Course: Digital Control

A report
of

TP3: Modeling on command of a level regulation model

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List of tables

List of figures

Table of contents

1.Introduction

Industrial applications of liquid level are employed in many industrial and chemical areas, e.g., in food processing, beverage, dairy, effluent treatment, filtration, and nuclear power generation plants; industrial chemical processing and spray coating; boilers; and automatic liquid dispensing and replenishment devices. Their level must be keep a defined point or between maximum-minimum points depending on changing of inlet and outlet liquid quantities. In order to overcome the problem, many level control methods have been developed. Process control very often implements level regulations. Their command can be performed using standard closed loop commands using PID correctors. However, the components used in these processes often have complex and non-linear behaviors, which can lead to adjustment difficulties disappointing PIDs and performance [1–4]. The typical actuators used in liquid level control systems during this lab include pumps, controlled valves and on-off manual valves. In additional, also the level sensor has been used during this lab.

In the lab, the purpose was to study, on an educational model, the real behaviors of these components, their non-linearity and the alternatives to the classic PID for their closed loop control. More specifically, the objectives of this lab was to identify the non-linearity of a dynamic system, understanding and trace the Input/output characteristics of a system, (re) condition MISO → SISO signals / systems, and control a non-linear system with low dynamics; linearizing a nonlinear system.

2. Background and Preparation

2.1 Presentation of the model

System model: The schematic Description of the model including practical work in figure 1 represents the model of a three water tanks and one water reservoir and the level sensors at the top of each tank and a pump. All the three tanks have different dimensions as show in the figure 1. In this lab setup, the pump provides infeed to upper tank and the outflow of upper tank becomes infeed to middle tank and also the outflow of middle tank becomes the infeed of the lower tank as shown. The outflow of the lower tank is emptied into the water reservoir which is connected to the pump. There is also a computer system and input/output boards on PCI bus to control the pump and the solenoid valves. Despite for what described above, the system was subjected to several physical quantities including the weight due to gravity, the density of the water and the atmospheric pressure. Due to those quantities which imposed to the systems and bring the non-linearties, so the result are not hundred percent accurate.

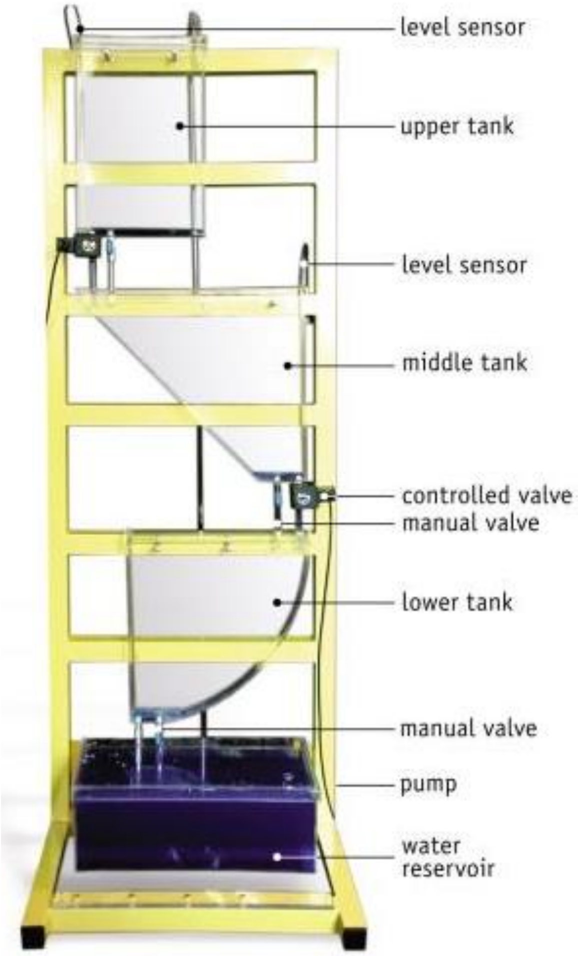

Figure 1: Description of the model used in this practical work

2.1.1 Solenoid valve

Solenoid valves are used wherever fluid flow has to be controlled automatically. They are being used to an increasing degree in the most varied types of plants and equipment. In this lab, they have been used to outflow the water from the tank automatically. Solenoid valves are control units which, when electrically energized or de-energized, either shut off or allow fluid flow. The actuator takes the form of an electromagnet. When energized, a magnetic field builds up which pulls a plunger or pivoted armature against the action of a spring. When de-energized, the plunger or pivoted armature is returned to its original position by the spring action [3].

2.1.2 The constitutive law

By considering the Bernoulli's principle for energy conservation, and this principle is a direct application of the energy conservation principle to the emptying of a tank through a section S located at the bottom of the tank. If we make the assumption that the heating and the losses are negligible. Emptying the tank without loss of energy, and the potential energy of gravitation $V(h) = \rho gh$ of an elementary volume of drained fluid is then completely transformed in kinetic co-energy $T^*(v) = \frac{1}{2}\rho v^2$ at the outlet of the drain orifice (v is the speed of the fluid at the outlet of the drain orifice).

$$V(h) = T^*(v) \tag{1}$$

For laminar flow, the drain rate is $q = \int_S v dS \approx v \cdot S$ which gives:

$$\rho \cdot g \cdot h = \frac{1}{2} \cdot \rho \cdot v^2 \Rightarrow q = S.\sqrt{2gh}$$

In practice, the flow at the outlet of the orifice is never perfectly laminar and a flow coefficient of this orifice ks <1 is then used.

$$\Rightarrow q = ks.S\sqrt{2gh} \tag{2}$$

since $P = \frac{1}{2}v^2 = \rho h$ we can get the following:

$$q = ks.S\sqrt{\frac{2}{\rho}\Delta P(t)} \tag{3}$$

Now, let consider mass conservation knowing that the mass $m(t)$ of water stored in the reservoir is given as a conservative quantity as stated in the following equation:

$$\frac{dm(t)}{dt} = \rho\left(q_{in}(t) - q_{out}(t)\right) \tag{4}$$

Where , ρ, $q_{in}(t)$ and $q_{out}(t)$ is the density of water, the volume inflow rate, and the volume outflow rate respectively. In a tank of constant section area A, we can find the expression of mass as follow:

$$m(t) = \rho A h(t)$$

Now equation (4) above becomes:

$$A\frac{dh(t)}{dt}=q_{in}(t)-q_{out}(t) \tag{5}$$

From Pascal's principle with Newton's law in static, we have that If the vertical acceleration of the fluid particles at the bottom of the tank is sufficiently small to be neglected (relatively slow emptying and filling), the sum of the vertical forces at the bottom of the tank is zero. The pressure difference $\Delta p(t)=p_2-p_1$ between the bottom and the top of the tank is then only due to the weight w of the body of water. From this we can have the following equation

$$w-\left(p_2-p_1\right)A=0$$

$$\Delta p(t)A=w \Leftrightarrow \Delta p(t)A=\rho Ahg$$

$$\Rightarrow h=\frac{\Delta p(t)}{\rho g} \tag{6}$$

Replacing the value above into the equation (5) to get:

$$\Rightarrow \frac{A}{\rho g}\frac{d(\Delta p(t))}{dt}=q_{in}(t)-q_{out}(t) \tag{7}$$

2.2 PID controller

PID control is a name commonly given to three-term control. The mnemonic PID refers to the first letters of the names of the individual terms that make up the standard three-term controller. These are P for the proportional term, I for the integral term and D for the derivative term in the controller. Three-term or PID controllers are probably the most widely used industrial controller. Even complex industrial control systems may comprise a control network whose main control building block is a PID control module**.** A PID controller will correct the error between the output and the desired input or set point by calculating and give an output of correction that will adjust the process accordingly [2].

It has three terms which are:

Proportional

Proportional control is denoted by the P-term in the PID controller. It used when the controller action is to be proportional to the size of the process error signal.

Integral

Integral control is denoted by the I in the PID controller and is used when it is required that the controller correct for any steady offset from a constant reference signal value. Integral control overcomes the shortcoming of proportional control by eliminating offset without the use of excessively large controller gain.

Derivative control

If a controller can use the rate of change of an error signal as an input, then this introduces an element of prediction into the control action. Derivative control uses the rate of change of an error signal and is the D-term in the PID controller.

The following is the equation of this PID corrector with a $u(t)$ as the input signal.

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_d \frac{de}{dt} \tag{8}$$

Where k_p is proportional gain, k_i is the integral gain, and k_d is the derivative gain.

The transfer function of the analog PID controller is found by applying the Laplace transform to the equation above and is found to as follow:

$$G_c(s) = k_p + \frac{k_i}{s} + k_d s \tag{9}$$

3. Experiments

The model is controlled by a PCI Input/output card connected to a PC This the latter is programmable and controllable using Matlab Simulink. Conversion and the compilation of the block diagram drawn under Simulink into a C program is carried out in using the Matlab Real Time Workshop toolbox. Launching and steering in time real C program compiled for the PC processor is made using the toolbox Real Time Windows Target from Matlab. This relation is linked to a law of conservation of mass and also to the Pascal's principle.

3.1 Identification and characterization of the system

As given, parameters of the system model which consists of an input and an output were changed without real control, and to be able to control the system we must have its Simulink model and simulate it. Now you can be able to control the system by using input/output command. The Simulink model is as shown in the figure 2 below;

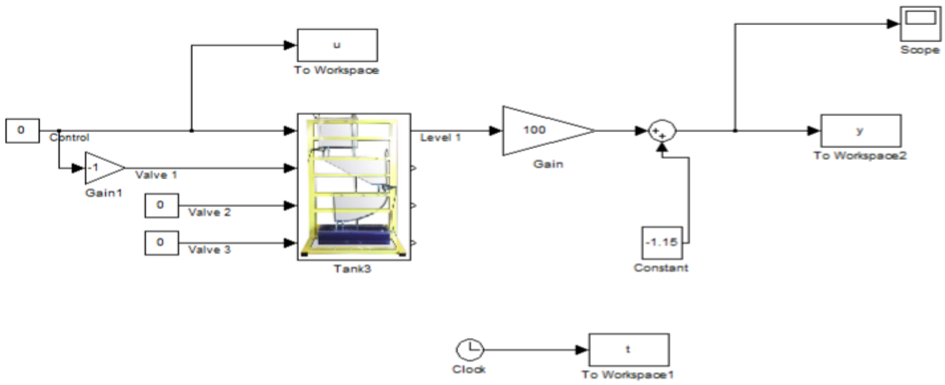

Figure 2: Simulink model of the system

The following result has been obtained by knowing that with different set-points of control direct of the pump by keeping the drain valves on the upper tank closed and we have filled this upper tank with water up to the level of $10cm^3$.

As shown in this figure 3, the straight line which is horizontal indicates that the level of the water in tank was increasing with time. This time is one taken for the water to move from the pump and filling to the upper tank and touch its level sensor. As said also in introduction there are also nonlinearities in the system behaviour This is due to different forces and the atmospheric pressure which the system has been subjected to, and also the non-linearity in the system design components and turbulence of the fluid in the tank and it is clearly shown in the graph.

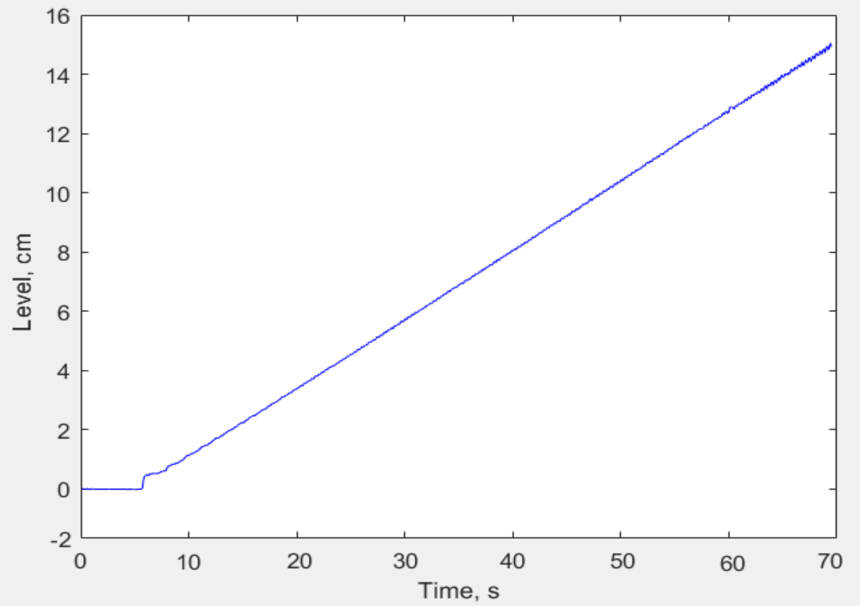

Figure 3: Graph for tank filling

3.1.1 Control/flow relationship of the pump

By still considering the upper tank, its volume can be give as $V = A.h$

$V = 87.5\times10^{-4}\times15\times10^{-2} = 13\times10^{-4} m^3$

During this lab, we have recorded the value values of the flow rate for different applied control voltage of pump. Those values are shown in the table 1 below:

Table 2: Relationship between the flowrate and the pump control voltage

Table 1: The data obtained of the infeed flow rate with different control voltage and time taken

trial	Time in sec	Control voltage in volts	The infeed flow rate
1	-	0	0
2	69,2	0,2	0,000020
3	41,6	0,3	0,000031
4	30,4	0,4	0,000043
5	22,8	0,5	0,000059
6	20,3	0,6	0,000068
7	15,4	0,7	0,000089
8	14,1	0,8	0,000092
9	13,8	0,9	0,000095
10	13,5	1,0	0,000095
11	13,7	1,1	0,000095

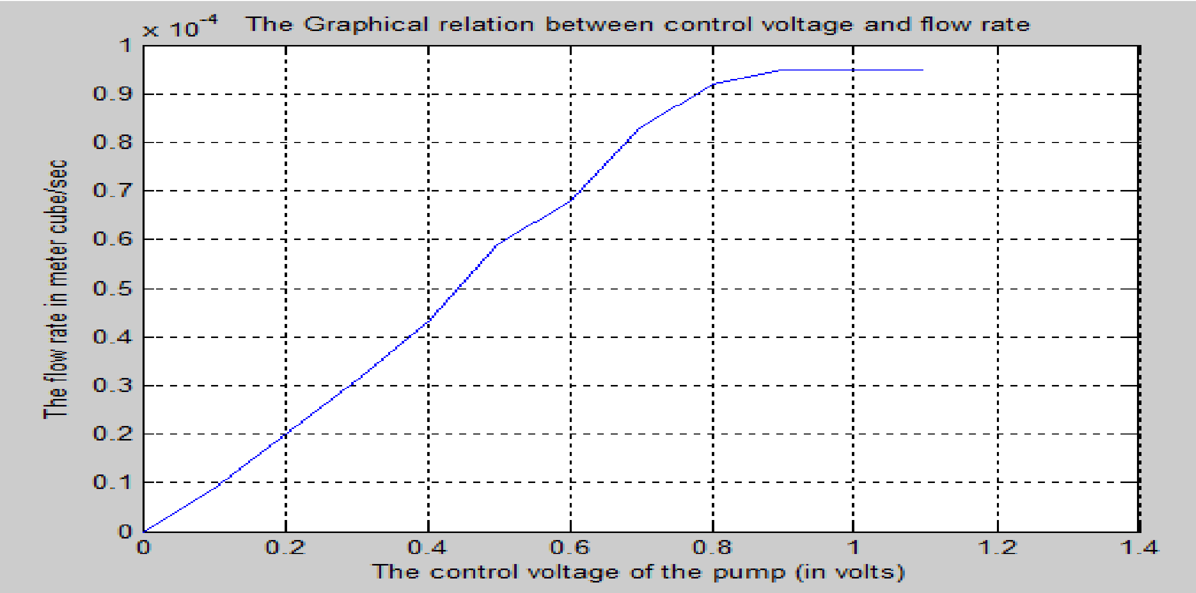

Figure 4: Graph of the infeed flow rate against control voltage

By look to this figure you can observed that at the values of flow rate which is equal to 0.95*10^-4m^3/s is constant at the applied control voltage which is equal to 1.0 volts.

3.1.2The test to determine the constitutive

Once the upper tank is opened and emptying this tank, we have applied the different control voltage the following graphical result have been recorded. Once we wanted to empty the tank, it has taken a quiet long time for this tank to be empty due to the reduced pressure. Since we have used the solenoid valve for draining, the flow was a laminar (we have laminar flow for draining once solenoid is used).

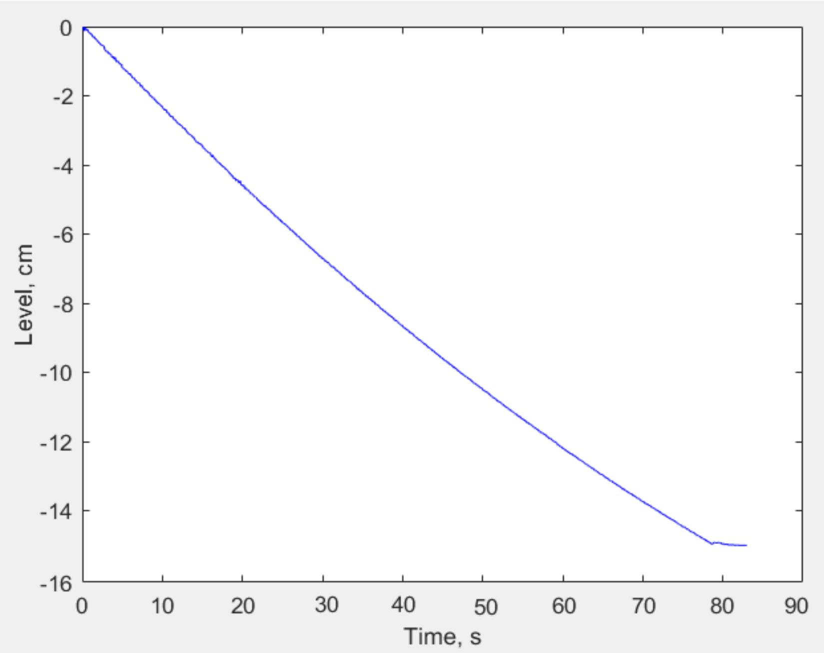

Figure 5: Graph for emptying the tank

By using the drain valve, we have recorded the flowing data of the control voltage and the outflow rate for different time and this is recorded in the following table 2.

Table 2: The data obtained of the outfeed flowrate with different control voltage and time taken

Trial	Time in sec	Control voltage in volt	Outfeed flow rate
1	-	0	0
2	-	0,2	0
3	-	0,3	0
4	-	0,4	0
5	387,2	0,5	0,0000039
6	136,7	0,6	0,0000096
7	86,3	0,7	0,0000152
8	66,2	0,8	0,0000198
9	65,9	0,9	0,0000199
10	65,6	1,0	0,0000200
11	65,6	1,1	0,0000200

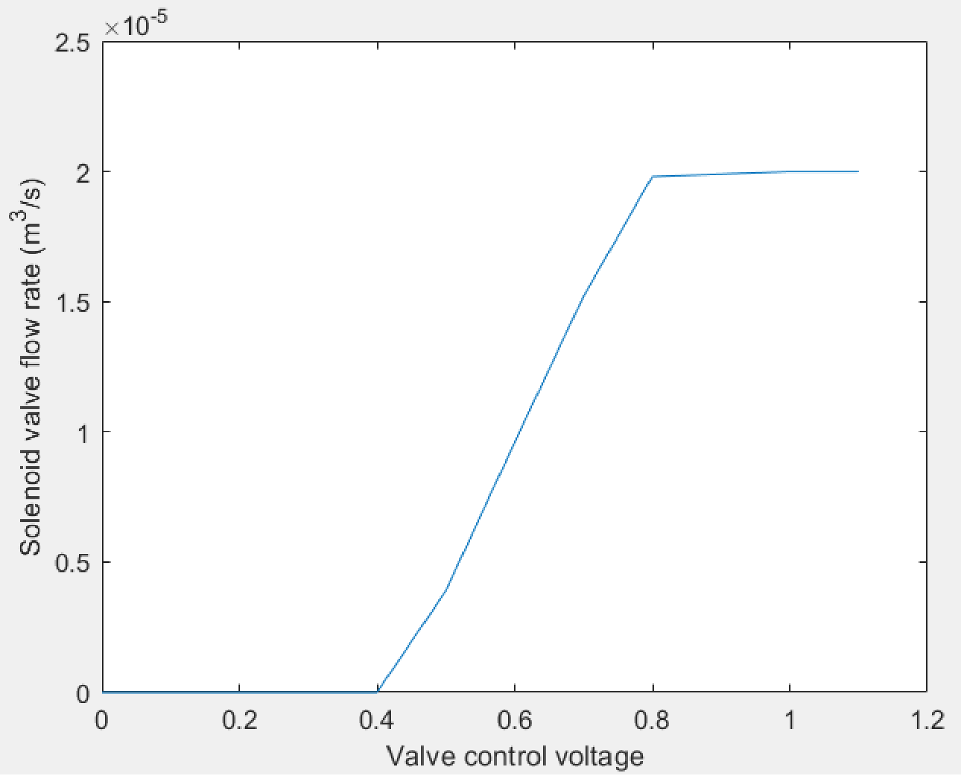

Figure 6: Graph of outfeed flow rate against control voltage

As the graph above shows, from 0 to 0.4 of the control voltage, we have a dead zone where the drain valve displayed no action. The graph also shows the saturation is at 2*10^-5m^3/s of the outflow rate of the drain valve.at the control voltage value from 1.0 and above.

3.1.3 Filling and Emptying Non-Linearity Behaviours

By changing the control voltage of the pump we have monitored the variation of the flow rate. Where this rate has been calculated by tanking the infeed flow rate minus the outfeed flow rate as shown below:

$q = q_{in} - q_{out}$,where q_{in} and q_{out} are the infeed flow rate and outfeed flow into the tank respectively.

With this we were able to determine the constitutive law of the controllable drain valve experimental and the result are shown graphically in the figure 7 below. Before the graphical result let us show the obtained result in the table 3.

Table 3: The table combining the infeed and outfeed flow rate with control voltage of the pump

Control voltage in volts	q_{in} **(m³/s)**	q_{out} **(m³/s)**
0	0	0
0,2	0,000020	0
0,3	0,000031	0
0,4	0,000043	0
0,5	0,000059	0,0000039
0,6	0,000068	0,0000096
0,7	0,000089	0,0000152
0,8	0,000092	0,0000198
0,9	0,000095	0,0000199
1,0	0,000095	0,0000200
1,1	0,000095	0,0000200

By plotting the value of in the table 3 above and having that $q = q_{in} - q_{out}$ the result is shown below. This graph shows the non-linearity behaviour of the pump and the solenoid valve while filling and emptying the system tank. By observing the graph, we have showed different zone of this system which includes the saturation zone which starts from -1.1 of the voltage value to -0.8v and again at 1 and above, heterogeneity between -1.0 and -0.6, and the dead zone where there is no action of the solenoid valve and is between -0.6 and 0.

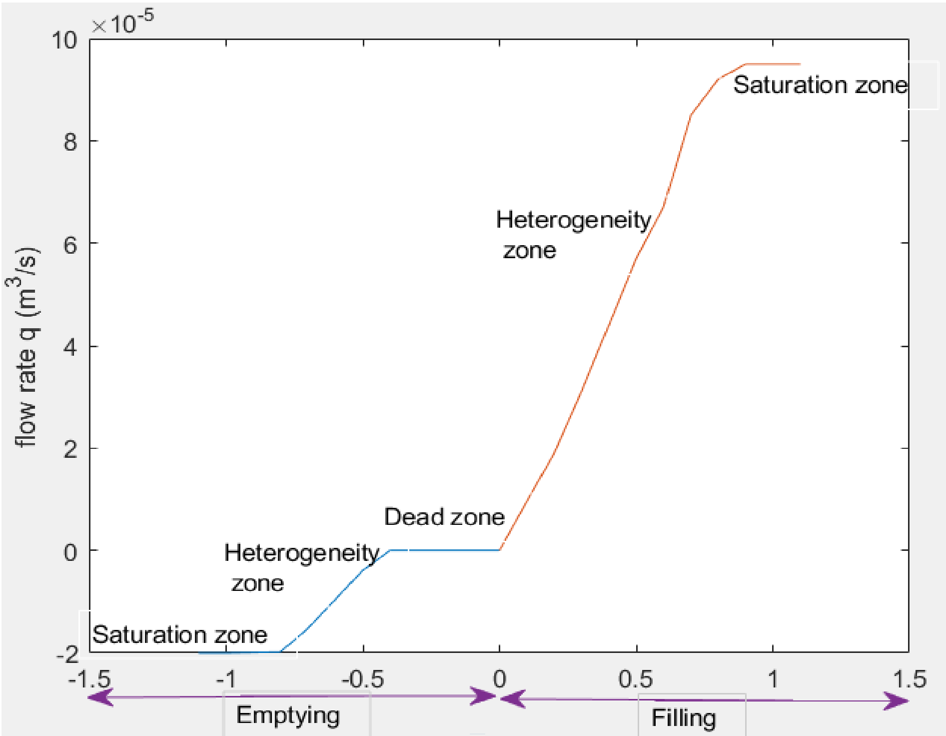

Figure 7: Graphical representation of filling and emptying the tank at the same time

2. Implementation of level regulation

2.1 switching from a multiple input single output (MISO) control to single input single output (SISO) control of the system.

The Simulink model in the figure below is showing the proposed solution for switching from MISO to SISO. During this lab, we have controlled the level of the fluid by setting-up a point for the valve and pump. According to what we have done during this lab, in order to have the same instructions as for filling the tank, we have taken the negative value of the gain for emptying or draining, and the positive gain value for filling-up the pump. The model used is shown in the figure below:

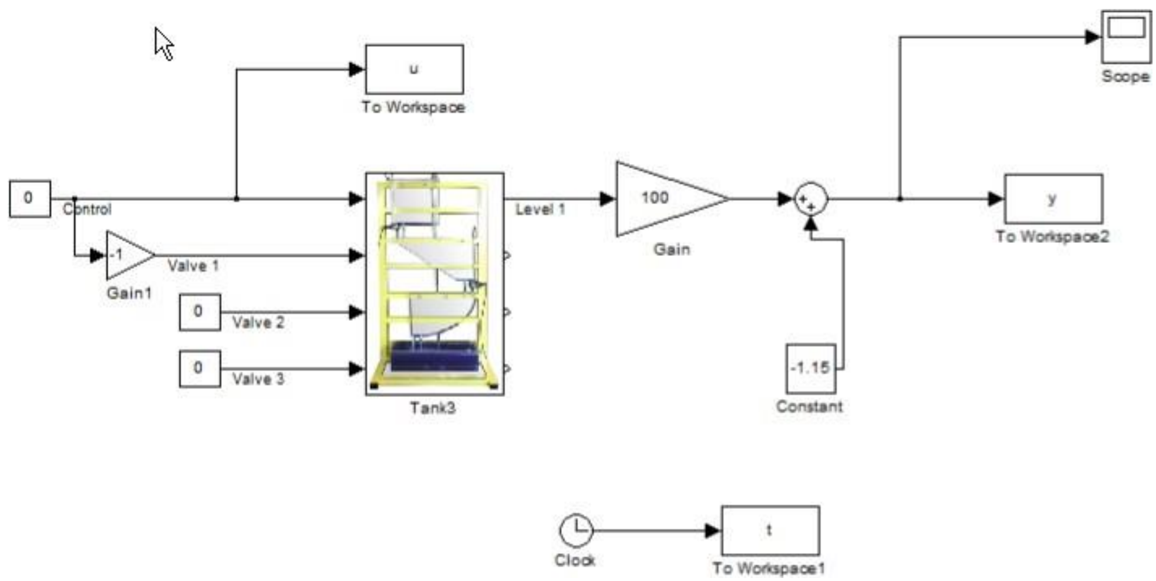

Figure 8: Simulink model for the solution of switching from MISCO to SISO

2.2 The implementation of the digital control

The closed loop used for implementing the digital control of the upper tank is shown below:

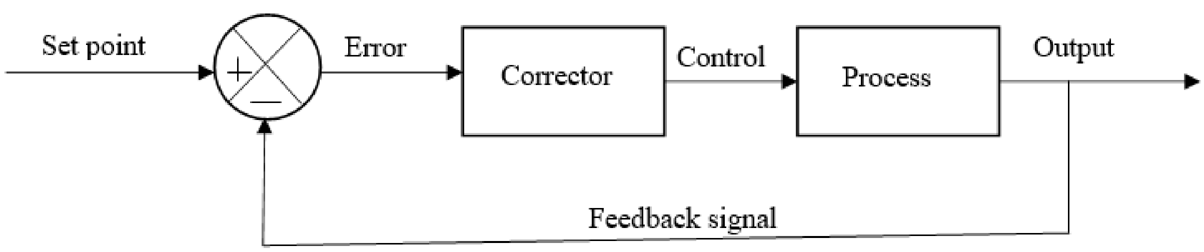

Figure 9: Level regulation of the upper tank

There are some general guidelines followed in order to find the best fit controller to be used in our system to be controlled. The one we followed are:

1. Always perform sizing to take in account the load to motor inertial mismatch, which is the most common problem and the source of loop instability
2. Remove system backlash as much as possible in the driven components

3. Use the step response method (command vs. response) to see how the system is reacting. This is commonly performed using an oscilloscope or is sometimes provided with the controller manufacturer's software. You need to see what you are doing; otherwise, you are just shooting in the dark
4. Start tuning with integral gain at zero; increase proportional gain to get a bit of overshoot response; and then adjust the derivative gain a bit at the same time to damp the oscillations. Add integral gain at the end to remove the static error. Think of it as a pyramid. The base of the pyramid is K_D; the middle of the pyramid is K_P; and the top of the pyramid is K_I. The K_D (derivative gain) would have the highest value, followed by K_P (proportional gain) with a lower value, followed by K_I (integral gain) with the lowest value. Manual tuning is a trial-and-error process.
5. At all time, make sure the current output of the amplifier is not saturated; otherwise, this procedure is invalid, and tuning is impossible. Saturated current can mean you are asking too much torque from the motor and amplifier or you are asking for a speed higher than what your system can achieve. A deeper analysis of the complete system might still be needed to help diagnose flaws or weaknesses.

After simulation by following the above guidelines, we have found that the best fit to control the upper tank is when we set the proportional gain K_P to be 1 and let K_I and K_D to be zero. And the Simulink model of our complete system with PID controller is shown in the figure10 below.

