A novel surface-cluster approach towards transient modeling of hydro-turbine governing systems in the start-up process

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Abstract:
Transient process, an essential condition for the operation of the hydro-turbine governing system, is critical for the safety and stability of a hydropower station. This research focuses on the transient modeling and dynamic analysis of the hydro-turbine governing system in the start-up process. A novel approach is developed to establish the transient model of the hydro-turbine governing system. The flow equation and torque equations were improved to reflect the dramatic changes of system parameters during the start-up process. As a pioneering work, the effect of guide vane opening law on the dynamic characteristics of the hydro-turbine governing system in start-up process was investigated by numerical simulations. The results of this research can promote the development of transient modeling and performance improvement of the hydro-turbine governing system in transient process.

Keywords: hydro-turbine governing system; start-up process; transient modeling; dynamics; surface-cluster method.

1. Introduction

The transient modeling and simulation of hydro-turbine governing systems is always a challenging problem for researchers [1]. Start-up transient process is an important issue for hydro-turbine governing system (HTGS). During the process, dramatic changes in flow, rotational speed and water head, which make the hydro-turbine governing system unstable and unsafe, are worth studying.

The transient process includes small oscillation process and large oscillation processes [2-4]. For the first aspect, a lot of achievements have been gained by researchers. For example, Zhang et al. [5] proposed supplementary control strategy of hydro-turbine governor and they proved the effectiveness of the strategy. Khan et al. [6] studied a micro hydropower generation system in Pakistan and CFD analysis of the turbine geometry was carried out to evaluate the optimal recouping of flow properties for maximum electricity generation. Thapa et al. [7] investigated the effects of sediment erosion of turbine components on the flow phenomenon, and developed better design of hydro turbines to minimize those effects. Aggidis et al. [8] presented a technology that can accelerate the development of hydro turbines by fully automating the initial testing process of prototype turbine models and automatically converting the acquired data into efficiency hill charts. However, few researchers have focused on their researches on the transient modeling of the HTGS in the start-up transient process. The conventional research method for the HTGS in the small oscillation process cannot be applied to the large oscillation especially the start-up process because of the dramatic changes of flow, rotational speed and water head in the start-up process that result in the frequent changes of transfer coefficients and the conventional model that cannot describe the transient process [9-11].

To overcome the problem, a surface cluster method is proposed in this paper. The characteristic equations of the HTGS are improved to describe the frequent changes of transfer coefficients during the start-up transient process. Essentially, the regulation and control of the HTGS is the changing law of the guide vanes. Therefore, the effects of the guide vanes on the dynamic characteristics of HTGS in the start-up transient process are investigated. A new dynamic model of the HTGS which can describe the effect of the guide vanes in the start-up transient process is established. The results of this paper reveal the influence of the guide vane opening law on the transient characteristic of the HTGS in the start-up transient process. Further, to obtain a better dynamic characteristic, the guide vane opening law of the HTGS is improved during the start-up transient process.

To achieve the above goal, this paper is organized as follows: In Section 2, the dynamic equations of the hydro-turbine output torque and flow are improved by using the surface-cluster method and the transient dynamic model of the hydro-turbine governing system is established in the start-up process. Section 3 presents the transient characteristics of the transient model in start-up process with different opening laws, and analyzes the effects of the opening law of the guide vanes on the transient characteristics of the hydro-turbine governing system in the start-up process. Finally Section 4 presents the conclusions to this paper.

2. Method

For the condition of rigid water hammer, the Francis turbine is chosen as the research object. The characteristic equation of the HTGS is improved in this section to describe the frequent changes of transfer coefficients in the start-up transient process.

2.1 Conventional characteristic equations of the hydro-turbine

When calculating the hydro-turbine output torque and flow during the start-up transient process, the transient coefficients of the HTGS change frequently [12-14]. This results to the non-negligible accumulated error, as shown in Fig. 1.

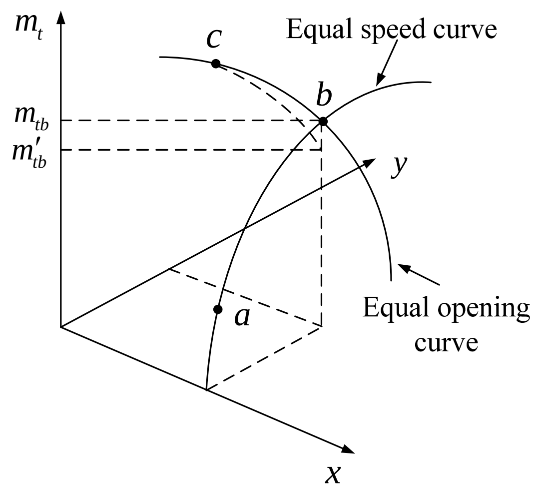


Fig. 1. The accumulated errors of hydro-turbine output torque during the start-up process.

The transfer coefficients of the hydro-turbine which are approximately calculated lead to the non-negligible accumulated error in the start-up process. From Fig. 1, when the operating point moves from point a to point b with a fixed rotational speed (x), the increment of torque is $\Delta m_{ab} = \int_a^b e_y dy$ where e_y is the slope of $a-b$ curve. Thus, the torque of operating point b is $m_{tb} = m_{ta} + \Delta m_{ab}$. When the guide vane opening is constant from operating point c to b, the increment of torque is $\Delta m_{cb} = \int_c^b e_x dx$ in which e_x is the slope of the $c-b$ curve. Therefore, the torque of operating point b is $m'_{tb} = m_{tc} + \Delta m_{cb}$. Due to the approximate values of e_x and e_y, m'_{tb} may not be equal to m_{tb}. This means that the operating point b has different torque values. More importantly, the accumulated error increases with the changes of rotational speed and guide vane opening in the start-up process. Therefore, the conventional equations of torque and flow must be improved in order to study the dynamic characteristics of the hydro-turbine governing system in the start-up process.

2.2 Improved dynamic equations of the hydro-turbine output torque and flow

To overcome the problem, the dynamic equations of the hydro-turbine output torque and flow are improved by using the surface-cluster method (see Fig. 2).

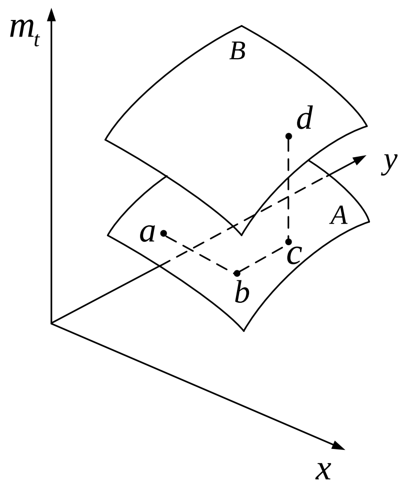


Fig. 2. The surface-cluster method to improve the dynamic equations of hydro-turbine output torque and flow in the start-up process.

As shown in Fig. 2, $a-b-c-d$ is the integration path of the torque. Points a, b and c are on surface A and d is on surface B. The path $a-b$ is equal guide vane opening line with the fixed guide vane opening (y) and water head (h).

The path $b-c$ is equal rotational speed line with fixed rotational speed (x) and water head (h). The path $c-d$ is changing water head line with fixed guide vane opening (y) and rotational speed (x).

From Refs. [15-17], m_t is the function of rotational speed, guide vane opening and water head which means $m_t = m_t(x \quad y \quad h)$. The torque (m_t) is a space surface in $x-y-m_t$ coordinate when water head (h) is constant. For different water head (h), the torque (m_t) is the surface cluster in $x-y-m_t$ coordinate (see surface *A* and *B* in Fig. 2). When the torque of operating point a is known $m_{ta}(x_a \quad y_a \quad h_a)$, for an arbitrary operating point d, its torque can be written as

$$\begin{aligned} m_{td}(x_d \quad y_d \quad h_d) &= m_{ta}(x_a \quad y_a \quad h_a) + \int_a^d dm_t \\ &= m_{ta}(x_a \quad y_a \quad h_a) + \int_a^b dm_t + \int_b^c dm_t + \int_c^d dm_t \\ &= m_{ta}(x_a \quad y_a \quad h_a) + \int_{x_a}^{x_d} e_x dx + \int_{y_a}^{y_d} e_y dy + \int_{h_a}^{h_d} e_h dh \end{aligned} \tag{1}$$

where e_x, e_y and e_h are partial derivatives of the turbine torque with respect to the rotational speed, guide vane opening and water head.

Similarly, when the flow of operating point a is known $q_{ta}(x_a \quad y_a \quad h_a)$, for an arbitrary operating point d, its flow can be expressed as

$$q_{td}(x_d \quad y_d \quad h_d) = q_{ta}(x_a \quad y_a \quad h_a) + \int_{x_a}^{x_d} e_{qx} dx + \int_{y_a}^{y_d} e_{qy} dy + \int_{h_a}^{h_d} e_{qh} dh \tag{2}$$

Eqs. (1) and (2) are the improved characteristic equations of torque and flow to describe the dynamic characteristics of the hydro-turbine governing system.

2.3 Transient modeling of the hydro-turbine governing system

The sketch map of the hydro-turbine governing system is shown in Fig. 3.

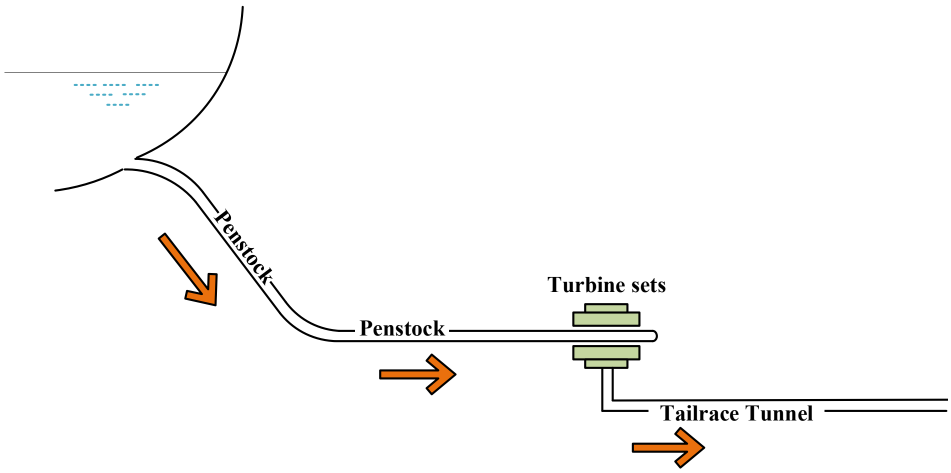


Fig. 3. The sketch map of the hydro-turbine governing system.

When the elasticity of water and tube wall shows no significant effects on the water hammer, we consider it as rigid water hammer [18-20]. And the dynamic characteristics of the penstock system can be described as [21]

$$h = -T_w \frac{dq}{dt}, \tag{3}$$

where T_w denotes the water inertia time constant of the pressure diversion system.

The rotational speed vibrations caused by the unbalance of the hydro-turbine torque and mechanical torque are presented as follows [22]:

$$T_{ab} \frac{dx}{dt} + e_n x = m_t - m_{g0}, \tag{4}$$

where T_a, T_b denote the inertia time constant of generator and load, respectively, $T_{ab} = T_a + T_b$ and e_n is the synthetic self-regulation coefficient.

From Refs. [23-25], the relationships between the system parameters and the transfer coefficients of the hydro-turbine governing system can be concluded as follows

$$e_x = -0.16x - 0.3,\ e_h = 1.67y,\ e_y = 1.548(1 - 0.6x) \tag{5}$$

$$e_{qx} = -0.15,\ e_{qy} = 1.65 - y,\ e_{qh} = 0.17 + 0.4y \tag{6}$$

For the start-up process, the torque of the initial point a is $m_{ta} = 0$. Then, the torque of an arbitrary operating point can be expressed as

$$\begin{aligned} m_t\left(x \quad y \quad h\right) &= 0+\int_{-1}^{x}\left(-0.16x-0.3\right)dx+\int_{0}^{y}1.548\left(1-0.6x\right)dy+\int_{0}^{h}1.67ydh \\ &=1.67yh-0.08x^2-0.3x-0.279+1.548\left(1-0.6x\right)y \end{aligned} \quad (7)$$

Similarly, the flow of the initial point a is $q_{ta}=0$ and the flow of an arbitrary operating point can be obtained as

$$\begin{aligned} q_t\left(x \quad y \quad h\right) &= 0+\int_{-1}^{x}-0.15dx+\int_{0}^{y}\left(1.65-y\right)dy-\left(0.17+0.4y\right)T_w\frac{dq}{dt} \\ &=-0.5y^2+1.65y-0.15x-0.15-\left(0.17+0.4y\right)T_w\frac{dq}{dt} \end{aligned} \quad (8)$$

From Eqs. (3)-(8), the transient model of the HTGS can be obtained as

$$\begin{cases} \dfrac{dx}{dt}=\dfrac{1}{T_{ab}}\left(m_t-e_nx-m_{g0}\right) \\ \dfrac{dq}{dt}=\dfrac{1}{\left(0.17+0.4y\right)T_w}\left(-0.5y^2+1.65y-0.15x-0.15-q\right) \\ \dfrac{dh}{dt}=\dfrac{\left(0.17+0.4y\right)\left(yw-1.65w+0.15\dot{x}+\dot{q}\right)-\left(0.2y^2w-0.66yw+0.06xw+0.06w+0.4qw\right)}{\left(0.17+0.4y\right)^2} \\ \dfrac{dm_t}{dt}=1.67hw+1.67y\dfrac{\left(0.17+0.4y\right)\left(yw-1.65w+0.15\dot{x}+\dot{q}\right)-\left(0.2y^2w-0.66yw+0.06xw+0.06w+0.4qw\right)}{\left(0.17+0.4y\right)^2} \\ -\dfrac{\left(0.16x+0.3\right)}{T_{ab}}\left(m_t-e_nx-m_{g0}\right)+1.548w-\dfrac{0.9288y}{T_{ab}}\left(m_t-e_nx-m_{g0}\right)-0.9288xw \\ \dfrac{dy}{dt}=w \end{cases}$$

（9）

3. Results and discussion

As the effect of guide vane opening is considered in the dynamic model of the hydro-turbine governing system in Eq. (9), in order to research the effect of guide vane and improve the opening law in the start-up process, the assumptions of the opening law of the guide vane are shown in Fig. 4.

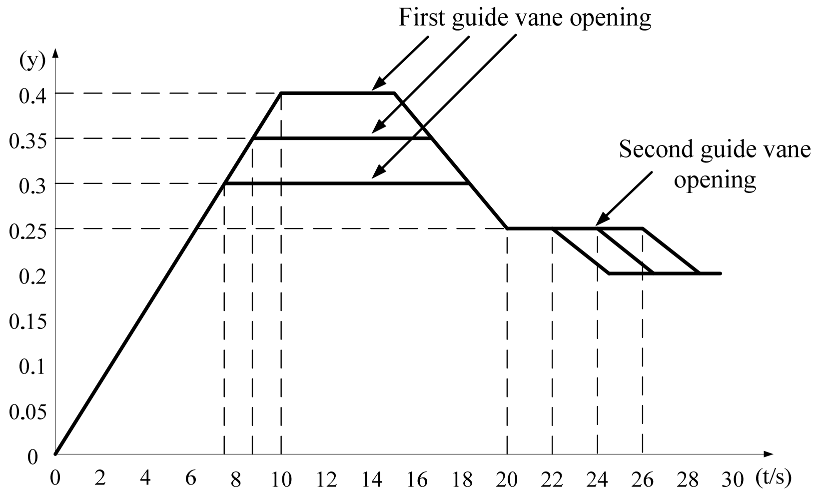


Fig. 4. The two-stage opening laws of the hydro-turbine governing system in the start-up process.

As shown in Fig. 4, the two-stage opening law is applied in the start-up process. For the first guide vane opening, three openings (0.3, 0.35 and 0.4) are chosen in order to study its influence on the dynamic characteristics of the hydro-turbine governing system at the beginning of the start-up process. For the second guide vane opening, three holding times (2s, 4s and 6s) are selected to investigate its effect on the stability of the system at the end of the start-up process.

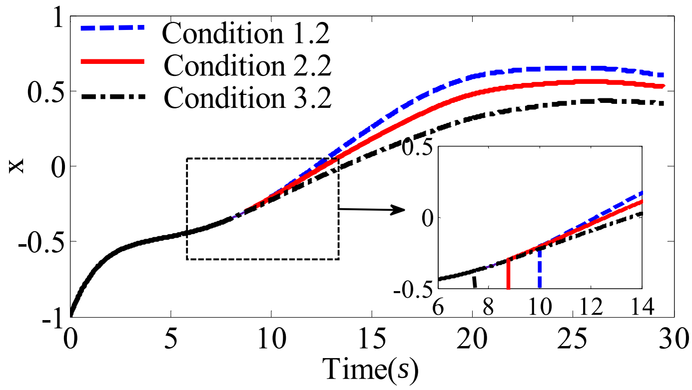
The main parameters of the guide vane opening law are shown in Table. 1. The opening law of the Fig. 4 is divided into nine Conditions (see Table. 1): Condition 1.1-1.3, Condition 2.1-2.3 and Condition 3.1-3.3.

Table. 1 Guide vane opening law for start-up process.

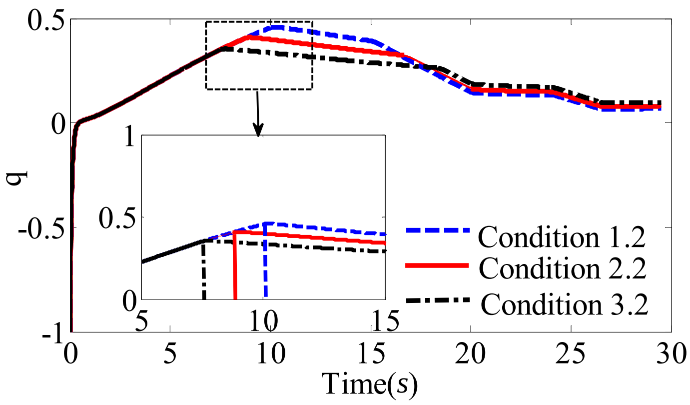
Condition	First guide vane opening (p.u.)	Second guide vane opening (p.u.)	First guide vane opening time (s)	Hold time for first opening (s)	Hold time for second opening (s)	Total time (s)
1.1	0.4	0.25	10	5	6	29.5
1.2	0.4	0.25	10	5	4	29.5
1.3	0.4	0.25	10	5	2	29.5

2.1	0.35	0.25	8.75	7.92	6	29.5
2.2	0.35	0.25	8.75	7.92	4	29.5
2.3	0.35	0.25	8.75	7.92	2	29.5
3.1	0.3	0.25	7.5	10.83	6	29.5
3.2	0.3	0.25	7.5	10.83	4	29.5
3.3	0.3	0.25	7.5	10.83	2	29.5

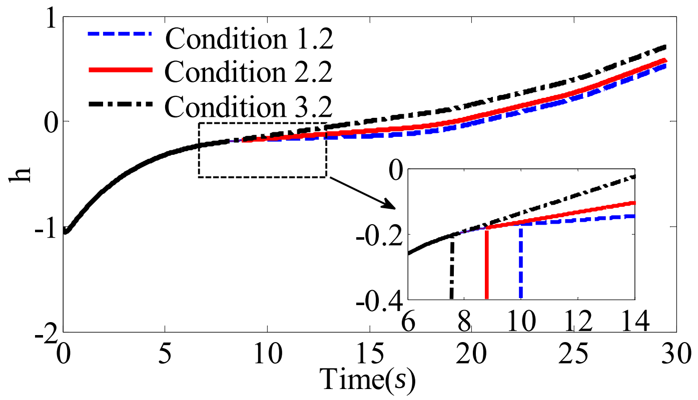
The following simulations are carried out with the opening law of Table. 1. In order to research the effect of the first guide vane opening on the transient characteristics of the hydro-turbine governing system, conditions 1.2, 2.2 and 3.2 are chosen and the dynamic characteristics of the hydro-turbine governing system in the start-up process are shown in Fig. 5.



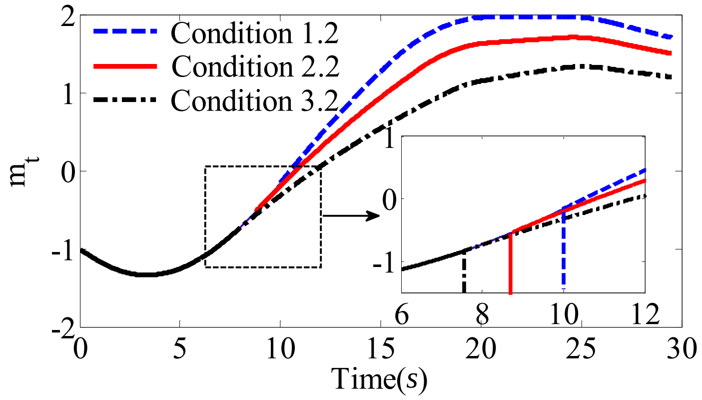
(a) Transient characteristics of the rotational speed in the start-up process



(b) Transient characteristics of the flow in the start-up process



(c) Transient characteristics of the water head in the start-up process



(d) Transient characteristics of the turbine torque in the start-up process

Fig. 5. The transient characteristics of the hydro-turbine governing system in the start-up process under conditions 1.2, 2.2 and 3.2.

The transient characteristics of the hydro-turbine governing system in the start-up process under conditions 1.2, 2.2 and 3.2 are shown in Fig. 5. For conditions 1.2, 2.2 and 3.2, the first guide vane openings are 0.4, 0.35 and 0.3, respectively. The opening speed of the guide vanes is the same before reaching the first guide vane opening and the reaching times are 10s, 8.75s and 7.5s, respectively. For the second guide vane opening, conditions 1.2, 2.2 and 3.2 have the same changing rule.

From Fig. 5(a), the fluctuation rules of rotational speed are the same for conditions 1.2, 2.2 and 3.2 before 7.5s. Then, the rising speed of the rotational speed for condition 3.2 becomes slow because the guide vane stops opening at 7.5s. Correspondingly, the rising speeds of the rotational speed for condition 1.2 and 2.2 slow down with the stop of guide vane at 10s and 8.75s, respectively. The changing rules of the rotational speed have the similar trend after 20s because of the same changing law of the guide vane. The maximum rotational speeds of conditions 1.2, 2.2 and 3.2 are 0.65, 0.56 and 0.43, respectively. The results indicate that the maximum rotational speed decreases with the first guide vane opening decreasing and the earlier stop of the guide vane at first opening is able to improve the transient characteristics of the rotational speed.

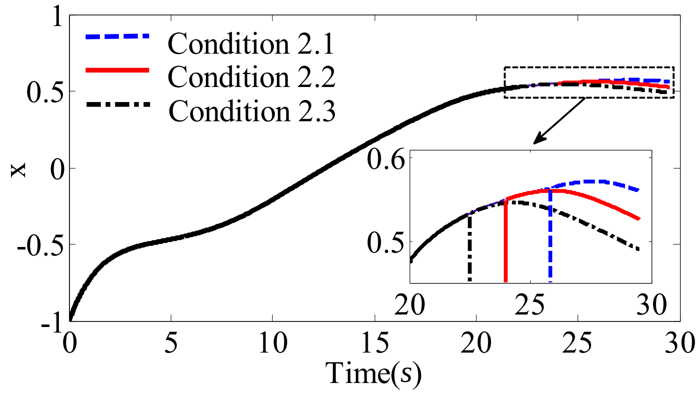
As shown in Fig. 5(b), the flows of the conditions increase dramatically with the guide vane opening from 0s to 7.5s. Interestingly, the flow shows a downward trend when the guide vane stops opening. The figures for the three conditions have the similar trend after 15s. Note that the flows intersect at about 17s and then the figure for condition 1.2 decreases from the biggest to the smallest among the three conditions. The figure for condition 3.2 is consistently higher than the others after 17s. The flow of condition 1.2 which has the biggest first guide vane opening reaches its peak (0.46) at about 10.4s. Conditions 2.2 and 3.2 reach their highest points (0.41 and 0.35) at 9.1s and 7.8s. The results indicate that the maximum value of the flow increases with the first guide vane opening increasing. More importantly, the peak times of the three conditions are later than the corresponding stopping time of the guide vane, which means that the transient model of the hydro-turbine governing system is able to reflect the flow inertia in the start-up process.

The water head of the conditions show an upward trend during the process (see Fig. 5c). The figure for condition 1.2 is consistently lower than the others after 10s, while there is a dramatic increase in the water head of condition 3.2. The gap between conditions 1.2 and 2.2 is smaller than the one between conditions 3.2 and 2.2. The results show that the water head experiences a sharp increase in the start-up process. The earlier stopping time of the guide vane leads to the higher water head, which is bad for the hydro-turbine governing system.

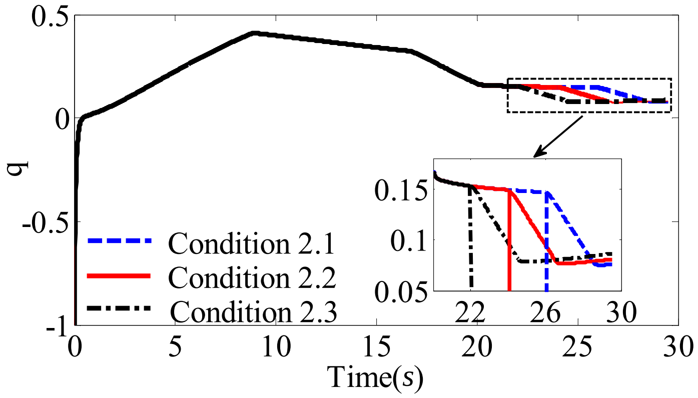
From Fig. 5(d), the turbine torque shows a downward trend initially and then increases dramatically from 5s to 20s. The figure for condition 1.2 remains stable at 2 form 20s to 25s, while that for conditions 2.2 and 3.2 increases slightly. The figures for conditions 1.2, 2.2 and 3.2 reach their highest point (1.97, 1.71 and 1.33) at 25s, respectively. The results indicate that the stopping of the guide vane can reduce the growth rate of the turbine torque effectively and the maximum turbine torque increases with the first guide vane opening.

The results of the Fig. 5 indicate that the smaller first guide vane opening is able to improve the transient characteristics of the rotational speed, flow and turbine torque, while it has opposite effect on the water head. On the other hand, if the stopping time of the first guide vane opening happens earlier, the transient performances of the rotational speed, flow and turbine torque can be optimized while it is bad for the water head.

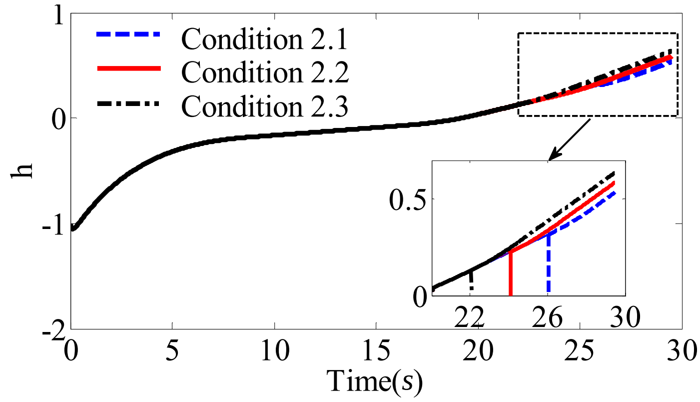
To research the influence of the second holding time of the guide vane in the start-up process, conditions 2.1, 2.2 and 2.3 are selected and the simulation is shown in Fig. 6.



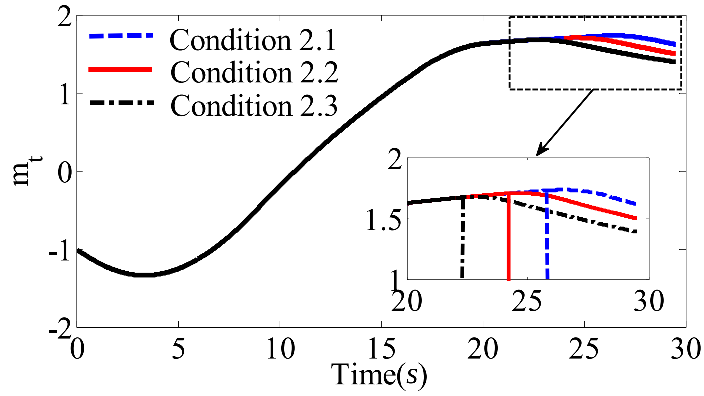
(a) Transient characteristics of the rotational speed in the start-up process



(b) Transient characteristics of the flow in the start-up process



(c) Transient characteristics of the flow in the start-up process



(d) Transient characteristics of the turbine torque in the start-up process

Fig. 6. The transient characteristics of the hydro-turbine governing system in the start-up process under conditions 2.1, 2.2 and 2.3.

The transient characteristics of the hydro-turbine governing system in the start-up process under conditions 2.1, 2.2 and 2.3 are shown in Fig. 6. For conditions 2.1, 2.2 and 2.3, the first guide vane opening is 0.35. For the first guide vane opening, conditions 2.1, 2.2 and 2.3 have the same changing rule. The second holding times of the guide vane are 6s, 4s and 2s, respectively.

From Fig. 6(a), the changing trends of the rotational speed are the same for conditions 2.1, 2.2 and 2.3 before 22s. The rotational speed increases with the second holding time of the guide vane and the maximums rotational speed of conditions 2.1, 2.2 and 2.3 are 0.57, 0.56 and 0.55, respectively. Then, the rotational speeds of the conditions gradually decrease with the guide vane closing. The results indicate that the maximum rotational speed increases with the second holding time of the guide vane and a shorter holding time is able to improve the transient characteristics of the rotational speed.

As shown in Fig. 6(b), the flow experiences dramatic fluctuations from 0s to 22s.

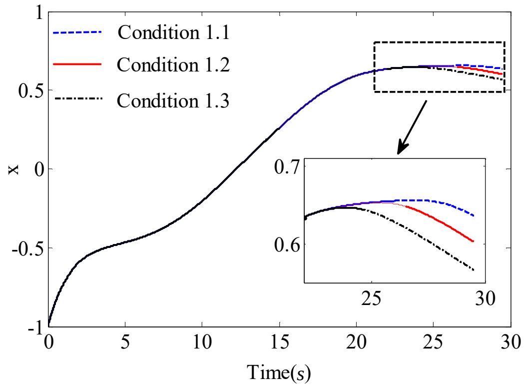
The stopping time of the first guide vane opening for the three conditions is 8.75s, while the flow reaches its peak (0.41) at 9.1s.This indicates that the transient model of the hydro-turbine governing system is able to describe the inertial fluctuations of the flow in the start-up process. Then, the flow decreases gradually with the second holding time of the guide vane and the earlier ending of the second guide vane opening can increase the stability of the flow.

From Fig. 6(c), the water head increase gradually in the start-up process. The differences of the water head are shown after 22s. Then, the water head for condition 2.3 is consistently higher than that for conditions 2.1 and 2.2. The water head increase slowly during the holding time and the rising rate increases rapidly when the second holding time is over. The results reveal that the second holding time enables to slow the growth of the water head in the start-up process.

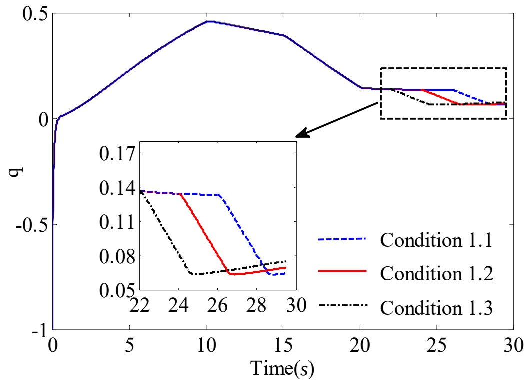
Fig. 6(d) shows the transient characteristics of the turbine torque in the start-up process. The figures for the conditions experience a slight decrease firstly and increase dramatically from 5s to 22s. Then, with different second holding times of the guide vane, the figures for conditions 2.1, 2.2 and 2.3 reach their peak (1.74, 1.71 and 1.67) at 22s, 24s and 26s, respectively. The results indicate that the turbine torque increases gradually with the second holding time of the guide vane and the earlier ending of the second guide vane opening is able to improve the transient performance of the turbine torque.

The results of the Fig. 6 indicate that the shorter second holding time of the guide vane is able to improve the transient characteristics of the rotational speed, flow and turbine torque, while it has opposite effect on the water head.

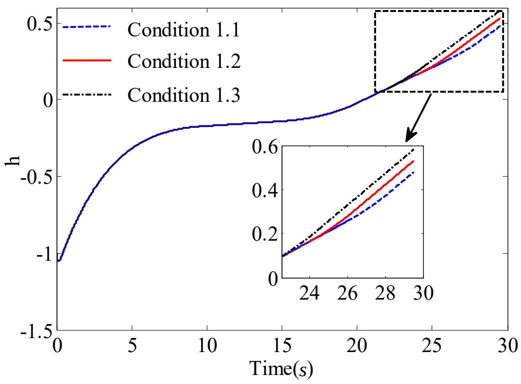
As shown in Figs. 5 and 6, the effects of the first opening and second holding time of the guide vane in start-up process are investigated. To further verify the above conclusions and optimize the opening law of the guide vane, the simulations of condition 1.1-1.3 and 3.1-3.3 are presented in Figs. 7 and 8.



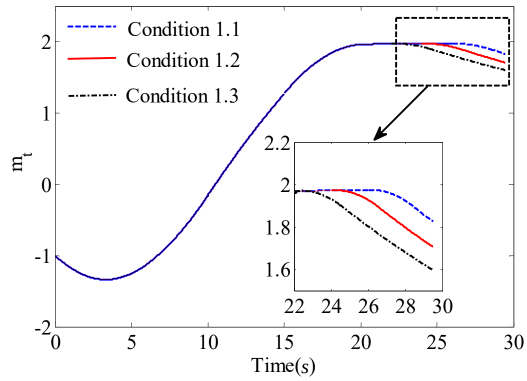
(a) Time waveforms of the rotational speed



(b) Time waveforms of the flow



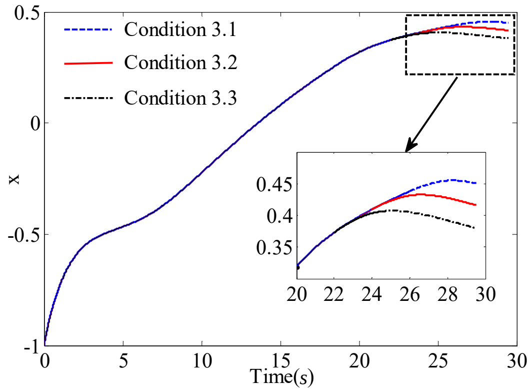
(c) Time waveforms of the water head

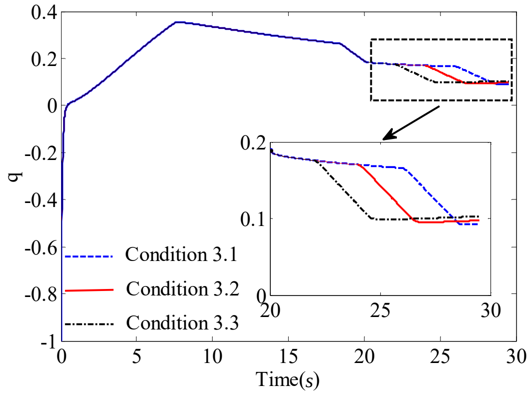


(d) Time waveforms of the turbine torque

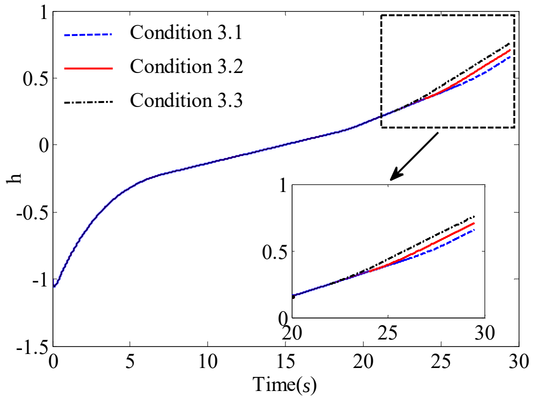
Fig. 7. The transient characteristics of the hydro-turbine governing system in the start-up process under conditions 1.1, 1.2 and 1.3.

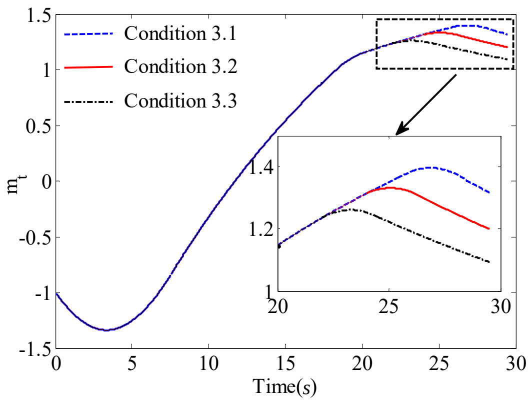
The effect of the second holding time of guide vane in the start-up process is investigated in Fig. 7. The results indicate that the transient characteristics of the rotational speed, flow and turbine torque can be improved with the decrease of the second holding time of the guide vane, while it has opposite effect on the water head.





(a) Time waveforms of the rotational speed (b) Time waveforms of the flow





(c) Time waveforms of the water head (d) Time waveforms of the turbine torque

Fig. 8. The transient characteristics of the hydro-turbine governing system in the start-up process under conditions 3.1, 3.2 and 3.3.

As shown in Fig. 8, the effect of the second holding time of guide vane in start-up process is studied. The results also reveal that the shorter second holding time of the guide vane is able to improve the transient characteristics of the rotational speed, flow and turbine torque, while it has opposite effect on the water head.

To optimize the opening law of the guide vane in the start-up process, the transient characteristics of the hydro-turbine governing system are summarized in Table.2.

Table. 2 Transient characteristics of the hydro-turbine governing system in the start-up process.

Condition	Maximum rotational speed (p.u.)	Maximum flow (p.u.)	Maximum water head (p.u.)	Maximum turbine torque (p.u.)
1.1	0.66	0.46	0.48	1.98
1.2	0.65	0.46	0.53	1.97
1.3	0.64	0.46	0.58	1.97
2.1	0.57	0.41	0.53	1.74
2.2	0.56	0.41	0.58	1.71
2.3	0.55	0.41	0.64	1.67
3.1	0.46	0.35	0.66	1.40
3.2	0.43	0.35	0.71	1.33
3.3	0.41	0.35	0.76	1.26

From Table.2, compared with the figures for conditions 1.1-1.3 and 2.1-2.3, the figures for conditions 3.1-3.3 are smaller expect the maximum water head. The results are summarized as follows.

For the two-stage opening law of the guide vane in the start-up process, the decrease of the first guide vane opening can reduce the maximum rotational speed, flow and turbine torque of the hydro-turbine governing system, while it increases the maximum water head. Furthermore, lengthening the second holding time of the guide vane is able to reduce the maximum water head.

4. Conclusions

This research develops a new method in order to establish the transient model of the hydro-turbine governing system in the start-up process. The proposed surface-cluster method makes it possible to achieve the precise transient model that could be used to study the transient characteristics of the system with different opening laws of the guide vane in the start-up process. For the two-stage opening law of the guide vane in start-up process, the simulation analyses reveal that the increase of the first guide vane opening can increase the maximum rotational speed, flow and turbine torque of the hydro-turbine governing system, while it reduces the maximum water head. Furthermore, lengthening the second holding time of the guide vane is able to reduce the maximum water head.

It is worthy to highlight that the surface-cluster method presented for this study could be of use for transient modeling of hydro-turbine governing system in transient processes, that allows to investigate the open-close laws of the guide vane in transient process and improve the transient characteristics of the system.

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