The influence of surge tanks on the water hammer effect at different hydro power discharge rates

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Abstract

This paper provides an overview of different types of surge tanks used in hydropower systems. The water mass oscillation inside the simple, sharp orifice type, throttle valve, and air-cushion surge tanks are studied. It is found that the diameter of the sharp orifice and the throat plays an important role in obstructing water mass flowing inside the surge tank which consequences to reduce the effect of water hammer over times in the pressure tunnels. Sharp orifice type surge tanks are more efficient to reduce the allowed maximum height of surge tank for avoiding water spilling out of the surge tank during the total load rejection from the prime movers. However, throttle valve surge tanks are more efficient for decaying of pressure surges sooner. It is also found that the difference-amplitude of water mass oscillation inside the air-cushion surge tank is insignificant. Conclusions are drawn based on the case study of Trollheim and Torpa hydroelectric plants in Norway.

Keywords: water mass oscillation, surge tanks throttling, sharp orifice type surge tank, air-cushion surge tank, throttle valve surge tank, water hammer

1 Introduction

1.1 Background

A high-head reaction-turbine hydro power system basically consists of an intake tunnel via a high-pressure steep penstock tunnel to the reaction turbines (eg., Francis turbine). A surge tank is usually placed between the intake pressure tunnel and the penstock. In case of a load rejection[1], the turbine valve is rapidly positioned for a required volumetric flow (discharge) of water through the turbine. During rapid closing of the turbine valve, the water masses flowing in the intake tunnel and in the penstock are suddenly decelerated. A high-pressure region is created at the lower end of the penstock because of the obstructed water-inertia[2] which causes pressure waves to travel in the upward direction[3]. The magnitude of the travelled pressure wave after sudden closure of the turbine valve is termed as a *water hammer*. The energy of the pressure wave is released at the nearest low-pressure free water surface, i.e, at the surge tank placed between the intake tunnel and penstock (Mosonyi, 1991, p. 129).

In this regard, it is of interest to see the effect of the water hammer at different discharges through the turbine during the load acceptance or rejection. The water inside the surge tank oscillates after the energy from the pressure wave is released at the free water surface inside the surge tank. The oscillation of water mass lasts until the pressure wave energy is fully dissipated. The design height and length of the surge tank should thus depend on the amplitude of the pressure wave, i.e., the water hammer. The amplitude of water mass oscillation inside the surge tank can be decreased using water flow-obstruction in the inlet of the surge tank, eg., in case of throttle valve surge tank and sharp orifice type surge tank (Aronovich et al., 1970). Similarly, energy from the pressure wave can be dissipated using pressurized air inside a closed surge tank, usually referred to as an air-cushion surge tank (Vereide et al., 2014). This paper will mainly focus on the simulated response at different discharge for *manifold pressure*[4], velocity, mass flow rate and water mass oscillation inside the different kinds of surge tanks.

1.2 Previous studies

A detailed overview of the time evolution of water mass oscillation inside a surge tank is given in (Guo et al., 2017) with differential equations governing the oscillation phenomenon. Similarly, a law governing oscillation phenomenon inside the simple surge tank is explored in (Travaš, 2014). The water mass oscillation control analysis using a self-adaptive auxiliary control system in the surge tank has been done in (Wan et al., 2019). The solution of water mass oscillation mathematical equations has been done using the finite element method in (Wan et al., 2019).

[1] Load rejection is simply a phenomenon where load connected to a prime mover, for eg., Francis turbine, is suddenly disconnected or decreased. However, in case of a load acceptance, a load is connected to the prime mover. A load is anything which is operated with the help of prime mover. For a hydroelectric plant, loads are electrical units connected through the grid in an interconnected electrical network.

[2] The obstructed water mass flowing through the pressure tunnel is generally called as water inertia.

[3] The pressure wave traveled from higher pressure to lower pressure region and dissipated near to free water surface.

[4] It is a bottom pressure point of the surge tank where the outlet of the intake tunnel and inlet of a steep penstock meet.

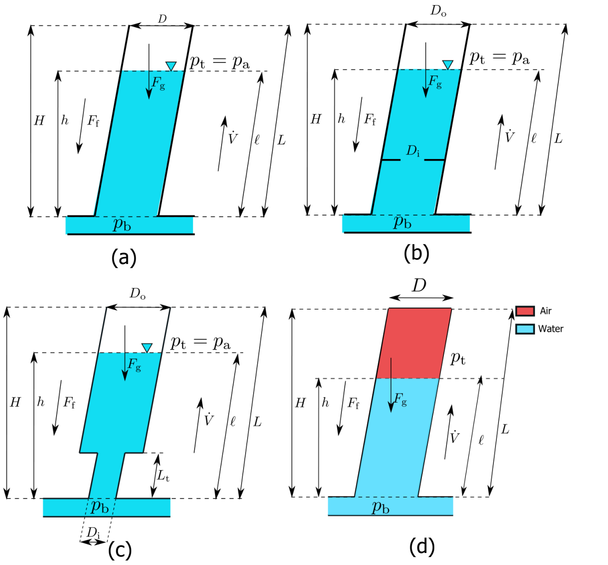

Figure 1. Different types of surge tanks. (a) Simple surge tank without hydraulic resistance. (b) Sharp orifice type surge tank with hydraulic resistance of horizontal bars forming an orifice of a diameter D_{i}. (c) Throttle valve surge tank with hydraulic resistance of diameter D_{i}at the entry of surge tank with square expansion from diameter D_{i} to diameter D_{o}. The length of the throat is L_{t}. (d) Air-cushion surge tank filled with air at pressure $p_{\mathrm{t}}$and diameter D.

1.3 Outline of the paper

The paper is organized by providing a brief introduction to different types of surge tanks and their operation in Section 2. Section 3 provides the simulated responses for Trollheim and Torpa hydro power plants with different types of surge tanks at different discharges. Results and discussions are provided in Section 4 while conclusions and future works are explained in Section 5.

2 Surge tanks and their operation

A detailed mechanistic model of simple, sharp orifice type, throttle valve, and air-cushion surge tank are articulated in (Pandey and Lie, 2020, Submitted) for a Modelica[5] based hydro power library- OpenHPL[6]. OpenHPL is an open-source hydropower library consisting of models for hydropower components that are developed based on mass and 1D momentum balance. It consists of mechanistic models for the flow of water in filled pipes (inelastic and elastic walls, incompressible and compressible water), a mechanistic model of a Francis turbine (including design of turbine parameters), friction models, etc.

The different types of surge tanks are shown in Figure 1. For a simple surge tank shown in Figure 1 (a), during the load acceptance/rejection, a high-pressure region is created at the end of the penstock and at the end of the turbine. The high pressure region thus creates pressure wave which traveled through the penstock releasing pressure wave energy by the means of water mass oscillation inside the surge tank. The height and length of surge tank thus depends on the water mass oscillation inside the surge tank. For a simple surge tank, the maximum height of surge tank would be sum of piezometric height from surge tank bottom to resorvoir surface and the highest amplitude of water mass oscillation during a *total load rejection*[7].

If the height of surge tank is not practically possible then other surge tanks with hydraulic resistances like horizontal bars forming a sharp orifice as in sharp orifice type surge tank or a throat in the entry of surge tank as in throttle valve surge tank can be used. Figure 1 (b) shows a sharp orifice type surge tank with orifice diameter D_{i} which obstructs water mass moving from the base of surge tank towards the free water surface inside the surge tank. This will cause the oscillation of water mass to dies out sooner than in the simple case. Similarly, the highest amplitude of water mass oscillation is decreased which decreases the practical height of the surge tank. The throat with diameter D_{t} and length L_{t}, in case of the throttle valve surge tank as shown in Figure 1 (c), has the same operation as that of sharp orifice type surge tank. Figure 1 (d) shows air-cushion surge tank.

[5]https://www.modelica.org
[6]https://github.com/simulatino/OpenHPL

3 Simulated Responses

3.1 Case study: Trollheim HPP

The case study for the simulated responses for different types of surge tanks at different discharge rates is studied for Trollheim and Torpa hydro power plant. The general layout diagram is shown in Figure 2.

3.1.1 Total Load Rejection (TLR)

First, we consider a case of a simple surge tank for Trollheim Hydro Power Plant (HPP) for a layout shown in Figure 2 (a) Trollheim HPP for a total load rejection. Assuming frictionless intake pressure tunnel and ideal gate valve for turbine (i.e., time of opening and closure of the gate valve is *zero*), the maximum allowable height of a simple surge tank for restriction of water-spilling from surge tank is given by the expression as in Eq. 1,

$$H_{\mathrm{ST}} = H_{\mathrm{res}} + H_{\mathrm{in}} + Y_{\mathrm{max}}, \tag{1}$$

where Y_{max} is the maximum surge or maximum water mass oscillation height during total load rejection (Mosonyi, 1991, p. 162)given as in 2,

$$Y_{\mathrm{max}} = \frac{\dot{V}_{\mathrm{n}}}{A_{\mathrm{in}}} \sqrt{\frac{L_{\mathrm{in}}}{g} \left(\frac{A_{\mathrm{in}}}{A_{\mathrm{ST}}} \right)}, \tag{2}$$

where H_{ST}, H_{in}, and $H_{\mathrm{res}}$are height difference for surge tank, intake and resorvoir, respectively. A_{in} and L_{in} are

[7]A total load rejection is a phenomenon where a hydroelectric plant running with full discharge through the turbine is completely shutdown. The turbine valve signal is instantaneously changed from full opening to full closed.

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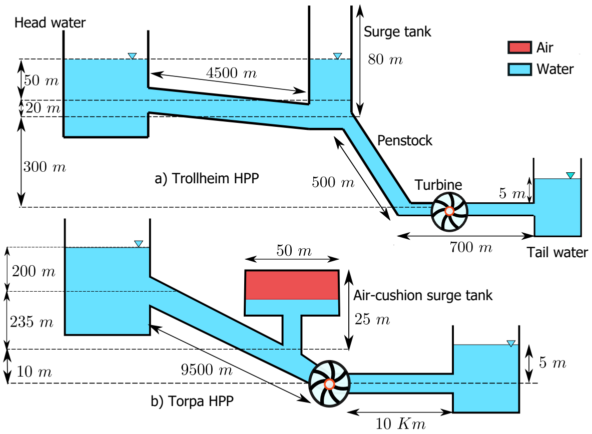

Figure 2. Layout diagram for Trollheim (Vytvytskyi and Lie, 2019) and Torpa Hydro Power Plant (HPP) (Vereide et al., 2014). Nominal head, nominal discharge, and nominal power output are 370 m, 40 m^3/s and 130 MW for Trollheim HPP, and 445 m, 35 m^3/s and 150 MWfor Torpa HPP. Torpa HPP has two turbine units each having nominal power output of 75 MW. The air-cushion surge tank for Torpa HPP has air volume of 13,000 m^3 initially pressurized at 4.1 Mpa. For Trollheim HPP, the diameter for both of the penstock and the surge tank is 4 m while for both of the headrace and the tailrace tunnel is 6 m. Similarly, for Torpa HPP, the diameter of both of the headrace and the tailrace tunnel is 7 m.

cross-sectional area and length of intake pressure tunnel, respectively. $\dot{V}_n$ is the nominal discharge with g as the acceleration due to gravity. From Figure 2 (a) Trollheim HPP we have $H_{res} = 50$ m, $H_{in} = 20$ m and Y_{max} is calculated using expression Eq. 2 as 45 m. Thus, the height of surge tank for avoiding water spilling out for a simple surge tank for Trollheim HPP during total load rejection is 115 m.

Figure 3 shows the turbine valve signal creating a total load rejection at 1500 s and plots of water mass oscillation for simple, sharp orifice type and throttle valve surge tank. It shows that hydraulic resistances in case of sharp orifice type and throttle valve surge tank dampens out the mass oscillation sooner than that of the simple surge tank and the maximum allowed height of surge tank H_{ST} for avoiding water spilling out of surge tank is less for sharp orifice type surge tank during TLR.

3.1.2 Effect of diameter of orifice and throat for TLR

The maximum allowed height of sharp orifice type and throttle valve surge tank for avoiding water spilling through the surge tank can be decreased based on decreasing diameter of orifice and throat as shown in Figure 4.

3.1.3 Total Load Acceptance (TLA)

A case of a total load acceptance is created using turbine guide valve control signal $u_v = \begin{cases} 0.01 & 0 < t \leq 200 \text{ s} \\ 1 & t > 200 \text{ s} \end{cases}$ at time 200 s for Trollheim HPP. The simulated response for water mass oscillation for simple, sharp orifice and throttle

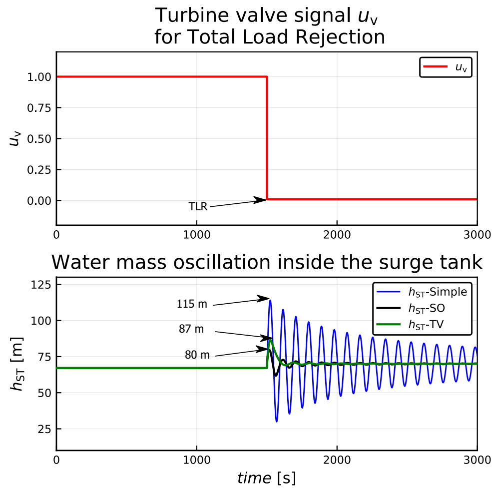

Figure 3. Water mass oscillation inside the surge tank for Trollheim HPP. A total load rejection is created using control signal $u_v = \begin{cases} 1 & 0 < t \leq 1500 \text{ s} \\ 0.01 & t > 1500 \text{ s} \end{cases}$ at time 1500 s. In the figure, TLR repesents total load rejection, SO and TV depicts sharp orifice type and throttle valve surge tank. The maximum amplitude of water mass oscillation h_{ST} is 115 m at around 1500 s for simple surge tank. While for sharp orifice type and throttle valve surge tank it is 80 m and 87 m, respectively. The diameter of orifice for sharp orifice type surge tank D_{so} and that of throat for throttle valve surge tank D_t are both 1 m. The length of throat for throttle valve surge tank is 20 m.

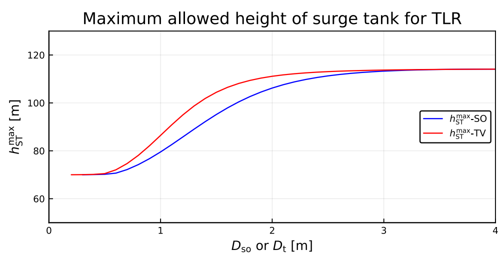

Figure 4. Maximum allowed height of surge tank for different diameter of sharp orifice (SO) type and throttle valve (TV) surge tank. h_{ST}^{max} represent the maximum amplitude of water mass oscillation during TLR. As the diameter of hydraulic resistances like sharp orifice or throat at the entry of the surge tank is decreased the maximum height of water mass oscillation decreased. For example when D_t and D_{so} both are 1 m, h_{ST}^{max} for sharp orifice type surge tank is 80 m and for throttle valve surge tank is 87 m.

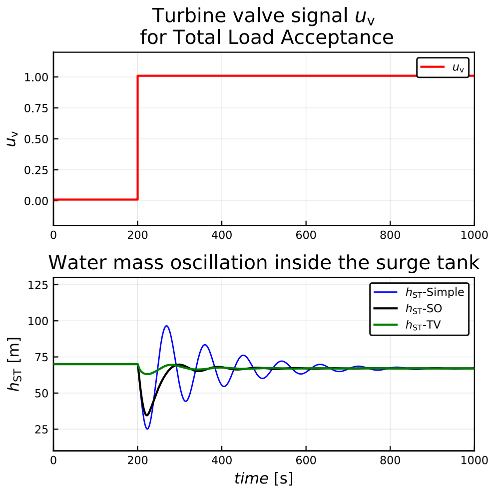

Figure 5. Water mass oscillation inside the surge tanks for TLA. The oscillation dies out soon in case of both sharp orifice and throttle valve surge tank.

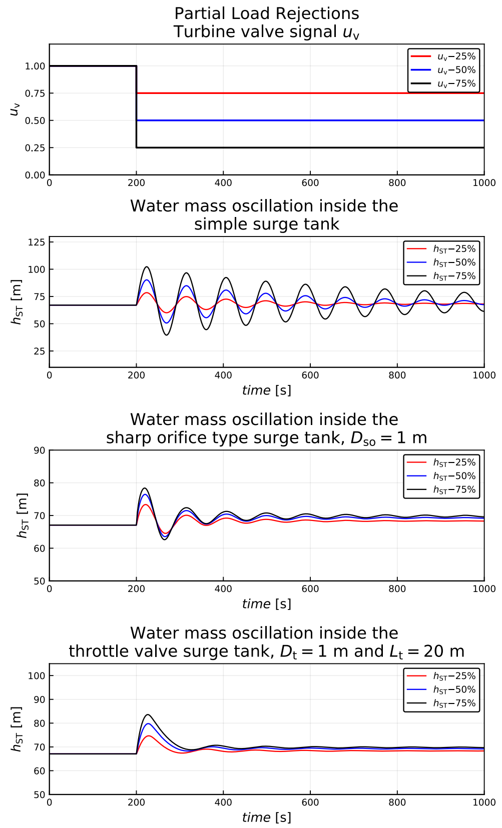

Figure 6. Water mass oscillation inside the surge tanks for PLR. In the figure, $u_v - 25\%$ represents the gate signal for a partial load rejection of 25% of the total load capacity of the plant. Similarly, $h_{ST} - 25\%$ represents water mass oscillation for a load rejection of 25%.

valve surge tank is shown in Figure 5.

3.1.4 Partial Load Rejection (PLR)

Partial load rejections and acceptances can be created by changing the turbine's gate signal.

For a 25 % load rejections while the hydropower plant is running at total load the turbine gate signal is generated as,

$$u_v = \begin{cases} 1 & 0 < t \leq 200 \text{ s} \\ 0.75 & t > 200 \text{ s} \end{cases},$$

where the plant is running at total load up to 200 s and with partial load (75 %) after 200 s.

Similarly, for a 50 % load rejection the turbine's gate signal is generated as,

$$u_v = \begin{cases} 1 & 0 < t \leq 200 \text{ s} \\ 0.50 & t > 200 \text{ s} \end{cases},$$

and for for a 75 % load rejection,

$$u_v = \begin{cases} 1 & 0 < t \leq 200 \text{ s} \\ 0.25 & t > 200 \text{ s} \end{cases}.$$

Figure 6 shows water mass oscillation inside the simple, sharp orifice and throttle valve surge tank during the partial load rejections.

3.1.5 Partial Load Acceptance (PLA)

For a 25 % load acceptance while the hydropower plant is running at no load condition, the turbine gate signal is generated as,

$$u_v = \begin{cases} 0 & 0 < t \leq 200 \text{ s} \\ 0.25 & t > 200 \text{ s} \end{cases},$$

where as for a 50 % load acceptance,

$$u_v = \begin{cases} 0 & 0 < t \leq 200 \text{ s} \\ 0.50 & t > 200 \text{ s} \end{cases},$$

and for a 75 % load acceptance,

$$u_v = \begin{cases} 0 & 0 < t \leq 200 \text{ s} \\ 0.75 & t > 200 \text{ s} \end{cases}.$$

Figure 7 shows water mass oscillation inside the simple, sharp orifice and throttle valve surge tank during the partial load rejections.

3.2 Case study: Torpa HPP

The water mass oscillation and the air pressure inside the air-cushion surge tank during load rejections and acceptance for Torpa HPP is shown in Figure 8 and 9, respectively.

4 Results, and Discussions

For Trollheim HPP, from Figure 3 in case of a TLR, the maximum allowed height of the surge tank for restriction of water spilling out of a simple surge tank is 115 m. Similarly, for sharp orifice type surge tank it is 80 mand for

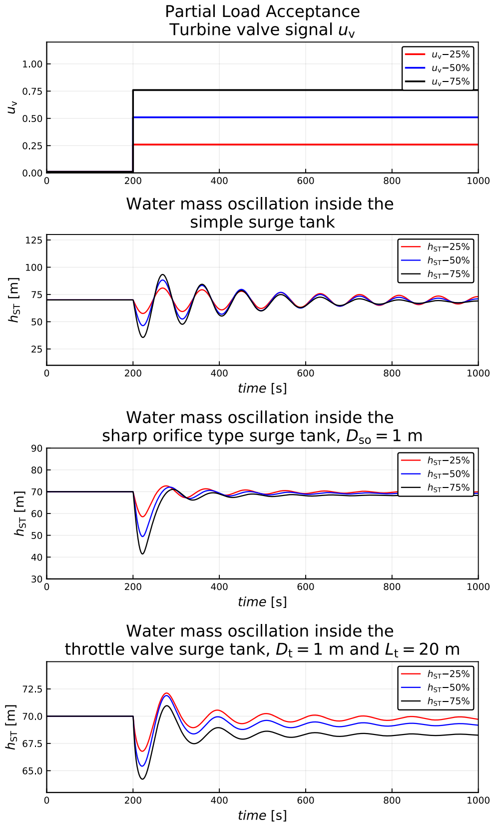

Figure 7. Water mass oscillation inside the surge tanks for PLA. In the figure, $u_v - 25\%$ represents the gate signal for a partial load acceptance of 25% of the total load capacity of the plant. Similarly, $h_{ST} - 25\%$ represents water mass oscillation for a load acceptance of 25% from a no load condition.

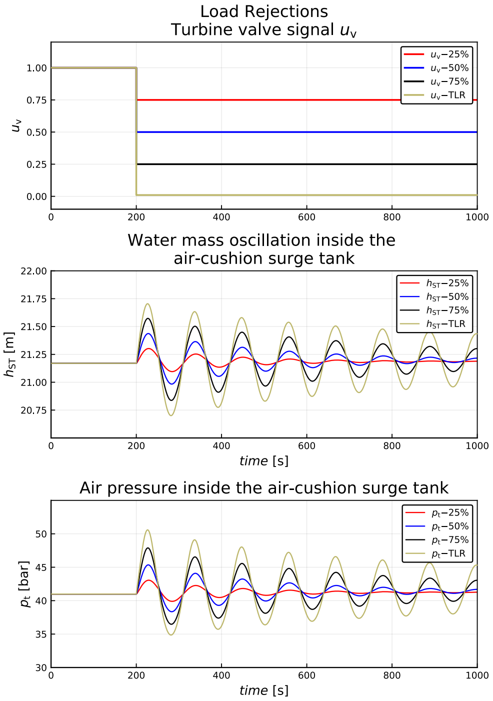

Figure 8. Water mass oscillation and air pressure inside the air cushion surge tank for load rejections. In figure, TLR represents a total load rejection.

throttle valve surge tank it is 87 m. From Figure 4 it can be seen that the maximum allowed height of surge tank in case of a total load rejection is decreased as the diameter of sharp orifice and diameter of the throat is decreased. For a surge tank of diameter 4 m, in case of Trollheim HPP, the maximum allowed height of the simple surge tank, h_{ST}^{max} during TLR is same for sharp orifice type surge tank with $D_{so} \in [3,4]$, however, h_{ST}^{max} decreases as $D_{so} \in [0.5,3)$. Similarly, in case of throttle valve surge tank h_{ST}^{max} is same for $D_t \in [2,4]$ and simple surge tank, however, h_{ST}^{max} decreases as $D_t \in [0.1,2)$.

For Torpa HPP, from Figure 8 and 9 in case of load rejections and acceptance, respectively, manifold pressure inside the surge tank does not vary much in case of load acceptance than in case of rejections.

5 Conclusions

The maximum allowed height of a simple surge tank, considering the TLR operation of the plant, can be decreased using a suitable diameter of the sharp orifice in case of a sharp orifice type surge tank and with a throttle valve surge tank with suitable diameter of the throat. The maximum allowed height of the surge tank is lowest in case of sharp orifice type surge tank, however, the mass oscillation dies out soon in case of throttle valve surge tank with an inference that impact of water hammer in the pressure tunnel is less in case of throttle valve surge tank.

In the case of a sharp orifice type surge tank, the maximum allowed height of the surge tank in comparison with a simple surge tank decreases exponentially for $D_{so} \leq 0.5 \cdot D$ where D and D_{so} are the diameter of the simple surge tank and the diameter of the sharp orifice. Similarly, for throttle valve surge tank $D_t \leq 0.375 \cdot D$ where D_t is the diameter of the throat. Both for load rejections and acceptance, mass oscillation inside the surge tank dies sooner in case of a throttle valve surge tank. The frequency of water mass oscillation in the case of a simple surge tank is the same for both load rejections and acceptance.

For the air-cushion surge tank, water mass oscillation inside the surge tank is insignificant for both load acceptance and rejections. The varying of air pressure inside the surge tank for partial load rejections is greater than that for the partial load acceptance.

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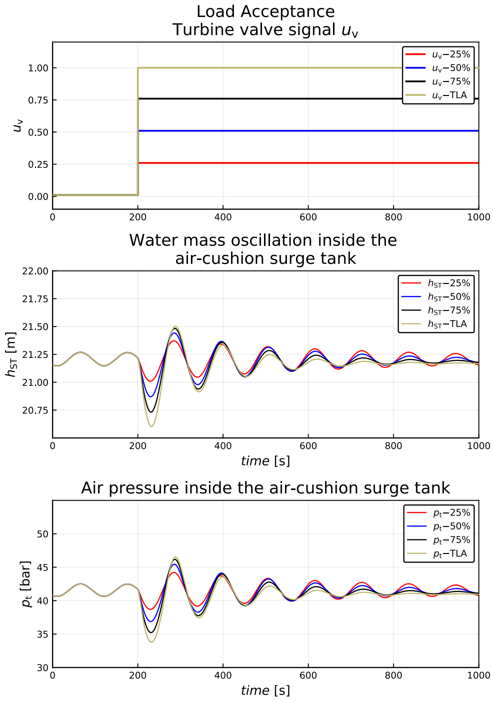

Figure 9. Water mass oscillation and air pressure inside the air cushion surge tank for load acceptance. In figure, TLA represents a total load rejection.

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