

Simulation of Transient Flow in Hydroelectric Power Plants Using Unsteady Friction

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In this paper the influence of surge tanks on transient flow generated by changing turbine gate opening has been numerically studied. For this purpose, the governing equations of transient flow are solved using the method of characteristics and considering unsteady friction. The surge tank and the hydraulic turbine are considered as internal boundary conditions. Comparison of transient results for pressure oscillations with the available experimental data shows good agreement. The surge tanks lower down the pressure levels at the upstream side of turbine and stabilize the pressure at the downstream side. Also, surge tanks delay the time occurrence of the maximum and minimum pressure. Finally, the effect of wicket gate closing followed by wicket gate opening on the so called speed no load operation (SNLO) on the transient flow is investigated and transient conditions improved by this sequence are found.

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Key words: hydraulic turbine, hyperbolic PDE, surge tank, transient flow, unsteady friction

0 INTRODUCTION

Unsteady flow analysis in water power stations is one of the most significant issues in the prediction of undesirable pressure variations in waterways as well as probable changes in rotor speed for the power plants safe operation.

Hydraulic transient in a hydroelectric power plant is usually caused by various turbine operations such as start up, load acceptance and load rejection. Changing conditions in the power market have led to an increase in the demand of peak energy generation, short response time and fast frequency changes. Consequently, there is a need for accurate simulation of transient flow in hydroelectric power plants.

Traditionally, transient flow in a water power station is simulated using well-known water hammer equations and considering the steady state skin friction. However, it was found that the use of steady friction approximation does not produce sufficient damping comparison to the measured data [1] to [3]. Therefore, unsteady friction models must be adopted to account for this damping deficit.

Surge tanks are installed at the upstream or downstream sides of hydropower plant waterways. These are of the main components that equilibrate pressures and thus need a careful optimization. The main hydraulic requirements to be met by the designers of surge tanks include

damping of the water hammer effect as well as accelerating and decelerating tunnel flows, improving the response capabilities of the mechanical equipment and sometimes used as a gate shaft at the same time.

Wicket gate opening at speed no load operation (SNLO) is the wicket gate opening at which unit (turbine and generator) rotate at synchronous speed with zero output. At SNLO, the turbine output is equal to the turbo generator windage and friction losses at synchronous speed. When the load rejection phenomenon occurs in a hydropower plant, wicket gates are completely closed and in some conditions the wicket gates are reopened from complete closing to SNLO opening under the governor control. In this new situation the unit operates in the standby mode. In the present paper, this type of transient is called a wicket gate closing followed by an opening to SNLO.

The main objectives of this paper are to simulate the transient flow in hydroelectric power stations using the method of characteristics and unsteady friction model and to investigate the effects of the surge tank and wicket gate closing followed by an opening to SNLO on transient conditions.

To fulfill these aims, the governing equations including continuity and momentum equations are numerically solved along the water ways. The upstream and downstream reservoirs

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are considered as constant head boundary conditions. Also, surge tank and Francis hydraulic turbine in waterway are considered as internal boundary conditions. To verify the numerical method, the pressure oscillations at upstream and downstream of the turbine formed by the load rejection are compared with the measured data of a real test case. Finally, the influence of surge tanks and wicket gate closing followed by an opening to SNLO on transient conditions has been investigated.

1 MATHEMATICAL MODEL AND NUMERICAL PROCEDURE

Unsteady closed conduit flow equations consist of one-dimensional, hyperbolic partial differential equations, in which the continuity and momentum equations are, [4] and [5]:

$$\begin{aligned} \frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} + \frac{a^2}{g} \frac{\partial V}{\partial x} &= 0 \\ \frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + g \frac{\partial H}{\partial x} + \frac{4}{\rho D} \tau_w &= 0 \end{aligned} \quad (1)$$

where $H(x,t)$ is piezometric head and $V(x,t)$ is average axial velocity.

The wall shear stress is the sum of the steady and unsteady wall shear stresses as

$$\tau_w = \tau_{ws} + \tau_{wu} \quad (2)$$

in which the steady state wall shear stress is defined as

$$\tau_{ws} = \frac{\rho f}{A^2} \frac{Q|Q|}{8} \quad (3)$$

where Q is flow rate; A is cross section area of the conduit and f is Darcy-Weisbach friction factor.

The above steady state friction formula (Darcy-Weisbach) fails to reproduce the pressure variation held beyond the first wave cycle [1] to [3]. To remedy this failure, the modified model of Brunone et al. [6] is implemented in the method of characteristics to solve the governing equations. Bergant et al. [7] and Pezzinga [8] found that the model of Brunone et al. [6] fails to correctly represent the unsteady friction for some transient event types and thus the model modifications are proposed. The modified model of Pezzinga [8] is expressed as:

$$\tau_{wu} = \frac{k\rho D}{4A} \left(\frac{\partial Q}{\partial t} + \text{sign}(Q) \frac{\partial Q}{\partial x} \right) a \frac{\partial Q}{\partial x} \quad (4)$$

where k is empirical coefficient and $\text{sign}(x)$ is sign function. The term $\text{sign}(Q \cdot \partial Q / \partial x)$ is added

to the original Brunone model by Pezzinga in order to make the model applicable for both upstream and downstream transient flows. For a power station with upstream and downstream waterways and also considerable length, this term is very important. This is because of the transient flow behaviour in upstream and downstream of the hydraulic turbine.

The method of characteristics (MOC) is a common method for solving the water hammer equation. The convective term in the continuity and momentum equations can be neglected due to a small Mach number ($V/a \ll 1$). With linear combination of water hammer equations, the following systems of compatibility equations for positive and negative characteristics lines are given [9]:

$$C^+ : \frac{dQ}{dt} + \frac{gA}{a} \frac{dH}{dt} + \frac{4A}{\rho D} \tau_w = 0 \quad (5a)$$

$$C^- : \frac{dQ}{dt} - \frac{gA}{a} \frac{dH}{dt} + \frac{4A}{\rho D} \tau_w = 0 \quad (5b)$$

With reference to the grid shown in Fig.1, the discretization of Eqs. (5a) and (5b) along the positive and negative characteristics gives:

$$\begin{aligned} (Q_i^{n+1} - Q_{i-1}^n) + C(H_i^{n+1} - H_{i-1}^n) + \\ \frac{4A\Delta t}{\rho D} \tau_w^n = 0 \end{aligned} \quad (6a)$$

$$\begin{aligned} (Q_i^{n+1} - Q_{i+1}^n) - C(H_i^{n+1} - H_{i+1}^n) + \\ \frac{4A\Delta t}{\rho D} \tau_w^n = 0 \end{aligned} \quad (6b)$$

where Δt is time step; C is gA/a ; superscript n is temporal location and subscript i is spatial location.

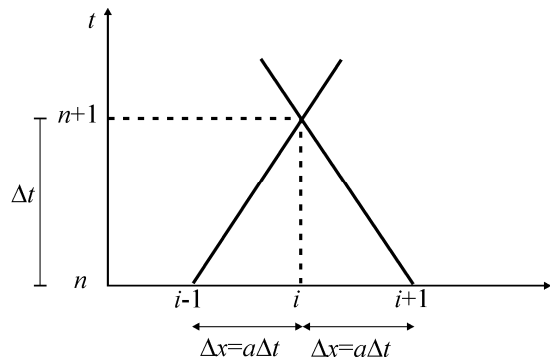


Fig.1. x - t plane showing characteristics for Eq. (6)

1.1 Boundary Conditions

Constant head boundary condition is applied for the upstream and the downstream reservoir. To simulate Francis hydraulic turbine as internal boundary condition, the relation between the net head and discharge has to be specified. Fluid flow through a Francis turbine depends upon various parameters such as net head, rotational speed of the unit and the wicket gate opening. Curves representing the relationship between these parameters are called turbine characteristics (Hill Chart). No data has been reported in the literature for turbine characteristics during transient conditions. Therefore, the steady state model test results (Hill Chart) are used to plot the experimental prototype turbine characteristics and these are assumed to be valid during the transient state as well. Also, very little data are available for small wicket gate openings and to cover the range, the characteristic curves are extrapolated.

Furthermore, the positive and negative characteristics equations are valid for upstream and downstream of the turbine. The mentioned equations with the aid of continuity equating for flow before and after the turbine are solved simultaneously for the hydraulic turbine as an internal boundary condition [4], [5] and [10]. In contrast to reaction turbines, the impulse type turbine dynamic equations and water hammer equations are solved separately [11].

Also, the surge tank is an internal boundary condition which is fully described in the next section.

2 SURGE TANK

One of the components to control the transients is the surge tank. This is an open chamber or a tank connected to the pipeline which reflects the pressure waves by supplying or storing excess liquid. As shown in Fig. 2, in this study a surge tank with a standpipe is considered for numerical simulation.

The positive and negative characteristic equations are valid for nodes i and $i+1$, respectively Eqs. (6a) and (6b).

The continuity equation is:

$$Q_i^{n+1} = Q_{i+1}^{n+1} + Q_{sp}^{n+1}, \tag{7}$$

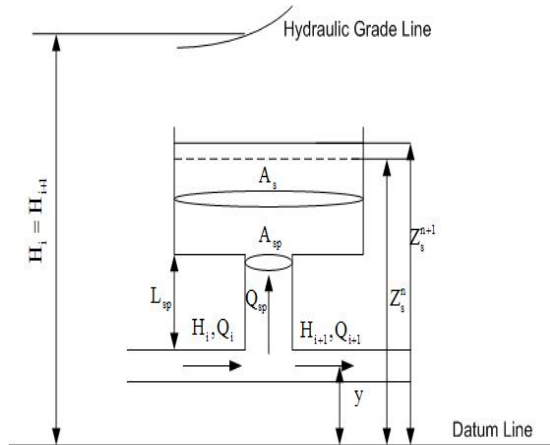


Fig. 2. Notations for a surge tank with stand pipe

where Q_{sp} is the flow rate in the standpipe (flow in the upward direction is considered positive). The pressure losses between nodes i and $i+1$ can be neglected, thus

$$H_i^{n+1} = H_{i+1}^{n+1}. \tag{8}$$

Since the length of the standpipe is usually short compared to the length of the pipe of the system, the liquid inside the standpipe may be considered as a lumped mass.

Considering that the weight of the liquid in the standpipe is, $\rho g A_{sp} L_{sp}$, and the friction force is, $\rho g A_{sp} f L_{sp} Q_{sp}^n / (2 g A_{sp}^2 D_{sp})$, the following differential equation may be written for the acceleration of the flow in the standpipe [4]

$$\frac{L_{sp}}{g A_{sp}} \frac{dQ_{sp}}{dt} = H_i^{n+1} - \frac{f L_{sp}}{2 g A_{sp}^2 D_{sp}} Q_{sp}^n |Q_{sp}^n| - Z_s^{n+1}, \tag{9}$$

where Z_s is the height of the water surface in the tank above the datum.

The elevation of the liquid surface in the tank above the datum line at the beginning and the end of the time step can be related to each other with the Eq. (10):

$$Z_s^{n+1} = Z_s^n + \frac{\Delta t}{2 A_s} (Q_{sp}^{n+1} + Q_{sp}^n). \tag{10}$$

Eqs. (6a, b) and (7) to (10) should be solved at the end of each time step for the six unknowns H_i^{n+1} , H_{i+1}^{n+1} , Q_i^{n+1} , Q_{i+1}^{n+1} , Q_{sp}^{n+1} and Z_s^{n+1} .

3 CASE STUDY AND NUMERICAL RESULTS

In the following, an application of the developed computer program for a prediction of the transient flow behaviour in Karun3 hydropower plant is presented. This power station is a 2000 MW (8 × 250 MW) Francis type hydropower plant, located in Khuzestan province on the Karun river in the South of Iran. Four surge tanks are located on the upstream water ways and eight surge tanks are located on the down stream water ways. The main characteristics of this hydropower plant are listed in Table 1.

Table 1. The main characteristics of Karun 3 hydro power plant [12]

Parameter	Value
Rated power [MW]	255.0
Rated head [m]	161.0
Rated flow [m ³ /s]	171.3
Rotational speed [rpm]	187.5
Head water level [m]	820.0
Tail water level [m]	660.0
Moment of inertia [ton.m ²]	29500
Turbine elevation [m]	653.1

The profile of this power station is shown in Fig. 3 and its schematic for the four units is shown in Fig. 4. The average acoustic wave velocity is about 1100 [m/s].

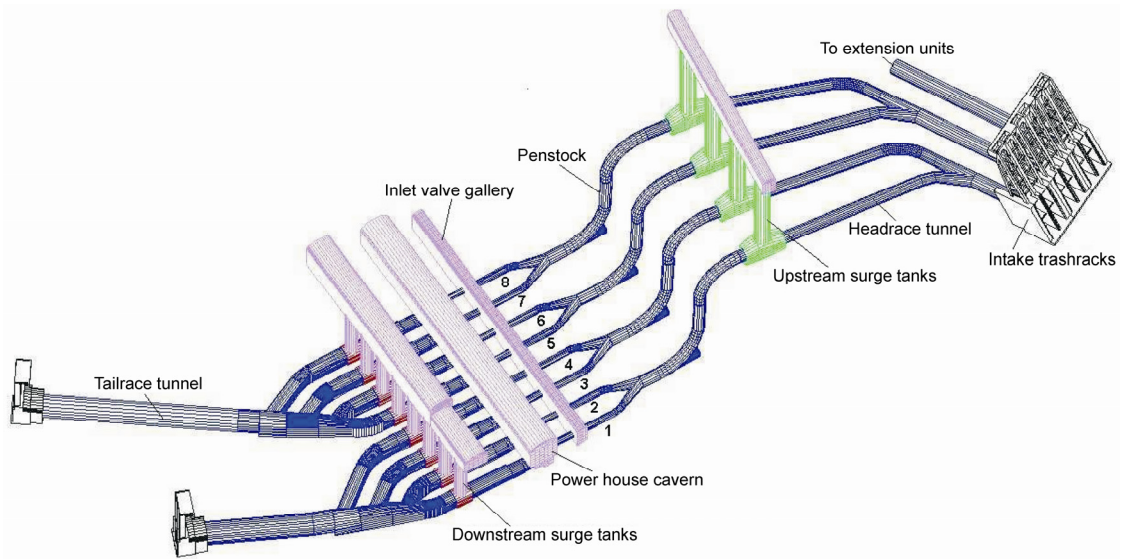


Fig. 3. Power station profile [12]

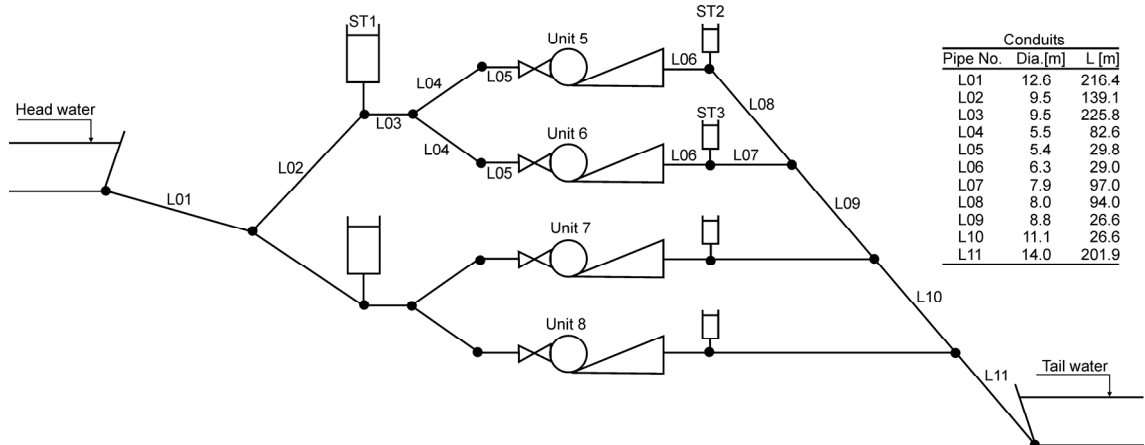


Fig. 4. Schematic of the waterways [12]

Transient flow due to a sudden closing of the guide vanes (generator load rejection) has been considered in this case study for the two units fed with a main penstock (units 5 and 6). The wicket gates are closed in 20 seconds. The pressure oscillations were measured by pressure transducers attached to the spiral case and to the draft tube.

In Fig. 5 pressure oscillations at the spiral case and the draft tube are compared with the measured data. The numerical results are in good agreement with the measured data. Moreover, the maximum and minimum pressure and also the pressure amplitude and the pressure phase of the transient wave are well computed by numerical method.

Slight differences between the computed and the measured data are due to uncertainties in

the estimation of friction factor, waterway diameter, waterway length and especially the wave speed.

The wave propagation speed varies along the concrete and steel lined tunnel and depends on the elastic properties of the fluid and pipe material, as well as on geometry and the pipe anchorage [13]. Therefore, the value of the wave speed is not precisely known due to errors in the estimation of the mentioned parameters.

The path which is passed by Francis turbine during wicket gate closing is shown in the approximated characteristics curves (Hill chart) of this hydropower plant (Fig. 6). As shown in Figure 6, during wicket gate closing the discharge approaches zero whereas the net head slightly increases.

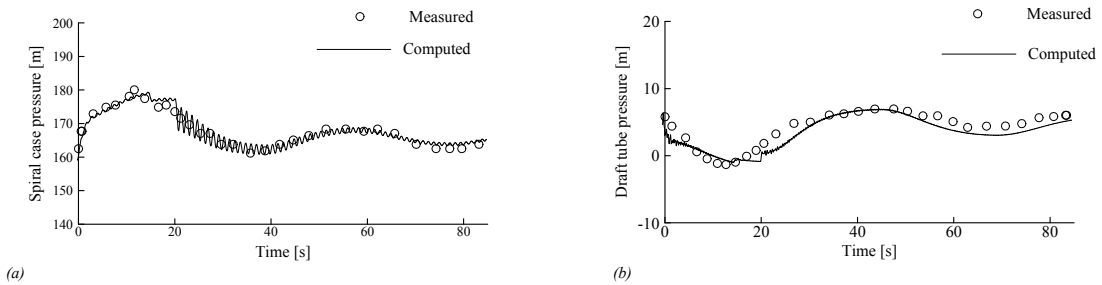


Fig. 5. Pressure oscillations: a) at the spiral case and b) at draft tube

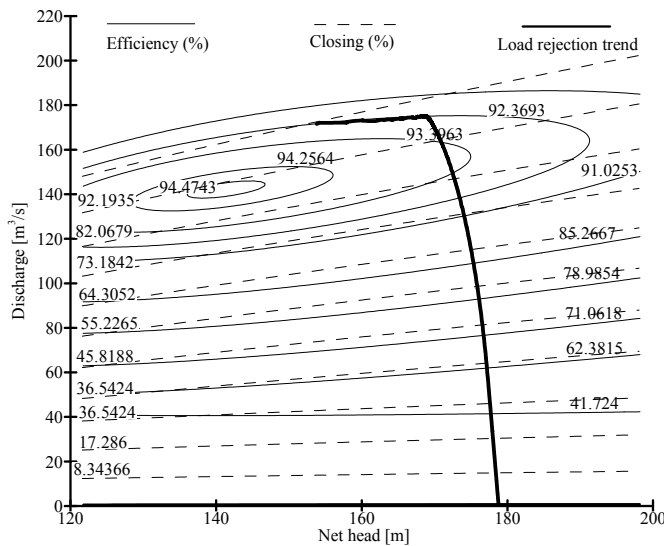


Fig. 6. Path which is passed by Francis turbine during complete wicket gate closing

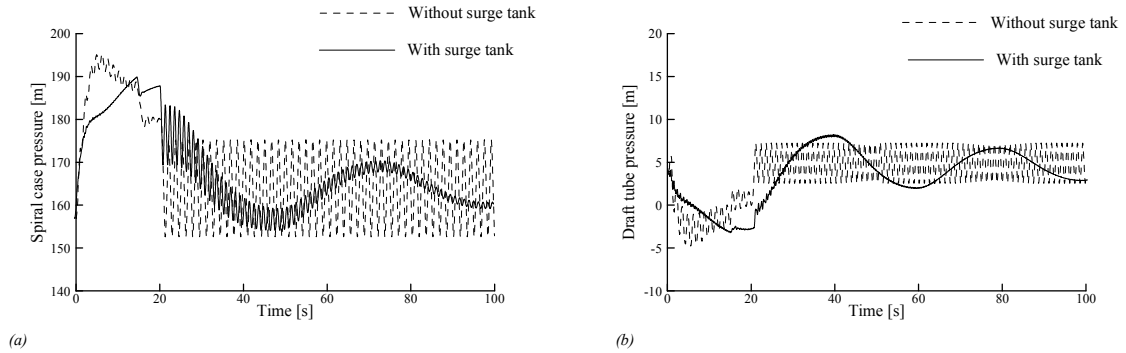


Fig. 7. Effect of the surge tank on pressure oscillations: a) at the spiral case and b) at the draft tube

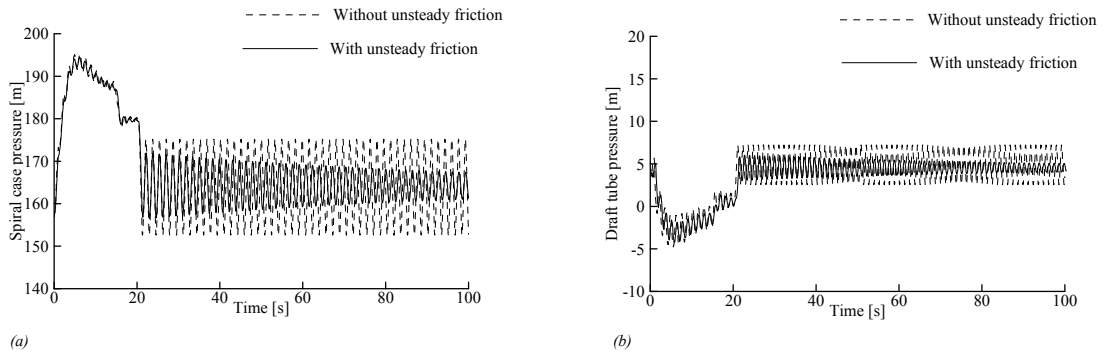


Fig. 8. Effect of unsteady friction on pressure oscillations when surge tank is not used: a) at the spiral case and b) at the draft tube

To study the influence of surge tanks on the transient conditions, Fig. 7 shows the effect of surge tank in two cases: a) at the spiral case and b) at the draft tube. As shown in Fig. 7 the maximum and the minimum pressure decrease by using surge tank and also a considerable delay in the time of the maximum and the minimum pressure occurs. The pressure pulsations with higher frequency at the upstream and downstream side of the hydraulic turbine are nearly eliminated by using a surge tank.

To investigate the effect of unsteady friction on transient conditions, Fig. 8 presents a comparison between pressure variations at the spiral case and the draft tube considering steady state friction and unsteady friction. In this simulation, surge tanks are not considered.

Although the steady state friction model predicts the maximum and the minimum pressure

well, the pressure damping is not correctly predicted by this model.

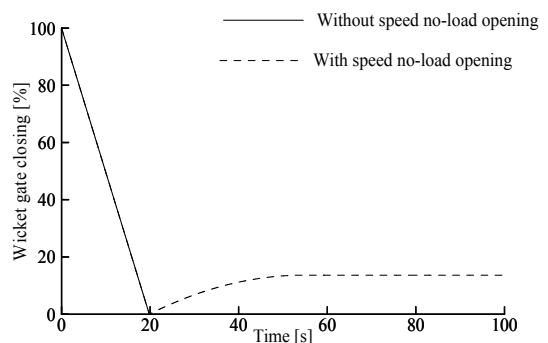


Fig. 9. Comparison between complete wicket gate closing and wicket gate closing followed by opening to SNLO

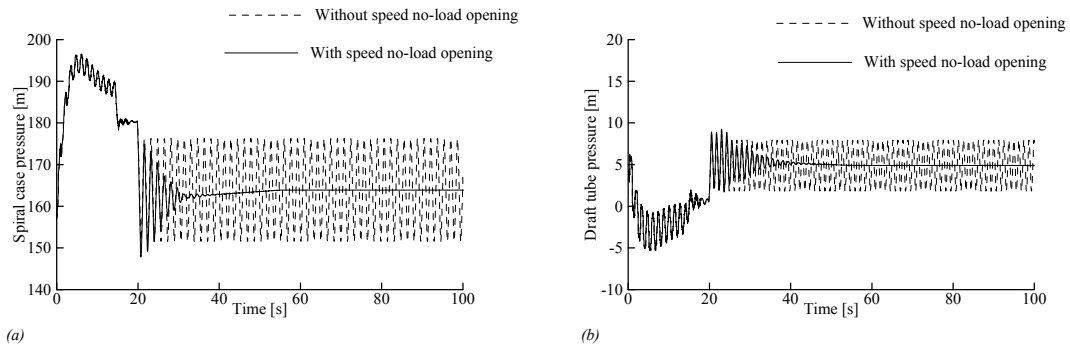


Fig. 10. Effect of wicket gate closing followed by opening to SNLO on pressure oscillations when surge tank is not used: a) at the spiral case and b) at the draft tube

To study the influences of wicket gate closing followed by opening to SNLO on transients caused by load rejection, Fig. 9 shows the complete wicket gate closing and also wicket gate closing followed by an opening to SNLO for this hydro power plant. The transient conditions occurring by these two kinds of closing are shown in Fig. 10. Although the maximum and minimum pressure is equal in both closings, the pressure oscillations in the case of the wicket gate closing followed by an opening to SNLO disappear after the time the wicket gates are completely closed. Thus, the transient conditions caused by the load rejection phenomenon are improved by using the wicket gate closing followed by opening to SNLO.

5. CONCLUSION

The primary objective of this study was to develop a better insight into the dynamics of flow transient in the hydropower plants waterways considering the effects of surge tanks, unsteady friction and wicket gate closing followed by opening to SNLO. A mathematical model employing a computer-simulation technique is used based on the method of characteristics considering unsteady friction. Stabilization in pressure and also a delay in the maximum and minimum pressure are produced by using a surge tank installation. The results also show that the steady state friction is not able to reproduce the pressure damping in comparison to the unsteady friction model. Finally, the transient flow behaviour is improved by wicket gate closing followed by opening to SNLO.

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NOMENCLATURE

a	acoustic wave velocity
A	pipe cross section
A_s	cross section area of surge tank
A_{sp}	cross section area of standpipe
C	constant
C^+	positive characteristic line
C^-	negative characteristic line
D	pipe diameter
D_{sp}	Standpipe diameter
f	Darcy-Weisbach friction factor
g	gravity acceleration
H	piezometric head
k	empirical coefficient for Brunone model
L_{sp}	standpipe length
Q	flow rate
Q_{sp}	flow rate in standpipe
t	time
V	average axial velocity
x	distance along the pipe
y	Pipe elevation above the datum
Z_s	water level in surge tank above the datum

Greek letters

ρg	unit gravitational force
ρ	mass density
τ_w	wall shear stress
τ_{ws}	steady state wall shear stress

τ_{wu} unsteady wall shear stress

Subscripts

i spatial location

s steady

u unsteady

w wall

Superscripts

n temporal location

+ related to positive characteristic

- related to negative characteristic

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