University of Strathclyde

Department of Electronic and Electrical Engineering

EE472 Coursework

Assessment

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Glasgow, 2017

1. Construct the system model in Simulink

1a) Implement the two valves and plot their input-output characteristics.

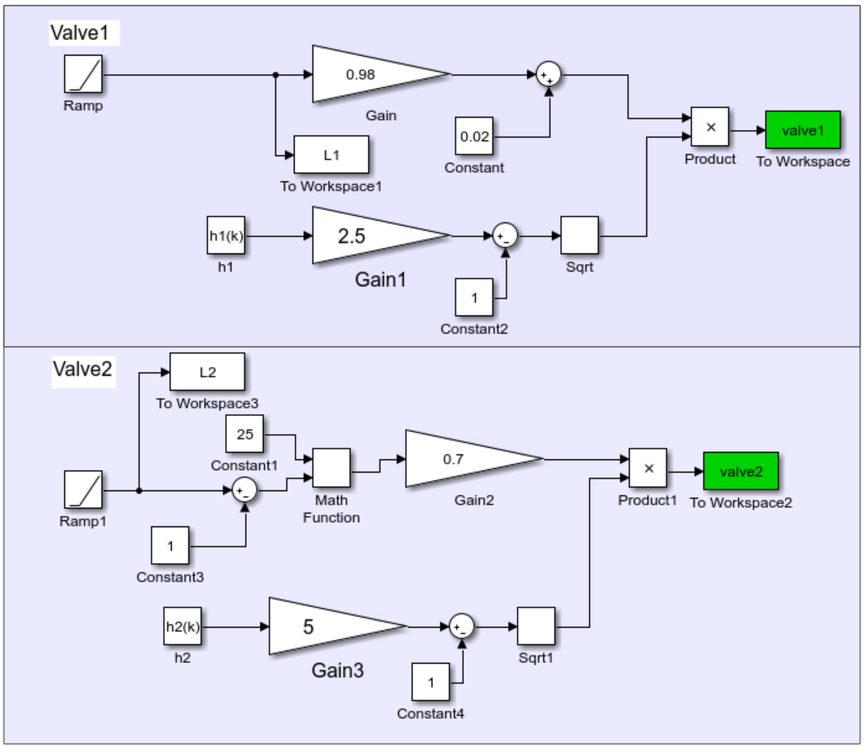

Fig.1. Valve 1 and Valve 2 simulink model.

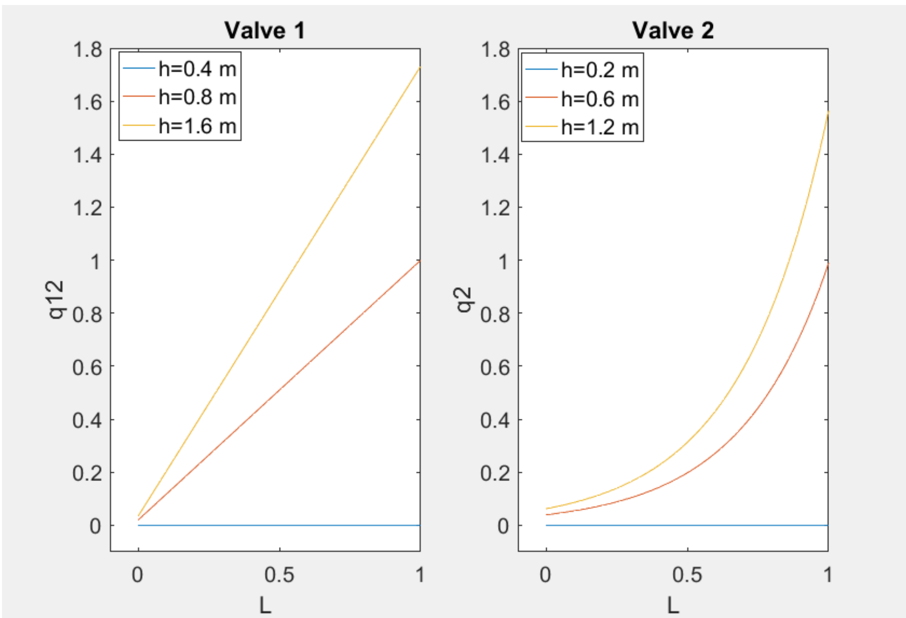

Fig. 2. Input-output characteristics of the valve 1 and valve 2.

Valve 1 is linear, but valve 2 is strong nonlinear. q12(L=0) and q2 (L=0) signals for any of h greater than the minimal value, is greater than zero. It means that the valves cannot be fully switched off at all times using only control signal.

1b) Implement two tanks

Tanks can be described by equation 1.1., then taking the Laplace transform, one can obtain the transfer function.

$$D\frac{d}{dt}(h(t)) = q_{in}(t) - q_{out}(t) \tag{1.1}$$

$$D(sH(s)) = Q_{in}(s) - Q_{out}(s) \tag{1.2}$$

$$H(s)) = \frac{1}{s}\frac{1}{D}(Q_{in}(s) - Q_{out}(s)) \tag{1.3}$$

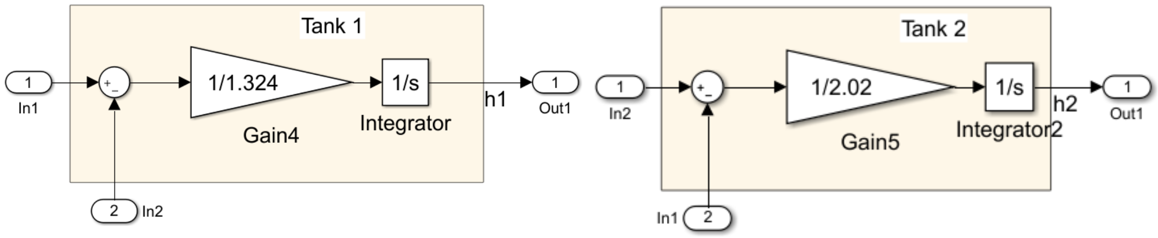

Fig. 3. Simulink models of tank 1 and tank 2.

1c) Implement PI controllers and the valve lift constraints.

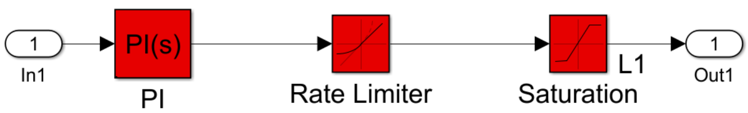

Fig. 4 Simulink models for PI controllers and the valve lift constraints (both are the same).

1 d) Link the sub-systems to construct the whole closed-loop system.

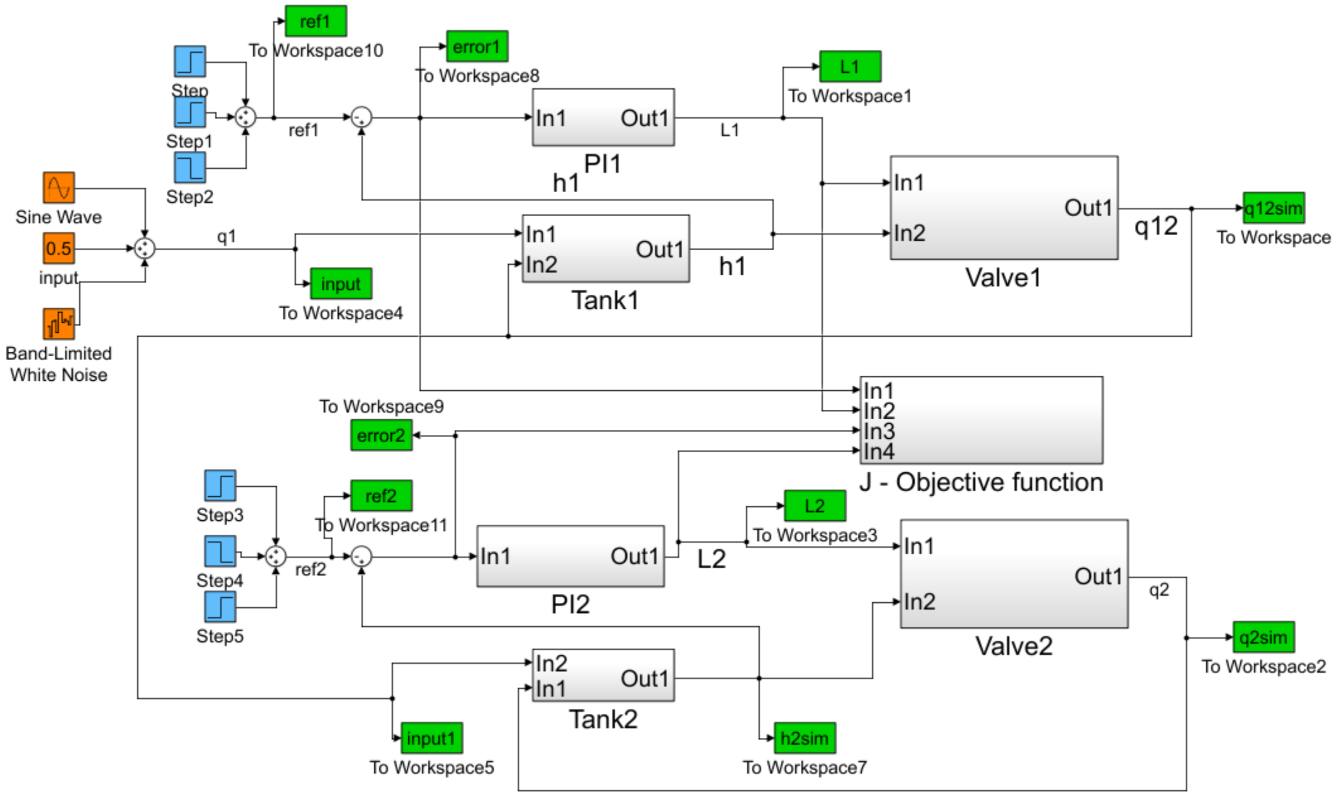

Fig. 5 Simulink model of the entire system.

2. Tune the two PI closed-loop control system

2 a) Tune the PI controllers to give satisfactory step responses (PI1)

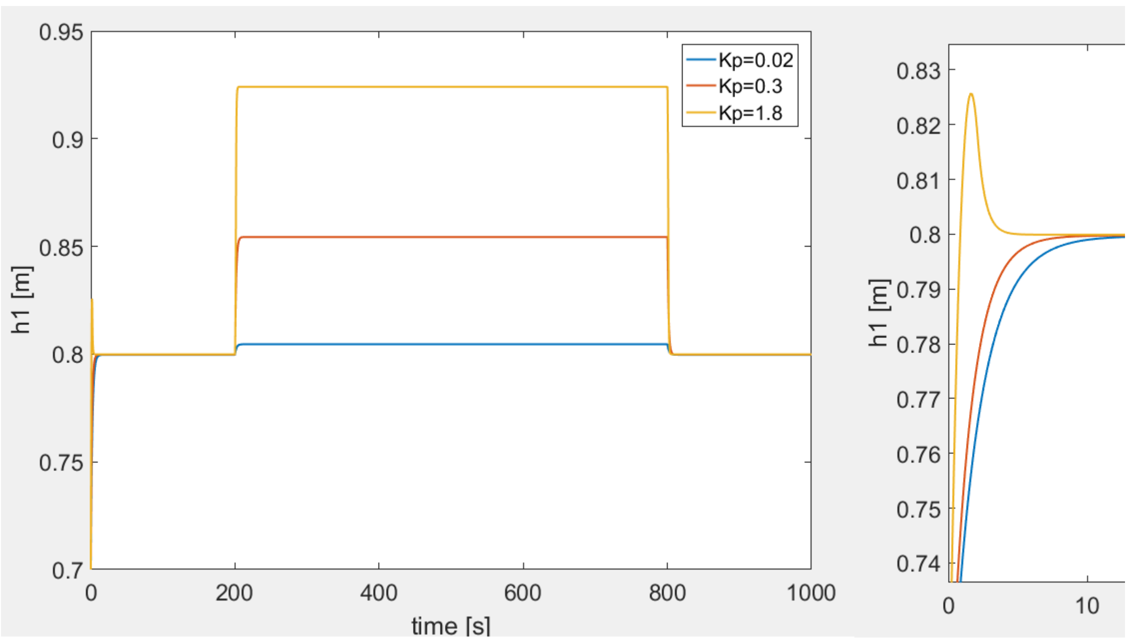

Fig. 6 Tuning Kp, Ki=0, constant q1, best Kp=0.3,

System 1 (tank1 + PI1 + valve1) was separated from the system for tuning. At first Ki=0, input signal q1 equals to 0.5 (no sine), and various values of Kp are checked. The bigger is the Kp, the smaller is steady state error, however, more oscillation at time=0 s (caused by initial condition of the tank). Critically response at time=0 was prioritized, over steady state error, because steady state error will be diminished by integrator gain (Ki). Best proportional gain equals to 0.3.

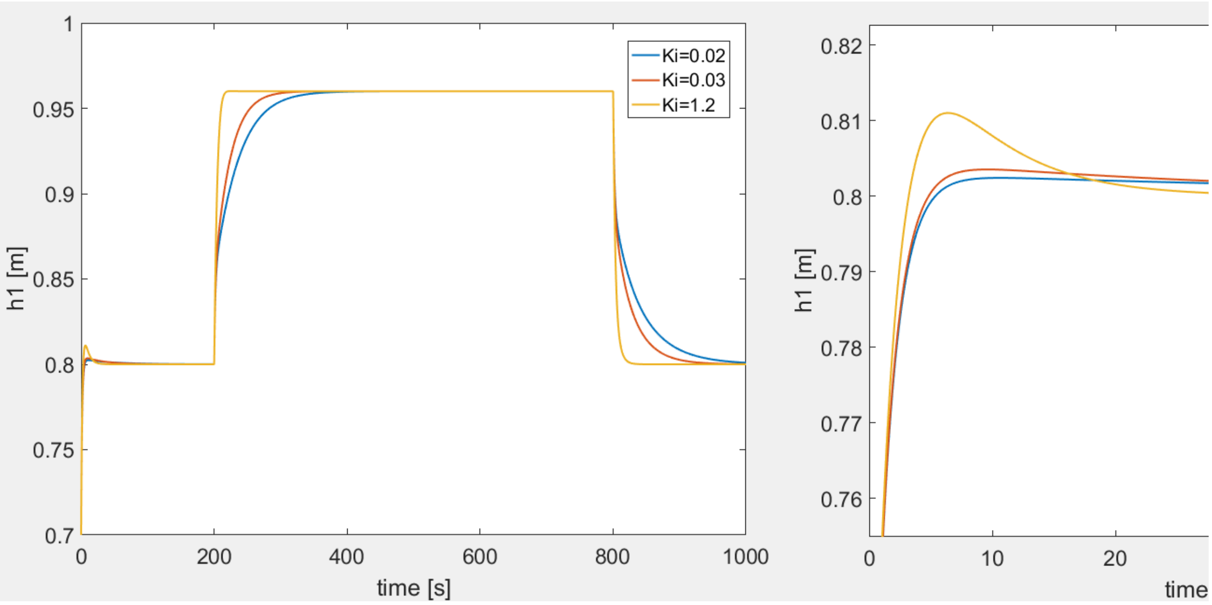

Fig. 7 Tuning Ki, Kp=0.3, constant q1, best Ki=0.02

Kp=0.3, input signal q1 equals to 0.5 (no sine), and various values of Ki are checked. The bigger is the Ki, faster the system responds and smaller is steady state error, however, more overshoot at time=0 s (caused by initial condition of the tank). Critically response at time=0 was prioritized, over faster response in the second stage (t=200 s and t=800 s) and smaller steady state error. Best integral gain equals to 0.02.

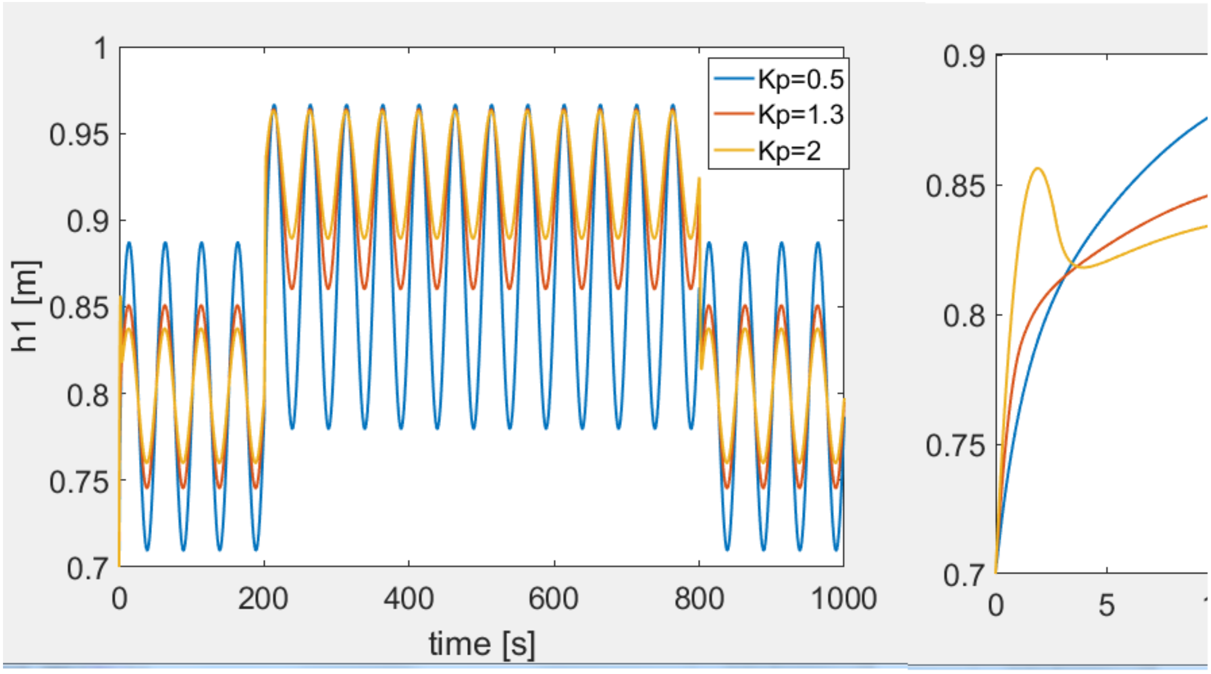

Fig. 8 Tuning Kp, Ki=0, sine added, best Kp=1.3.

At first Ki=0, input signal q1 equals to 0.5 + sine, and various values of Kp are checked. The bigger is the Kp, the smaller is steady state error, however, more oscillation at time=0 (caused by initial condition of the tank). Small overshoot at time=0 was prioritized, over steady state error. Best proportional gain equals to 1.3.

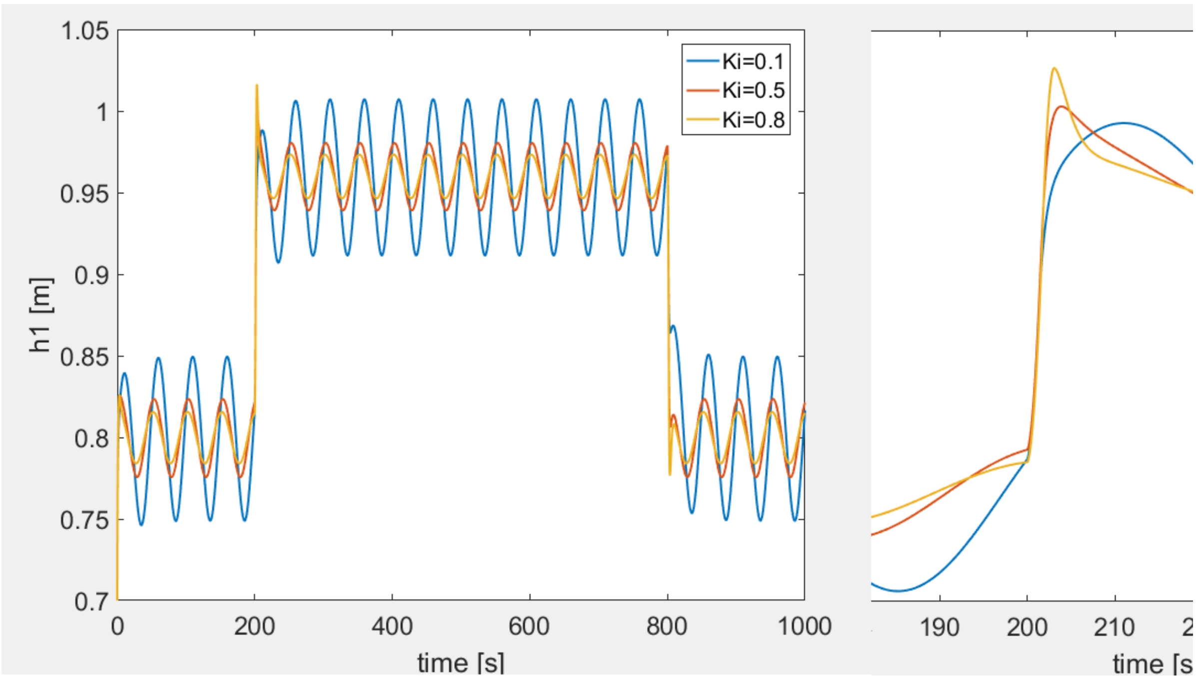

Fig. 9 Tuning Ki, Kp=1.3, sine added, best Ki=0.5.

Kp=1.3, input signal q1 equals to 0.5 + sine, and various values of Ki are checked. The bigger is the Ki, the smaller is steady state error, however, more overshoot at time=200 (caused by change of reference signal). Small overshoot at time=200 s was prioritized, over small steady state error. Best integral gain equals to 0.5.

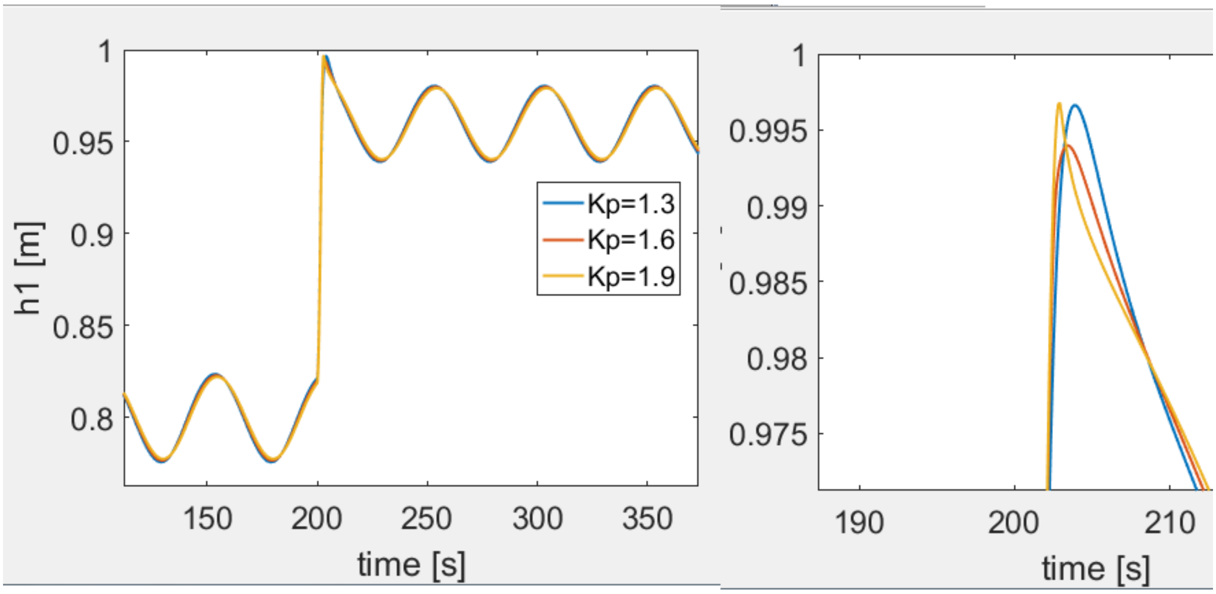

Fig. 10. Tuning Kp, Ki=0.5, sine added, best Kp=1.6.

After performing many simulations, it turned out that sine wave in the input introduce more error than steady state error transient error without it. That is why values close to Kp=1.3 and Ki = 0.5 where further evaluated. Then small correction of Kp=1.6 was performed, due to slightly smaller oscillaton at time=200s. Best proportional gain equals to 1.6.

Final values for PI1:

Kp=1.6

Ki=0.5

2 a) Tune the PI controllers to give satisfactory step responses (PI2)

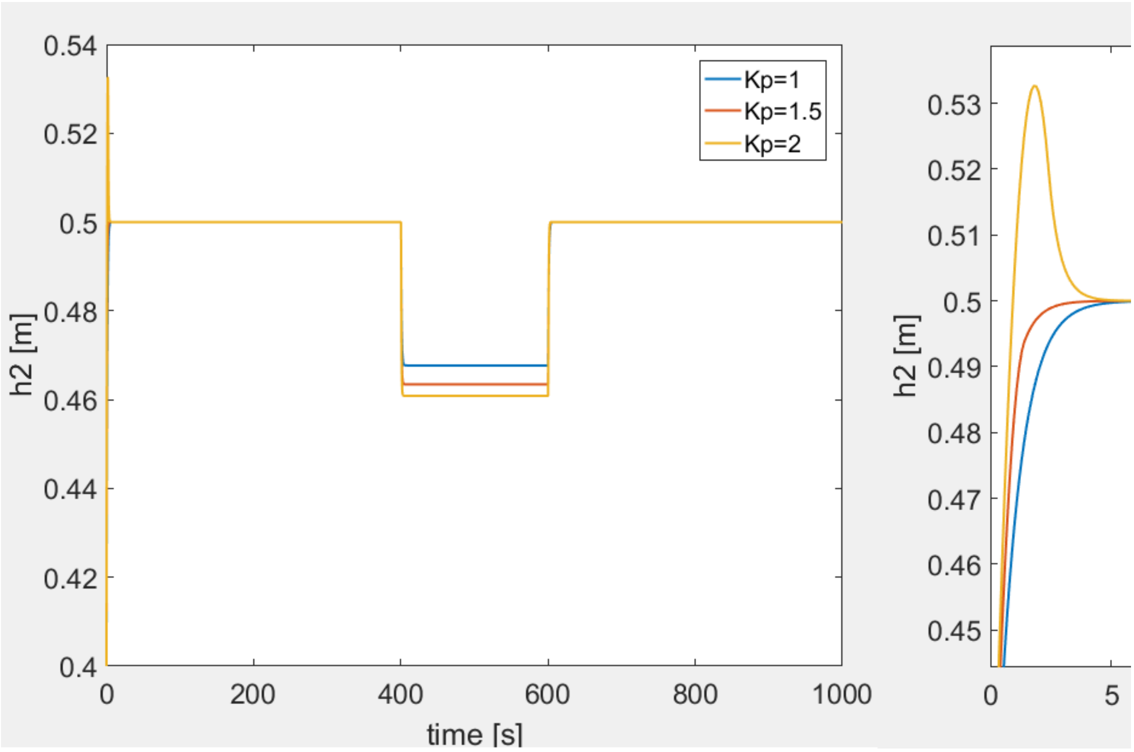

Fig. 11. Tuning Kp, Ki=0, constant q12, best Kp=1.5,

System 2 (tank2 + PI2 + valve2) was separated from the system for tuning. At first Ki=0, input signal q12 equals to 0.5 (no sine), and various values of Kp are checked. The bigger is the Kp, the smaller is steady state error, however, more oscillation at time=0 (caused by initial condition of the tank). Critically response at time=0 was prioritized, over steady state error, because steady state error will be diminished by integrator gain (Ki). Best proportional gain equals to 1.5.

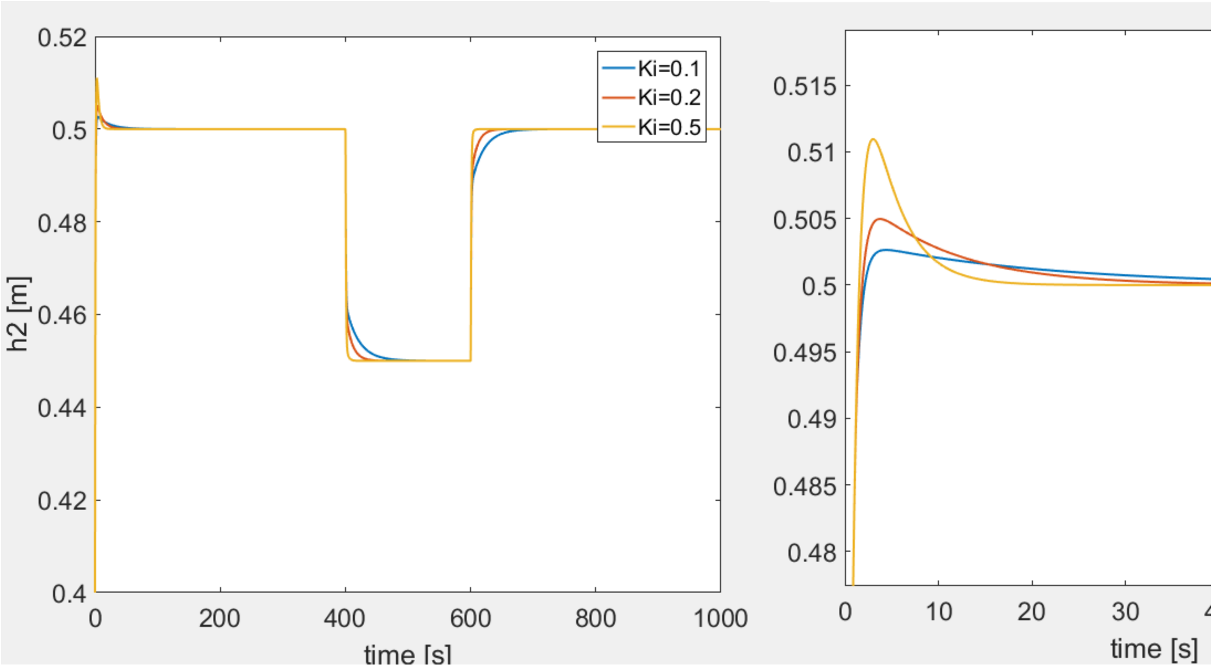

Fig. 12. Tuning Ki, Kp=1.5, constant q12, best Ki=0.2.

Kp=1.5, input signal q12 equals to 0.5 (no sine), and various values of Ki are checked. The bigger is the Ki, the faster responds the system and smaller is steady state error, however, more overshoot at time=0 s (caused by initial condition of the tank). Critically response at time=0 was prioritized, over faster response in the second stage (t=400 s and t=600 s) and smaller steady state error. Best integral gain equals to 0.2.

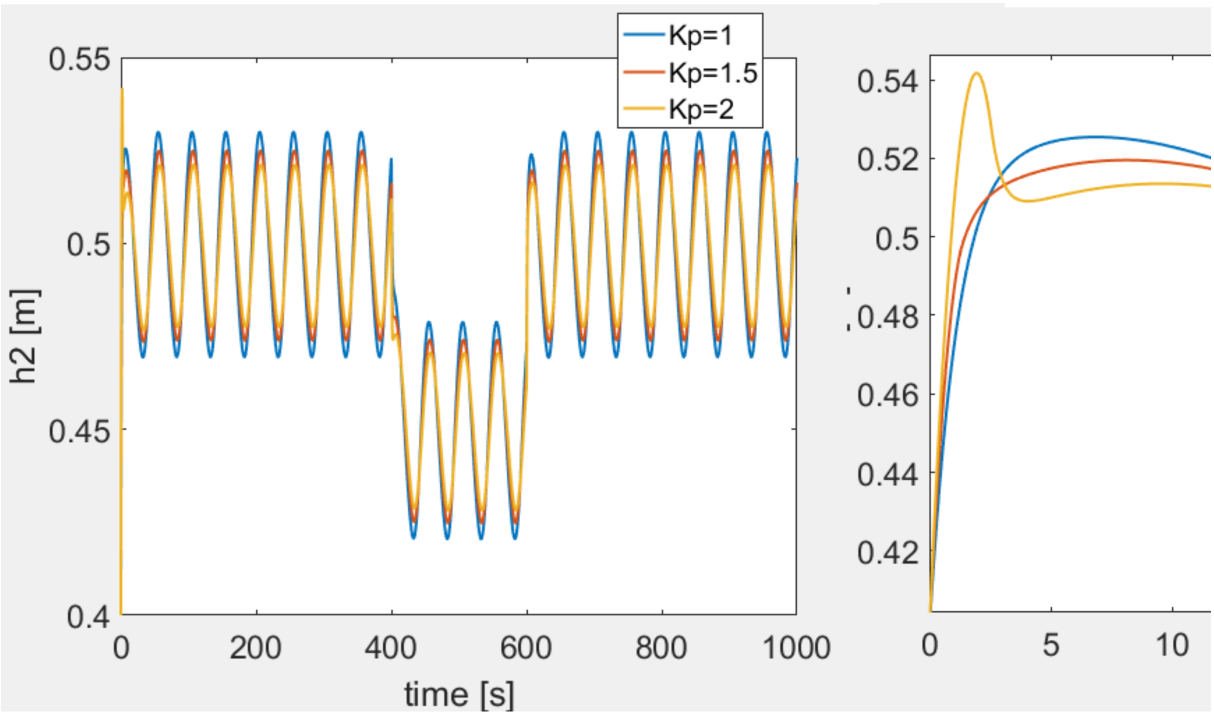

Fig. 2 Tuning Kp, Ki=0, sine added, best Kp=1.5.

At first Ki=0, input signal q12 equals to 0.5 + sine, and various values of Kp are checked. The bigger is the Kp, the smaller is steady state error, however, more oscillation at time=0 (caused by initial condition of the tank). No overshot at time=0 was prioritized, over steady state error. Best proportional gain equals to 1.5.

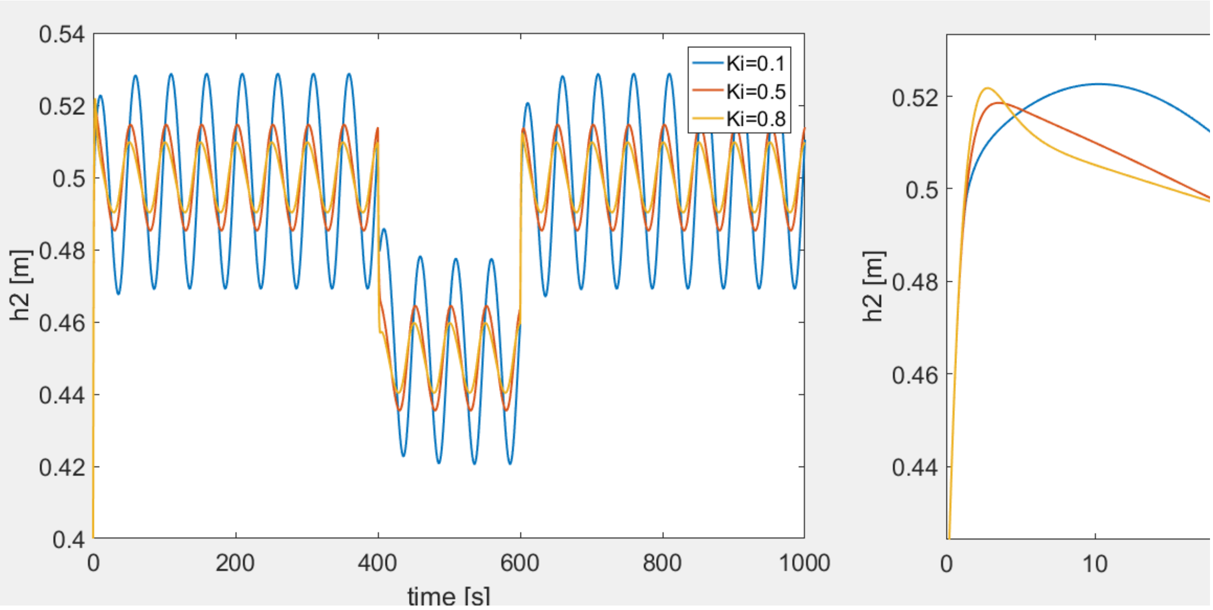

Fig. 13. Tuning Ki, Kp=1.3, sine added, best Ki=0.5.

Kp=1.5, input signal q12 equals to 0.5 + sine, and various values of Ki are checked. The bigger is the Ki, the smaller is steady state error, however, more overshoot at time=0 (caused by initial condition of the tank). Small overshoot at time=0 s was prioritized, over small steady state error. Best integral gain equals to 0.5.

After performing many simulations, it turned out that sine wave in the input introduce more error than steady state error transient error without it. That is why Values close to Kp=1.3 and Ki = 0.5 where further evaluated, but any other value of any gain seemed to be better. No corrections were made.

Final values for PI2:

Kp=1.5

Ki=0.5

Finally linking the system together and adding the noise, one can see the result:

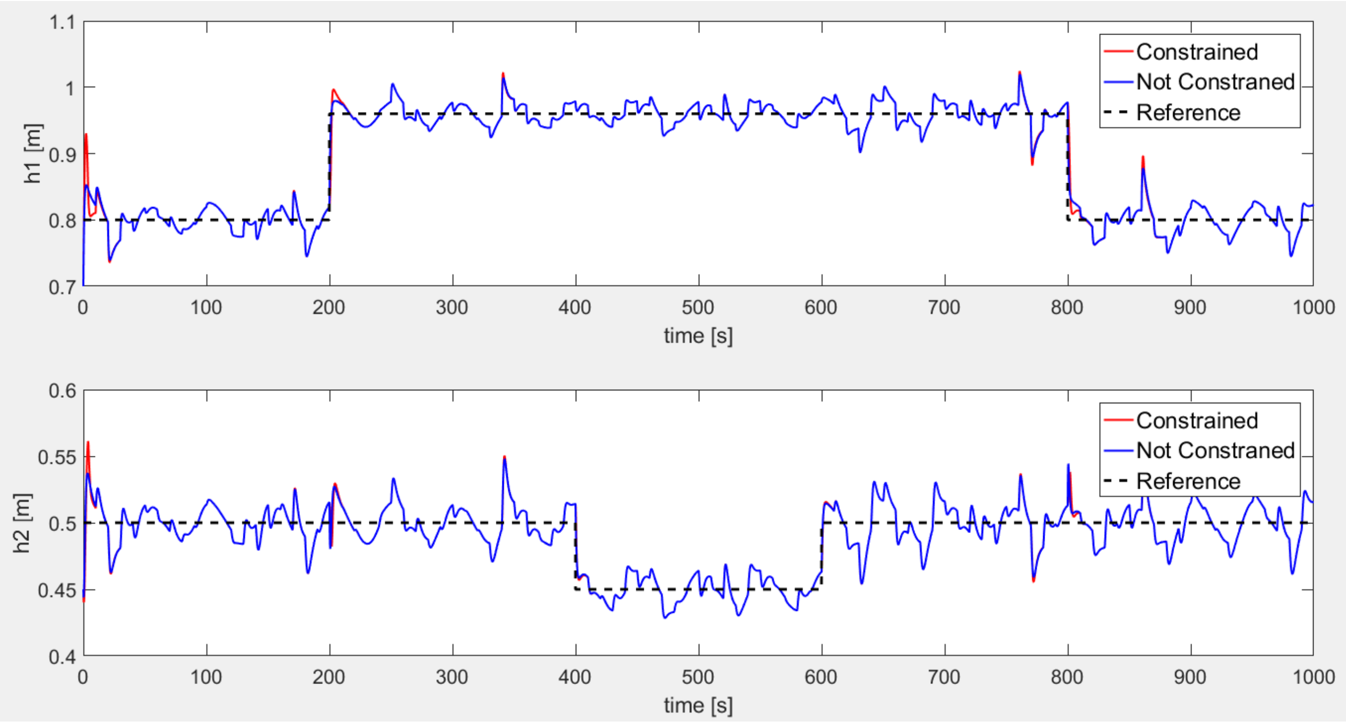

*Fig. 2 Tank**s** level together with the reference tank level, for constrained and unconstrained valve lift signal Kp1=1.6 Kp2=1.5, Ki1=Ki2=0.5.*

2 a) Plot the unconstrained control signal together with the constrained valve lift. (when the controller is tuned, it is difficult to see the difference, that is why NOT tuned system is shown)

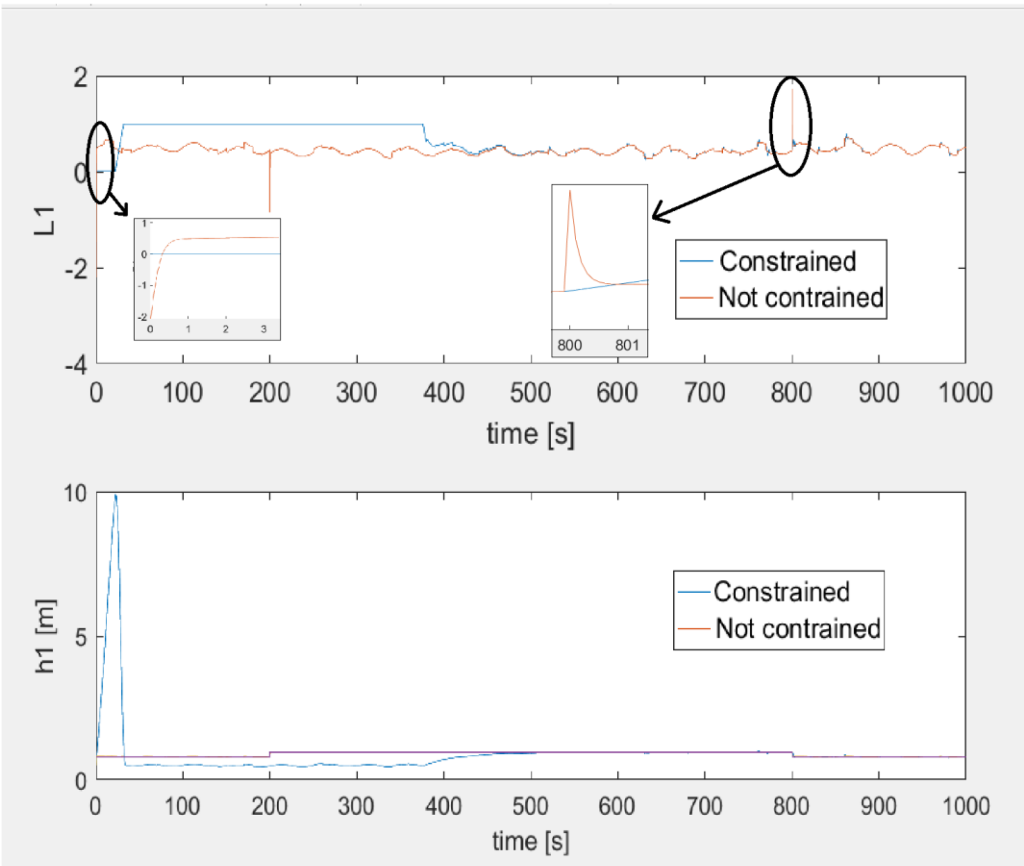

Fig. 2 Unconstrained/Constrained valve lift and h(t) for Tank 1.

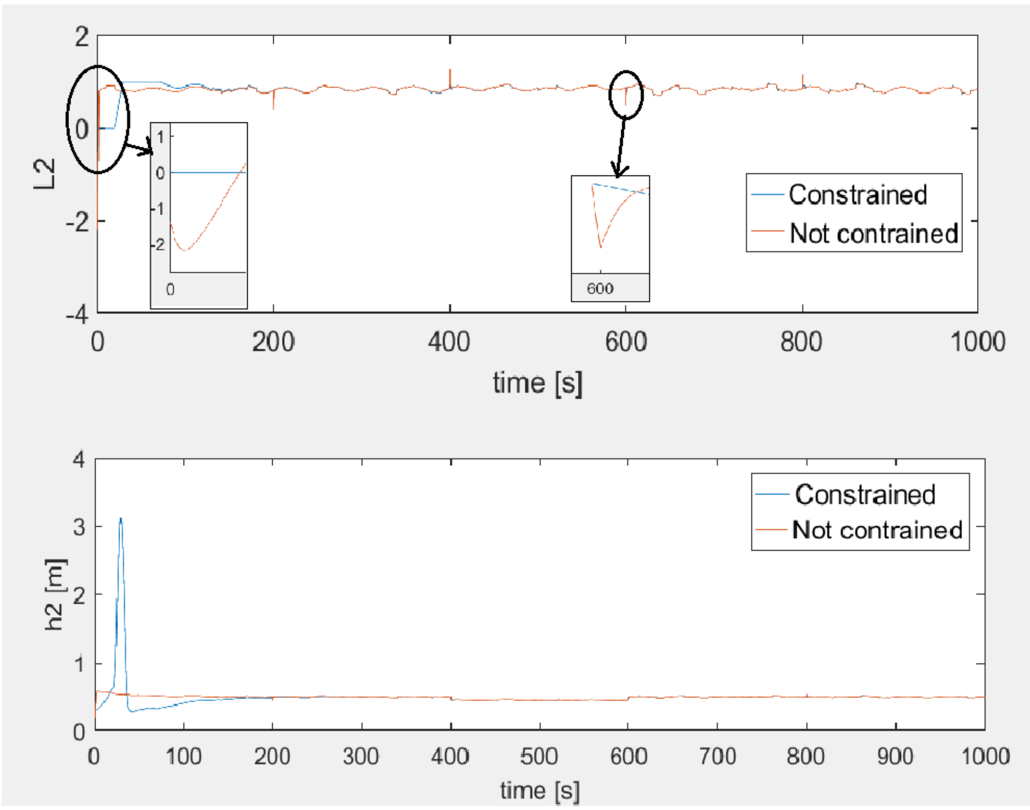

Fig. 14. Unconstrained/Constrained valve lift and h(t) for Tank 2.

2 b) Discuss when and why is the valve lift saturating?

Saturation occurs at any time that there is a mismatch between desired value and actual value of h e.g. at t=0. Saturation occurs because controller responds too fast than the saturation constraint allows. Saturation constraint has to be used, because it carries the physical meaning of the system (It is not possible to open the lift more than 100%, or less than 0%)

2 c) Discuss how does the noise term in the inflow affect the performance?

The noise is a signal with high rate of change. Normally control system is designed to respond as fast as possible, yet not causing an overshoot, thus system responds very rapidly to keep up the quick change. Unfortunately due to the nature of noise it drops quickly one more time. It means that the control signal cannot be too fast because it will hit the saturation limit and then drop very quickly again. It would not be the best option to increase time constant of the controller, because the system would be too slow for normal signal change (not noised). Time rate-limiter is used not to hit the saturation too fast. Control with no constraints is also very unrealistic. In real world rate limiter may be also necessary if the control signal has a form of voltage, very high dv/dt will cause undesired high current flow.

3. Improve the performance using a controller design method.

3 a) Implement the objective function in Simulink.

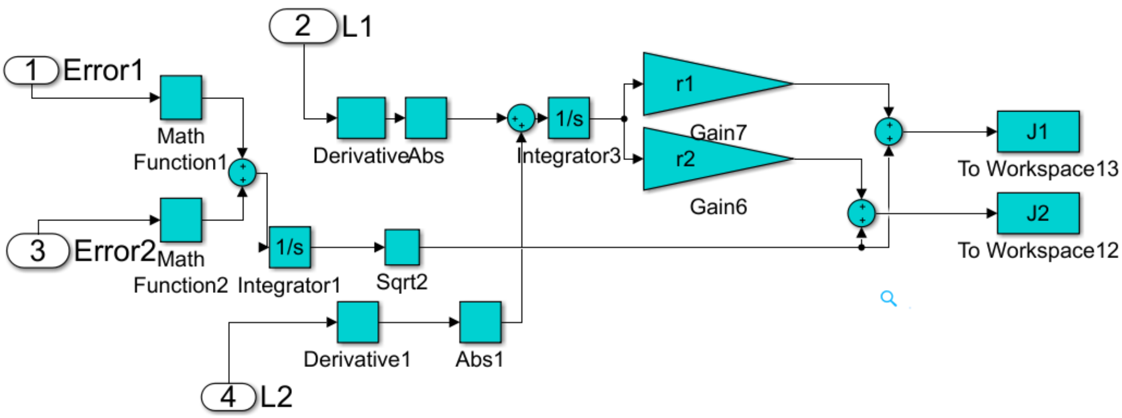

Fig. 15. Objective function, r1=0.1, r2=10.

3 b) Choose two different values of r, tune the PI controller to get the minimum J for each r.

The values of gains were chosen experimentally.

kp1	ki1	kp2	ki2	J1 (r=0.1)	J2 (r=10)
1.6	0.5	1.5	0.5	2,658972	185,6397
1.5	0.5	1.5	0.5	2,65383	184,6767
0.5	0.5	1.5	0.5	2,754262	181,276
0.8	0.5	1.5	0.5	2,691133	180,7649
0.8	0.5	0.5	0.5	2,778487	181,7776
0.8	0.5	0.8	0.5	2,734092	180,5329
0.8	0.5	1.5	0.5	2,691133	180,7649
0.8	0.5	2	0.5	2,677177	181,4474
0.8	0.2	0.8	0.5	3,031953	164,2326
0.8	0.4	0.8	0.5	2,787314	176,6017
0.8	0.5	0.8	0.5	2,734092	180,5329
0.8	0.7	0.8	0.5	2,691353	186,9228
0.8	1	0.8	0.5	2,709333	195,7297
0.8	0.8	0.8	0.2	2,864019	168,991
0.8	0.8	0.8	0.4	2,755182	177,7827
0.8	0.8	0.8	0.5	2,734092	180,5329
0.8	0.8	0.8	0.7	2,720031	184,7529
0.8	0.8	0.8	1	2,730144	189,754
0.8	0.2	0.8	0.05	3,173657	139,8979
0.8	0.2	0.8	0.1	3,163799	145,3411
0.8	0.2	0.8	0.2	3,110489	154,0301
0.8	0.2	0.8	0.4	3,042896	161,9709
0.8	0.05	0.8	0.05	3,347626	118,8125
0.6	0.05	0.8	0.05	3,859707	104,8132
0.4	0.05	0.8	0.05	3,347626	118,8125
1.2	0.05	0.8	0.05	3,130048	129,711
0.2	0.05	0.2	0.05	4,704037	88,53145
			Min:	2,65383	88,53145

Table 1. 15. Finding minimum of the objective function, r1=0.1, r2=10.

For r=0.1 → kp1=1.5 ki1=0.5 kp2=1.5 ki2=0.5

For r=10 → kp1=0.2 ki1=0.05 kp2=0.2 ki2=0.05

3 c) Comparing the two design in (3b), discuss the effects of the weighting factor (r) on control performance

$$J = \sqrt{\int_0^{t_f}\left[\left(h_1(t)-h_{1REF}(t)\right)^2+\left(h_2(t)-h_{2REF}(t)\right)^2\right]\mathrm{d}t} + r\int_0^{t_f}\left[\left|\frac{\mathrm{d}L_1(t)}{\mathrm{d}t}\right|+\left|\frac{\mathrm{d}L_2(t)}{\mathrm{d}t}\right|\right]\mathrm{d}t \qquad (3.4)$$

The formula for the objective function can be divided into two parts, one comprising of height error, and one comprising of rate of change of valve control signal. The first one represent the error from the desired value and the other how much the actual plant (valve) has to be used (it is associated with the degradation cost of physical parts of the plant, like bearings). It is not surprising that original design was very close to the minimal objective function for r equal to 0.1, because it almost does not include the second part of the formula. The rate of change of control signal of the signal will be smaller if the gains of the controller are smaller, however, the control will be slower which will lead to increase of the error of the first part of the formula 3.4. In the final design not only the error of desired quantity, but also the cost related to the active part of the plant (like bearings or transistors). Additional data, like cost of these parts, cost of not providing the service (power if, that is a wind turbine), should be taken into account, together with additional reliability calculation.

DEPARTMENT OF ELECTRONIC & ELECTRICAL ENGINEERING

University of Strathclyde Engineering

EE472 Control Principles

Semester 2 Project Assignment 2016/2017

Lecturer: Dr. Hong Yue

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Project sessions: 9:00am – 11:00am, Mondays (Group A) and Wednesdays (Group B), Weeks 29, 31 and 33.
Laboratory: RC446 and RC448, Royal College Building

Project report submission

The project report should be submitted as a single pdf document, maximum 20 pages, to MyPlace by **Friday, 24th March 2017.** A late penalty of 10% for the first week followed by 5% per day will be applied to submissions after the deadline.

Plagiarism

Please read the University's policy and guidance on plagiarism, here:
http://www.strath.ac.uk/media/ps/cs/gmap/plagiarism/plagiarism_student_booklet.pdf

A plagiarism declaration – attached to this booklet and available on MyPlace – must be signed and handed to the EEE Resources Centre by **Friday, 24th March 2017**.

1. Project description

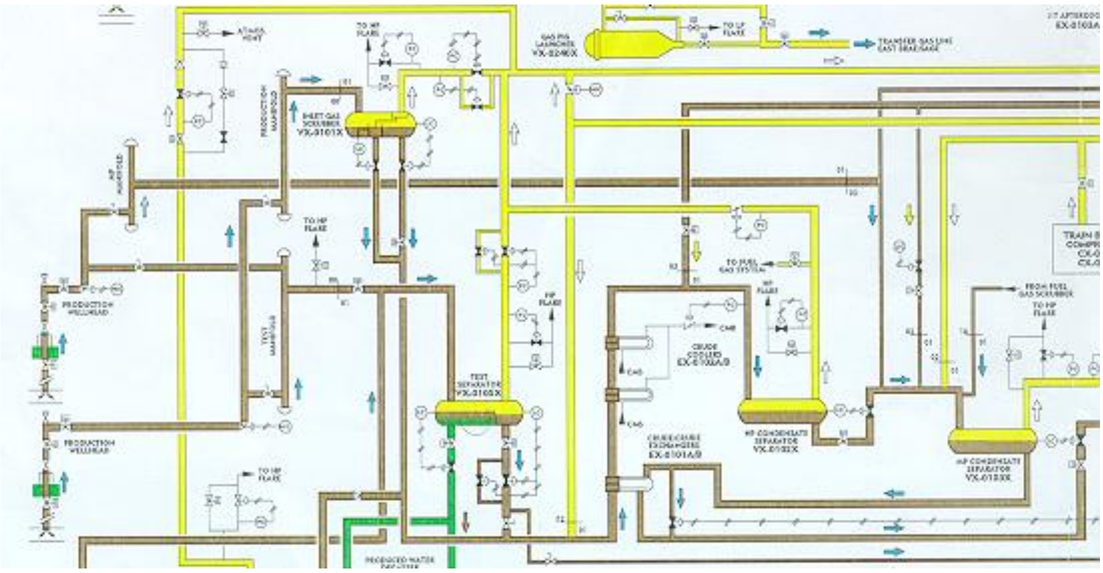

Fig. 1: Slug catcher installation platform

Slug catcher is the part of the oil platform installation where the crude oil excavated from the bottom of the sea enters the platform (Fig.1). The crude oil consists of three main components: the oil, the gas and the water. Due to physical phenomena occurring during the transportation of crude oil through the long pipes, so called “slugs” are formed. These are high concentration of gas in the pipe travelling with the oil. When a slug of gas reaches the platform, the proportion of the three components in the crude oil changes. The purpose of the slug catcher installation is to act as a buffer, to remove the water, to separate the gas from the oil and to supply this ‘cleaned’ crude oil to other plants downstream in the installation.

For the purpose of this project we will consider a simplified scheme consisting of two tanks in the installation: the *Slug catcher vessel* and the *Free-water-knock-out vessel* (Fig. 2). In order to make the Slug catcher plant function effectively, the level of crude oil in both tanks has to be maintained between an upper and lower limit. The level is also used as surge capacity to ensure a continuous and constant flow of crude oil downstream to other units. Each of the tanks is equipped with a level control loop, which is a PI controller acting on a valve downstream. For the first tank the valve is a proportional one; for the second tank, it is an equal percentage valve. The process outputs to be controlled are tank levels h_1 and h_2, and the controller output are the valve lifts L_1 and L_2.

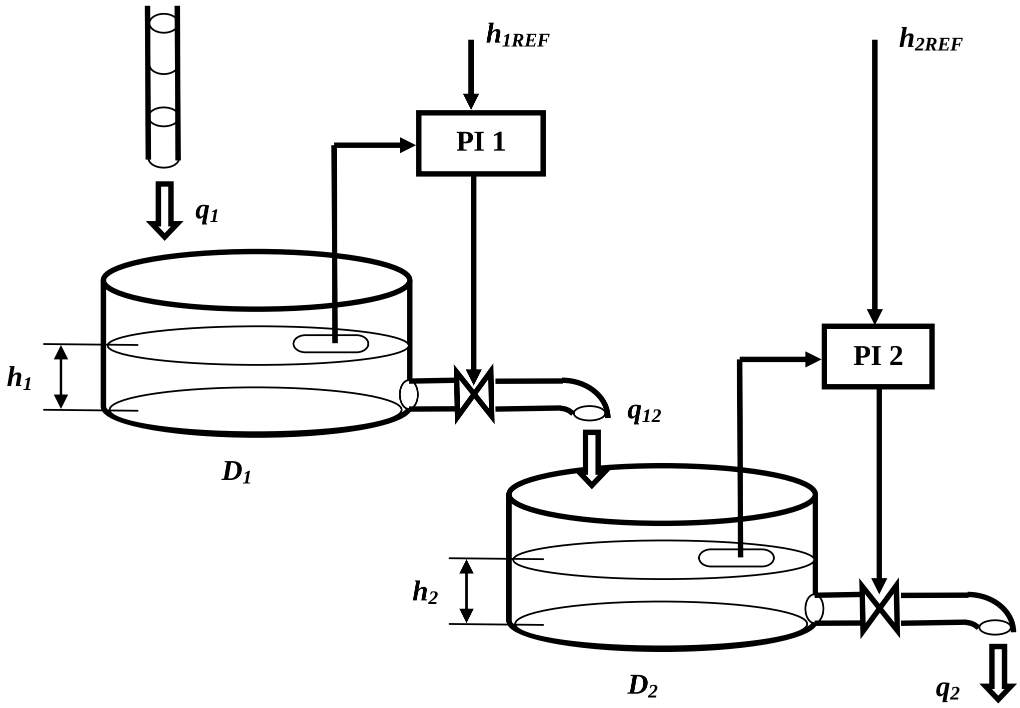

Fig. 2: Schematic diagram of the two-tank system

The system consists of the following components:

Tanks

$$D_i \frac{\mathrm{d}}{\mathrm{d}t} h_i = q_{in} - q_{out}, \qquad i = 1,2$$

D_i - tank area, h_i - tank level, q_{in} - inlet flow rate, q_{out} - outlet flow rate.

Valve 1 (Proportional valve)

$$q_{12} = q_{1nom}\left(\left(1 - f_{1\min}\right)L_1 + f_{1\min}\right)\sqrt{\frac{h_1}{h_{1\min}} - 1} \qquad \text{with} \qquad f_{1\min} = 0.02$$

Valve 2 (Equal percentage valve)

$$q_2 = q_{2nom} R^{L_2 - 1}\sqrt{\frac{h_2}{h_{2\min}} - 1} \qquad \text{with} \quad R = 25$$

L_1, L_2 - valve lift (controller output u_1 and u_2).

Valve lift constraints

The valve lift L_i are subject to the following opening and varying speed constraints:

$$0 \le L_i \le 1, \qquad -0.1 \le \frac{\mathrm{d}}{\mathrm{d}t} L_i \le 0.1, \qquad i = 1,2$$

PI Controllers (controller output u_i are valve lift L_i).

$$u_i(s) = \left(K_i + \frac{1}{T_i s} \right) \left(h_i(s) - h_{iREF}(s) \right), \qquad i = 1,2$$

Model Parameters

Table 1 Model parameters

Tank	$h_{i\,\min}$	$h_{i\,\max}$	D_i	q_{inom}
1	0.4m	1.6m	$1.324\,\mathrm{m}^2$	1
2	0.2m	1.2m	$2.02\,\mathrm{m}^2$	0.7

Note: the units used in this model are always based on meters (m) and seconds (s)

Reference tank levels
The reference heights for the two tanks, between 0 to 1000 seconds, are given in Table 2.

Table 2 Reference heights for two tanks

	Tank 1			**Tank 2**		
Time (s)	0-200	200-800	800-1000	0-400	400-600	600-1000
h_{iREF} **(m)**	0.8	0.96	0.8	0.5	0.45	0.5

Inflow
The flow to the first tank is a sum of a constant flow, a sinusoidal flow (slug formation) and a stochastic noise, which can be described as

$$q_1(t) = \left(0.5 + 0.1 \sin\left(\frac{2\pi}{50} t \right) + n(t) \right)$$

where $n(t)$ is a band-limited white noise with noise power 0.02 and sampling time 10 seconds.

2. Project tasks

(1) Construct the system model in Simulink

(1a) Implement the two valves and plot their input-output characteristics (q vs. L) for minimum, maximum and half of tank level h. **(10%)**

(1b) Implement the two tanks. **(5%)**

(1c) Implement the two PI controllers and the valve lift constraints. **(10%)**

(1d) Link the sub-systems to construct the whole closed-loop system. **(10%)**

(2) Tune the two PI closed-loop control systems

(2a) Considering the reference signal for tank levels given in Table 2, tune the PI controllers to give satisfactory step responses. Justify your choice in PI controller design. For each tank, plot the tank level together with the reference tank level in one scope. Also plot the unconstrained control signal together with the constrained valve lift.

(20%)

(2b) Discuss when and why is the valve lift saturating?

(5%)

(2c) Discuss how does the noise term in the inflow affect the performance?

(5%)

(3) Improve the performance using a controller design method of your choice, minimising the following objective function at $t_f = 1000$:

$$J = \sqrt{\int_0^{t_f} \left[\left(h_1(t) - h_{1REF}(t)\right)^2 + \left(h_2(t) - h_{2REF}(t)\right)^2 \right] \mathrm{d}t} + r\int_0^{t_f} \left[\left| \frac{\mathrm{d}L_1(t)}{\mathrm{d}t} \right| + \left| \frac{\mathrm{d}L_2(t)}{\mathrm{d}t} \right| \right] \mathrm{d}t$$

hint: you do not need to find the theoretical optimal solution. Instead, use the trial-and-error method to get your best solution.

(3a) Implement the objective function in Simulink. **(10%)**

(3b) Choose two different values of *r*, tune the PI controller to get the minimum J for each *r*.

(20%)

(3c) Comparing the two design in (3b), discuss the effects of the weighting factor (*r*) on control performance.

(5%)

Appendix:

Plagiarism Declaration

Student name:

Student registration number:

I certify that:

- I have read and understood the University of Strathclyde Student Guide on Good Academic Practice and the Avoidance of Plagiarism;

www.strath.ac.uk/media/ps/cs/gmap/plagiarism/plagiarism_student_booklet.pdf

- This assignment is all my own work, and no part of this assignment has been copied from another person;

- I have not allowed my work to be copied by another person.

Signature:

Date:

Students must produce their own individual written work. Copying someone else's work is plagiarism, and is unacceptable. The University may impose severe penalties for plagiarism.