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Averaging level control with Skogestad PI level controller tuning

Figure 1 shows a buffer tank with a level control system aiming at averageing (or equalizing, or attenuating) inflow variations so that the outflow becomes smoother than the inflow.

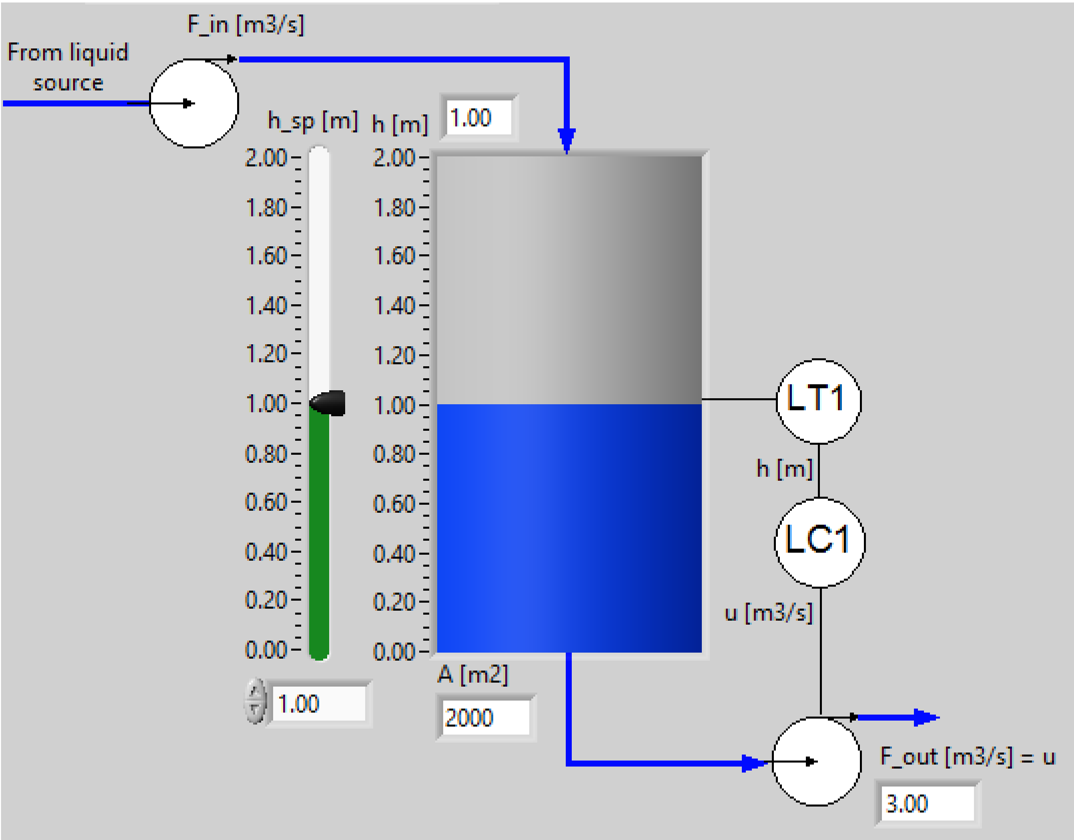

Figure 1: Averaging level control of a buffer tank.

Averaging level control is an important part of several process systems. Some important practical examples are:

- The equalization or buffer magazine at the inlet of a wasteater treatment plant.
- Oil/water separators in the oil industry.

Both the equalization magazine and the separator can here be regarded as liquid *buffer tanks*. In both examples, the level should be compliant to flow variations so that variations in the inflow are damped through the tank, making the outflow considerably smoother than the inflow. Smoother outflow is advantageous for the subsequent processes, e.g. for the biological treatment processes and the oil production. The level controller must tuned for compliant (or soft, or sluggish) level control so that the volume of the tank can absorb the inlet variations.

How to tune the level controller of the buffer tank? The Ziegler-Nichols controller tuning methods - both their ultimate gain method (or closed loop method), and the process reaction method (or open loop method) are designed for giving as fast control as possible. These methods are therefore useless for tuning of the level controller of a buffer tank since we want sluggish control of such tankes. However, the Skogestad method is suitable here since the speed of the controller can be tuned with the closed loop time constant, T_c, as tuning parameter. Skogestad tuning of the level controller is explained below.

