IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Hydraulic transient simulation and characteristic investigation on Kaplan type hydroelectric power Plant with open channel

To cite this article: S Chen *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **240** 082013

Hydraulic transient simulation and characteristic investigation on Kaplan type hydroelectric power Plant with open channel

S Chen, J Zhang and X D Yu

College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China

E-mail: chensheng@hhu.edu.cn

Abstract. Kaplan type of turbines are meant for low head hydro development and sometimes are installed in systems with long open channels. Transient flow analysis in Kaplan hydroelectric power plants (HPP) is one of the most important issues for the prevention of undesirable pressure fluctuations in waterways. To keep efficient operation of a Kaplan turbine, the wicket gates and the runner blades position should be regulated as water head changed. Therefore, the hydraulic transients of Kaplan type HPP with open channel is more complex, exhibiting unique hydraulic characteristic. Based on the transient flow theory, both implicit difference method and method of characteristic are introduced to establish the mathematic model of hydraulic transients calculation for Kaplan type HPP with open channel. Then the fluid transients due to load rejection is simulated to investigate the hydraulic behaviors. The results show that different blades movements give different hydraulic behaviors. If the blades are not involved in the regulation, the hydraulic behavior is exactly the same as that of Francis turbines. If the blades adopt closure mode, the maximum spiral case pressure will slightly increase and the maximum rotating speed rising rate will obviously decrease with the increase of closing time. While the blades adopt opening mode, it will give the opposite hydraulic behavior compared to closure mode. Opening of the runner blades during the turbine shutdown can improve over-speed performance and worsen the spiral case pressure, and vice versa. Additionally, taking open channel into consideration, the influence on hydraulic characteristic is enlarged, while the length of the open channel has little effect on it.

1. Introduction

The layout of the water conveyance system for the HPP mainly depends on the terrain, geology and hydrology conditions, as well as the selection of turbines. With the development and utilization of hydropower resources, purely pressurized pipeline system for HPP sometimes is inappropriate constrained by the topographical geological conditions and construction conditions. Instead, water diversion system consisting of headrace (tailrace) open channels and pressurized pipelines is usually adopted, which is especially common in small and medium HPP. When the HPP employs the layout of open channels combined with pressurized pipelines, a pressure forebay is usually provided between the end of the diversion open channel (or head of the tailrace open channel) and the pressurized pipelines. The forebay serves as a connecting structure to provide functions of stabilizing water head, discharging excess water, intercepting and removing dirt, sediment, ice floes and so on. However, the capacity of pressure forebay and open channel is usually limited, which will result in a wide range of variation for the water head and output. Kaplan turbine is a kind of propeller turbine with adjustable blades, and can maintain peak efficiency over a wide range of power levels since the runner blades are adjustable and the guide vanes can be turned to any angle to match the blade angle [1]. Therefore, the Kaplan turbine is the best choice and meant for low head hydro development in such a diversion HPP with open channel, which can ensure the turbine always operates in a high efficiency zone.

During the operation of the HPP, load rejection is often encountered because of power failure, device malfunction, or other accidents [2]. The following severe water hammer induced from quick closure of wicket gates may pose serious threat to the safe operation of the water diversion system and the units, for example the runner blades. Therefore, transient flow analysis in Kaplan HPP is one of the most important issues for the prevention of undesirable pressure fluctuations in waterways. And the complete analysis of transient events is necessary, to obtain quantities of concern, such as maximum spiral case pressure (SCP), minimum draft tube pressure (DTP), and maximum rising rate of rotating speed (RRRS). Currently, transient analyses on pure Francis type HPP [3-8] and Francis type HPP with open channel [9-10] have been extensively investigated.

However, due to the double-regulated characteristic and on-cam relationship between the wicket gate opening and the runner blade angle, the transient simulation of the Kaplan type HPP is different from that of Francis type HPP, becomes even more complicated. Bergant et al. [11] investigated critical flow regimes that may induce unacceptable water hammer in Kaplan turbine hydroelectric power plants and the rigid water hammer theory is used for transient calculation. Cao et al. [12] analyzed and optimized the current calculation model of Kaplan turbine, and its rationality is validated by the field test data of one low head Kaplan type HPP.

For Kaplan type HPP with open channel, the hydraulic parameters of open channel and pressurized pipelines will be inevitably affected by each other through the pressure forebay. Thus, it is necessary to simulate the transient process of both open channel and pressurized pipelines at the same time, which further increasing the difficulty in transient simulation. In practice, the unsteady flow differential equations of pressurized pipelines and open channel are introduced for the hydraulic transient calculation. However, the large discrepancy on wave speed between open channel and pressure flow determines the calculation should be conducted separately. This problem could be solved by coupling the hydraulic parameters of the two sections at the boundary. The transient simulation model of a Francis type HPP was developed by the authors and colleagues [10], and it has succeeded in guiding design work of a practical project.

Currently, most studies are forced on pure Kaplan type HPP or Francis type HPP with open channel, investigations of hydraulic transient on Kaplan type HPP are limited [13]. This paper, based on the transient flow theory, establishes the mathematic model of hydraulic transient calculation for Kaplan type HPP with open channel. An interpolation method for Kaplan turbine characteristics is proposed as well. Finally, the hydraulic characteristics is investigated during the fluid transients when load rejection occurs.

2. Mathematic models

The governing equations for pressurized pipeline and open channel can be referred to in references [10, 14]. Herein only gives the turbine equations, and the governing equations at the connection between forebay and pressurized pipelines.

2.1. Turbine equations

The head balance equation of the turbine is

$$H = \left(H_1 + \frac{|Q|Q}{2gA_1^2} \right) - \left(H_2 + \frac{|Q|Q}{2gA_2^2} \right) \tag{1}$$

in which H_1 and H_2 are head at the end of spiral case and head at the draft tube inlet, respectively; A_1 and A_2 are area of spiral case outlet and draft tube inlet, respectively; and Q is demand discharge of the turbine.

Whenever there is a change in the power demand of the electrical system, a different level of power is absorbed by the generator and an unbalanced torque exists on the turbine, which gives rise to a speed change. The basic equation for speed change is

$$J\frac{d\omega}{dt} = M - M_g \tag{2}$$

in which J is the polar moment of inertia of rotating fluid and mechanical parts in the turbine-generator combination ($J = WR^2/g$, where W is the weight, and R is the radius of gyration), $d\omega/dt$ is the angular acceleration, M is shaft torque of the turbine, and M_g is electromagnetic torque of the generator.

When load rejection occurs, the unit is instantly disconnected from the system and thus becomes isolated (i.e., $M_g = 0$). Then, the unit has to be quickly closed according to the emergency closure law that is set to the governor in advance to prevent extended periods of high overspeed, which may induce severe spiral case pressure increments and draft tube pressure decrements. This type of regulation is more severe and more critical to the safety of the whole system, which is considered in this study. Equation (2) can be transferred to algebraic equations by integration and the Taylor expansion method, which can be expressed as

$$n_t = n_{t0} + \frac{\Delta t}{T_m}\left(1.5\beta_{t0} - 0.5\beta_{t0-\Delta t}\right) \tag{3}$$

where n is dimensionless rotating speed ratio, N/N_r; β is dimensionless torque ratio, M/M_r; Δt is time step; and T_m is mechanical starting time, defined as $T_m = I\omega^2 r/P_r$.

2.2. Governing equations at connection of forebay and pressurized pipelines

The pressurized pipelines are connected to the end of the pressure forebay, and the flow conservation equation is

$$Q = \sum_{i=1}^{n} Q_i \tag{4}$$

in which, Q is discharge at the end of pressure forebay, and Q_i is demand discharge of the ith pipeline.

Because the wave speed of open channel is hundreds of times smaller than that of pressurized pipelines, it will be quite time consuming if a unified time step is adopted to conduct calculation. Since Preissmann four-point difference scheme is an implicit format, the calculation is unconditionally converged. Therefore, a larger ΔT can be selected as the time step of the unsteady open channel flow to reduce the amount of computation. Setting $\Delta T = k\Delta t$, where Δt is the time step of the water hammer in pressurized pipelines, and k is an integer. Suppose that the flow into the forebay at $t_0 + \Delta t$, $t_0 + 2\Delta t$, …, $t_0 + k\Delta t$ is Q_1, Q_2, …, Q_k, respectively, and the flow into the forebay within ΔT is

$$Q = \frac{Q_1 + Q_2 + \cdots + Q_k}{k} \tag{5}$$

3. Hydraulic behavior during load rejection

One run-of-river HPP in China is equipped with three Kaplan turbines, and each units have been installed in one water conservancy system, consisting of the headrace open channel, pressure forebay, penstocks, power house and tailrace open channel. The length of headrace and tailrace open channel is 450.4m and 382.3m, respectively, with rectangular cross-section. The water level of upstream open channel is 78.9m, and that of tailrace pressure forebay is 60.3m. The other main technical parameters of the Kaplan turbine are listed as follows: rated output is 48 MW, rated head is 22.5 m, rated speed is 125 r/m, rated discharge is 227.5 m^3/s, and blade angle varies from -14°~14°.

3.1. Regulation manoeuvre of wicket gate and runner blade

The emergency closure manoeuvre of Kaplan turbine during load rejection is complex. When the wicket gates are closing, the runner blades can simultaneously close or open, or just keep still. The influence of the regulation manoeuvre of wicket gate and runner blade on the hydraulic transient is mainly performed by the above three operation modes. Figure 1 gives the schematic of the regulation manoeuvre of wicket gate and runner blade. And the calculation results are listed in Table 1. In figure 2, τ is dimensionless wicket gate opening; y is dimensionless blade angle with reference opening 14°; h_{sc} (= H_{sc} / H_r) is dimensionless pressure head in the spiral case; n (= N / N_r) is dimensionless rotating speed; h_{dt} (= H_{dt} / H_c) dimensionless pressure head in the draft tube with H_c = 10m; q (= Q / Q_r) dimensionless discharge of the turbine.

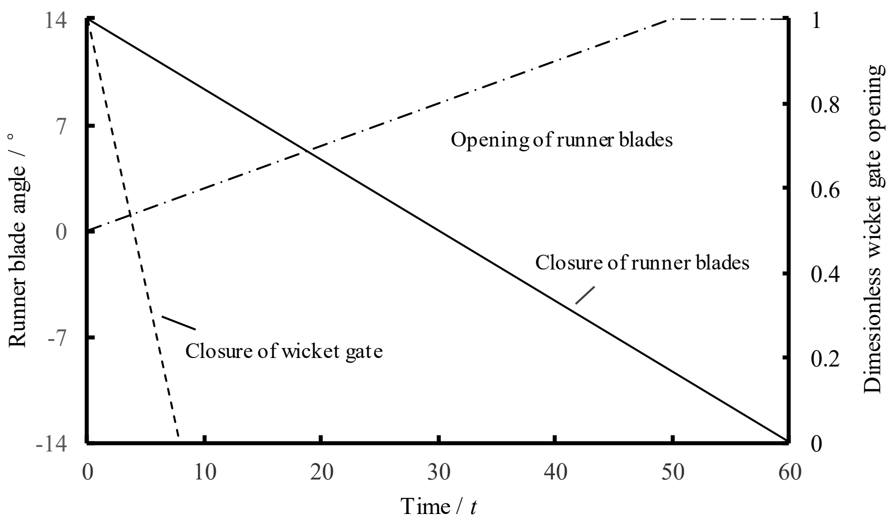


Figure 1. Schematic of the regulation manoeuvre of wicket gate and runner blade (Taking wicket gate closing down linearly in 8s, runner blades closing and opening linearly in 60s and 50s, respectively for example).

Table 1. Calculation results of different regulation manoeuvres of wicket gate and runner blades.

Closing Time of Wicket Gate (s)	Regulation Manoeuvre of Runner Blade	Variation of Blade Angle (°)	Maximum SCP (m)	Maximum. RRRS (%)	Minimum DTP (m)
7	Keep still	7.8→7.8	58.41	46.1	6.69
8			55.78	46.2	8.86
9			53.24	46.4	9.23
10			51.34	46.7	9.51
8	Close in 30s	7.8→-14.0	54.45	51.1	9.10
	Close in 40s		54.67	49.8	9.08
	Close in 50s		54.74	49.1	9.03
	Close in 60s		54.88	48.7	9.00
8	Open in 20s	7.8→14.0	57.54	35.7	8.61
	Open in 30s		57.27	39.9	8.62
	Open in 40s		57.01	42.3	8.70
	Open in 50s		56.69	43.8	8.74

Table 1 gives the calculation results of different regulation manoeuvres of wicket gate and runner blades. When the runner blades remain stationary, the Kaplan turbine is just operated as a fixed blade type. As the closing time of wicket gate increases, the maximum SCP gradually decreases, while the maximum RRRS presented a slight increase. This hydraulic behavior during transition process is consistent with the fixed blade type and conventional knowledge. When the wicket gate is closed linearly with a fixed closing time (8s for example), the runner blades can either close or open. If the blades adopt closure mode, the maximum SCP will slightly increase and the maximum RRRS will obviously decrease with the increase of closing time. While the blades adopt opening mode, it will give the opposite hydraulic behavior compared to closure mode.

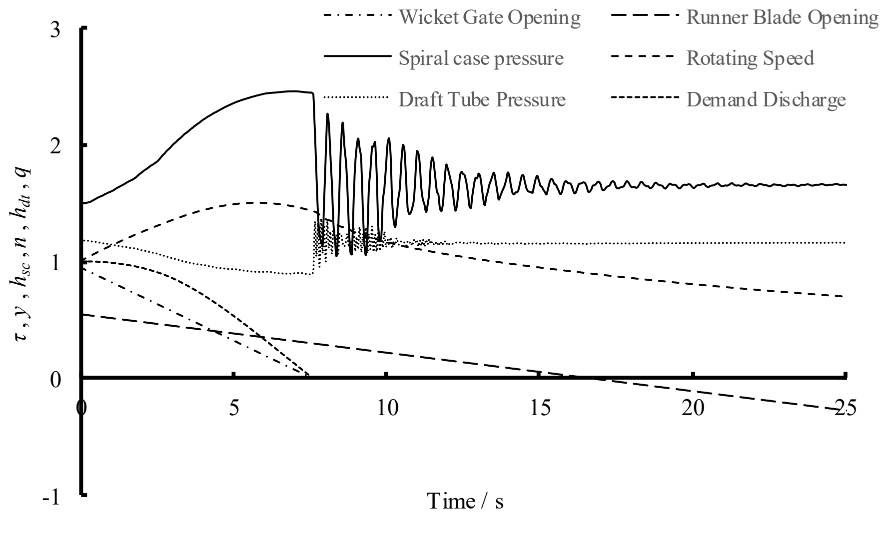
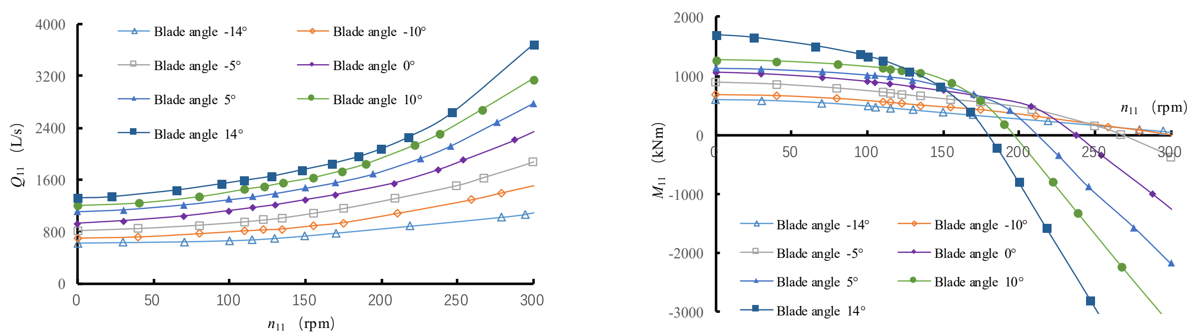


Figure 2. Time history of the hydraulic parameters for wicket gate closing linearly in 8s and runner blade opening linearly in 60s.

Furthermore, the maximum SCP of blade open mode > that of keep still > that of close mode. While maximum RRRS of blade close mode > that of keep still > that of open mode. That is, opening of the runner blades during the turbine shutdown can improve over-speed performance and worsen the spiral case pressure, and vice versa, which can be illustrated by figure 3. Figure 3 presents the relationship of unit speed-discharge and unit speed-torque under the same wicket gate opening and different blade angles. With the increase of blade angle φ, the demand discharge is increasing. Since the closure time of wicket gate is fixed, the opening of the runner blade increases the flow gradient in the pipeline, finally resulting in an increase in the water hammer pressure. And the faster the blade opens, the greater the water hammer will be induced. The rotating speed change is opposite to that of pressure.



(a) Unit rotating speed – unit discharge **(b)** Unit rotating speed – unit torque.

Figure 3. Relationship between unit parameters under different blade angles (wicket gate open is 36°).

3.2. Influence of open channel on hydraulic parameters

For HPP with large reservoirs, the elevation of the hydraulic grade line normally can be assumed constant during a short-duration transient. However, for HPP with open channels, the pressure forebay, served as the connecting construction between open channel and pressurized pipelines, is generally limited in volume. When load rejection or load acceptance occurs, the pressure forebay is just like a simple surge tank, and the water level will fluctuate up and downs. The oscillated surge imposes a certain influence on the hydraulic parameters compared to the constant water level in the reservoir.

Table 2. Hydraulic parameters with or without open channels.

With or without open channel	Regulation manoeuvre of wicket gate and runner blade	Maximum SCP (m)	Maximum RRRS (%)	Minimum DTP (m)
With	Manoeuvre 1: wicket gate closing in 8s, blade keeping still	55.78	46.2	8.86
	Manoeuvre 2: wicket gate closing in 8s, blade closing in 60s	54.88	48.7	9.00
	Manoeuvre 3: wicket gate closing in 8s, blade opening in 50s	56.69	43.8	8.74
Without	Manoeuvre 1: wicket gate closing in 8s, blade keeping still	55.36	46.0	9.37
	Manoeuvre 2: wicket gate closing in 8s, blade closing in 60s	54.08	47.4	9.41
	Manoeuvre 3: wicket gate closing in 8s, blade opening in 50s	55.56	45.2	9.34

Note: without open channel treats forebay as a large reservoir.

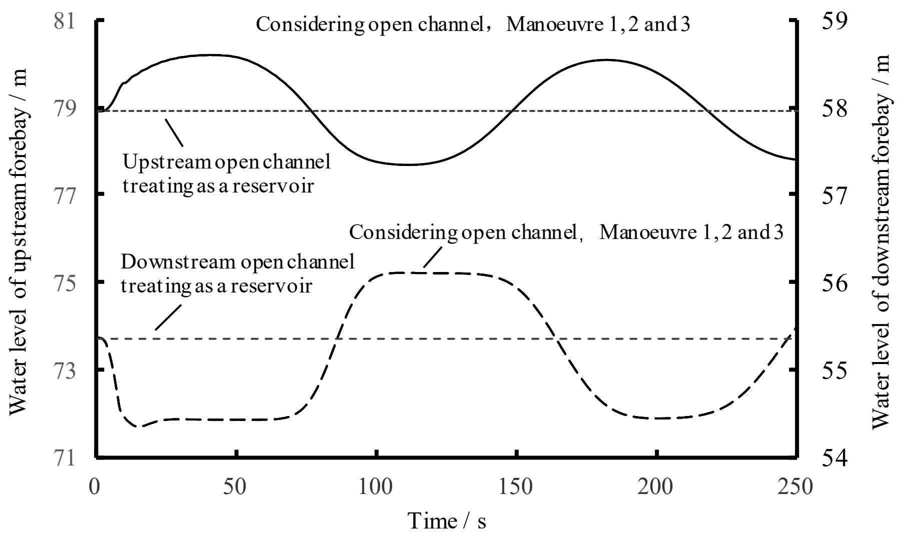


Figure 4. Time history of water level of upstream and downstream forebay.

From figure 4, it is known that water level fluctuations in the forebay are induced when load rejection occurs because of the limited capacity of the forebay and the lagging response of the open channel. The maximum difference between the peak and valley reaches about 3.0m. As shown in figure 5, the water level fluctuation between the upstream and downstream forebay then causes a gradually increasing head difference on the Kaplan units. As a result, the maximum spiral case pressure is slightly larger compared to the case without open channels (seen in Table 2). So does the rotating speed. However, since the total length of the open channels is only 832.7m, the impact on the hydraulic parameters is not significant. The maximum difference in maximum SPC is about 1m, and 1.4% in RRRS. As mentioned previously, the pressure forebay is just like a surge tank, connecting the open channel and the pressure forebay. The influence of the open channel on the hydraulic parameters is equivalent to that of the pressure forebay. Since the period of water level fluctuation in the pressure forebay is much larger than that of water hammer, the effect is relatively small.

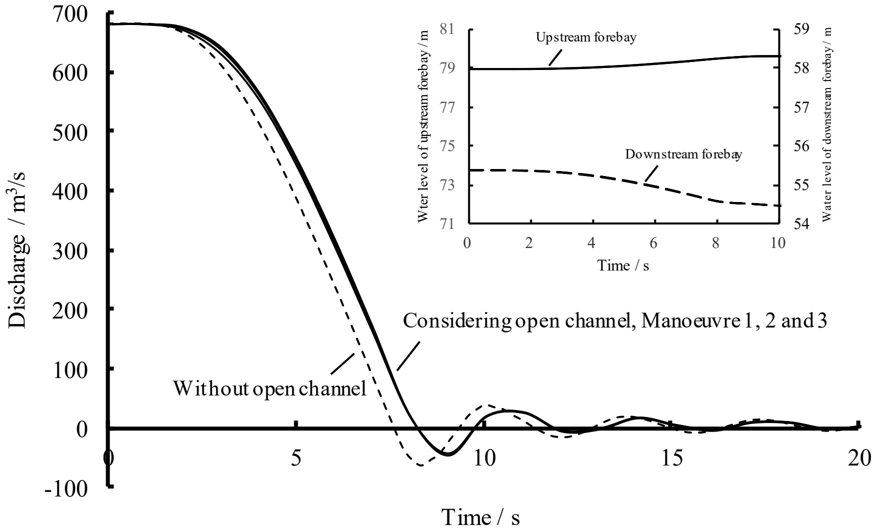


Figure 5. Time history of discharge of upstream and downstream forebay or reservoir.

However, taking the influence of open channels into account, the difference in hydraulic parameters between different regulation manoeuvre of wicket gate and runner blade is greater than that of without open channel. For example, considering the effects of open channels, the difference in the maximum RRRS between manoeuvre 2 and 3 is 4.9%. While the difference is only 2.2% if the forebay is treated as a reservoir. The consideration of open channels enlarges the influence of the blade action on the hydraulic characteristics of the Kaplan units.

Table 3 also gives the influence of different open channel lengths on the hydraulic parameters for the Kaplan type HPP during load rejection. The results indicate that further increase in the length of the open channel has little effect on the control parameters. This is due to the behavior of the unsteady open channel flow, which is slow in propagate and lags in adjustment. Before the SCP and rotating speed reach the maximum value (before 7.5s), it is mainly depended on the adjusting ability of the pressure forebay. Therefore, the length changes of the open channel have little effect on the fluctuation of the water level in the pressure forebay at this stage, resulting no effect on the hydraulic parameters.

Table 3. Influence of different open channel lengths on hydraulic parameters.

Total length （m）	Description	Max. Spiral Case Pressure (m)	Max. Rising Rate of Rotating Speed (%)	Min. Draft Tube Pressure (m)
832.7	Upstream 450.4m, downstream 382.3m	54.88	48.7	9.00
1800	Upstream 1000m, downstream 800m	54.89	48.7	9.00
2800	Upstream 1500m, downstream 1300m	54.89	48.7	9.01
3800	Upstream 2000m, downstream 1800m	54.90	48.7	9.01

4. Conclusions

The double-regulated characteristic makes the hydraulic behavior of the Kaplan turbine is different from the conventional Francis turbine. Considering open channels in the calculation further complicated the hydraulic transient. Based on the transient flow theory, both implicit difference method and method of characteristic are introduced to establish the mathematic model of hydraulic transients calculation for Kaplan type HHP with open channel. Then the fluid transients due to load rejection is simulated to investigate the hydraulic behaviors. In summary, the key conclusions are:

(1) Different blades movements give different hydraulic behaviors. If the blades are not involved in the regulation, the hydraulic behavior is exactly the same as that of Francis turbines. If the blades adopt closure mode, the maximum SCP will slightly increase and the maximum RRRS will obviously decrease with the increase of closing time. While the blades adopt opening mode, it will give the opposite hydraulic behavior compared to closure mode.

(2) Opening of the runner blades during the turbine shutdown can improve over-speed performance and worsen the spiral case pressure, and vice versa.

(3) Taking open channel into consideration, the influence on hydraulic characteristic is enlarged, while the length of the open channel has little effect on it.

Acknowledgments
This paper was supported by the National Natural Science Foundation of China (grant numbers: 51709087), and the Priority Academic Program Development of Jiangsu Higher Education Institutions. The authors are grateful to everyone who has supported us in technical and financial terms.

References

[1] Luo Y Y, Wang Z W, Zhang J, Zeng J D, Lin J Y and Wang G Q 2013 Vibration and fatigue caused by pressure pulsations originating in the vaneless space for a Kaplan turbine with high head *Engineering Computations* **30** 448-63
[2] Chen S, Zhang J, Li G H and Yu X D 2017 Load rejection test and numerical prediction of critical load case scenarios for pumped storage plant *ASME 2017 Fluids Engineering Division Summer Meeting* (Waikoloa, HI, United states)
[3] Chaudhry M H 1987 *Applied Hydraulic Transients* (New York: Van Nostrand Reinhold)
[4] Fang HQ, Chen L, Dlakavu N and Shen ZY 2008 Basic modeling and simulation tool for analysis of hydraulic transients in hydroelectric power plants *IEEE Trans. on Energy Conversion* **23** 834-41
[5] Zhang G T, Cheng Y C and Lu N 2015 Research on Francis turbine modeling for large disturbance hydropower station transient process simulation *Mathematical Problems in Engineering* **2015** 1-10
[6] Nicolet C, Alligne S, Bergant A and Avellan F 2012 Simulation of water column separation in Francis pump-turbine draft tube *26th IAHR Symposium on Hydraulic Machinery and Systems* (Beijing, China)
[7] Selek B, Kırkgöz M S and Selek Z 2004 Comparison of computed water hammer pressures with test results for the Çatalan power plant in Turkey *Can. J. Civ. Eng.* **31** 78-85
[8] Calamak M and Bozkus Z 2013 Comparison of Performance of Two Run-of-River Plants during Transient Conditions *J. Perform. Constr. Facil.* **27** 624-32
[9] Yang J D, Wang M J, Wang C and Guo W C 2015 Linear Modeling and Regulation Quality Analysis for Hydro-Turbine Governing System with an Open Tailrace Channel *Energies* **8** 11702-17
[10] Cui W J, Zhang J and Chen S 2017 Transient flow and scheduling strategy of long diversion open channel in a hydropower station *South-to-North Water Transfers and Water Science & Technology* **15** 138-142 (in Chinese)
[11] Bergant A and Sijamhodžić E 2000 Water hammer control in Kaplan turbine hydroelectric power plants *8th International Conference on Pressure Surges* (Hague, Netherlands) 55-65
[12] Cao L L, Zheng S G and Shen Z Y 2003 Optimization of hydraulic transient calculation for Kaplan turbine model *Water Resources and Power* **21** 78-80 (in Chinese)
[13] Bergant A, Gregorc B and Gale J 2012 Numerical and in-situ investigations of water hammer

effects in Drava river Kaplan turbine hydropower plants *26th IAHR Symposium on Hydraulic Machinery and Systems* (Beijing, China)
[14] Wylie EB, Streeter VL and Suo LS 1993 *Fluid Transients in Systems* (New Jersey:Prentice-Hall)