Sheet 1

[1] Define the term process and give some examples.

[2] State some goals of process control.

[3] In the hierarchy of control systems, for which layer does a simple feedback control loop lie?

[4] List some types of control systems.

[5] In a single-loop PID controller, why is there an option to turn the controller OFF by switching into Manual mode?

[6] In a DCS system, why is there a secondary control processor and even a secondary network?

[7] Compare DCS to a PLC in terms of scan time, analog/digital focus, and the need for a network.

[8] What do the following terms refer to?

ESD - HMI - P&ID

[9] Why does the standard output range, 4-20 mA, of a transmitter in process control start from 4 mA and not 0 mA?

Sheet 2

[1] What are the three questions that a mathematical model attempts to answers in the context of process control?

[2] State suitable material balance to use when modeling systems involving the following variables: **liquid level** – **temperature** – **concentration**.

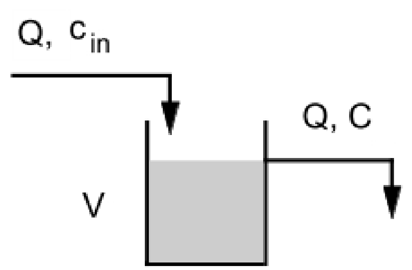
[3] Consider the following model for the stirred tank heater

$$T(s) = \frac{5}{s+1} T_H(s) + \frac{1}{s+1} T_i(s)$$

Where $\boldsymbol{T}$ is the temperature of the liquid in the tank, $\boldsymbol{T_i}$ is the inlet liquid temperature, $\boldsymbol{T_H}$ is the temperature of the heating liquid. It is required to control the liquid temperature $\boldsymbol{T}$ using feedback control with a PI controller $G_c(s) = \left(2 + \frac{1}{s}\right)$.

(a) Which variable do you suggest being the manipulated variable? And what is the disturbance variable?
(b) Draw a block diagram of the closed-loop system showing all relevant variables: the set-point, the manipulated variable, the disturbance, and the process (controlled) variable.
(c) From the block diagram, find the transfer function **T(s)/T$_i$(s)**.
(d) What is the dc gain of the transfer function **T(s)/T$_i$(s)**? Is the system able to fully reject a unit step load disturbance?

[4] Consider the following continuous-flow stirred-tank. The inlet flow has a rate of **Q** (m^3/s) and a concentration of a certain material of $\mathbf{C_{in}}$ ($gram/m^3$) while the outlet flow has the same rate **Q** and concentration **C** of the same material. The volume of liquid in the tank is **V**. Find the transfer function of the system assuming that the input and output are $\mathbf{C_{in}}$ and **C**, respectively, and the concentration in the tank and the outlet concentration are the same.



Final answer:

$$\frac{C(s)}{C_{in}(s)} = \frac{1}{\tau s + 1}, \quad \tau = \frac{V}{Q}$$

[5] What are the main four blocks and variables in a feedback loop?

[6] Compare servo to regulatory control.

[7] Given the following nonlinear system

$$\frac{dy}{dt} + y = u^2,$$

where y is the output and u is the input.

(a) Using linearization, find a linear approximation for the system.
(b) If the input u experiences a step change from 5 to 5.1, draw the approximate response of the system. Show the initial and final values of the <u>exact</u> and <u>approximate</u> responses on the graph.
(c) Repeat part (b) if the input changes from 5 to 6.
(d) Comment on the results of part (b) and (c).

[8] With the aid of linearization, find the transfer function of the following nonlinear system around u = 0. Then, sketch the approximate step response:

$$\frac{dy}{dt} + y = \sin(u).$$

Final Answer:

The given equation can be rewritten as:

$$\dot{y}(t) = f(y, u) = -y + \sin(u)$$

$$\rightarrow \quad \frac{\partial f}{\partial y} = -1, \quad \frac{\partial f}{\partial u} = \cos(u)$$

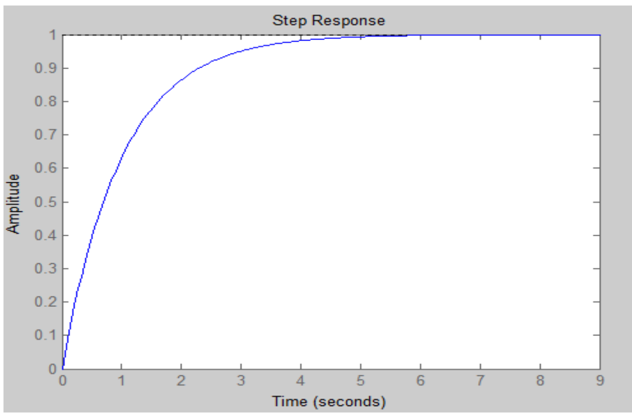
In terms of deviation variables, $u^*=u-u_0$ and $y^*=y-y_0$:

$$\dot{y}^*(t) = \left.\frac{\partial f}{\partial y}\right|_{u=0} y^* + \left.\frac{\partial f}{\partial y}\right|_{u=0} u^*$$

$$\rightarrow \quad \dot{y}^*(t) = -y^* + u^*$$

$$\rightarrow \quad \frac{Y^*(s)}{U^*(s)} = \frac{1}{s+1}$$

Thus, the step response will be as shown.



Sheet 3

[1] True or False:

1. Safety is one of the main objectives in process control.
2. In servo control, the goal is to track set-point changes.
3. To formulate a model involving temperature, we employ energy balance.
4. To formulate a model involving concentration, we should apply energy balance.
5. With the aid of linearization, we can obtain a transfer function of nonlinear systems.
6. The higher the time constant, the faster is the process.
7. Dead-time is usually the result of material transportation through e.g. a pipe.
8. The larger the time delay in a control loop, the less stable it becomes.
9. First-order processes are self-regulating while integrating processes are not.
10. Non-self-regulatory processes must be put under feedback control.

[2] Classify each of the following processes into *self-regulatory* or *non-self regulatory*.

$(a)\ \frac{1}{(s+1)},$

$(b)\ \frac{1}{(s+1)(s+2)},$

$(c)\ \frac{1}{s(s+1)},$

$(d)\ \frac{1}{s(s-1)}\ .$

[3] Consider the following process graph.

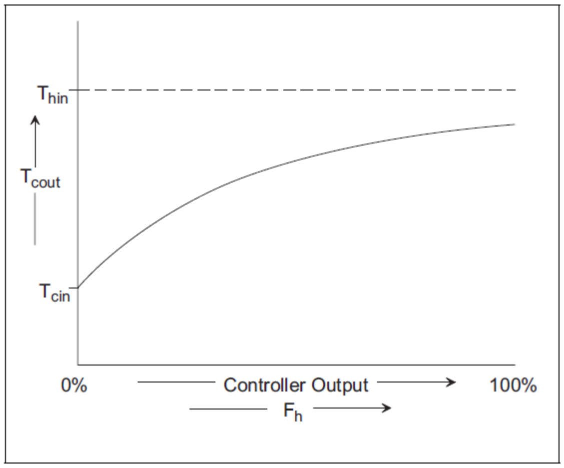


Figure 3-2. The Process Graph

a. Can we predict the shape of the step response from this graph? Why or why not?

b. For which values of controller output (low or high) is the process gain maximum?

c. If you are asked to design a controller for this process, which value of gain (low or high) do you assume or take into account?

[4] Why are processes with long dead-time difficult to control?

[5] Find a first-order plus time delay (FOPDT) approximation of the following transfer function:

$$\frac{Y(s)}{U(s)} = \frac{1}{(s+1)(2s+1)(3s+1)(10s+1)}$$

Use MATLAB commands to plot the exact and approximate step responses.

Sheet 4

[1] True or False Questions

1. Higher-order plants can be well approximated by first-order system with time delay.
2. Parallel structures result from more than one path, with different time constants, between input and output.
3. The zero in a transfer function can result due to more than one path, with different time constants, between input and output.
4. The presence of a zero in the transfer function always results in an inverse response in the step response.
5. Systems with recycle tend to be slow.
6. Recycle structure increases both the gain and time constant of the system.

[2] What does FOPDT stands for? Draw unit step response of this model.

[3] Name two possible dynamic structures and state the situations in which they usually occur in practice.

[4] What is inverse response? Which process structure causes this type of response?

[5] Sketch the step response of the following process:

$$\frac{Y(s)}{U(s)} = \frac{10e^{-6s}}{10s+1}.$$

Rewrite the transfer function using a first-order Pade approximation of the time delay.

[6] For each of the following transfer functions, sketch the unit step response showing the final value, and state why, if any, there is *overshoot* or *inverse response*?

$$(a)\ \frac{T(s)}{F(s)} = \frac{2s+1}{s^2+2s+1}, \qquad (b)\ \frac{T(s)}{F(s)} = \frac{-s+9}{s^2+6s+9}$$

[7] The following two dynamic systems form a parallel structure:

$$G_1(s) = \frac{2}{(s+1)}, \quad G_2(s) = \frac{-1}{(5s+1)}$$

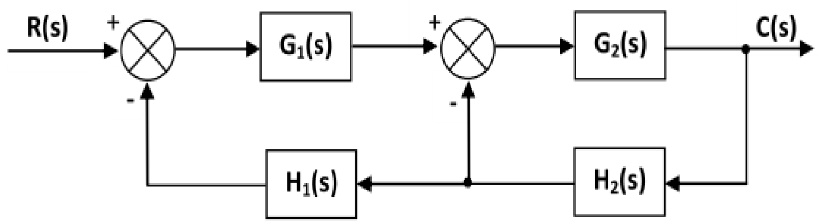
a) What is the steady state gain of the whole system?
b) State whether the response has an *overshoot* or *inverse response*.

Answer: The parallel structure has the following transfer function:

$$G(s) = G_1(s) + G_2(s) = \frac{2}{(s+1)} + \frac{-1}{(5s+1)} = \frac{9s+1}{(s+1)(5s+1)}$$

a) The dc gain is 1.
b) The step response has an *overshoot* since we have a *negative* zero.

[8] Find the transfer function C(s)/R(s) using Mason's gain formula for the following control loop.



Sheet 5

[1] True or False Questions

1. One drawback of ON-OFF control is the oscillation of process variable around set point.
2. The Increasing proportional gain speeds up the system but reduces its stability margin.
3. Controller bias signal is the controller output when the error is non-zero.
4. In a direct action control, as the process output increases, the controller output also increases.
5. The proportional control action depends on past errors.
6. Proportional control cannot remove steady state error.
7. Integral control is used to eliminate offset.
8. Integral action is referred to as the "predictive mode".
9. Integral control is slow compared to proportional control.
10. Too much integral action may make the system unstable.
11. Integral action is good for fast processes.
12. When use integral action, we should lower the proportional gain.
13. Derivative control action is used to reduce overshoot in the transient response.
14. Proportional derivative (PD) control is suitable for noisy signals.
15. Derivative controller action depends on the past values of the error.
16. Derivative control is termed the "persistent mode".
17. Flow rate is the most common manipulated variable in industry.
18. Derivative action is not suitable for flow control.

[2] In a temperature control system, the controlled variable ranges from -20 to 80°C. The set point is 40°C. Assume that the controller is **reverse-acting** (i.e. $e = r - y$, where e is the error, r is the set point, and y is the process variable).

a. What is the value of the error, in percentage of span notations, if the controlled variable is 30°C?
b. If the controller proportional band is 50%, what is the range of **temperature** for which the controller output will change from 0% to 100%? Assume that the controller bias output m_0 is 50%.

Answer: The error as a percentage of span is given by

$$e(t) = \frac{r - y(t)}{y_{\max} - y_{\min}} \times 100\% = \frac{40 - 30}{80 - (-20)} \times 100\% \quad \Rightarrow e(t) = 10\%$$

As the PB = 50%, the controller gain is K_c = 2.

$$m(t) = K_c e(t) + m_0$$

$$0\% = 2(e(t)) + 50\% \qquad \Rightarrow e(t) = -25\% \quad \Rightarrow y = 65°\text{C}$$

$$100\% = 2(e(t)) + 50\% \qquad \Rightarrow e(t) = 25\% \quad \Rightarrow y = 15°\text{C}$$

So, the range of temperature is 15 to 65°C.

[3] Define the controller proportional band.

[4] What is the difference between direct and reverse action controllers

[5] In a level control system with proportional controller, the controlled variable ranges from 4 to 8m. The set point is 6m. Calculate the error as a percentage of span for the following values of the controlled variable: 5, 6, and 7m.

[6] What is the reason for using time proportional controller?

[7] If the controller proportional band is 50%, what is the liquid level that will result in a controller output of 80%? Assume that the controller bias output p_0 is 50%.

[8] A PI controller (G_c = 1+2/s) is applied to a two-tank mixer with transfer function G = $1/(s+1)^2$. Prove that the steady-state offset for a unit step set-point input is zero.

[9] Define integral controller reset time.

[10] Consider a unity feedback system where the process transfer function is:

$$G(s) = \frac{1}{(2s+1)}.$$

What is the offset (steady state error) for a unit-step **load disturbance** at the process input if we use the following PI controller C(s) = 1+1/s. Give your comments.

[11] Consider a unity feedback system where the process transfer function is

$$G(s) = \frac{1}{s(s+1)}.$$

(a) If we use a proportional controller K, what is the offset for a unit-step set point input? Give you comment.

(b) If we use a proportional controller K, what is the offset for a unit-step load disturbance at the process input? Give you comment.

(c) Repeat part (b) using PI controller C(s) = 1+2/s.

ANSWER

(a) With proportional controller K, and a unit-step set-point:

$$E(s) = \frac{1}{1+KG}R(s) = \frac{s(s+1)}{s(s+1)+K}\frac{1}{s}, \quad \Rightarrow e_{ss} = \lim_{s\to 0} sE(s) = \lim_{s\to 0}\frac{s(s+1)}{s(s+1)+K} = 0.$$

Proportional controller **alone** achieves zero steady state error! The reason is that the process is itself *integrating*.

(b) With proportional controller K, and a unit-step load disturbance at the process input:

$$E(s) = \frac{-G}{1+KG}D(s) = \frac{-1}{s(s+1)+K}\frac{1}{s}, \quad \Rightarrow e_{ss} = \lim_{s\to 0} sE(s) = \lim_{s\to 0}\frac{-1}{s(s+1)+K} = \frac{-1}{K} \neq 0.$$

In contrast to set point changes (part (a)) where P control achieves zero $\boldsymbol{e_{ss}}$, the same controller is not sufficient to fully reject the disturbance.

The conclusion is that servo and regulator control are two separate problems. If a good controller is designed for one problem, this does not mean it will be good for the other. Tradeoff or compromise is to be made to obtain a controller which is acceptable in both cases.

(c) With PI controller and a unit-step load disturbance at the process input:

$$E(s) = \frac{-G}{1+G_cG}D(s) = \frac{-s}{s^2(s+1)+s+2}\frac{1}{s}, \quad \Rightarrow e_{ss} = \lim_{s\to 0} sE(s) = \lim_{s\to 0}\frac{-s}{s^2(s+1)+s+2} = 0.$$

PI controller achieves zero steady state error in this case.

Sheet 6

[1] What is the derivative controller kick? How to eliminate it?

[2] How to get rid of proportional kick?

[3] How derivative action is usually implemented to reduce the effect of noise?

[4] What is the maximum gain for the following filtered derivative transfer function

$$G(s) = \frac{2s}{10s+1}$$

[5] What is reset windup? And what are its drawbacks on PV response?

[6] How to solve the reset windup problem?

[7] **True or False:**

a. Quick set point changes result in quick error changes as seen by the controller.
b. Quick disturbance changes cause quick error changes as seen by the controller.
c. Tuning for load rejection is more aggressive than for setpoint changes.
d. Tuning for set point changes gives a more relaxed controller than that tuned for load disturbance changes.

[8] What is the purpose of using set point filtering?

[9] Consider the following lag-lead filter

$$SP_f(s) = \frac{\beta T_i s + 1}{T_i s + 1} SP(s)$$

Derive the unit step response for β = 0, 0.5, and 1.0.

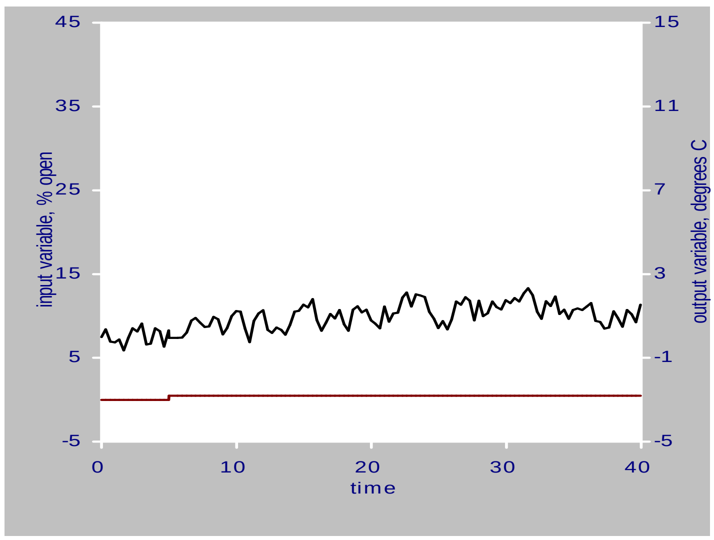
[10] What is meant by bumpless transfer? And how to achieve it?

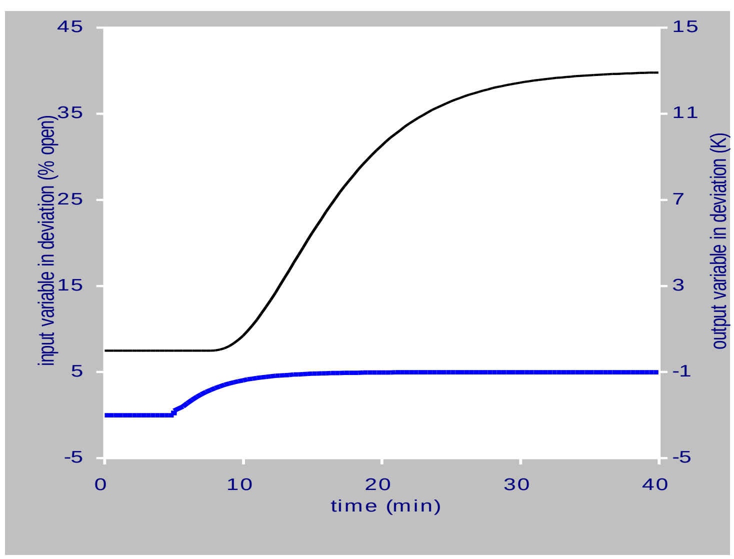
Sheet 7

[1] State whether the first PID tuning method of Ziegler Nichols is applicable for the following systems:

$$(a)\ G(s)=\frac{1}{(s+1)^2}e^{-2s}, \qquad (b)\ G(s)=\frac{1}{s(s+1)}, \qquad (c)\ G(s)=\frac{1}{s^2+s+1}$$

[2] In the first method of Ziegler Nichols, a step test is performed to find a FOPDT approximate model of the process. For each of the following input-output data, state why the test is *not well designed*.

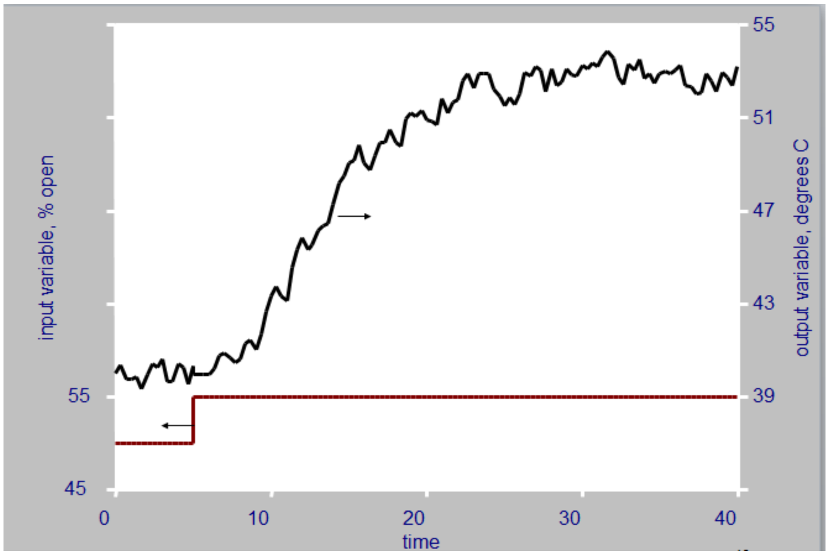




[3] The open-loop step response of a system is shown below.

(a) Find a FOPDT model for the system using the two-points method.

(b) Use Ziegler–Nichols tuning rules to find the parameters of the PID controller for this process.



Two-point method: $K=\Delta/\delta,\quad \tau=1.5(t_{63\%}-t_{28\%}),\quad \theta=t_{63\%}-\tau$
ZN tuning rules: $K_P=\dfrac{1.2\tau}{KL},\quad T_i=2L,\quad T_d=0.5L$

[4] Given the following transfer function:

$$G(s)=\frac{1}{(s+1)(2s+1)(3s+1)(10s+1)},$$

(a) What is the system dc gain?

(b) Which time constant is dominant?

(c) Suggest a first-order plus time delay (FOPDT) approximation of $G(s)$. Using this model, plot the approximate step response of $G(s)$.

(d) In order to design a PID controller for the given process, which of the two methods of Ziegler-Nichols should be used? Why?

Sheet 8

[1] Given the following control system where

$$P_1 = \frac{1}{s+1}e^{-s}, P_2 = \frac{2}{2s+1}e^{-s}, P_3 = \frac{3}{3s+1}e^{-2s}.$$

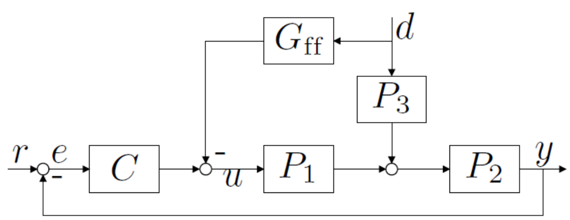
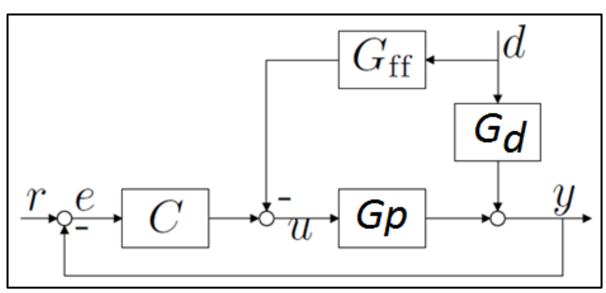


Fig. 1. Closed-loop structure.

(a) Design a feedforward controller $\mathbf{G_{ff}}$.
(b) If P_1 and P_3 are swapped, find $\mathbf{G_{ff}}$.

[2] Given the following feedback feedforward control system where

$$G_p(s) = \frac{0.5}{2s+1}e^{-s}, G_d(s) = \frac{1}{s+1}e^{-2s}$$



(a) Design the feedforward controller $G_{ff}(s)$.
(b) Write the characteristic equation of the whole system? Does the feedforward controller $G_{ff}(s)$ affect system stability?
(c) If you have to use only one controller, which one do you choose: the feedback controller C(s) or the feedforward controller $G_{ff}(s)$? State two reasons for your choice.