PAPER • OPEN ACCESS

Simulation study on the oscillation characteristics of pipeline pressure under the guide vane disturbance

To cite this article: Y Zeng et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 163 012113

View the article online for updates and enhancements.

You may also like

 Application of pipeline leakage detection based on distributed optical fiber acoustic sensor system and convolutional neural <u>network</u>
 Yuxing Duan, Lei Liang, Xiaoling Tong et

Yuxing Duan, Lei Liang, Xiaoling Tong et al.

- <u>The Mechanical Effect of Pit Excavation</u> with Protection on Adjacent Pipelines Hao Wen, Kaihong Li, Yanjie Jia et al.
- <u>An ultrasonic in-line inspection data</u> processing method considering invalid <u>data caused by sensor failure</u> Zhenning Wu, Hanyang Huang, Runjiang Zhang et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 18.190.156.212 on 21/05/2024 at 15:26

Simulation study on the oscillation characteristics of pipeline pressure under the guide vane disturbance

Y Zeng¹, S G Yu², J Qian³, Y K Guo⁴ and Y L Wang¹

¹ Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, China.

² Department of Engineering Mechanics, Kunming University of Science and Technology, Kunming 650500, China.

³ College of Electric Power Engineering, Kunming University of Science and Technology, Kunming 650500, China.

⁴ School of Engineering, University of Bradford, Bradford, BD7 1DP, UK.

zengyun001@163.com.

Abstract: the oscillation characteristics of pipeline pressure is an important factor affecting the operation stability of hydro turbine generating sets (HTGS), and is also the basis of the optimal control design of the HTGS. A nonlinear simulation model is established based on the Simulink, which is suitable to research the oscillation characteristics of pipeline pressure. The simulation model is verified by using the classic pipeline method of characteristic line (MOC). Simulating the guide blade disturbance signal by the Simulink module, the oscillation characteristics of pipeline pressure is simulated under different disturbance frequencies. The simulation results show that the natural period of the pipeline pressure oscillation and the guide vane disturbance is opposite. Under a certain frequency of guide vane, the guide vane disturbance can significantly reduce the oscillation amplitude of pipeline pressure. The simulation method proposed in this paper is simple and practical, and the obtained the oscillation characteristics of pipeline pressure provide a useful reference for the control design of governor.

1. Introductions

The pressure oscillation of pipeline in hydropower plant affects directly the pressure head of the hydro turbine inlet, and causes the oscillation of hydro turbine torque. Many studies have shown that hydraulic characteristics have a direct impact on the stability of itself and the power system ^[1-4]. Studying and utilizing oscillation characteristics of pipeline pressure to improve the operation stability of the hydro turbine generating sets (HTGS) is continuous ^[5-7].

The most classical method, computing the pressure oscillation of the hydraulic system, is the method of characteristic line (MOC). However, the influence of the hydraulic transient on the HTGS is only reflected by the changes of head and flow in the hydro turbine inlet. In the hydraulic transient related study, rarely use the MOC due to its large amount of calculation and poor real-time performance. Although the three-dimensional computation of the hydraulic transient based on the CFD method has had some of application ^[8, 9], the application of more is the transfer function model describing dynamic characteristics of the pipeline port where deals with the control issue and transient

Asian Working Group- IAHR's Symposium on Hydraulic Machinery and	Systems	IOP Publishing
IOP Conf. Series: Earth and Environmental Science 163 (2018) 012113	doi:10.1088/1755-131	5/163/1/012113

process ^[10-13]. The transfer function is inconvenient when applied to control design and nonlinear analysis. Therefore, many models of the hydro turbine including the hydraulic dynamic have been developed, including nonlinear differential equation model ^[14-16], identifying model ^[17-19], and other forms. The water pressure oscillation in the HTGS is caused by the guide vane movement. Therefore, the most direct way to study the oscillation characteristics of the pipeline is through the given guide vane disturbance. Obviously, these nonlinear models are applied to this study with limitations.

Using the transfer function model and setting its initial value system, the nonlinear simulation model is established based on the Simulink tool. It can be used to research the pressure oscillation of the pipeline due to set the simulation module of guide vane disturbance. The research method proposed in this paper is convenient and has certain universality.

2. Problem description

According to the control structure of the HTGS, the pressure oscillation of hydraulic system is mainly influenced by the movement of guide vane. The motion of the guide vane is controlled by the control unit of the governor. The control structure of the HTGS and its signal flow is shown in figure 1.



Figure1. Control channel from guide vane to hydraulic pressure oscillation

In figure.1, ΔY_{PID} is the output signal of the control unit of governor, Δy is the increment of guide vane opening in relative value, Δh and Δq are the head and flow of hydro turbine inlet in relative value respectively, T_y is the time constant of the electro-hydraulic servo system.

Given the figure 1, the purpose includes two aspects, (i) emphasize the relationship between the hydraulic oscillation and the guide vane, which is the open loop control in some extent; (ii) proposed method in this paper also adapts to the open loop control of the gate closing law and hydraulic fluctuation of pipeline.

When the guide vane is regulated due to the power change of the HTGS, the water hammer wave travels from the guide blade to the upstream, then returns, its oscillation period is $2L/\alpha$. The L is the length of the pipeline, the α is the wave speed of water hammer. The oscillation of water hammer causes the pressure fluctuation in the inlet of the turbine, which is finally reflected as the fluctuation of the input power of hydro turbine. For the specific hydropower station, the pipeline layout is unchanged, so the basic characteristic of the hydraulic pressure fluctuation of pipeline is that the pressure fluctuation period is constant.

3. System modelling

Considering the hydraulic system with single penstock and single machine, the transfer function given by Ref.[10] is following.

$$G_{\rm D}(s) = \frac{\Delta h_q}{\Delta q} = Z_{\rm n} \frac{sT_{\rm e} \prod_{n=1}^{n=\infty} \left[1 + \left[sT_{\rm e} / (n\pi) \right]^2 \right]}{\prod_{n=1}^{n=\infty} \left[1 + \left\{ 2sT_{\rm e} / \left[(2n-1)\pi \right] \right\}^2 \right]}$$
(1)

where Δq is the flow increment in per unit, Δh_q is the head increment generated by change of pipeline flow in per unit, T_e is the elastic time, is defined as $T_e=L/\alpha$. The Z_n is the surge impedance in per unit, it is defined as

$$Z_{\rm n} = \frac{\alpha}{Aa_{\rm g}} \frac{Q_{\rm r}}{H_{\rm r}}$$
(2)

where a_g is the acceleration due to gravity in m/s², A is the cross sectional area of pipeline in m². Let n=2, accurate model with elastic hammer can be obtained from equation (1) as following.

$$G_{\rm D}(s) = Z_{\rm n} \frac{sT_{\rm e}(\pi^2 + s^2 T_{\rm e}^2)(\pi^2 + s^2 T_{\rm e}^2/4)}{(\pi^2 + 4s^2 T_{\rm e}^2)(\pi^2 + 4s^2 T_{\rm e}^2/9)}$$
(3)

The direct variable of the guide vane governed is the flow. It is necessary to establish the transmission relation between the guide blade movement and the flow change, so as to establish the signal transmission channel of the guide vane - flow - water pressure.

According to orifice flow principle $Q = KY\sqrt{H}$, the flow of hydro turbine can be written as following

$$\Delta Q = \frac{\partial Q}{\partial Y} \Delta Y + \frac{\partial Q}{\partial H} \Delta H = K \sqrt{H} \Delta Y + \frac{1}{2} KYH^{-0.5} \Delta H$$
(4)

Using the expression $Q_r = KY_r \sqrt{H_r}$ at rated operation point, following expressions can be obtained.

$$\Delta q = \sqrt{h} \Delta y + \frac{1}{2} y h^{-0.5} \Delta h \tag{5}$$

$$q = y\sqrt{h} \tag{6}$$

where *K* is the coefficient of orifice flow, *Q*, *H* and *Y* are the flow in m³/s, head in m and the guide vane opening in cm respectively; *Q*_r, *H*_r and *Y*_r are the rated values, *q*, *h* and *y* are the relative value in per unit; $h=h_0+\Delta h$, $y=y_0+\Delta y$, $q=q_0+\Delta q$. Δh , Δq and Δy are the increment in per unit; h_0 , q_0 and y_0 are the initial value at steady in per unit.

