NTNU – Trondheim
Norwegian University of
Science and Technology
Department of Chemical Engineering

Exam paper for TKP4140 – Process Control

Academic contact during exam: Sigurd Skogestad

Phone: 91371669

Academic contact present at the exam location: Yes (estimated 11:00)

Examination date: 11 December 2023

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)**

Informasjon om trykking av eksamensoppgave

Originalen er:

1-sidig ☐ **2-sidig** ☐

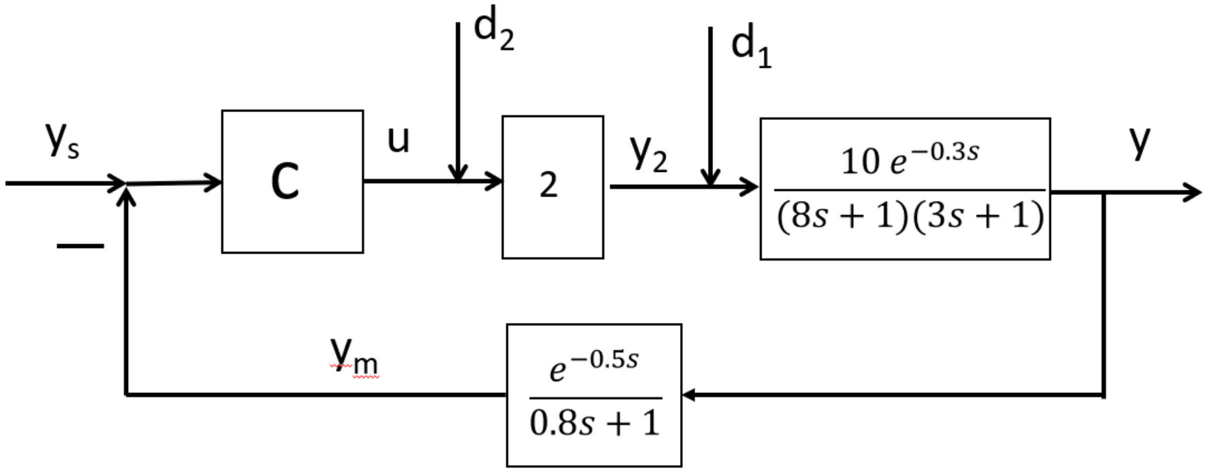
sort/hvit ☐ **farger** ☐

skal ha flervalgskjema ☐

Checked by:

Date Signature

Problem 1 (35%). Controller tuning



(a) (5%) What is the disturbance transfer function G_d from d_2 to y? Sketch y(t) for a unit step change $d_2(t)=1$ for the case with no control (c=0). Assume that we want $|y(t)| \leq 1$: Do we need control?

(b) (10%) Design a PI-controller for c using the SIMC-rule with "tight" tunings.

(c) (7%) Design a PID-controller for c using the SIMC-rule with "tight" tunings.

(d) (3%) Will PI- or PID-control give acceptable disturbance rejection for disturbance d_2? (assuming that $|d_2| \leq 1$ and that you want to keep $|y-y_s| \leq 1$)

(e) (5%) Consider adding feedforward control. Show c_{ff} on the block diagram. Propose a constant gain feedforward controller, $c_{ff} = k_{ff}$. Do you recommend using feedforward control in this case?

(f) (5%) Consider using cascade control. Show the slave controller c_2 on the block diagram. Design c_2 using the SIMC rule with $\tau_c = 0.6$ (when is this value reasonable?). Do you recommend using cascade control in this case? Why would you need to change the design of c if you add a slave controller c_2?

(g) Extra credit (3%): Propose new PI-tunings for c for the case with cascade control.

Problem 2 (35%). Closed-loop stability

Consider control of the process

$$G(s) = \frac{4(-2s+1)}{(20s+1)(6s+1)}.$$

It is proposed to use a PI-controller with integral time τ_I=20 and gain K_c=1. We want to find out if the closed-loop system stable and how far it is from instability.

(a) (8%) All closed-loop transfer functions can be written on the form n(s)/d(s) where d(s) is always the same. Find the expression for d(s). The closed-loop system will be unstable if some of the coefficients in d(s) are negative (or more precisely if they have different signs). Is the closed-loop system stable? Is this condition necessary and sufficient?

(b) (5%) What is the gain margin? You can find it by computing for which value of K_c one of coefficients in d(s) becomes zero. Alternatively, you can use the Bode stability condition.

(c) (10%) Sketch the Bode plot and indicate the gain and phase margins.

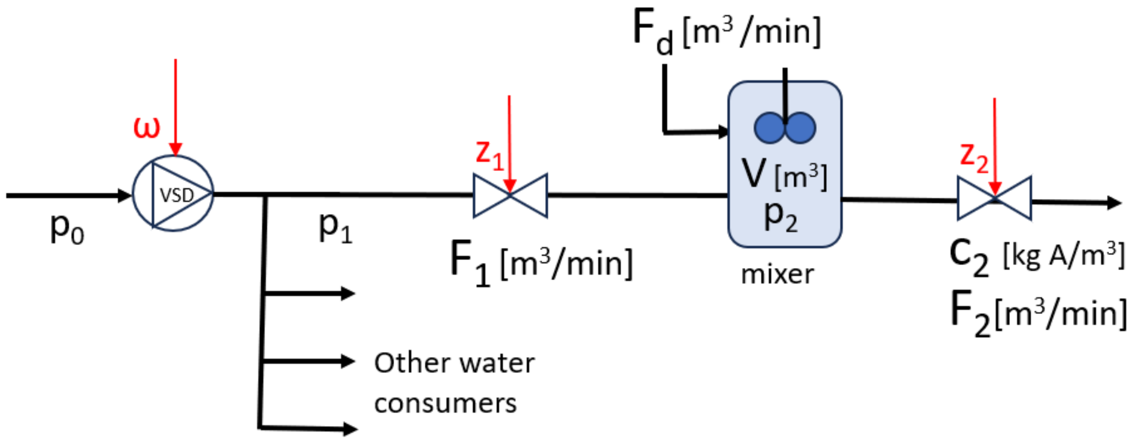
(d) (5%) What is the time delay margin (that is, how much time delay can be added before get closed-loop instability)?

Now consider other controllers for G(s).

(e) (7%) Assume that we use pure P-control. At what value K_u does the system become unstable and what is the corresponding period of oscillations P_u? Use this to find the Ziegler-Nichols PI-tunings for the process G (K_c = 0.45 K_u and τ_I = P_u/1.2).

(f) (3%) Extra credit: What are the SIMC PI-settings for the process G?

Problem 3 (30%). Modelling and control of mixing process



The flowsheet shows a process for producing a product F_2 with concentration c_2 by mixing water F_1 with a solid F_d (which is pure A, for example, A=sugar). The main control objective is to keep the composition c_2 constant, but there is some delay in the measurement of c_2. The main disturbances are related to F_d and the other water consumers (which may result in varying pressure p_1). It is desirable to keep the pressures p_1 and p_2 constant. There are three available manipulated inputs, namely the valve positions z_1 and z_2 and the speed ω of the pump (VSD=variable speed drive).

(a) (5%) Formulate a static model (valve equation) for F_1 and find the gain k from z_1 to F_1 (analytical expression only; show how it depends on pressure). You can assume a linear valve characteristic.

(b) (10%) (i) Formulate a dynamic model for the mixer involving the total and component mass balances. (ii) What is the steady-state value of F_d at the nominal point? (iii) Derive the transfer function (with numbers) from F_1 to $y=c_2$ assuming that V and p_2 are constant.
Data: F_1 is pure water and the concentration of F_d is c_d [kg/m3], *Nominal steady-state data:* c_2=20 kg A/m^3, c_d=700 kgA/m^3, F_2=2 m^3/min, V=0.36 m^3.

(c) (15%) Propose a control system which also includes ratio and cascade control. Explain your thinking and comment on in which order the control elements should be added and tuned. You may add flow, pressure and concentrations measurements as needed. Note that F_d sets the production rate for the process (so it's the TPM).

Bode paper: