TTK4210 Advanced Control of Industrial Systems, Exercise 6

Kristian Løvland

Contents

1 Abstract

In this project, a model of a butane distillation column was used to design a controller for the composition of two product streams consisting of n-butane and iso-butane, respectively. By identifying characteristics of relevant subsystems, PI controllers for the states of these systems were designed with the ultimate goal of keeping the purity of the products at a satisfactory level.

2 Introduction

The stream of control engineers is flowing slower than before, but still steadily into lucrative jobs in the process industry. As a part of this, all children learn about hydrocarbon chains in middle school, and every cybernetics student at NTNU learns how to control plants that are common in the petroleum industry. This report is simply me doing my part.

A good introduction to the control problem we're faced with is given in the assignment text . A short summary of this follows here.

Legg til kilde

Our final goal is to have a control system giving two product flows out of the distillation column having the desired compositions x_D^* and x_B^*. In practice, we control our compositions x_D and x_B indirectly through the temperatures in the locations of the product streams, denoted T_D and T_B.

To achieve this, some more control is needed. The levels M_D and in the top accumulator and M_B in the destillation column needs to be controlled to stable setpoints. The same goes for distillation column pressure p.

To control these five variables, five degrees of freedom is needed. These are all flow rates, denoted V_T, L, D, V, B. Each of these is controlled more or less directly by a valve.

Independent control of all of the variables are used. Table **??** shows the pairing of manipulated and controlled variables. It is assumed that choosing godd setpoints for T_D and T_B gives satisfactory product quality. The control structure used here is called LV-control, after the manipulated variables used to (indirectly) control product quality.

Manipulated variable	Controlled variable
V_T	p
D	M_D
B	M_B
L	T_D
V	T_B

Table 1: Variable pairings

2.1 A few words on scaling

The scaling and units used in this report might seem a bit arbitrary. Despite how it might seem, I have tried to be consistent. For my own sake, all plots of variables are in engineering units, the same goes for all controller gains K_p. These have been converted to internally scaled gain when implementing the controllers in K-spice. Units (or the lack of them) for plots used in frequency analysis and loop-shaping are hopefully unambiguous.

3 Tuning secondary controllers

The secondary controllers were tuned individually using the SIMC method for PI controllers. A step in process input with an amplitude small enough to not cause problems (usually meaning 50% of maximum accepted input magnitude) in other parts of the system was used for all the secondary controllers, controlling the states D, L, B, V and p.

In short, the SIMC tuning method can be summarized as follows (using notation from [?])

Legg til kilde, regtek-boka

1. Fit the step response to a first order model. This means finding time delay τ, slope $k' = \frac{dy/dt}{\Delta u}$ and time constant T_1 from the plot of the step response.

2. To achieve the desired time constant T_L, use the PI controller parameters $K_p = \frac{1}{k'}\frac{1}{\tau+T_L}$, $T_i = \min(T_1, 4(\tau + T_L))$.

The data from these experiments can be seen in figures 1, 3, 5, 7 and 9. The reference signals should have been omitted from these plots since we are dealing with open loop systems, and can safely be ignored here.

The plots show that for the first three variables, the accuracies of the simulations are clearly not sufficient for fitting a first order model (they behave in a stepwise fashion). Inspecting the order of magnitude of the gains and time constants is, however, still useful. An attempt at making sense of these parameters is shown in table 2, together with the fitted values for V and p.

Simple linear fitting from initial to steady-state value was used for the three quick states, which gives conservative estimates of k' and T_1. In the table, a desired time constant for the controlled system T_L is shown in the rightmost column. For a quick response, choosing $T_L = 0,3\tau$ is suggested in [?]. Some simple trial and error in K-spice showed that this lead to oscillation and unfortunate interaction between control loops, especially the controllers for D and L. This is probably partly due to the underestimates of k' and T_1 for these variables, since conservative estimates of these results in more aggressive controllers (to compensate for the slow system) when using the SIMC method.

Due to this unsatisfactory behaviour, $T_L = 2\tau$ was chosen for the three fastest control loops instead. The time delay was hard to make a meaningful reading of for the two other systems, so a somewhat arbitrary choice of

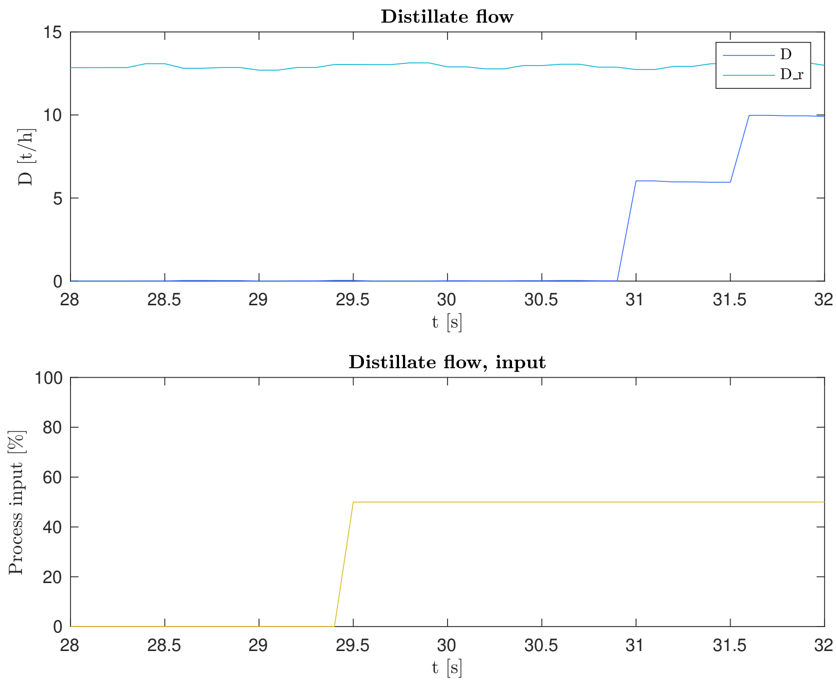

Fig. 1: Open-loop step response of D

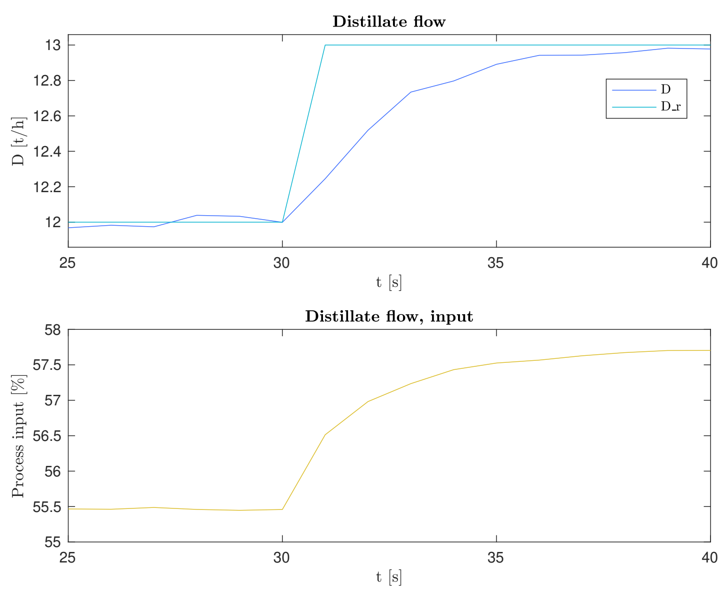

Fig. 2: Closed-loop step response of D

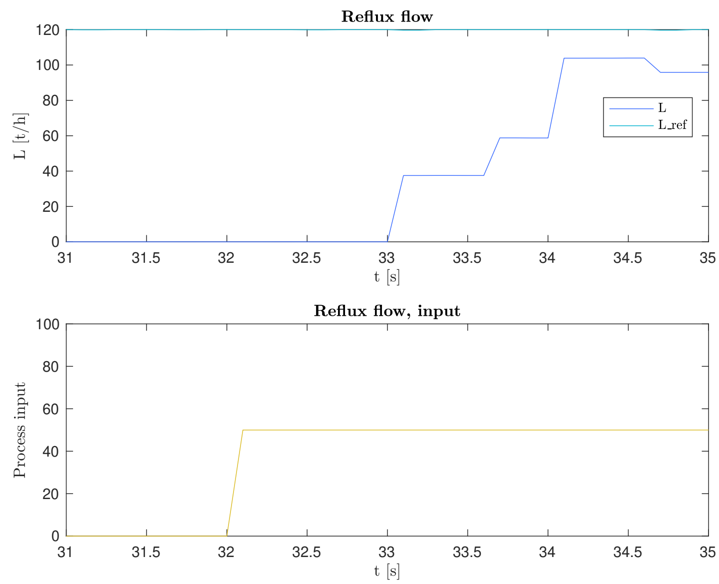

Fig. 3: Open-loop step response of L

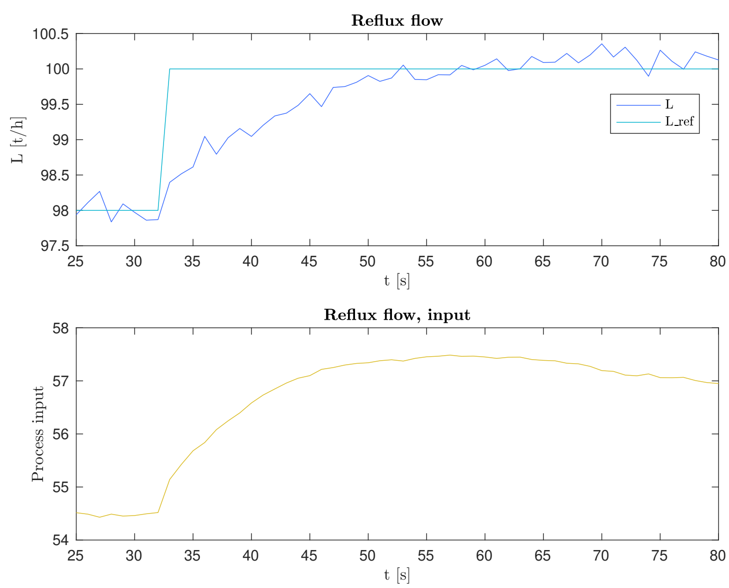

Fig. 4: Closed-loop step response of L

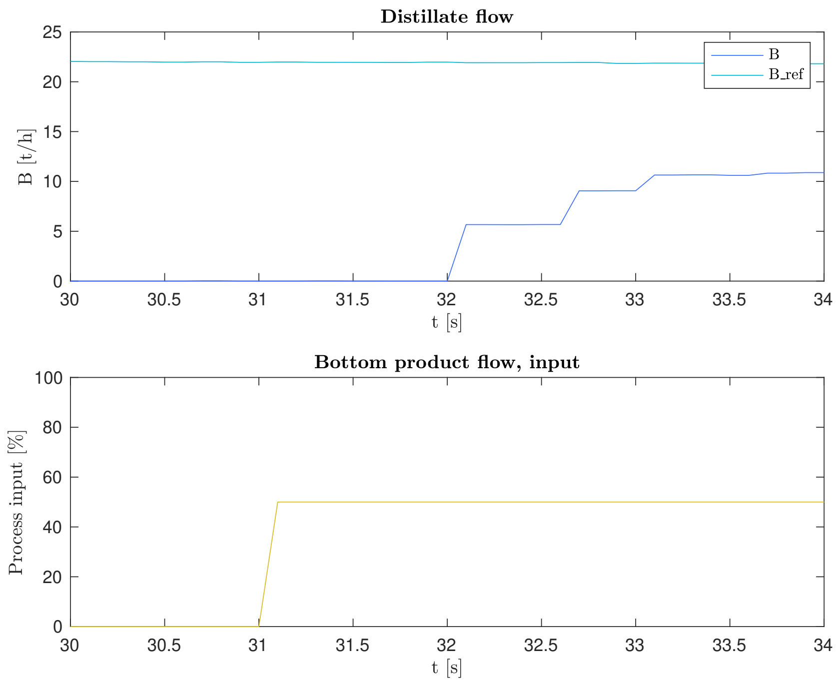

Fig. 5: Open-loop step response of B

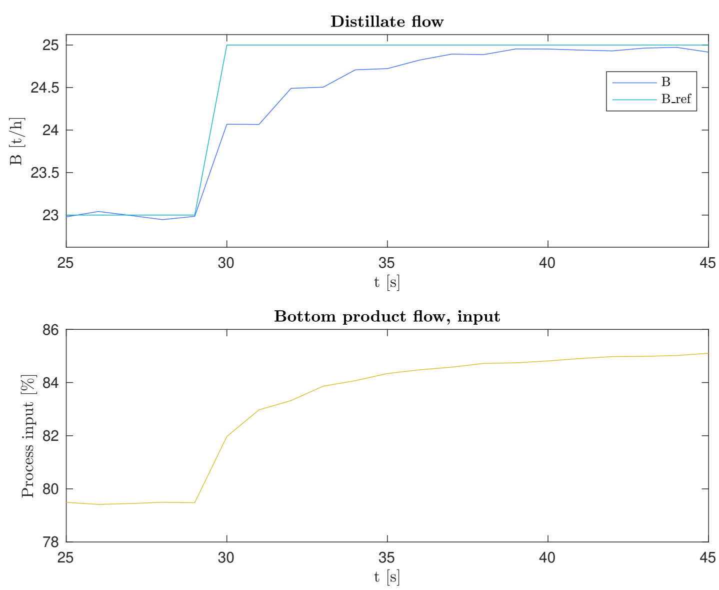

Fig. 6: Closed-loop step response of B

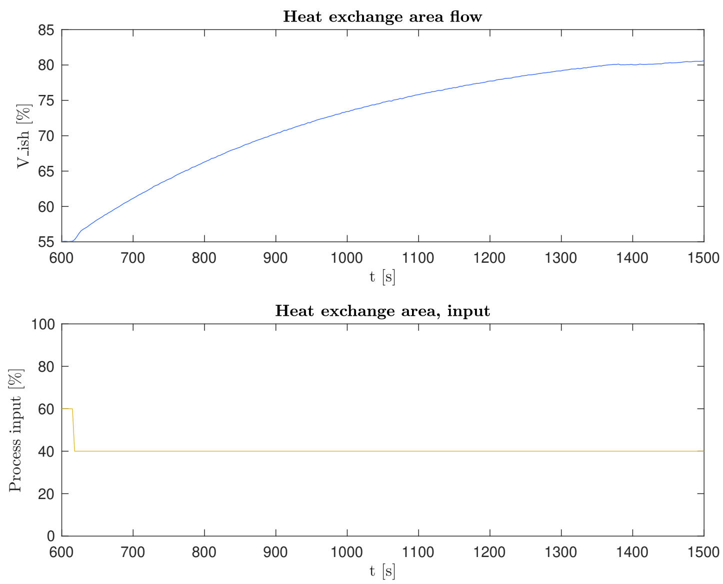

Fig. 7: Open-loop step response of heat exchanger area, related to V

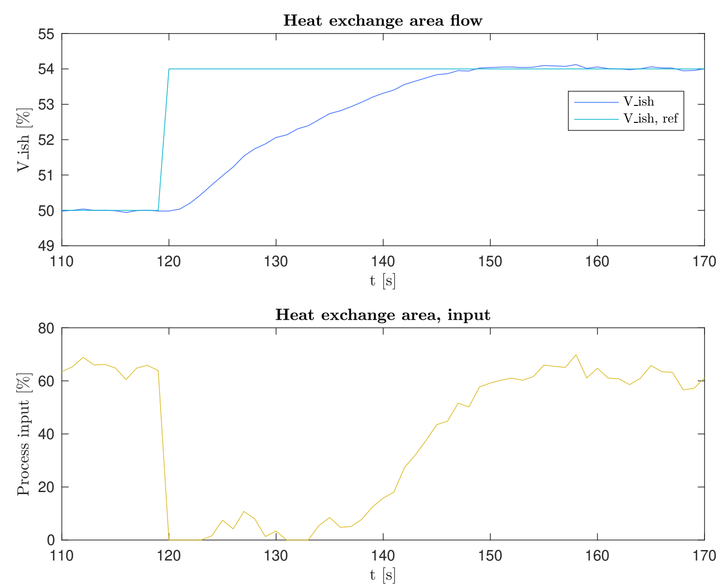

Fig. 8: Closed-loop step response of heat exchanger area, related to V

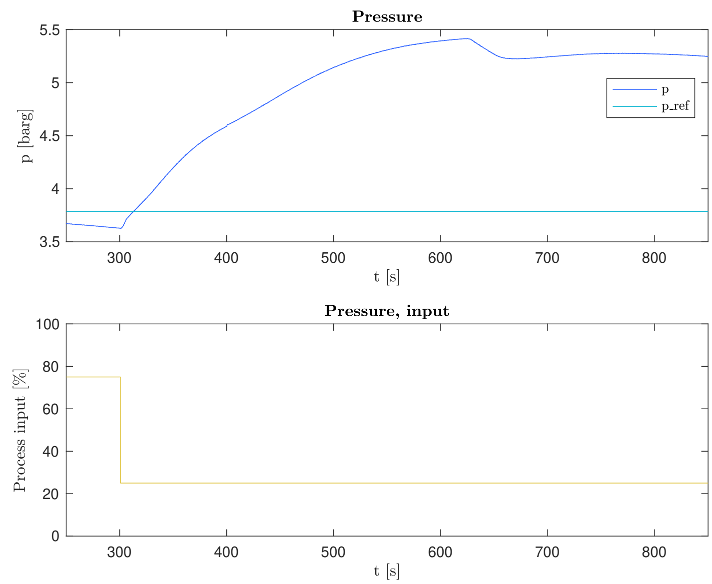

Fig. 9: Open-loop step response of p

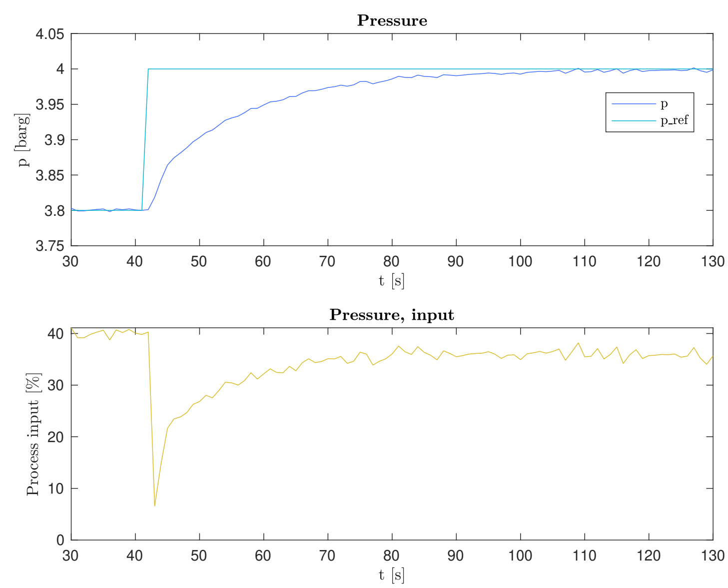

Fig. 10: Closed-loop step response of p

	τ	T_1	$\frac{dy}{dt}$	Δu	k'	T_L
D	1,0s	0,4s	14,3	50%	28,6	2s
L	1,0s	1,0s	47,5	50%	95,0	2s
B	1,0s	0,6s	10,0	50%	20,0	2s
V	≈ 0	400s	0,028	20%	0,14	10s
p	≈ 0	200s	0,088	50%	0,18	10s

Table 2: Identified parameters for inner loop

	$K_{p,\text{SIMC}}$	$T_{i,\text{SIMC}}$	$K_{p,\text{final}}$	$T_{i,\text{final}}$
D	0,012	0,4s	0,0035	0,4s
L	0,035	1,0s	0,0018	1,0s
B	0,016	0,6s	0,0025	1,0s
V	0,71	40s	1,65	10s
p	0,57	40s	0,25	20s

Table 3: PI controller parameters for inner loop

$T_L = 10s$ was chosen for these systems (instead of using the $T_L = 2\tau$ rule). Like all the other parameters, these were not absolute choices, but a good starting point for further tuning.

After calculating the SIMC controller values some qualitative tuning using K-spice simulations was, not surprisingly, needed. For D and L, the integral times were kept fixed, and the gain was decreased to avoid oscillations. For B, it was necessary to reduce the integral time in addition to reducing the gain, to avoid oscillation. The response of V was slow, and to avoid bandwith limitations in the control of T_B later, both controller parameters were changed to give dramatically more aggressive behaviour. For p, the stationary deviation was removed a bit slowly, so the integral time was reduced, while also reducing gain to avoid oscillation.

The results of implementing these controllers in K-spice, using the internally scaled gain $G = K_p \frac{(y_{\max} - y_{\min})}{(u_{\max} - u_{\min})}$ for all controllers, are shown in figures 2, 4, 6, 8 and 10.

Sørg for å få p skalert riktig (enhet er trykk, ikke flow)

4 Level controllers

In this section, the subsystem consisting of the levels in the reflux drum and distillation column is identified, using the inputs D and B. Let $y = [M_D \quad M_B]^T$ and $r = [M_{D,\text{ref}} \quad M_{B,\text{ref}}]^T$. By exciting the controlled system

$$y(s) = L(s)e(s) = G(s)K(s)(y(s) - r(s)) \tag{1}$$

with changes in the reference r, the loop transfer function $L(s)$ may be identified. Using the P controller $K(s) = K_p$, where K_p is known, makes it possible to use loop-shaping methods to design a controller $K(s)$.

4.1 System identification and analysis

4.1.1 Experiment

The level controllers in the distillation column and reflux drum were expected to be more or less independent, but a MIMO experiment followed by identification using the `d-sr` toolbox was used anyway, due to the convenience of being able to reuse code in the composition control task. The system was excited by step changes in reference for M_D and M_B, which were controlled with P controllers, both with $K_p = 1200$. The step changes were chosen such that the system had time to settle, making the full step response available to analysis. The states were attempted held in a reasonable window, to avoid nonlinear effects such as saturation. The experiments are shown in figures 12 and **??**.

4.1.2 Analysis

The identified model was, not surprisingly, chosen to have order 2, decided from figure 13, showing the minimum singular value and condition number of $G(s)$ as a function of system dimension. Another non-surprise is shown in figure 14. Inspecting this plot shows that the magnitudes of the off-diagonal elements are small, while the diagonal elements have gain close to unity at the bandwith frequency (meaning the area around $\omega = 0,01$). Since interaction is low, a diagonal controller

$$K(s) = \begin{bmatrix} k_1(s) & 0 \\ 0 & k_2(s) \end{bmatrix} \tag{2}$$

with PI controllers $k_1(s)$ and $k_2(s)$ may be designed independently based on the diagonal elements in the identified $G(s)$. In the following, $L(s)$ is used for simplicity, since it is simply a scaled version of $G(s)$.

The most important information is however shown in figures 15 and 16. These show the Bode plots of the transfer functions in the diagonals of the identified model. The gain margin of loop transfer function $l_{11}(s) = \frac{M_D}{M_{D,ref}}(s)$ may by inspection of the plot be found to be 6,74dB as $\omega \to \infty$. Likewise, the gain margin of $l_{22}(s) = \frac{M_B}{M_{B,ref}}(s)$ is read to be 10,7dB as $\omega \to \infty$. Using the 6dB gain margin rule of thumb, $K_{p,D}$ should not be increased by any significant amount, while $K_{p,B}$ might be increased by a factor of $10^{(10,7-6)/20} \approx 1,7$, yielding the controller gain $K_{p,B} = 2000$.

The phase plot of l_{11} shows that the integral controller should be operative in the lower frequency spectrum. To avoid the phase crossing the $-180°$ line, the inequality $\frac{1}{T_{i,D}} < 2 \cdot 10^{-4}$ should be respected. Choosing $T_i = 5000s$ satisfies this. The phase response of l_{22} is pretty similar to the one of l_{11}, so initially choosing the same integral time for control of M_B should be reasonable.

The loop transfer functions $l_{11}(s)k_1(s)$ and $l_{22}(s)k_1(2)$ using $k_1(s) = K_{p,D}\frac{1+T_{i,D}s}{T_{i,D}s}$ and $k_2(s) = K_{p,B}\frac{1+T_{i,B}s}{T_{i,B}s}$, are shown in figures 17 and 18. Both systems has (in theory) 6dB gain margin and a bit under 60° phase margin.

Figures 19 and 20 shows complementary sensitivity functions for the two systems.

Noe analyse på dette?

4.2 Controller tuning

Simulation in K-spice showed stationary deviation in M_D. To counteract this, the integral time was reduced. Control of M_B worked satisfactory using the PI controller derived from the frequency analysis above.

Dette er teknisk sett transferfunksjon fra feil til tilstand, ikke fra referanse

The initial parameters based on loop-shaping, and the final ones are shown in table 4.

	$K_{p,\text{initial}}$	$T_{i,\text{initial}}$	$K_{p,\text{final}}$	$T_{i,\text{final}}$
M_D	1200	5000s	1200	1000s
M_B	2000	5000s	2000	5000s

Table 4: Parameters for level controllers

Simulate and plot step re-

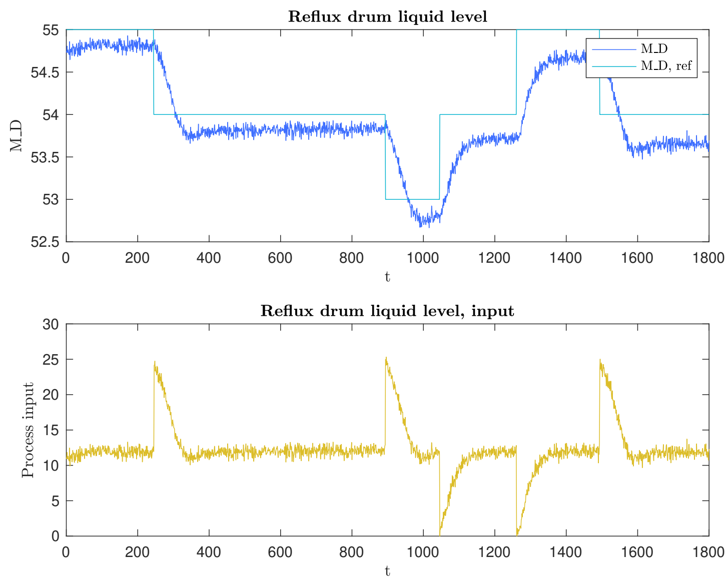

Fig. 11: System identification experiment for M_D controller

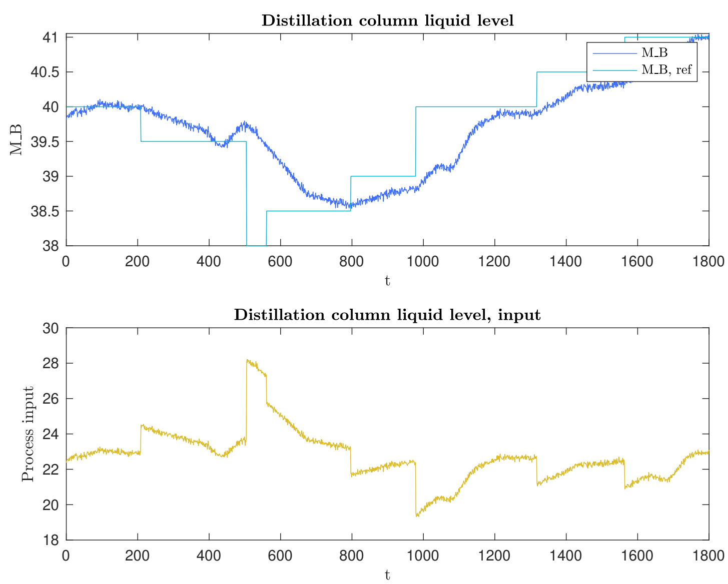

Fig. 12: System identification experiment for M_B controller

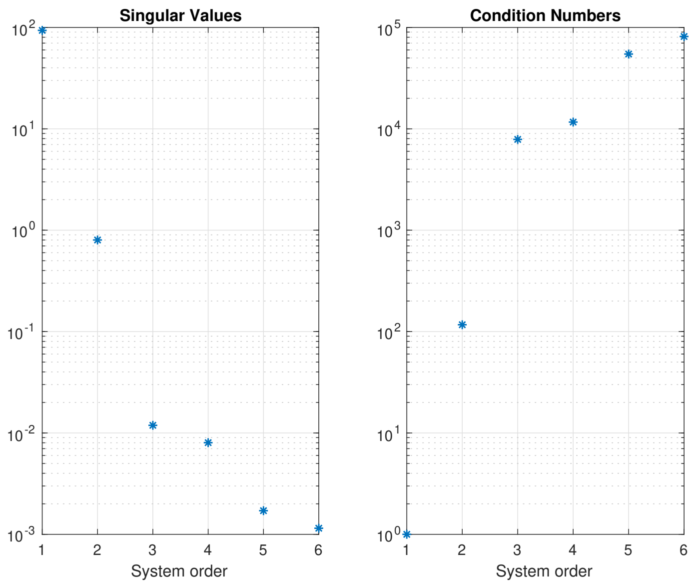

Fig. 13: Minimal singular value and condition number

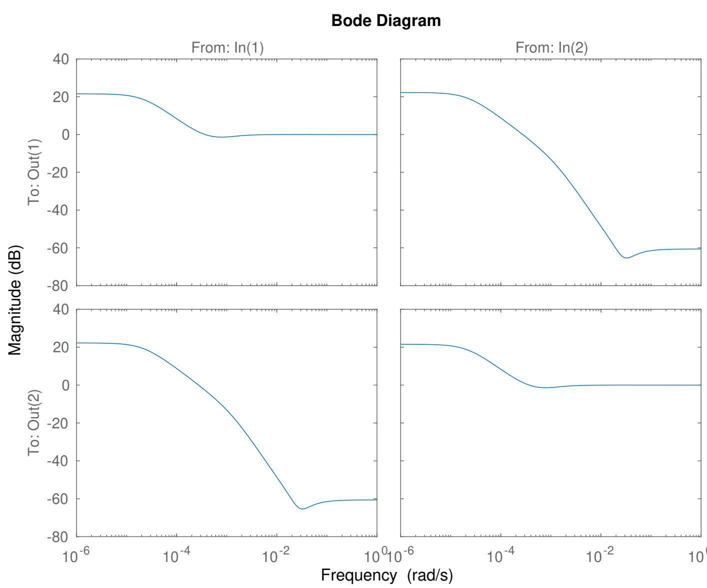

Fig. 14: Magnitude of RGA of identified system

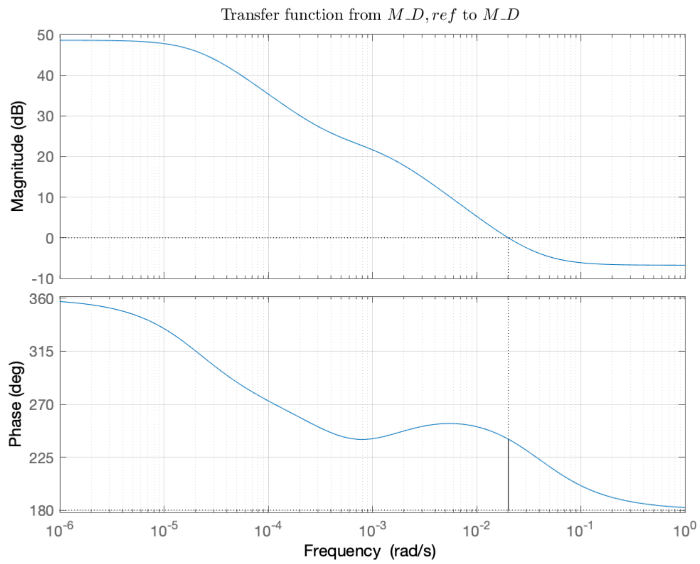

Fig. 15: Magnitude and phase response of reflux drum level from reflux drum level reference

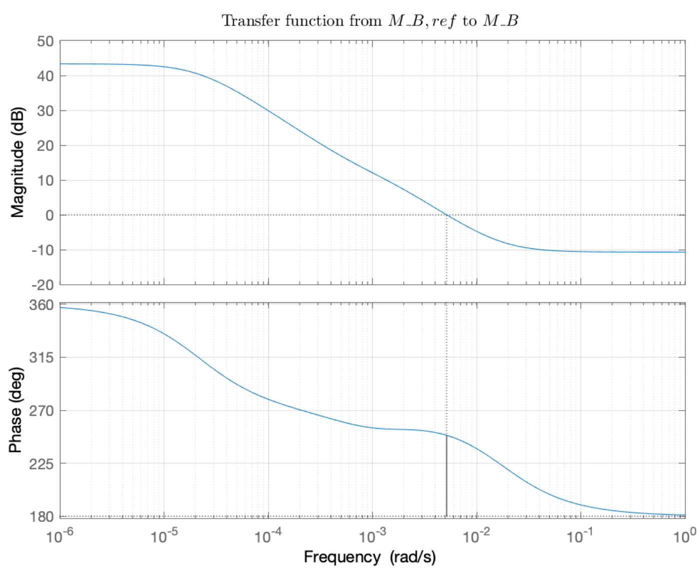

Fig. 16: Magnitude and phase response of distillation column level from distillation column level reference

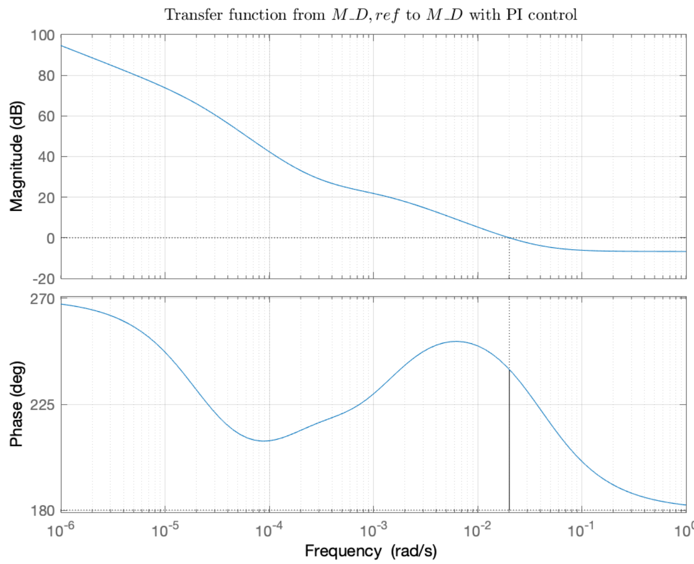

Fig. 17: Magnitude and phase response of reflux drum level from reflux drum level reference, using suggested PI controller