The transient head of hydro turbine is

$$h = h_s - f_p q^2 - \Delta h_q \tag{7}$$

where h_s is the static head of hydro turbine in per unit, f_p is the loss coefficient of pipeline, f_pq^2 loss head of pipeline in per unit.

From Ref.[16], the loss coefficient of pipeline is

$$f_p = L \frac{0.014^2}{(0.25D)^{4/3}} \left(\frac{4Q_r}{\pi D^2}\right)^2 \frac{1}{H_r}$$
(8)

where constant 0.014 is the manning roughness coefficient of steel pipe. The equation (1) can be written as $\Delta h_q = G_D(s)\Delta q$, so the equation (6) can be rewritten as. Asian Working Group- IAHR's Symposium on Hydraulic Machinery and Systems IOP Publishing IOP Conf. Series: Earth and Environmental Science **163** (2018) 012113 doi:10.1088/1755-1315/163/1/012113

$$\Delta h = -\frac{2hG_{\rm D}(s)}{2\sqrt{h} + yG_{\rm D}(s)}\Delta y \tag{9}$$

From view of form of the equation (9), the transfer function from Δy to Δh is established in form. However, due to implicit expression $h=h_0+\Delta h$ and $y=y_0+\Delta y$, the transitive relation from guide vane to the head of hydro turbine is an implicit nonlinear. The analytical expression is hard to derive from the equation (9). So, it is appropriate that use the simulation method to study the equation (9).

4. Simulation method

The nonlinear simulation module is established by using the Simulink as the figure 2.

• Simulink simulation can only calculate the transfer function that the numerator order is less than the denominator order. However, the transfer function of hydraulic system is improper fraction, it needs to be decomposed. For example, n=2, the transfer function equation (3) needs to be decomposed into:

$$G_{\rm D}(s) = K_{\rm GD}s + \frac{B_1 s + B_3 s^3}{A_0 + A_2 s^2 + A_4 s^4}$$
(10)

where $A_4 = 16T_e^4$, $A_2 = 40T_e^2\pi^2$, $A_0 = 9\pi^4$, $B_3 = (9/64)*40Z_nT_e^3\pi^2$, $B_1 = (9/64)*55Z_nT_e\pi^4$, $K_{GD} = (9/64)*Z_nT_e$. The equation (10) can be realized by two parallel modules.



Figure 2. Simulation framework of nonlinear model

- The transfer function is a kind of linearized model with increment, it needs to set initial value system when it is used to describe the nonlinear characteristics. In Fig.2, the initial value module is y₀, q₀ and h₀, and y=y₀+Δy, q=q₀+Δq and h=h_s-h_f-Δh_q.
- In equation (7), the head of hydro turbine at steady-state is h₀=h_s-f_pq², means that the head relates to the flow q. The steady state initial value of hydro turbine head is different under different operation point. For example, if the new steady state condition is q₀'=q₀+Δq, then the head is h₀'=h_s-f_p(q')². In nonlinear simulation, if the friction loss of pipeline is ignored, the h₀ is simply treated as a constant, which can make the simulation result unstable.
- According to the actual operation condition, oscillation of the guide vane will be induced under there cases, line fault, the low frequency oscillation of the power grid, and the larger diversion system and larger the water flow inertia time constant. The causes of the three conditions are different, but the pressure oscillation of the pipeline is directly related to the oscillation of active power of the HTGS. Therefore, the disturbance signal of the guide vane is given as follows:

$$\Delta u = A e^{-rt} \sin(\omega t + \varphi) \tag{11}$$

where A is the amplitude, r is the damping factor, ω is the angular frequency of the oscillation signal in rad/s, φ_1 is the initial phase angle in rad.

This type of signal can be used to simulate most of the signal types in the general controller output. A ramp signal is placed in the Fig.2 to be used to simulate the straight line close law of the guide vane.

After the above treatment, the simulation system shown in Fig.2 can achieve nonlinear simulation.

5. Simulation experiment

In order to facilitate the study, the water diversion system of a power station is simplified as a single penstock and single machine system based on the principle of the kinetic energy of the water, that is, $\Sigma L_i V_i$ keeps invariant. The main parameters, *L*=600m, *D*=3.1m, *Q*_r=53.5m³/s, *H*_r=312m, α =1000m/s, T_v =0.5s, Z_n =2.3159, T_e =0.6.

5.1. Model verification

Assuming that the HTGS runs at rated conditions, the initial operating point: y=1, h=1, and q=1. The HTGS generates load rejection, and the guide blade close in a straight line law, closing speed is 0.1 y_r /s. Assume that the guide vane close to the 8s in this speed, the opening is going to the 0.2 y_r , then remains unchanged. The purpose of using the closing law is to check the change of water pressure in the fast closing time, and to check the periodic oscillation of the pipeline pressure after the disturbance. This combination condition can better reflect the change of pipeline transient, and better verify the accuracy of the model algorithm.

In the MOC, assuming the upstream side is the reservoir without water level fluctuation, pipeline is simple long penstock, L=600 m, subsection length Δx =5 m, divided into 120 pieces. Close law of the guide vane is converted into the opening value of each calculating time. The impact of pipeline slope is ignored.

The friction loss coefficient of pipeline should be consistent with the coefficient given by the equation (8) used in Simulink. According to the concept of the head loss along the path, the hydraulic loss coefficient in the calculation of the MOC is following.

$$f = h_f H_r \frac{D}{L} \frac{2g}{V^2} \frac{\Delta x}{N}$$
(12)

where N is the numbers of subsection, Δx is the length of subsection, V is the velocity.

In the simulation calculation, the pressure of hydro turbine inlet is approximately equal to the head of hydro turbine while the effect of draft tube is ignored. Under the above simulation conditions, the pressure variation of the inlet section of the turbine by the Simulink and the MOC are shown in figure 3.



Figure 3. Head change in transient under two method

The hydraulic transient calculated by two methods is coincident. Because the MOC is classical method and is receivable, so the simulation model established in this paper is valid, and has enough computational accuracy.

In figure 3, the oscillation of pressure is the typical periodic damping motion when the guide vane stops motion. According to simulation computation, the oscillation period is 2.3953 s, which is called as the natural period of pressure oscillation. The natural period is four times of the elastic time T_e , $T_e=0.6s$. The round trip time of the pressure wave in pipeline is $2T_e$, which is usually regarded as the oscillation period of pipeline pressure. In order to verify this problem, given different length of pipeline and wave velocity of water hammer, simulation results all show that the natural period of pressure oscillation is $4T_e$. This phenomenon is worthy of concern.

5.2. Effect of guide vane oscillation on water pressure

Selected the oscillation period of guide vane is the natural period of water pipeline, that is $T_{wo}=4.0T_e$. In equation (2), let $\omega=2\pi/T_{wo}$, A=0.1, r=0.2, and $\varphi=0$. Initial operating point, $q_0=0.8$, $y_0=0.8$, $h_0=1.006$. Using the Simulink model given by the figure 2 to simulate, oscillation of the guide vane and water pressure are shown as figure 4. The figure (a), the initial phase angle is $\varphi=0$. In figure (b), the dashed line is $\varphi=\pi/3$, while solid line is $\varphi=\pi$.



Figure 4. Head change with guide vane opening

The figure 4 shows that the phase of water pressure oscillation and guide vane oscillation is opposite, and their error of the phase angle is 180° . Obviously, the phase of water pressure oscillation lag 180° , and this phenomenon is not fluctuates according to guide vane of the initial phase.

Further, selected different oscillation period of guide vane T_{wo} , let A=0.1, r=0.2, and $\varphi=0$, oscillation of the guide vane and water pressure are shown as the figure 5.



Figure 5. Head oscillation under different period of T_{wo}

In figure 5, solid line is the head of hydro turbine, while the dashed line is the guide vane opening. Coordinate of subgraph is same as one of the figure 3.

Some of results can be obtained as following.

- Under same oscillation of the guide vane, the oscillation frequency of the water pressure or head of hydro turbine oscillation and the guide vane is the same, their phase is opposite, and the characteristics is invariant at different oscillation period of the guide vane.
- The fluctuation period of the guide vane has a great influence on the oscillation amplitude of the water pressure. In the frequency of certain fluctuations, the water pressure fluctuation amplitude is small and damping is fast, which is the case of $T_{wo}=1.0T_e$ and $T_{wo}=2.0T_e$ in figure 5.
- The longer the fluctuation period of the guide blade, i.e. the slower the fluctuation, is favorable for reducing the fluctuation amplitude of the pipe water pressure, as shown in figure 5 T_{wo} =9.0 T_{e} and T_{wo} =11.0 T_{e} .

6. Conclusions

This paper uses the Simulink to establish the nonlinear simulation model of pipeline hydraulic pressure fluctuation, and researches the oscillation characteristics of pipeline pressure given different fluctuation law of guide vane. It provides a simple method of hydraulic characteristics study for turbine control strategy design and stability analysis of the HTGS. The following conclusions are given in this paper:

- After the initial value system is configured, the model established by the Simulink can be used to simulate the nonlinear hydraulic dynamic of the pipeline, and it has high numerical accuracy. Simplified the numerical calculation of the hydraulic dynamic of the pipe, the application is convenient.
- The pipeline pressure fluctuations follow-up to guide vane, their oscillation frequency are the same, the phase of the wave pressure fluctuation lag 180°. If the guide vane has variable frequency in transient, using the superposition characteristic of the water pressure travel phase to weaken the oscillation amplitude of pressure maybe an effective strategy. This problem remains to be further studied
- Research methods proposed in this paper are also applicable to the study of hydraulic transient characteristics of long water pipes and dynamic problem of other pipelines.

Acknowledgments

The research reported here is financially supported by the National Natural Science Foundation of China under Grant No. 51579124, 51469011.

References

- [1] Wei Z N, Chen J G, Pan X P, Ju P and Han J D 2000 Automat. Electr. Power Syst. 24 26.
- [2] Nicolet C, Greiveldinger B, Hérou J J, Kawkabani B, Allenbach P, Simond J J and Avellan F 2007 *IEEE T. Power Syst.* **22** 1870.
- [3] Sammartano V, Filianoti F, Sinagra M and Morreal G 2016 J. Hydraul. Eng. 143 04016071.
- [4] Pico H N V, Aliprantis D C, Mccallet J D, Elia N and Castrillon N J 2015 IEEE T. Power Syst. 30 632.
- [5] Zhou J X and Suo L S 2007 Adv. Sci. Tech. Water Resour. 27 86.
- [6] Cheng Y C, Sun Y H, Ye L Q and De-Hong X U 2008 Power Syst. Tech. 32 52.
- [7] Qian J, Zeng Y, Yu S G and Ye J 2017 J.Drain. Irrig. Mach. Eng. 35 674.
- [8] Wang C, Nilsson H, Yang J D and Petit O 2017 Comput. Phys. Commun. 210 1.
- [9] Wu D Z, Yang S, Wu P and Wang L Q 2015 J. Hydraul. Eng. 141 06015003.
- [10] Kundur 1994 Power System Stability and Control (New York: McGraw-Hill) pp 515-526.
- [11] Oldenburger R and Donelson J 1962 Power Apparatus Syst. 81 403.
- [12] Vournas C D and Zaharakis A 1993 IEEE T. Energy Conver. 8 527.
- [13] Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies 1992 *IEEE T. Power Syst.* **7** 167.
- [14] Zeng Y, Zhang L X, Qian J and Xu T M 2014 J.Drain. Irrig. Mach. Eng. 32 691.
- [15] Zhou K X, Zhang L X and Zeng Y 2105 Shuili Xuebao 46 1118.
- [16] Zeng Y, Guo Y K, Zhang L X, Xue T M and Dong H K 2103 Math. Comp. Model. Dyn. 19 12.
- [17] Trudnowski D J and Agee J C 1995 *IEEE T. Energy Conver.* **10** 768.
- [18] Liu Y J, Fang Y J and Zhu X M 2010 J. Zhejiang Univ. Sci. C 11 56.
- [19] Li C S, Zhou J Z, Xiao J and Xiao H 2013 Eng. Appl. Artif. Intel. 26 2073.