Dynamically, buffer tanks are integrators (or accumulators) since the process output variable, which is the liquid level, is proportional to the integral of (or accumulation of) the control signal, which is here assumed to be the inflow pump control signal. Let us recall the Skogestad formulas for integrating processes with zero time delay (in liquid buffer tanks, we can assume a negligible or zero time delay between the pump flow control signal and the level):

$$\text{Gain: } K_c = 1/(K_i * T_c)$$
$$\text{Integral time: } T_i = 2 * T_c$$

Here, K_i is the process integrator gain, or the normalized step slope of the process step response (step in the control signal). As explained below,

$$K_i = -1/A$$

where A [m^2] is the surface area of the liquid in the tank. T_c [s] is the time constant of the level control system, i.e. of the closed loop system from level set point, h_{sp}, to level measurement, h. A way of tuning T_c is suggested below.

Hence,

PI controller settings of the level controller of a buffer tank:

$$K_c = 1/(K_i * T_c) = -A/T_c$$
$$T_i = 2 * T_c$$

Note: The negative sign in K_c means that the controller has *direct* action.

We shall now deduce the relation $K_i = -1/A$ presented above. To that end, let us study an example in the form of a simulator of a level controlled buffer tank. Figure 2 shows the front panel of the simulator. The controller is in manual mode. The upper plot in Figure 2 shows the ramp-shaped response in the level, h [m], due to a step in the pump control signal, u. (The values of the model parameters are representative of wastewater treatment plants for cities of size same as Oslo.)

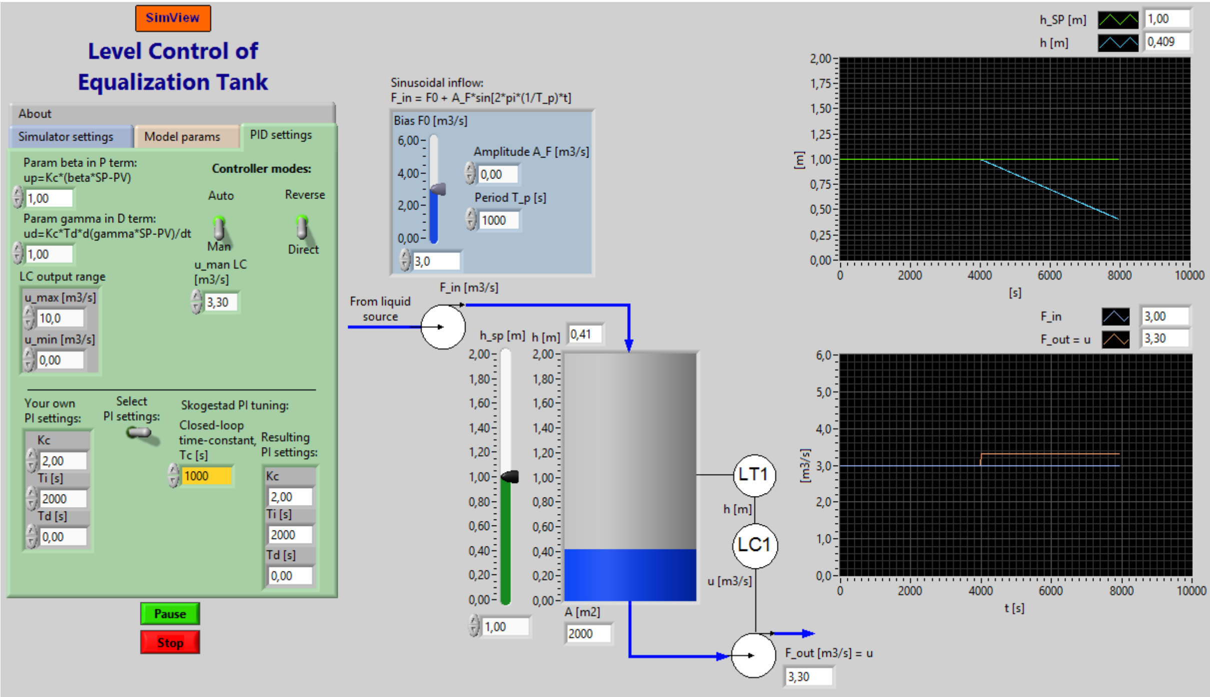

Figure 2: Front panel of a simulator of a level controlled buffer tank. The controller is here in manual mode. The upper plot shows the ramp-shaped response in the level due to a step in the pump control signal shown in the bottom plot. (The simulator is the "Level Control of Equalization Tank" simulator on http://techteach.no/simview.)

Assume that the pump control signal is changed as a step of amplitude U. Figure 2 shows such an experiment (applied there with U = 0.3 m^3/s). The ramp-shaped level response has slope S [m/s] equal to

$$S = -U/A$$

and the normalized slope becomes

$$K_i = S/U = -1/A$$

How to specify a reasonable value of T_c [s] needed in the PI settings of K_c and T_i? An interpretation of this time constant is how fast, in the form of 63% rise time, the level approaches to the level set point when the set point is changed as a step. This is illustrated in Figure 3 which shows an ideal, principal time constant response of a control system (numbers will, of course, be unique to each pertinent control system).

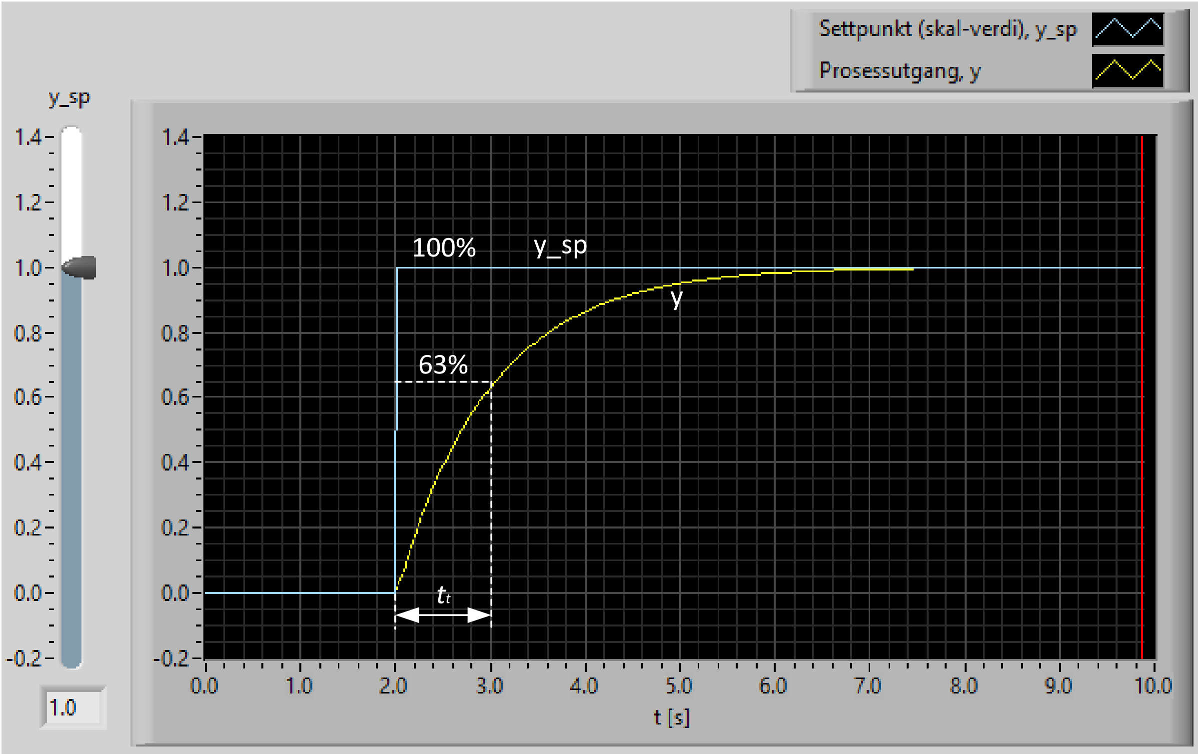

Figure 3: Ideal time constant response of a control system.

However, in level control systemts of buffer tanks the setpoint is typically constant, so specifying the 63% rise time of the setpoint step response is not particularly meaningful for such control systems. Instead, let's make a more meaningful specification of T_c, related to the response of an inflow change. We start by assuming that the level controller is a P (proportional) controller. It can be shown, from a mathematical model of the level control system, that

$$\Delta h_{max} = (T_c/A)*\Delta F_{in}$$

assuming a P-controller. Here, Δh_{max} is the maximum steady-state change in level due to an assumed maximum inflow step change of amplitude ΔF_{in} [m^3/s]. See the upper plot of Figure 4, which shows a simulated response with P-controller (yellow curve) due to a inflow step change at t = 2000 s (shown in the bottom plot of the figure). The response with a PI-controller is also shown (blue curve).

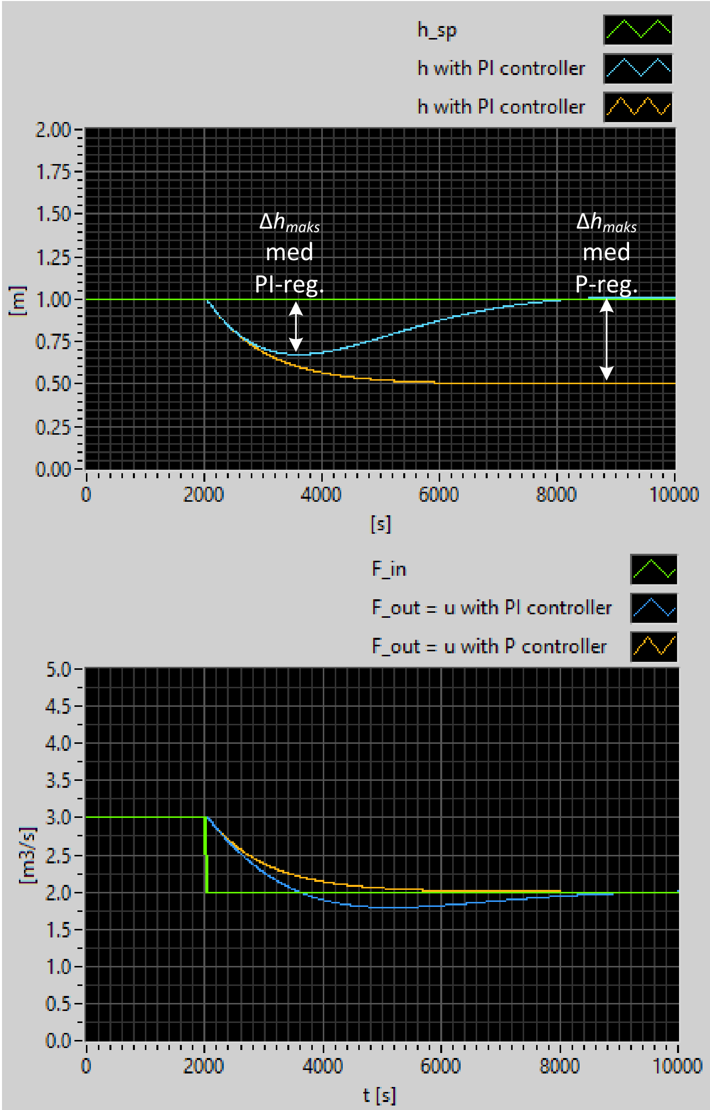

Figure 4: Simulations with P controller and with PI controller due to a step change of F_{in}.

With a PI controller that gives the same T_c as with the P controller (the controller gains will be equal, too), the following applies, as illustrated in Figure 4:

$$\Delta h_{max} <= (T_c/A)*\Delta F_{\text{in}}$$

Solving this inequality for T_c gives

$$T_c >= A*\Delta h_{max}/\Delta F_{\text{in}}$$

We may use this upper limit of T_c to specify T_c:

Specification of T_c in the PI settings (in the formulas for K_c and T_i):

$$T_c = A*\Delta h_{max}/\Delta F_{\text{in}}$$

Example 1: Tuning of the PI controller for compliant level control of a buffer tank

Assume A = 2000 m^2. Assume that the level is not to be reduced by more than 0.5 m by a stepwise reduction of the inflow of step amplitude 1 m^3/s. This gives the following value of T_c:

$$T_c = A * \Delta h_{max}/\Delta F_{in} = 2000*(-0.5)/(-1) = 1000 \text{ s}$$

Using this value in the formulas of K_c and T_i, gives

$$K_c = -A/T_c = -2000 \text{ m}^2/1000 \text{ s} = 2.0 \text{ m}^2/\text{s} = 2.0 \text{ (m}^3\text{/s)/m}$$
$$T_i = 2*T_c = 2*1000 = 2000 \text{ s}$$

Figure 5 shows a simulation with the level controller in automatic mode. There is a step change in the inflow of amplitude -1 m^3/s at t = 2000 s. We see that the level, as expected, is reduced somewhat less 0.5 due to the inflow step change. Thus, the specification of the control system is satisfied.

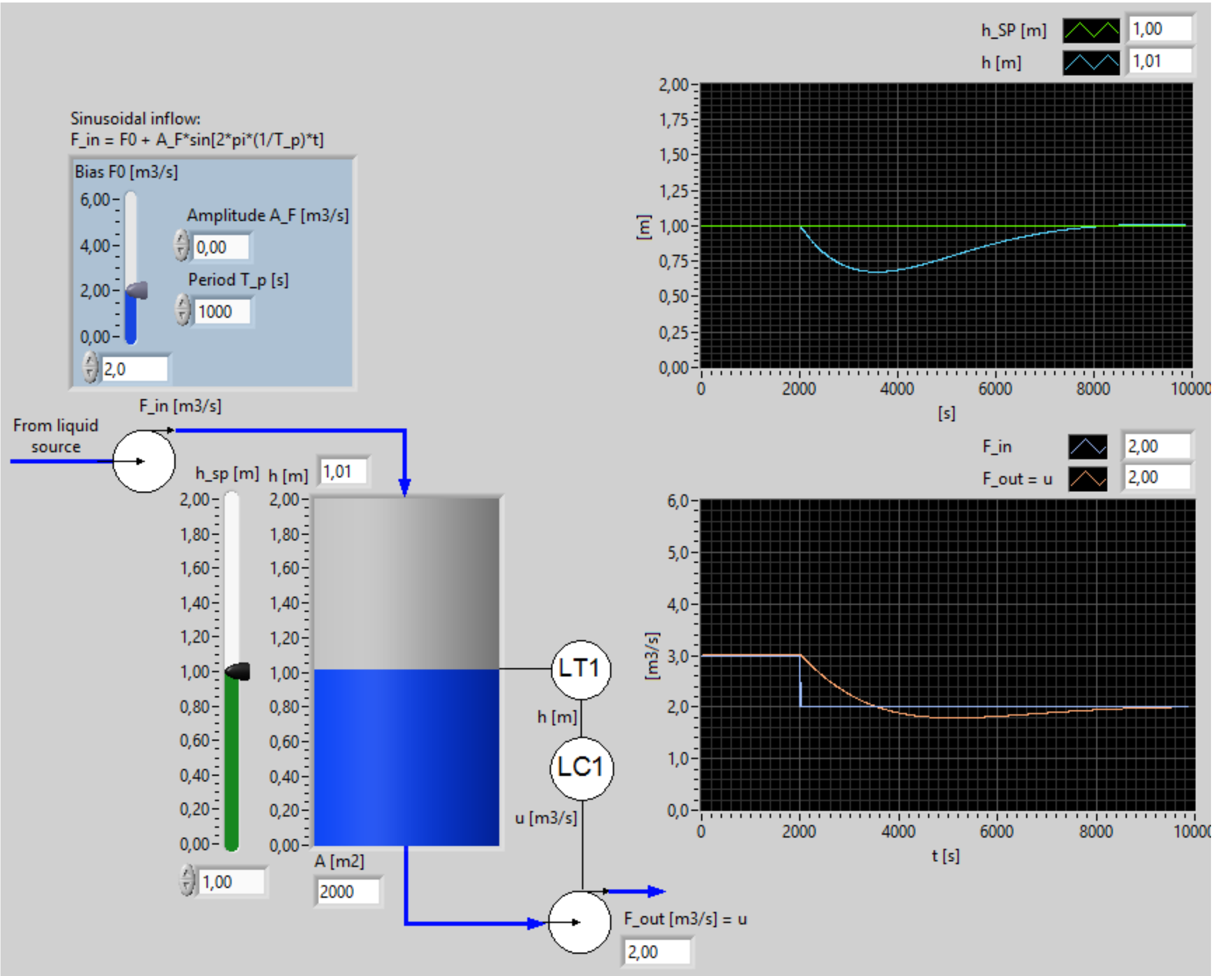

Figure 5: Simulation with the PI level controller in automatic mode. The controller is tuned with the Skogestad method. F_{in} is changed as a step of amplitude -1 m^3/s..

Figure 6 shows another simulation with the controller in automatic mode. The inflow is now sinusoidal, with a period of 1200 s (this intake variation may be washwater from the treatment processes subsequent to the inlet magazine in a wasterwater treatment plant). The bottom plot of the figure shows that the level controlled buffer tank (magazine) attenuates the flow variations. Even greater attenuation can be achieved by increasing the control system time constant T_c, but then with the disadvantage that the level may deviate too far from the setpoint due to severe inflow change.

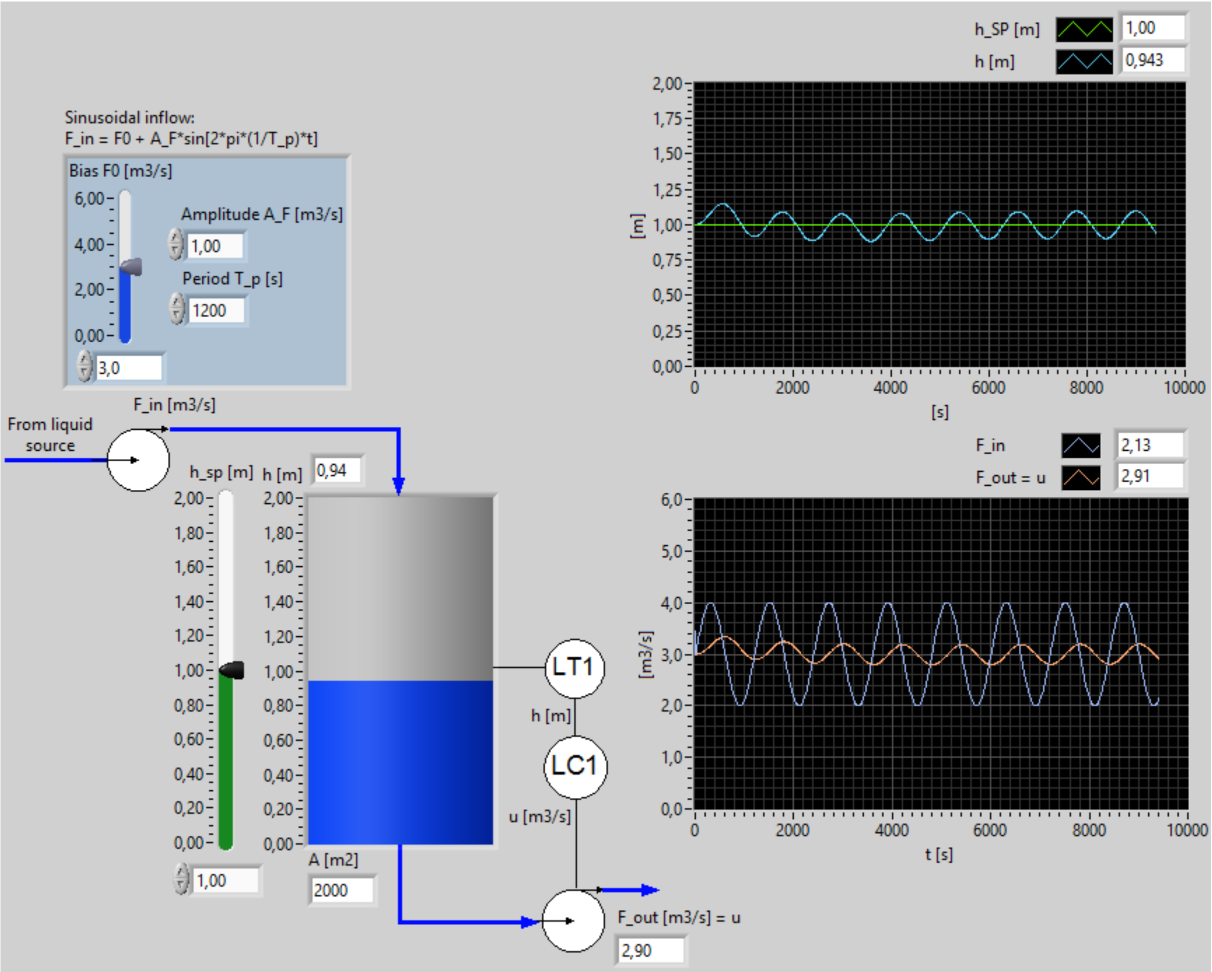

Figure 6: Simulation with the PI level controller in automatic mode. The controller is tuned with the Skogestad method. F_{in} *is changed as a step of amplitude -1* m^3/s. *There is a sinusoidal variation in the inflow. The bottom figure shows that the level controlled buffer tank attenuates the flow variations.*

End of Example 1