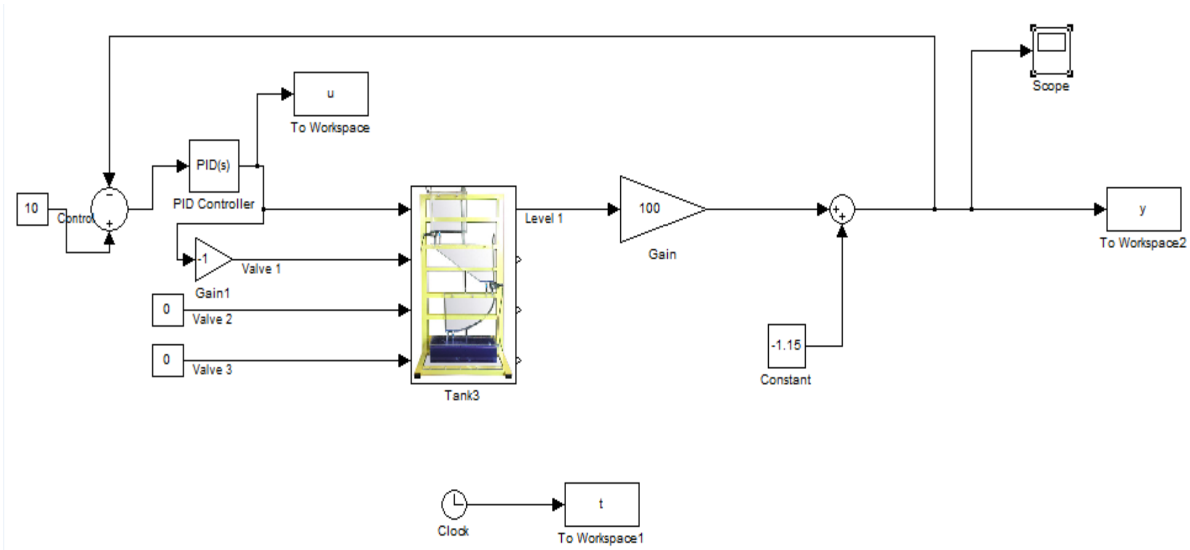

Figure 10: Simulink model for controlled upper tank by PID controller

The advantage of using this Proportional controller with the gain K_P of 1 is that with this we are able to control and determine the stability of the system at the level we want and the slow response of this system can be made faster with the help of this controllers. However, this controller has a disadvantage of that we still have error as show in the figure11 below.

The addition of a PID with K_P gain which is equal to 1 and with K_I and K_D gains of zero. We were able to control the level of the water in the upper tank by getting the stability at $10cm$ as shown in the figure below. This figure also shows that the system is subjected to disturbances and perturbations. Therefore, to minimize those errors, we can use the PID which have the all three gains and tune according to the way stated above by following the general guidelines for tuning. So, the result obtained after simulation of the complete system with PID Simulink model is shown below.

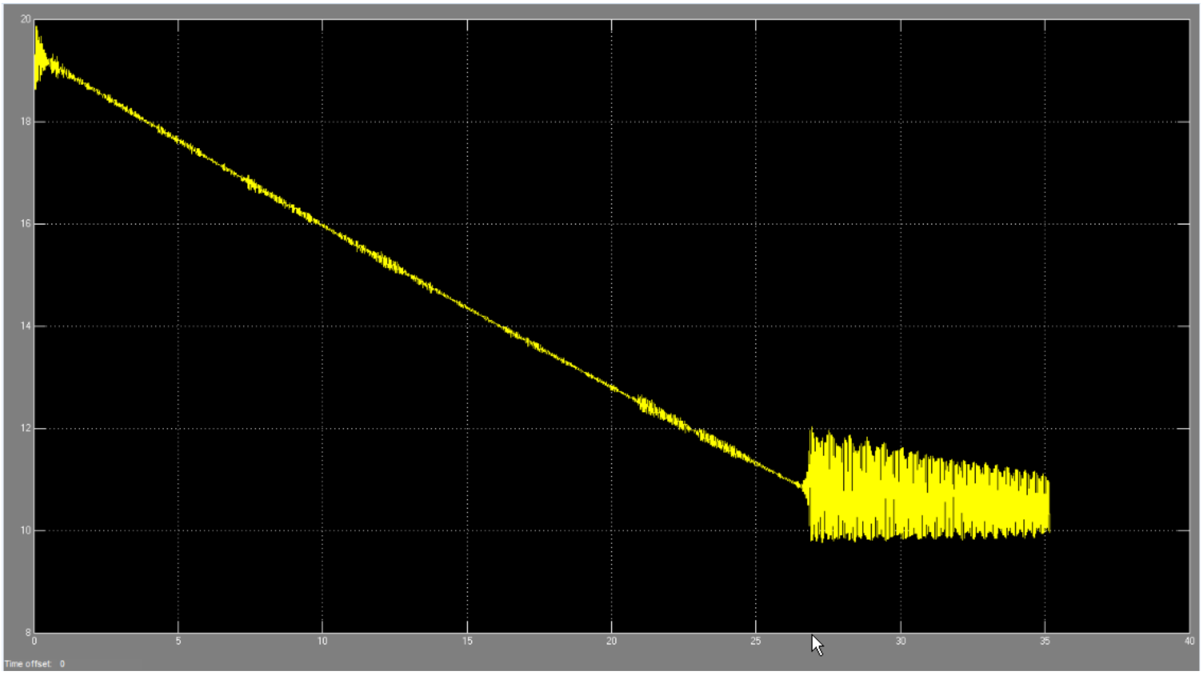

Figure 11: Result obtained after simulation of the controlled system

4.Conclusion

In this lab, modeling and application of a computer controlled fluid (water in this lab) level tank system was executed for practical applications of conventional PID control method. The results of the experimental studies were clearly carried out the fundamental control algorithms on the water level process and we have seen that the proportional controller is not well suited for the control of this system. By means of the Matlab/Simulink software, the process could be controlled by the computer-based control structures and analyzed under the different operating conditions in detail.

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