Examination paper for TKP 4140 – Process Control

Academic contact during examination: Sigurd Skogestad
Phone: 91371669

Examination date: 06 December 2017
Examination time (from-to): 09:00 – 13:00
Permitted examination support material: One (1) A4 double-sided piece of paper with your handwritten notes. Standard calculator.

Other information: State clearly all assumptions you make. You may answer in Norwegian or English

Language: English
Number of pages (front page excluded): 4 (including Bode paper which may be handed in)
Problem 1 - Mixing process (30%)

Two mixing tanks are used to produce a diluted acid ($q_2$) from concentrated acid ($q_A$) and water ($q_{w1}$ and $q_{w2}$), (see figure). The main part of the dilution is done in tank 1, while tank 2 is used to fine tune the dilution to obtain the desired concentration ($q_{w1}$ is about 10x $q_{w2}$).

(a) Write a dynamic model for the process (two balances for each tank). You may need to introduce symbols (variables) in addition to the ones given on the figure. No linearization or Laplace is required.

(b) Formulate the 2x3 transfer matrix $G_1$ for the first tank with $q_A$, $q_{w1}$ and $q_1$ as independent variables (inputs or disturbances) and $V_1$ and $c_1$ as dependent variables (outputs). No numbers are required, just the form (first-order, integrating, etc.) and sign of the gain.

(c) Now we consider control. The flow of dilute acid is set by the downstream process, so $q_2$ is a disturbance. Suggest a control structure on the flowsheet for each of the following two cases:

1) Measurements are $c_1$, $c_2$ and the two levels. Suggest a control structure with four feedback loops.

2) Measurements are $c_2$ and the two levels. Suggest a control structure that makes $q_{w2}$ return to its desired value at steady state.
Problem 2 – PID controller tuning (15%)

Consider a process given by the following process model

\[
G_p(s) = \frac{3}{(100s + 1)(10s + 1)} e^{-2s}
\]

In addition, the measurement has a time delay \( \theta_m \) given by \( G_m(s) = e^{-\theta_m s} \).

Design a PI- or PID-controller (say which one you suggest) using the SIMC rules with \( \tau_c = \theta \) (effective delay) for the following two cases:

a) \( \theta_m = 1 \).

b) \( \theta_m = 20 \).

Problem 3 – Closed-loop transfer functions and tuning (10%)

Consider a process \( G(s) \) with no measurement dynamics.

(a) We use a standard feedback controller, \( u = C(s)(y_s - y) \). Draw the block diagram. Derive the closed-loop transfer function \( T_1 \) from the setpoint \( y_s \) to the output (measurement) \( y \), and the closed-loop transfer function \( T_2 \) from the setpoint \( y_s \) to the input \( u \).

(b) Let \( G(s) = \frac{k}{\tau_i s + 1} \) and design a PI controller tuned with the SIMC rules and \( \tau_c = \tau_i \) (this choice for \( \tau_c \) is the basis for the so-called \( \lambda \)-tuning). Derive \( T_1 \) and \( T_2 \) for this case (make the result as simple as possible).

Problem 4 – Pairing and decoupling (15%)

The relative gain array (RGA) is a tool one can use to analyze interactions and decide on controller pairings in multivariable systems. Consider the following process and steady-state RGA:

\[
G(s) = \begin{bmatrix} 10e^{-5s} & -3 & 6 \\ 3 & 1.5 & -0.5 \\ 5 & 2 & -1.5 \end{bmatrix}, \quad \text{RGA(0)} = \begin{bmatrix} 0.45 & 0.22 & 0.33 \\ -0.82 & 2.45 & -0.64 \\ 1.36 & -1.67 & 1.31 \end{bmatrix}
\]

Note that input 1 corresponds to the first column in \( G \), output 1 to the first row in \( G \), etc.

a) How would you pair the inputs with the outputs (controlled variables)?

b) What are the implications if you pair on the following RGA values \( \lambda_{i,j} \)?

1. \( \lambda_{i,j} < 0 \)
2. \( 0 < \lambda_{i,j} < 1 \)
3. \( 1 < \lambda_{i,j} \)
   
   c) Explain what decoupling is and how it can be used to reduce the effect of interactions. Design a one-way decoupler for a 2x2 process \( G \) which may improve the control of \( y_1 \).
   Can the one-way decoupler always be realized?

**Problem 5 – Closed-loop stability of inverse-response process (15%)**

(a) Consider PI-control of the process \( G(s) = \frac{1-5s}{8s+1} \) with integral time \( \tau_I = 8 \). For what controller gain \( K_c \) is the closed-loop system stable?

(b) Design a SIMC PI-controller for this process with \( \tau_c = \theta \) (effective delay). What is the gain margin? What is the time delay margin?

**Problem 6 – Controllability (15%)**

We want to control the temperature \( (y=T) \) in a reactor. The MV is the cooling rate \( (u=Q) \) and the disturbance is the feed rate \( (d=F) \).

In the figure is shown the response in temperature to a large step disturbance \((F + 30\%)\) and to a change in the input \((Q + 10\%)\). Note that the largest possible input change is \( Q + 50\% \).

We would like the temperature deviations to stay within \(+ - 1K\).

(a) Suggest transfer functions for \( G(s) \) and \( G_d(s) \). For the scaling, let \( u=1 \) correspond to \( Q=50\% \), let \( d=1 \) correspond to \( F=30\% \) and let \( y=1 \) correspond to a temperature change of \( 1K \).

(b) Is the process controllable? Sketch the expected closed-loop response in temperature to a 30% increase in \( F \).
Bode paper: