NTNU – Trondheim
Norwegian University of
Science and Technology

Department of Chemical Engineering

Examination paper for TKP 4140 – Process Control

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Academic contact present at the exam location: YES (around 11)

Examination date: 10 December 2024

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: 5

(including Bode paper which may be handed in)

Informasjon om trykking av eksamensoppgave Originalen er:
farger Ja

Checked by:

Date Signature

Problem 1 (30%) – Control of inverse response process

Let y = g(s) u and consider the process

$$g(s) = 4\frac{-0.1s + 1}{0.5\,s + 1}$$

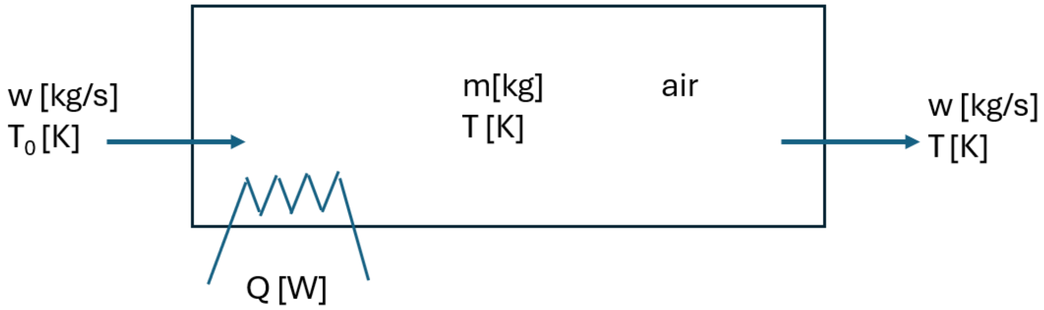
(a) (7%) Design a SIMC PI-controller with "tight" tunings (you may use the approximation $(-0.1\,s + 1) \approx e^{-0.1s}$). Sketch the closed-loop response to a step change in the setpoint.

In the rest of this problem, you should preferably <u>not</u> use the approximation $(-0.1\,s + 1) \approx e^{-0.1s}$.

(b) (7%) What is the open-loop response y(t) to a unit step change in u (give an analytical formula for y(t) involving an exponential term)? Plot the response y(t).
(c) (7%) Consider proportional control with gain K_c. For what values of K_c is the closed-loop system stable?
(d) (7%) Consider P-control with K_c=0.5. Plot the closed-loop response to a step change in the setpoint.
(e) (7%) Consider P-control with K_c=0.5. What is the gain margin? How much time delay can be tolerated before the closed-loop system goes unstable? (you may use the enclosed Bode paper for this part if desired)

Note: The five parts of this problem can be done independently. The sum is 35% but you can at most get 30%.

Problem 2 (50%) – Room heating control



We consider modeling and control of room temperature T with an electric heater with power Q [W]. Thus, y=T and u=Q. The outside temperature is T_o and the ventilation flowrate is w [kg/s]. The room is well insulated so we neglect heat losses through the wall. Assume that the mass of the air in the room (m) is constant. We make the simplifying assumption that the temperature of the air (T) is uniform (holds for well-mixed gas).

Data: m = 200 kg, w= 0.04 kg/s (nominal), c_p = 1 kJ/kg,K (air). Nominally (initial steady state) we have T=20C (293K) and T_o=0C (273K).

(a) (20%) First consider the above figure where the electric heater is in the room itself.

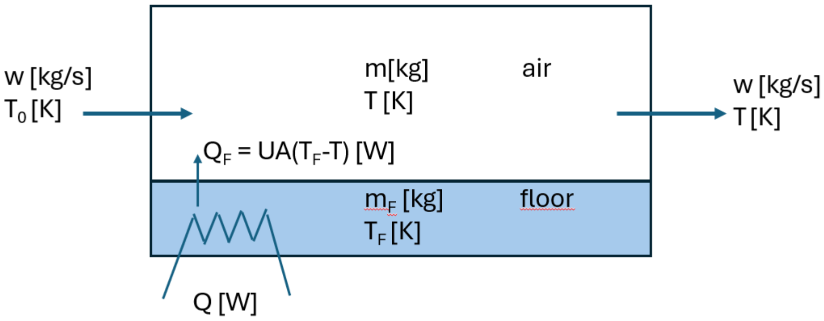
- **(i)** (6%) Formulate the dynamic energy balance for the room.
- **(ii)** (3%) What is the nominal value for Q [kW]?
- **(iii)** (6%) Linearize the model, take the Laplace transform and derive a model on the form

$$(\tau_a s+1)\, T(s) = k\, Q(s) + k_{d1}\, T_o(s) + k_{d2}\, w(s)$$

That is, we have $T(s) = G(s)\, Q(s) + G_{d1}(s)\, T_o(s) + G_{d2}(s)\, w(s)$ where $G(s)=k/(\tau_a s+1)$, $G_d(s)=k_{d1}/(\tau_a s+1)$, $G_{d2}(s)=k_{d2}/(\tau_a s+1)$. What are the values of the four parameters?

If you did not find the values then use in the following $G(s)=30/(4000\, s+1)$.

- **(iv)** (5%) We use a SIMC PI-controller (based on the model G(s)) with gain K_c=1.5 kW/K. What τ_c does this correspond to and what is the corresponding integral time τ_I ?



(b) (30%) Next, consider the above figure where the electric heater (u=Q) is in the floor. We make the simplifying assumption that the temperature of the air (y=T) and the floor (T) are uniform (holds for well-mixed gas and high heat conductivity in the solid).

Data: m = 200 kg, w= 0.04 kg/s, c_p = 1 kJ/K,kg (air), $m_F c_{pF}$ = 5000 kJ/K (floor), UA = 0.5 kW/K. Nominally (initial steady state) we T=20C (293K) and T_o=0C (273K).

(i) (5%) Formulate the dynamic energy balances for the room and floor.

(ii) (2%) What is the nominal value for Q [kW] and T_F [K]?

(iii) (4%) In this part you can assume that the flowrate w is constant. Linearize the model, take the Laplace transform and find the 5 parameters in the model below (you can put in numbers or keep it analytical)

$$(\tau_b s+1)\ T(s) = k_F T_F(s) + k_o\ T_o(s)$$

$$(\tau_F s+1)\ T_F(s)= k_T\ T(s) + k_Q\ Q(s)$$

(iv) (4%) Eliminate $T_F(s)$ from these equations to find a second-order model of the form

$$T(s) = G_b(s)\ Q(s) + G_{db} T_0(s)\ \text{, where}$$

$$G_b(s) = \frac{k_b}{(\tau_1 s+1)\ (\tau_2 s+1)},\ G_{db}(s) = \frac{k_{db}\ (\tau_F s+1)}{(\tau_1 s+1)\ (\tau_2 s+1)}$$

Find the numerical values for the five parameters.

Comment: If you are unable to find the model then use in the following: τ_1=150,000 s (41 h), τ_2=400 s, τ_F=15,000 s (4.1 h), k_b = 30 K/kW, k_{db} = 1 K/K.

(v) (4%) Use the half rule to derive a first-order approximation for $G_b(s)$ and tune a SIMC PI-controller with gain K_{c1}=1.5 kW/K. What is τ_{c1} and the integral time τ_{I1}?

(vi) (5% total) <u>Sketch</u> the open-loop (3%) and closed-loop (2%) response for y=ΔT for a step disturbance ΔT_0 = 1K.
Possible bonus points (4%): Sketch also the response for u(t)=ΔQ(t) (this is not easy).

(vii) (6% total) What would the tunings be with $\tau_{c2}=\theta$ (effective delay) (3%)? Which choice for τ_c would you recommend (1%)? Would you recommend introducing cascade control (with $y_2=T_F$) (2%)?

Comment: Note that the last part of (a) and the last three parts of (b) can be done independently of the rest.

Problem 3 (20%) – Advanced control

a) (7%) Consider a system with two inputs (u_1, u_2) and one output (y). What is (i) split range control and what is (ii) input resetting (also known as valve position control or midranging control)? Give examples of how you would you use them.

b) (7%) Consider a system with one input (u) and two outputs (y_1, y_2). What is (i) cascade control and what is (ii) selective (override) control? When would you use them? Give examples of how you would you use them.

c) (6%) How must the inventory control be arranged around the location where we have a given flow (throughput manipulator)? Consider a case with two tanks in series and three valves. Show the inventory control for the case when the TPM is at the feed and when the TPM is at the product (outflow of the second tank).

Bode paper: