

\[
\frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} + \frac{a^2}{g} \frac{\partial V}{\partial x} + V \sin \phi = 0
\]

(2)

Where: \(H\) is the piezometric head based on a certain horizontal plane; \(V\) is average flow velocity of the pipeline section; \(x\) is the distance from the upstream; \(D\) is pipe diameter; \(f\) is resistance coefficient along the pipeline; \(a\) is the water hammer wave velocity; \(\phi\) is the angle between the pipeline center line and the horizontal line.

2.2. Bifurcation boundary equation

The diagram of bifurcated pipe is shown in figure 1. The characteristic equation of bifurcated pipe can be expressed as follows:

\[
H_{p1} = H_{p2} = H_{p3} = H_p
\]

\[
C_1^+ \cdot Q_{p1} = QC_1P - CQP \cdot H_{p1}
\]

\[
C_2^+ \cdot Q_{p2} = QC_2M_2 + CQM_2 \cdot H_{p2}
\]

(3)

The continuity equation of branch pipe flow is as follows:

\[
Q_{p1} = Q_{p2} + Q_{p3}
\]

(4)

2.3. Mathematical model of governor

The frequency regulation adopted parallel PID governor, its block diagram is shown in figure 2, and the transfer function is as follows:

\[
G_i(s) = Y(s) = \frac{1}{X(s)} = \frac{K_Ds^2 + K_Ps + K_I}{b_pK_Ds^2 + (b_pK_p + 1)s + b_pK_I} \cdot \frac{1}{T_1s + 1}
\]

(5)

PI control mode is adopted for power regulation, and its block diagram is shown in figure 3. The transfer function is as follows:
Where: 

\[ G_i(s) = \frac{Y(s)}{C_i(s)} = \frac{K_p s + K_i}{C_p(s) = b_p (b_p K_p + 1) s + b_p K_i} \frac{1}{T_s s + 1} \]  

(6)

\[ G_i(s) = \frac{Y(s)}{C_i(s)} = \frac{K_p s + K_i}{(b_p K_p + 1) s + b_p K_i} \frac{1}{T_s s + 1} \]  

(6)

Where: \( C_f(s) \) is the frequency setting; \( C_p(s) \) is the power setting; \( K_p, K_i, K_D \) is the turbine governor parameters; \( b_p \) is the permanent slip coefficient; \( T_y \) is the main servomotor time constant.

**Figure 2.** Block diagram of parallel PID control  
**Figure 3.** Block diagram of PI control mode

3. Example analysis

3.1. Project overview

The example power station is equipped with one pipe and two units symmetrically arranged with upstream and downstream surge chambers. The rated head of the turbine is 379 m and the rated output is 61.5 mw. The basic layout and the variation diagram of the bifurcated pipe are shown in figure 4-5. The specific parameters of the original pipeline system are shown in table 1.

According to reference [10], the transient process of hydraulic disturbance is generally controlled by sudden load shedding of one or more units when the same hydraulic unit operates with rated head and rated output. So the calculation condition is as follows: the upstream reservoir is 877m while downstream is 483m, and the rated output of the two units is 61.5mw under the rated head, the unit 1 suddenly drops the full load and its guide vane is normally closed.

**Figure 4.** Schematic diagram of different positions of upstream bifurcated pipe  
**Figure 5.** Schematic diagram of different positions of downstream bifurcated pipe
Table 1. Parameters of the original water conveyance system

| Pipeline Section | Length /m | Section Area /m² | Head loss coefficients \(/(10^{-4} \cdot s^2 \cdot m^{-5})\) |
|------------------|-----------|------------------|-----------------------------------------------|
| Pipeline L1      | 78.29     | 9.62             | 3.04                                          |
| Pipeline L2      | 660.08    | 9.62             | 15.10                                         |
| Pipeline L3      | 202.58    | 3.80             | 47.81                                         |
| Pipeline L4      | 62.96     | 3.80             | 21.35                                         |
| Pipeline L5      | 231.00    | 8.04             | 8.33                                          |
| Pipeline L6      | 584.45    | 9.62             | 21.13                                         |
| Pipeline L7      | 202.58    | 3.80             | 47.81                                         |
| Pipeline L8      | 62.96     | 3.80             | 21.35                                         |

3.2. Influence of upstream branch pipe position on hydraulic interference
The results are shown in table 2. It is shown that no matter where the upstream bifurcated pipe is located, the maximum output of unit 2 under power mode is less than that under frequency mode, which indicates that power mode can control the output swing of normal operating unit better than frequency mode. Moving the upstream bifurcated pipe upstream can reduce the influence of load rejection of the same hydraulic unit on normal unit output. When the upstream branch pipe moves from 0 m to 200 m upstream, the relative value of maximum over output is also reduced from 26.03% to 19.98% and when the upstream bifurcation is not set, the relative value of maximum over output is reduced to 9.44% under frequency mode.

It can be seen from figure 6 that the longer the upstream bifurcated pipe moves upstream, the smaller the peak output is. This is due to the decrease of the length of main pipe and the decrease of water shock wave generated by load rejection unit, which also reduces the impact on the output of normal running unit. As the moving distance to upstream increases, the time for maximum output is also delayed because bifurcated pipe is farther away from the unit, and the slower the time for water hammer pressure generated by the load rejection unit to reach the normal operating unit after being reflected and transmitted by the hydraulic connection of the bifurcated pipe. The position of the upstream bifurcation has little influence on the tail wave of the output change of unit 2. Only the arrangement without bifurcated pipe has certain influence on the tail waves, which is more obvious in the frequency mode.

