Examination paper for TKP 4140 – Process Control

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Examination date: 18 December 2014
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: 6 (including Bode paper which may be handed in)

Checked by:
Problem 1 (25%) – Heat exchanger model

A heat exchanger with a heater and bypass is shown in the figure. The red numbers represent the nominal steady-state values. We have derived the following simple model of the system:

\[
\frac{d}{dt}(mc_P T_1) = w_1 c_P (T_{in} - T_1) + Q
\]

\[
0 = w_1 c_P T_1 + w_2 c_P T_{in} - (w_1 + w_2) c_P T
\]

(a) What balances do these equations represent and what assumptions have been made? We assume that Q is independent of T, for example, it could be an electric heater.

(b) Linearize the model, take the Laplace transform, and derive the following linear model (in deviation variables):

\[
T_1(s) = \frac{1}{\tau s + 1} [k_1 w_1(s) + k_2 T_{in}(s) + k_3 Q(s)]
\]

\[
T(s) = k_4 w_1(s) + k_5 w_2(s) + k_6 T_{in}(s) + k_7 T_1(s)
\]

Find analytical expressions for τ and the k_i’s. Also find their numerical value. Use \(c_P=4 \text{ kJ/kg.K}\).

(c) Use \(w=w_1+w_2\) to eliminate \(w_1\) and derive the linear model for the response in \(T\) in terms of the two inputs \(w\) and \(w_2\):

\[
T(s) = g_1(s) w(s) + g_2(s) w_2(s) + g_3(s) T_{in}(s) + g_4(s) Q(s)
\]

Show that the steady-state gain for \(g_2\) is zero, i.e. \(g_2(0)=0\). Explain why this is correct. What is the steady-state gain for the transfer functions \(g_1\) and \(g_3\)?
Problem 2 (25%) – Delay process

We consider an almost pure time delay process, \( G(s) = 1*e^{-10s}/(0.1s+1) \).

a) Tune a PI-controller using the SIMC rule with \( \tau_c \) selected equal to the delay.
   - What is \( K_c \) and \( \tau_I \)?
   - Sketch the closed-loop setpoint response (what is the steady-state offset?).
   - What is the gain margin? How much delay error can we tolerate before we get instability?
   - Would you recommend this controller?

b) Tune a proportional controller, \( c(s) = K_c \), such that we have a gain margin of 3.
   - What is \( K_c \)?
   - Sketch the closed-loop setpoint response (what is the steady-state offset?).
   - How much time delay error can we tolerate before we get instability?
   - Would you recommend this controller?

Problem 3 (20%) – Transfer functions

Consider a system with the block diagram in the figure.

a) Derive the following four transfer functions using symbols from the block diagram

\[
\begin{align*}
  y &= h_1(s)y_s + h_2(s)u_1 \\
  u_2 &= h_3(s)y_s + h_4(s)u_1
\end{align*}
\]

b) Evaluate the four transfer functions for the case with

\[
\begin{align*}
  g_1(s) &= \frac{2}{5s+1}, \quad g_2(s) = 3\frac{5s}{5s+1}, \quad c_2(s) = 0.1
\end{align*}
\]

c) The gain for the P-controller \( c_2 \) seems very low. Assume that the transfer functions \( g_2 \) has a small delay, and use this to explain why the controller gain cannot be increased by more than a factor of about 3.
d) It is suggested to use a PI-controller for $c_2(s)$, with $K_{c2}=2$ and $\tau_{c2}=5$. Find the four transfer functions in this case. Are all transfer functions stable? Would you recommend using P-control or PI-control for $c_2$?

**Problem 4 (10%) – Double integrating process**

A double integrating process, $g(s) = 1/s^2$, is quite difficult to control (and is fortunately not very common in process control).

(a) Can it be controlled with a P-controller (compute the closed-loop poles)?
(b) What controller would you suggest?

**Problem 5 (20%) – Heat exchanger control (nonlinearity)**

![Diagram of heat exchanger]

Cooling water (CW,1) is used to control the temperature ($y=T_2$) of a hot stream in a countercurrent heat exchanger. The flow of the cooling water ($q_1 [m^3/s]$) can be adjusted by changing the valve position ($z$). We have the following linear model for the heat exchanger:

Valve: $q_1 = g_v(s) \cdot z$

Heat exchanger: $y = g_p(s) \cdot q_1$

(a) Draw a flowsheet (with TC etc.) and a block diagram (with $g_v$, $g_p$, $c_1$, etc.) for each of the following two cases: (1) Without cascade control (temperature control only), (2) With cascade control (adding a flow controller). In the block diagrams, you can let $c_1$ denote the temperature controller and $c_2$ the flow controller.

(b) The solution with cascade control often is preferred because it counteracts nonlinearity in the valve ($g_v$). To show this, consider your block diagrams, and let $u$ denote the output of the temperature controller ($c_1$), that is, $u=z$ without cascade and $u=q_1s$ with cascade.
Determine for the two cases the transfer function $h(s)$ from $u$ to $y=T$, without the temperature loop ($c_1$) closed. How does $g_v$ affect the response $h(s)$ for the two cases? You can assume that the flow controller ($c_2$) is fast.

(c) There are some cases when it may not be desirable to use the cascade solution with a flow controller. This is when the process itself ($g_p$) is nonlinear, and we choose a “nonlinear” valve ($g_v$), so that the overall transfer function $g = g_v g_p$ becomes more linear than $g_p$. For example, for our heat exchanger, the steady-state effect of an increase in cooling water flow on temperature is smaller at larger flow rate, that is, $k_p=g_p(0)$ is smaller at large flow rates (The reason is that the temperature $T$ will approach the cooling water temperature at large cooling rates). This is illustrated for our heat exchanger in the figure, which shows the overall steady-state gain $k = k_p k_v$ as a function of the flowrate $q_1$ for the three different valves.

- Which valve would you recommend?
- For the linear valve, $k=3.5$ at low load ($q_1=0.05 \text{ l/s}$), and $k=0.2$ at high ($q_1=0.4 \text{ l/s}$). We tune the controller at high load such that the gain margin is 3. What is the gain margin when we another day operate at low load if it is assumed that the dynamics in $g(s)$ are unchanged.
Bode paper: