Indian Institute of Technology Madras
Department of Chemical Engineering
CH4030 - Process Control Laboratory

Deadline: 31st October 2021, 11:59 PM VIII Semester Max mark: 100

Attempt all the questions

1. **Objective:** You have been given a Simulink model for a 2x2 distillation column along with the open loop step response data for the same. Please refer to the model and data to answer questions that follow. Document your solution to each of the questions. Wherever information is not provided, you can make suitable assumptions. Ensure that you clearly articulate your assumptions before proceeding with the solution. Report figures and other screenshots of the Simulink model and its parameters.

   2x2 DISTILLATION COLUMN - PROCESS DESCRIPTION

   Distillation column is a separation unit used to separate a mixture into its constituents using their differences in volatilities. When a binary mixture containing two components L1 and L2 (L1 more volatile than L2) with comparable concentrations of each of these components are fed into the distillation column, this feed mixture is separated into a top product and a bottom product from the column. The top product, called the distillate is a mixture that contains liquid L1 at a high concentration compared with that of the feed and the bottom product is a mixture that contains liquid L2 at a high concentration in comparison with that of the feed. At the top of the column, the vapour from the column is condensed using a condenser; part of the liquid is sent back to the column (called reflux) and the remaining liquid is withdrawn as the desired product. At the bottom of the unit, the liquid is heated in a steam reboiler and is sent to the column through the bottom and part of the liquid is withdrawn as the bottom product. The important process variables of interest in the above-mentioned distillation column are the top product concentration (concentration of liquid L1), the temperatures at various points of the column and the pressure of the column. Usually, the column pressure is held at a desired value. **The bottom tray temperature and the top product concentration can be then considered as the two important process variables that are controlled to ensure the desired product quality and to maintain process safety in the operation of this distillation column.** The top product concentration is primarily controlled by changing the flow rate of the reflux liquid. The bottom temperature is primarily controlled by varying the pressure of the steam fed into the reboiler. This is shown in the control schematic given below.

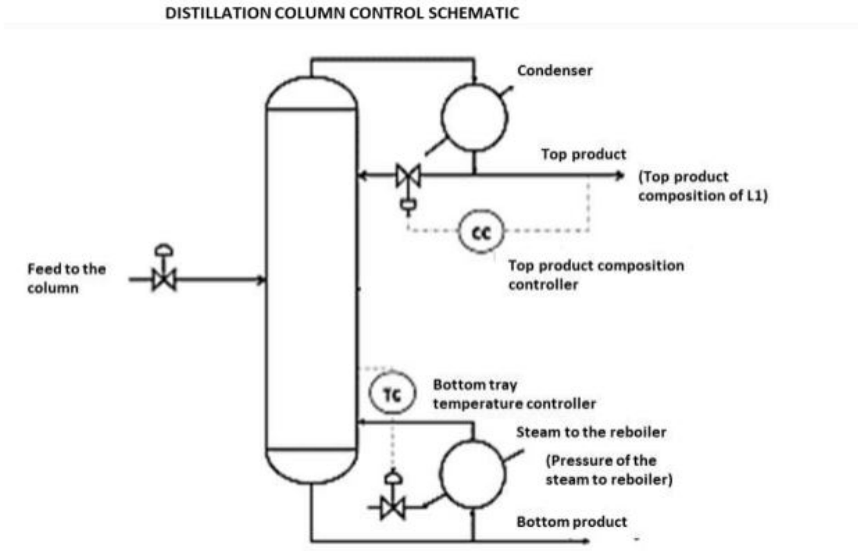

Figure 1: Distillation Column Control Schematic

In a process control viewpoint, the controlled and manipulated variables for the control objectives are given in the following table.

CONTROL OBJECTIVES	CONTROLLED VARIABLES	MANIPULATED VARIABLES
Control the concentration of L1 component in the top product at the desired value	Concentration of L1 component in the top product (**y1**)	Reflux flow rate to the column (**u1**)
Control the temperature of the column bottom tray to ensure the desired product quality and to sustain safe operation of the column	Temperature of the bottom tray (**y2**)	Pressure of the steam to the reboiler (**u2**)

Figure 2: Control Objectives

The corresponding deviation variables for these controlled and manipulated variables are denoted by the capital letters. For example, the temperature of the bottom tray is denoted as y2 and the corresponding deviation variable is denoted by Y2. It should be noted that that these variables can be scaled appropriately and can be expressed in any suitable unit. A detailed analysis of the process reveals that a change in the manipulated variable in one of these two loops also impacts the controlled variable in the other loop. Thus, an increase in the reflux flow rate to the column not only changes the product quality but also lowers the temperature of the bottom tray unless an appropriate control action is taken to counter this effect. Similarly, an increase in the steam pressure to the reboiler also lowers the top product quality by influencing the overall temperature profile of the column. In the attached Simulink models, the dynamics of the actual distillation column process is represented in a simplified manner by appropriate first order time-delay transfer functions that connect the various interrelated input and output variables explained previously.

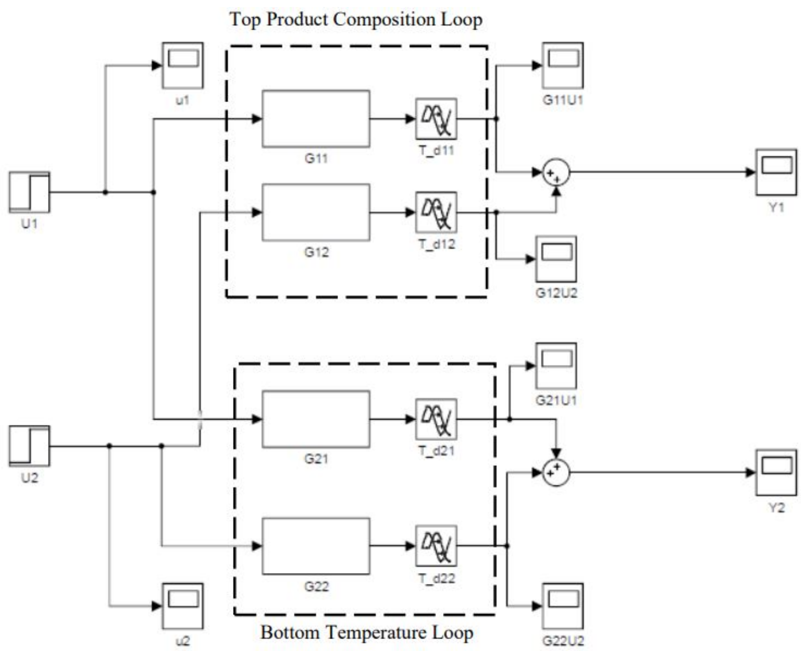

Figure 3: Process Schematic

(a) You have been given the step response data for the above process diagram. You have also been given the Simulink model for the same. However, the transfer functions G11, G12, G21, G22 in the model provided to you are reported incorrectly. From the data provided to you, estimate the correct process transfer functions G11, G12, G21 and G22. Report the transfer functions obtained. **(5)**

(b) Implement and tune PI and PID controllers for the following cases.

1. Operate this as a SISO system with regards to the top product composition loop. Perform set point tracking for a step change in set point such that you achieve a steady state top product composition of your choice.
2. Operate this as a SISO system with regards to the bottom temperature

loop. Perform set point tracking for a step change in set point such that you achieve a steady state bottom temperature composition of your choice.

3. Operate this as a MIMO system for controlling the top product composition with a constant re-boiler steam pressure. Perform set point tracking for a step change in set point such that you achieve a steady state top product composition of your choice for this MIMO system.
4. Operate this as a MIMO system for controlling the bottom temperature with a constant reflux flow rate. Perform set point tracking for a step change in set point such that you achieve a steady state top product composition of your choice for this MIMO system.
5. Operate this as a MIMO system where both the top product composition and the bottom reflux flow rate loops are active. Perform set point tracking for a step change in set points such that you achieve a steady state value for both the top product composition as well as the bottom temperature simultaneously. $(\mathbf{5} \times 5 = 25)$

Document your observations for each of the above cases. For each of the above cases you will need to provide the setpoint chosen and the corresponding response plots, Simulink model along with the parameters of the controller block. You can also provide any additional information as may be necessary.

(c) Now that you have designed and tuned the controllers, consider the following disturbance transfer functions:

$$\frac{-0.61e^{-3.5s}}{8.64s + 1}$$

is the disturbance transfer function for the top product composition loop

$$\frac{-6.2e^{-9.4s}}{10.9s + 1}$$

is the disturbance transfer function for the bottom temperature loop

1. Apply a **sinusoidal disturbance signal** with a magnitude of 1 unit and frequency of 0.01 Hz and apply it to both the top product composition loop as well as the bottom temperature loop, through the respective disturbance blocks given above. Operate the MIMO set up with both loops active. Evaluate the disturbance rejection capability of your PI and PID controllers for this MIMO setup. You can give a constant set point of your choice to both the control loops. Document your observations.
2. Apply a **step disturbance signal** of your choice and apply it to both the top product composition loop as well as the bottom temperature loop,

through the respective disturbance blocks given above. Operate the MIMO set up with both loops active. Evaluate the disturbance rejection capability of your PI and PID controllers for this MIMO setup. You can give a constant set point of your choice to both the control loops. Document your observations. **(10**$\times 2 = 20$)

2. **Objective:** You have been given a Simulink model for the FCC (Fluid Catalytic Cracking) system. Obtain the input and output data by running the simulation.

2x3 FCC SYSTEM - PROCESS DESCRIPTION

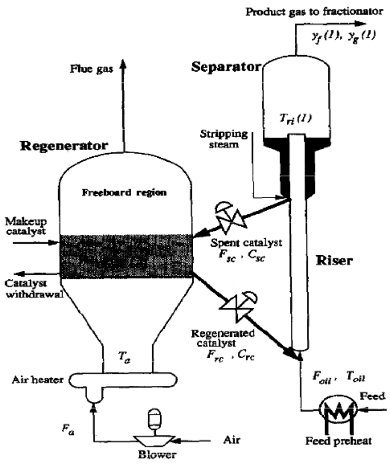

Figure 4: Schematic Diagram of the FCC Process

The FCC process is used in the refining of petroleum crude oils to lighter and more valuable hydrocarbons such as petrol. A typical FCC unit contains three major sections: a riser, a regenerator and a separator. The heavy feed oil is mixed with hot catalyst from the regenerator and reacts endothermically in the riser to form lighter hydrocarbons as well as coke. The lighter hydrocarbons are separated from the catalyst in the separator and sent to the fractionator for further refining. The coke is deposited on the catalyst which is returned to the regenerator, and is burnt off to ensure the regenerated catalyst maintains an acceptable level of activity.

The FCC unit displays complex dynamics due to strong coupling between the endothermic riser and the exothermic regenerator sections, apart from the non-linearity in reaction rates. A simplified model of the FCC system is adopted by Balchen et al., State—space predictive control, Chem Engg Sci 1992 787-807, which is also used in the given Simulink model.

To ensure efficient operations, the regenerator bed temperature, oxygen concentration in the regenerator bed and the amount of coke present in the regenerated catalyst are among the variables that are required to be controlled. During normal operation, the mass flow rates to and from the regenerator bed can be manipulated. The gas oil feed conditions, however, may potentially exhibit unpredictable variations which could affect the behaviour of the system. Therefore, the variables of interest are summarized as follows:

Controlled (Output) Variables:

- y_1: Coke weight fraction on regenerated catalyst (C_{rc})
- y_2: Oxygen mole fraction in Regenerator bed (O_d)
- y_3: Catalyst Temperature in Regenerator bed (T_{rg})

Manipulated (Input) Variables:

- u_1: Mass flow rate of air to Regenerator (F_a)
- u_2: Mass flow rate of spent catalyst (F_{sc})

Disturbance Variables:

- d_1: Temperature of gas oil feed (T_{oil})
- d_2: Mass flow rate of gas oil feed (F_{oil})

Assuming that the gas oil feed conditions are known to be constant, and **therefore no disturbances are produced during the process**, a state-space model may be estimated to approximate the relation between provided manipulated and controlled variables as a **2-input, 3-output LTI system**.

(a) A state-space model is to be estimated for the given FCC system. Report the estimated A, B, C and D matrices such that if u, x and y are the input, state and output vectors respectively,

$$\dot{\vec{x}} = A\vec{x} + B\vec{u}$$

$$\dot{\vec{y}} = C\vec{x} + D\vec{u}$$

Assume the total number of states to be 5. **Hint:** Check out the `n4sid` routine in MATLAB documentation. **(8)**

(b) Examine the stability of the open loop system using the estimated state-space model. **(4)**

(c) From the estimated state-space model, find the transfer functions for each of the input-output pairs. Construct a fresh Simulink block diagram using the obtained transfer functions and verify the correctness of your results through simulations. **(10)**

(d) Using the estimated transfer functions, operate a SISO system with regards to u_1 and y_1.

- Design a PI controller so as to achieve set point tracking of the first output (y_1) for a step change in the first input (u_1). Highlight the performance criteria that was considered during the design of your controller. **Hint:**You may use the PID Tuner Interface in Simulink to arrive at the controller.
- Verify the stability of the closed loop system using Routh Hurwitz criterion. Clearly show the code or the calculations performed to obtain the closed loop transfer function and deduce the stability results.
- If the structure of the PI controller is given by

$$G_c = K_P + \frac{K_I}{s}$$

  Given constant K_P, verify that the chosen K_I value renders the closed loop transfer function to be stable using Root Locus analysis. Explain how you have arrived at the conclusions with the help of codes and plots in detail.
- Summarize your findings and inferences about the stability of the system using the Bode Stability Criterion and the Nyquist Stability Criterion. Explain in detail, with the help of plots wherever necessary, how you arrived at the inferences.

(14)

(e) From the FCC system, a state-space model was estimated with the assumption that the number of states are 5. In general, what is the significance of the number of states used to describe a model? What would happen to the estimated model if the number of states was set to a smaller value like 2? **(6)**

(f) The state-space model that was estimated did not explicitly account for any process time delay. Give any one example of time delay occurring in a process. Mention the physical reason behind the generation of this time delay. Would the LTI model estimated for the FCC system improve significantly if a time delay parameter was also included? **(8)**

Best wishes