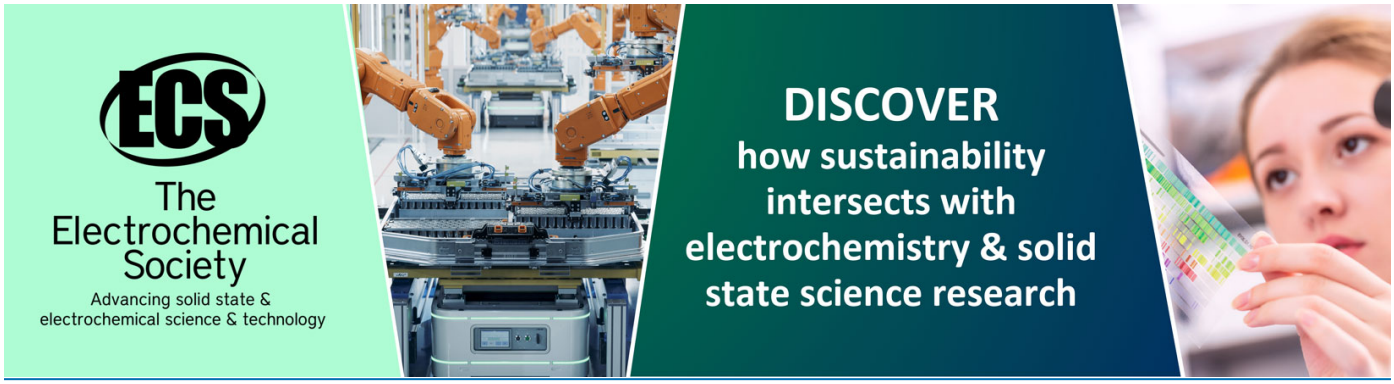
Analysis of Small Fluctuation Stability of Upstream and Downstream Double Surge chamber Diversion Power Generation System



Analysis of Small Fluctuation Stability of Upstream and Downstream Double Surge chamber Diversion Power Generation System

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Abstract. Installation of upstream and downstream surge chamber is a significant and feasible measure for peak pressure control in the hydropower system with long water diversion and drainage tunnel. This paper presents a study on the fluctuation stability with such a measure. For this system, a complete mathematical model including diversion pipeline, upstream surge tank, hydraulic turbine and downstream surge tank was developed, calculating the hydraulic transition characteristics and analyzing the fluctuation stability with different surge tank cross areas. The calculation shows that, the hydropower system with upstream and downstream surge chamber, can also be stable even if the surge tank cross area is smaller than the calculated value. In practice, in the condition of meeting the stability requirement, multiple schemes should be calculated in order to find out the minimum areas to reduce project investment.

1. Introduction

Fluctuation stability is that, after suffering a slight disturbance, the hydropower system recovers to its original status or maintains in a new equilibrium state under the action of the governor or other control equipment. The stability here only refers to the water regulating process and it does not contain operating index of generating units such as vibration. Little fluctuation is frequent when hydropower station is running, so it is particularly important to analyze the stability of little fluctuations.

Due to terrain factors, some hydropower stations need to be designed as underground powerhouse, causing the water diversion and drainage tunnel pressurized and longer. In this condition, installation of upstream and downstream surge chamber is usually used to balance the water pressure. At present, there are fewer hydropower stations that have been built with upstream and downstream surge chamber, and the studies on the little fluctuation are less either. Reference [1] derived the calculation formulas of upstream and downstream surge chamber cross areas, and analyzed how the governor parameters affected the little fluctuation stability in the condition of the unit moment of inertia, the turbine torque and the surge tank area were certain. Reference [2] studied water level fluctuation stability condition, and a case calculation was made to verify its availability. Reference [3] studied the factors that can influence the fluctuation in diversion system with double surge chamber upstream, and it showed that if the distance between the two surge chamber was longer, the total cross areas were larger, and the surge tank near the unit influenced the fluctuation more than the other one.

The size of the surge chamber cross areas directly affects the hydropower project investment. In the condition of meeting the stability requirement, using the smaller surge tank will largely reduce the project investment cost. This paper established a mathematical model for hydropower system with upstream and downstream surge chamber based on the characteristics method[4], calculated the little fluctuation hydraulic transition process in the condition of different surge chamber areas, and studied how the surge chamber areas affected the little fluctuation stability. The calculation shows that, the hydropower system with upstream and downstream surge chamber, can also be stable even if the surge tank cross area is smaller than the calculated value. In practice, in the condition of meeting the stability requirement, multiple schemes should be calculated in order to find out the minimum areas to reduce project investment.

2. Mathematical model

2.1. Basic assumptions

In analysis of little fluctuation stability, some assumptions are made as follows[5]:

- The turbine speed, water head and guide vane opening are certain.
- To ignore the voltage fluctuation.
- The turbine-generator unit is not connected to the power grid.
- To ignore adjustment coefficient of load.
- Governor permanent difference coefficient is 0.

2.2. Mathematical model

Hydropower system with long water diversion and drainage tunnel consists of reservoir, water diversion tunnel, surge tank, penstock, spiral casing, turbine, draft tube and drainage tunnel. In the little fluctuation working condition, the elasticity of water and pipe wall can be ignored, and rigidity water hammer theory can be used to analyze the hydraulic transition. Fig.1 shows the hydropower system with upstream and downstream surge chamber.

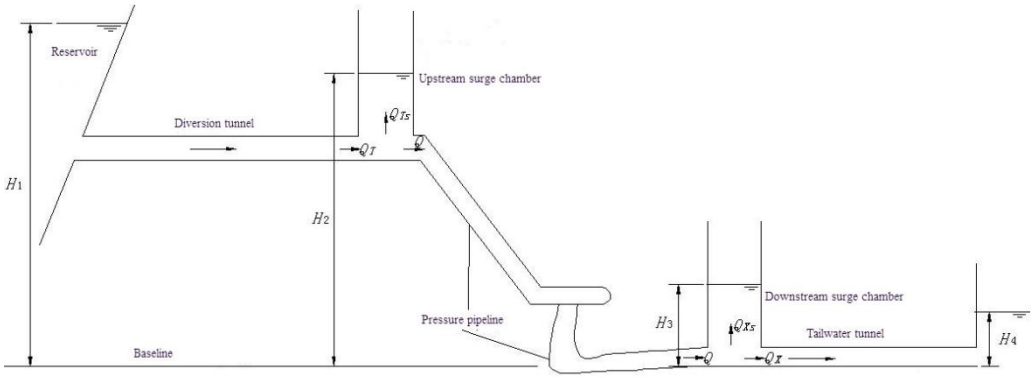


Fig.1 The hydropower system with upstream and downstream surge chamber

Motion equation of hammer：

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+g\frac{\partial H}{\partial x}+g\frac{fV|V|}{2D}=0 \tag{1}$$

Continuity equation：

$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}-V\sin\alpha+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \tag{2}$$

Where A is the cross area of the pipe, α is included angle between the pipe center line and level line, g is the gravitational acceleration, V is the water flow velocity, x is the distance, H is the water

head, f is the frictional resistant coefficient, a is the water hammer wave velocity, D is the inner diameter of the pipe, t is the time.

Characteristic equations:

$$\begin{aligned} C^+ &: H_P = C_P - BQ_P \\ C^- &: H_P = C_M + BQ_P \end{aligned} \tag{3}$$

Where:

$$C_P = H_A + BQ_A - R\,|Q_A|\,Q_A \tag{4}$$

$$C_M = H_B - BQ_B - R\,|Q_B|\,Q_B \tag{5}$$

$$B = \frac{a}{gA} \tag{6}$$

$$R = \frac{f\Delta x}{2gDA^2} \tag{7}$$

Where H_A is the water head at the "$i-1$"point at the "$t-\Delta t$" time point, H_B is the water head at the "$i+1$"point at the "$t-\Delta t$" time point, Q_A is the water flow at the "$i-1$"point at the "$t-\Delta t$" time point, Q_B is the water flow at the "$i+1$"point at the "$t-\Delta t$" time point, Δx is the distance between the two points, R is the resistance coefficient, C_P, C_M are both related with the water head and flow, and are both known at the "t" time point.

2.2.1.The upstream reservoir boundary equation

$$H_P = H_R - (1 \pm \xi)\frac{Q_P{}^2}{2gA^2} \tag{8}$$

In the formula: ξ is the head loss coefficient of the inlet resistance. "+" is taken when the water flow is flowing downstream, and "-" is taken when the water flow is flowing upstream.

2.2.2.Boundary equation of upstream surge chamber

$$Z_1 = H_{PS1} - k_1 Q_{S1}^2 \tag{9}$$

In the formula: Q_{S1} is the flow into the upstream surge chamber; Z_1 is the water level of the upstream surge chamber; k_1 is the local loss coefficient of the head when the water flows into the upstream surge chamber, and the outflow and inflow values are different; F_1 is the cross-sectional area of the upstream surge chamber . Subscripts 1 and 2 denote tunnel and pipeline parameters, respectively.

2.2.3. Boundary equation of downstream surge chamber

$$Z_2 = H_{PS2} - k_2 Q_{S2}^2 \tag{10}$$

2.2.4. Turbine boundary equation

$$\frac{d\omega}{dt} = \frac{1}{J}(M_t - M_g) \tag{11}$$

$$M_t = M_1^{'} \cdot D_1^3 H \eta_P / \eta_M \tag{12}$$

$$\omega = 2\pi n \tag{13}$$

2.2.5. Boundary equation of tailwater tunnel

$$H_P = H_R - (1+\alpha)Q_P{}^2 / (2gA^2) \tag{14}$$

$$C^+ : H_P = C_{PS} - B_S \cdot Q_P \tag{15}$$

2.2.6. Governor transfer function

$$G(s) = \frac{1 + T_d S}{T_d T_y S^2 + [T_y + T_d b_t]S + b_p} \cdot \frac{1 + T_n S}{1 + K_n T_n S} \tag{16}$$

Where: T_y is the reaction time of the guide vane servomotor; T_d is the buffer time constant of the governor; b_t is the transient slip coefficient of the governor; y is the relative value of the travel of the guide vane servomotor; σ is the relative value of the main pressure valve travel; T_n is the differential time constant of the governor; K_n is the proportional coefficient; ξ is the relative deviation of the transient feedback output; x is the relative deviation of the speed; γ is the relative deviation of the output.

3. Example calculation

3.1. Project Overview

The diversion tunnel of a hydropower station has a length of 6902.66*m* and an inner diameter of 11.0m, and it adopts full-section reinforced concrete lining. The maximum roughness of reinforced concrete lining is 0.016, the minimum roughness is 0.012, and the average roughness is 0.014. The inner diameter of the pressure pipe is 5.3*m*, the length of the 1# pressure pipe is 519.064*m*, the length of the 2# pressure pipe is 504.067*m*, the length of the 3# pressure pipe is 499.832*m*, and the roughness of the steel pipe is 0.012. The local head loss coefficient is determined according to the layout of the diversion system. The upstream surge chamber is in the form of a long corridor impedance. The initial diameter of the impedance orifice is 3.0*m*, and the designed net area of the surge chamber is 737.10m^2. The downstream tail water surge chamber is also a corridor-shaped impedance type. The initial diameter of the impedance orifice is 3.2*m*, and the designed net area of the downstream tail water surge chamber is 600.40m^2. The normal water storage level of the reservoir is 2920.00*m*, the extraordinary flood level of the reservoir is 2922.71*m*, the dead water level of the reservoir is 2918.00*m*, the normal tail water level of the plant is 2698.01*m*, the lowest tail water level of the plant is 2687.06*m*, and the normal operation flood level is 2694.44*m*. The flood level is 2694.97*m*.

3.2. Stable calculation of small fluctuations

According to the parameters of the diversion power generation system of the hydropower station, according to the calculation formula of the critical area of the Toma section [13-15], the critical stable cross-sectional area of the upstream surge chamber is 288.43m^2, and the critical stable cross-sectional area of the tailwater surge chamber is 247.83 m^2. Under the condition that the normal water storage level is unchanged and the load fluctuates by 5%, 5 different upstream and downstream surge chamber cross-sectional areas are selected. According to the stability conditions of Thomas, the small water fluctuations of different water level changes in the upstream and downstream surge chambers are calculated. The calculation results are shown in Table 1, Table 2 and Figures 6~12, respectively. In the figure, (a) upstream surge chamber, (b) downstream surge chamber and (c) speed change.

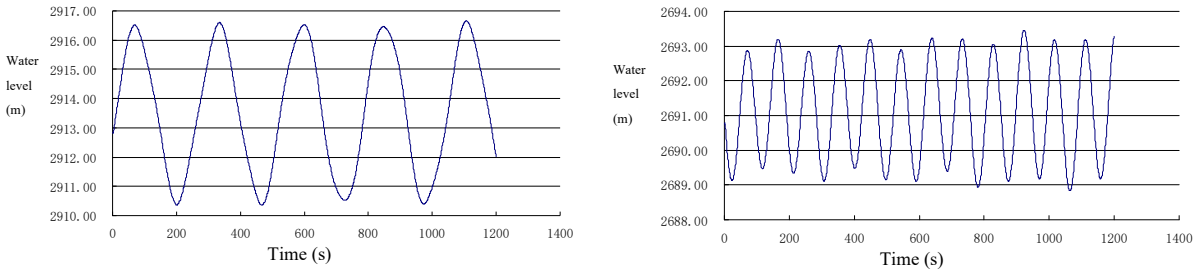
Table 1. Speed calculation results of small fluctuations in the cross-sectional area of different surge chambers at a normal water storage level of 2920.00*m*.

Upstream surge chamber area（m^2）	Downstream surge chamber area（m^2）	stability	Maximum speed（*r/min*）	Extreme value appearing time（*s*）	Overshoot σ	±0.4%Adjustment time（*s*）
230.00	110.00	Unstable	--	--	--	--
288.43	247.83	stable	217.63	4.86	1.55%	53.92
500.00	450.00	stable	217.61	4.74	1.54%	42.76

737.10	600.40	stable	217.61	4.70	1.54%	30.26
950.00	800.00	stable	217.61	4.70	1.54%	25.98

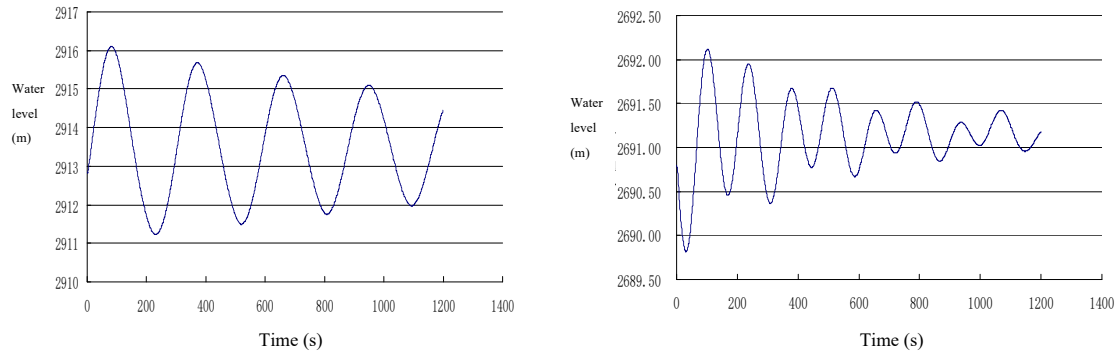
Table 2. Calculated water level results of small fluctuations in the cross-sectional area of different surge chambers at a normal water storage level of 2920.00*m*.

Upstream surge chamber area（m^2）	Downstream surge chamber area（m^2）	stability	Maximum water level of upstream surge chamber（*m*）	Minimum water level of upstream surge chamber（*m*）	Attenuation rate of upstream surge chamber	Maximum water level of downstream surge chamber（*m*）	Minimum water level of downstream surge chamber（*m*）	Attenuation rate of downstream surge chamber
230.00	110.00	Unstable	--	--	--	--	--	--
288.43	247.83	stable	2916.11	2911.22	1.00014	2692.12	2689.81	1.00006
500.00	450.00	stable	2915.20	2912.28	1.00026	2691.79	2690.17	1.00008
737.10	600.40	stable	2914.74	2912.73	1.00026	2691.68	2690.30	1.00008
950.00	800.00	stable	2914.50	2912.82	1.00024	2691.58	2690.41	1.00008

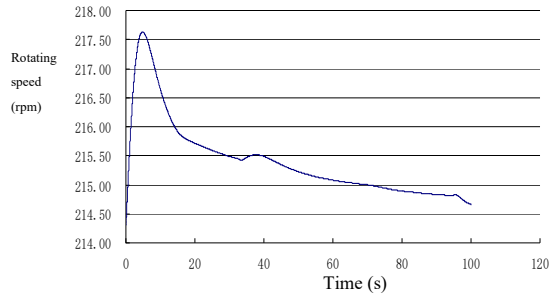


(a) (b)

Figure 2. The area of the upstream surge chamber is 230.00 m^2, and the area of the downstream surge chamber is 110.00 m^2

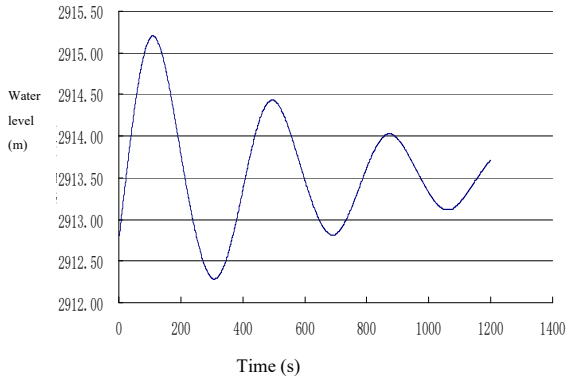


(a) (b)

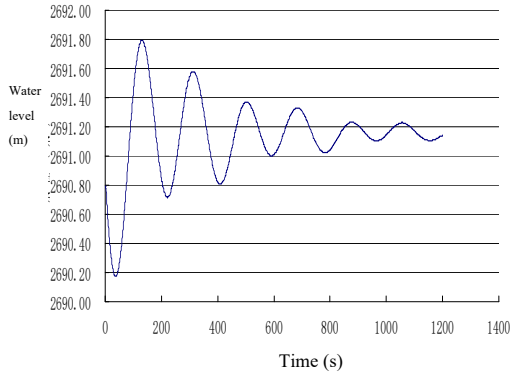


(c)

Figure 3. The area of the upstream surge chamber is 288.43 m^2, and the area of the downstream surge chamber is 247.83 m^2



(a)



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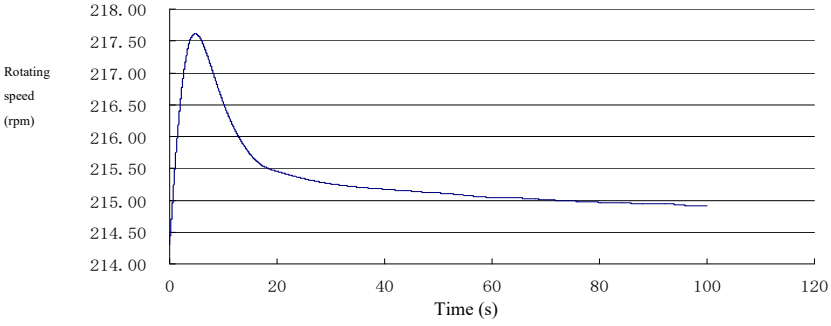
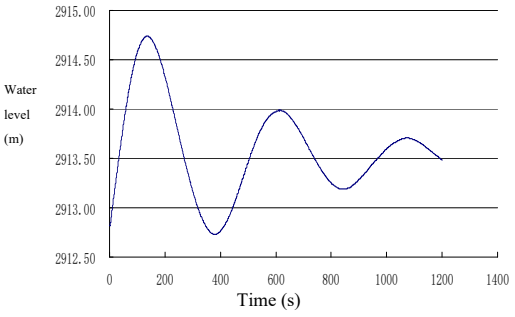
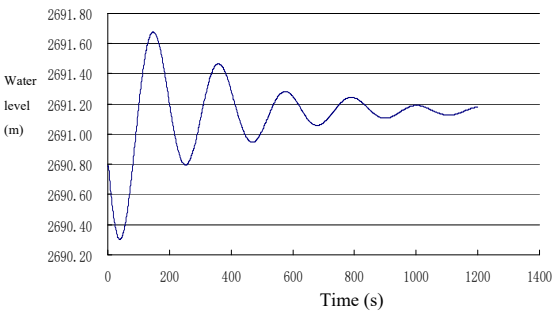


(c)

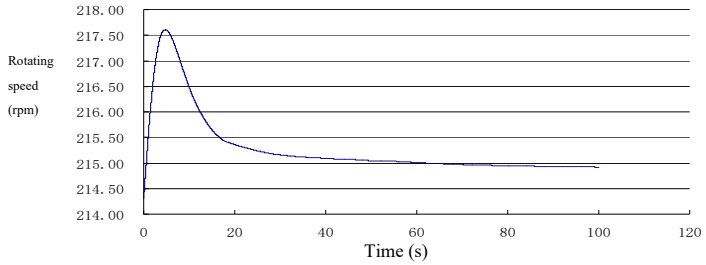
Figure 4. The area of the upstream surge chamber is 500 m^2, and the area of the downstream surge chamber is 450 m^2



(a)



(b)



(c)

Figure 5. The area of the upstream surge chamber is 737.10 m^2, and the area of the downstream surge chamber is 600.4 m^2

According to the analysis of Figures 2~5: The surge chamber is selected to have a smaller cross-sectional area than Toma's stable cross section, and the diversion and power generation system can also be stabilized. When the cross-sectional area of the upstream surge chamber is as small as 230 m2 and the cross-sectional area of the downstream surge chamber is as small as about 110 m2, the diversion and power generation system begins to become unstable, and the water level fluctuations in the upstream and downstream surge chambers diverge. When the cross-sectional area of the upstream and downstream surge chambers is the calculated critical stable cross-sectional area, the diversion and power generation system is stable, the maximum overshoot of the speed is 1.55%, the adjustment time of ±0.4% is 53.92 seconds, and the attenuation rate of the water level fluctuation of the upstream surge chamber It is 1.00014, and the attenuation rate of the water level fluctuation of the downstream surge chamber is 1.00006. At this time, the small fluctuation of the diversion system is stable, but the adjustment time is longer, the attenuation is slower, and the adjustment quality is not good; When the cross-sectional areas of the upstream and downstream surge chambers are respectively designed, the maximum overshoot of the speed is 1.54%, the adjustment time of ±0.4% is 30.26 seconds, the attenuation rate of the water level fluctuation of the upstream surge chamber is 1.00026, and the attenuation of the water level fluctuation of the downstream surge chamber The rate is 1.00008. At this time, the diversion power generation system has small fluctuations, stable adjustment time, short attenuation rate, and good adjustment quality; When the area of the upstream and downstream surge chambers was further increased, the adjustment time did not decrease significantly, the attenuation rate remained basically unchanged, and the adjustment quality did not increase significantly.

4. Conclusion

(1) When designing a hydropower station with upstream and downstream dual surge chamber systems, the requirements of the small fluctuation stability of the diversion system on the cross-sectional area of the surge chamber should be considered. Under normal circumstances, the total cross-sectional area of the upstream and downstream surge chamber stability requirements will be greater than the sum of the single upstream surge chamber and single downstream surge chamber stability requirements.

(2) In the diversion power generation system with dual upstream and downstream surge chambers, the water level in the upstream surge chamber first rises while the water level in the tail surge chamber drops first before fluctuating in their respective fluctuation cycles. Correspondingly, under load-increasing conditions, the water level of the upstream surge chamber first decreases, while the water level of the tail surge chamber first rises, and then fluctuates with their respective fluctuation cycles. In the diversion power generation system with dual upstream and downstream surge chambers, the fluctuation periods of the upstream and downstream surge chambers must avoid the similar fluctuation periods to avoid resonance.

(3) The diversion power generation system with dual upstream and downstream surge chambers, the stable cross-section of the surge chamber is larger than that of the single surge chamber system. In fact, the cross-section of the surge chamber of the double surge chamber system uses a smaller area

than the theoretically derived stable cross-section. The diversion and power generation system may also tend to be stable, but the quality of the regulation is often not ideal. It must be calculated through the transition process of multiple schemes. Combined with economic analysis, a reasonable cross-sectional area of the surge chamber is obtained.

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