Table 2. Calculation results of different positions of upstream bifurcated pipe

| Moving distance/m | Maximum output /MW | Relative value of maximum over output |
|-------------------|---------------------|---------------------------------------|
|                   | Frequency mode      | Power mode                            |
|                   |                     | Frequency mode                        | Power mode |
| No upstream bifurcation | 67.35                | 67.15                        | 9.44%       | 9.11%       |
| -200.00           | 73.84                | 73.50                        | 19.98%      | 19.43%      |
| -150.00           | 74.80                | 74.42                        | 21.55%      | 20.92%      |
| -100.00           | 75.71                | 75.31                        | 23.02%      | 22.38%      |
| -50.00            | 76.66                | 76.22                        | 24.56%      | 23.85%      |
| 0.00              | 77.56                | 77.03                        | 26.03%      | 25.16%      |

Figure 6. Output change process line of different positions of upstream bifurcated pipe
3.3. Influence of downstream bifurcation position on hydraulic interference
From table 3, in power mode, the maximum output of unit 2 decreases from 77.03MW to 73.34MW when the downstream bifurcated pipe moves 200 m from the original position to the downstream, and the relative value of the maximum excess output decreases from 25.16% to 19.17%. The effect of no turnout at downstream on output swing of unit 2 is smaller than that at upstream. When there is no downstream turnout, the relative value of maximum excess output of unit 2 under power mode is still 15.94%. According to figure 7, the position of the downstream bifurcated pipe mainly affects the main wave waveform. Before 30s, the main wave waveform without downstream bifurcation is quite different from others. After 30s, the tail wave of setting the downstream bifurcation point shows small periodic fluctuation, which is due to the slow attenuation of the mass wave period caused by the fluctuation of water level in the downstream surge chamber shared by the two units in the downstream main line.

| Moving distance/m | Maximum output /MW | Relative value of maximum over output |
|-------------------|---------------------|---------------------------------------|
|                   | Frequency mode | Power mode | Frequency mode | Power mode |
| 0.00              | 77.56            | 77.03      | 16.02%          | 15.49%      |
| 50.00             | 76.70            | 76.26      | 15.16%          | 14.72%      |
| 100.00            | 75.63            | 75.23      | 14.09%          | 13.69%      |
| 150.00            | 74.65            | 74.27      | 13.11%          | 12.73%      |
| 200.00            | 73.67            | 73.34      | 12.13%          | 11.80%      |
| No downstream bifurcation | 71.89          | 71.35      | 10.35%          | 9.81%       |

![Figure 7. Output change process line of different positions of downstream bifurcated pipe](image)

3.4. Calculation and analysis of influence of downstream surge tank
It can be seen from Section 3.3 that the waveform of output swing of unit 2 without downstream bifurcation is quite different from that when setting it. By removing the setting of downstream surge chamber, the working condition in Section 3.1 is still taken to calculate and analyze the influence of downstream surge chamber.

According to table 4, the maximum relative over output of the original position in the frequency mode is 35.46% when the downstream surge chamber is not set, and it is reduced to 25.16% after adding the downstream surge chamber layout, which indicates that the surge chamber located in the downstream main pipe can effectively reduce the output swing of disturbed unit. When there is no downstream bifurcation, the maximum output and the maximum relative over output of the downstream surge chamber in the frequency mode are greater than those in the layout without surge chamber, which indicates that the downstream surge chamber distributed on the two branches will worsen the transient process of hydraulic disturbance to a certain extent.
Table 4. Calculation results of different positions of downstream surge chamber

| Moving distance/m | No Downstream Surge Chamber | Setting up downstream surge chamber |
|------------------|-------------------------------|-------------------------------------|
|                  | Maximum output /MW | Relative value of maximum over output | Maximum output /MW | Relative value of maximum over output |
|                  | Frequency mode | Power mode | Frequency mode | Power mode | Frequency mode | Power mode | Frequency mode | Power mode |
| 0.00             | 83.36 | 82.48 | 35.46% | 34.03% | 77.56 | 77.03 | 26.03% | 25.16% |
| 50.00            | 82.63 | 81.84 | 34.26% | 32.98% | 76.70 | 76.26 | 24.63% | 23.92% |
| 100.00           | 81.91 | 81.23 | 33.11% | 32.00% | 75.63 | 75.23 | 22.90% | 22.24% |
| 150.00           | 81.09 | 80.47 | 31.76% | 30.76% | 74.65 | 74.27 | 21.30% | 20.68% |
| 200.00           | 80.29 | 79.70 | 30.47% | 29.50% | 73.67 | 73.34 | 19.71% | 19.17% |
| No downstream bifurcation | 70.65 | 70.22 | 14.81% | 14.11% | 71.89 | 71.35 | 16.81% | 15.94% |

4. Conclusion
In this paper, the influence of upstream and downstream bifurcation position on hydraulic interference process is studied, and the influence of downstream surge chamber position on disturbed unit is analyzed. The research results show that the position of bifurcation far from the units can reduce the influence of hydraulic interference transition process on the output swing of normal operating unit. And it is better to reduce the swing of the disturbed unit without bifurcations in the upstream than in the downstream. The common downstream surge tank layout can also effectively reduce the output swing, while the downstream surge chamber arranged in the tail water branch pipe will worsen the hydraulic interference transition process.

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