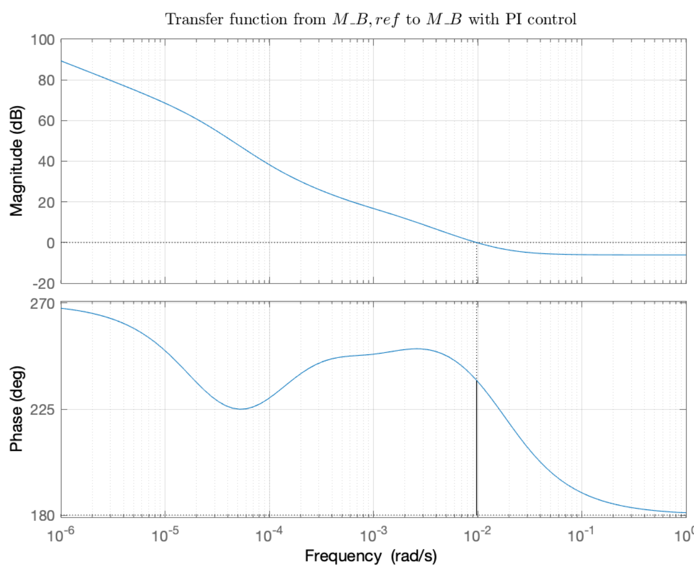

Fig. 18: Magnitude and phase response of distillation column level from distillation column level reference, using suggested PI controller

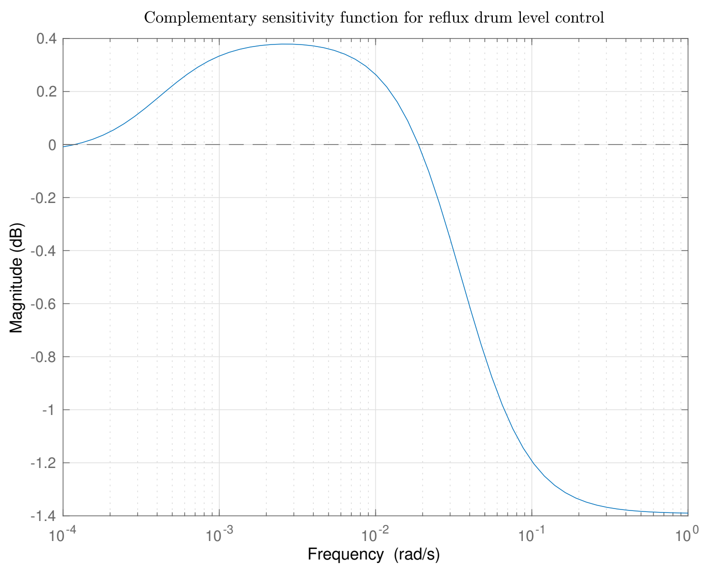

Fig. 19: Complementary sensitivity function for reflux drum level control

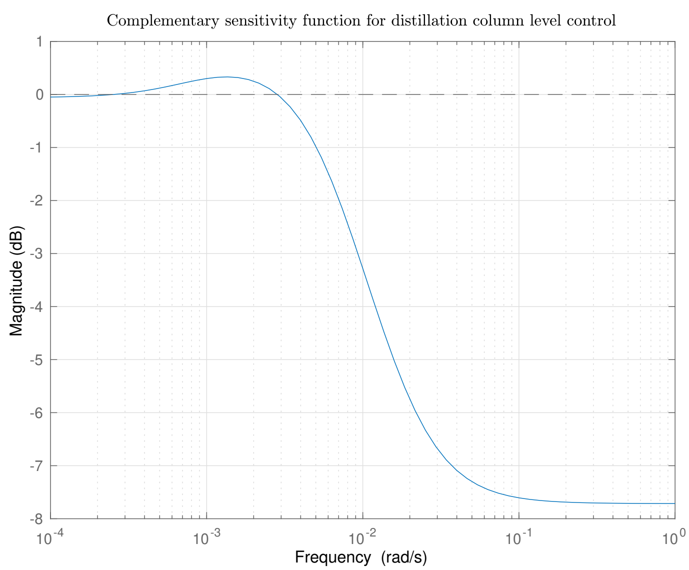

Fig. 20: Complementary sensitivity function for distillation column level control

5 Composition controllers

Let $y = [T_D \quad T_B]^T$, $r = [T_{D,\text{ref}} \quad T_{B,\text{ref}}]^T$ and $u = [L \quad V]^T$. By changing the setpoints for the manipulated variables L and V, the system transfer function

$$G(s) = \frac{y}{u}(s) \tag{3}$$

may be identified directly.

5.1 System identification and analysis

5.1.1 Experiment

Identification of the LV system was done in a similar manner as in the previous section, using step changes in input (but open-loop this time). Again, `d-sr` was used for identification.

Gjennomfør eksperiment

5.1.2 Analysis

Presenter relevant teori

5.2 Controller tuning

Tune i K-spice

	K_p	G	T_i
D (FC1005)	0,0035	0,42	0,4s
L (FC1015)	0,0018	0,22	1,0s
B (FC1019)	0,0025	0,3	1,0s
V (LC1028)	200	200	10s
p (PC1024)	5	30	20s
M_D (LC1016)	1200	10	1000s
M_B (LC1015)	2000	16,7	5000s
T_D (TC1015)	12	2,5	100s
T_B (TC1088)	30	6,3	1000s

6 Results

6.1 PI controller tuning

Table **??** shows the final PI controller parameters for all the control loops tuned in this project, also including the scaled gain G used in the K-spice implementation.

6.2 Reference tracking

The results of step changes in reference are shown in figures 21 and 22.

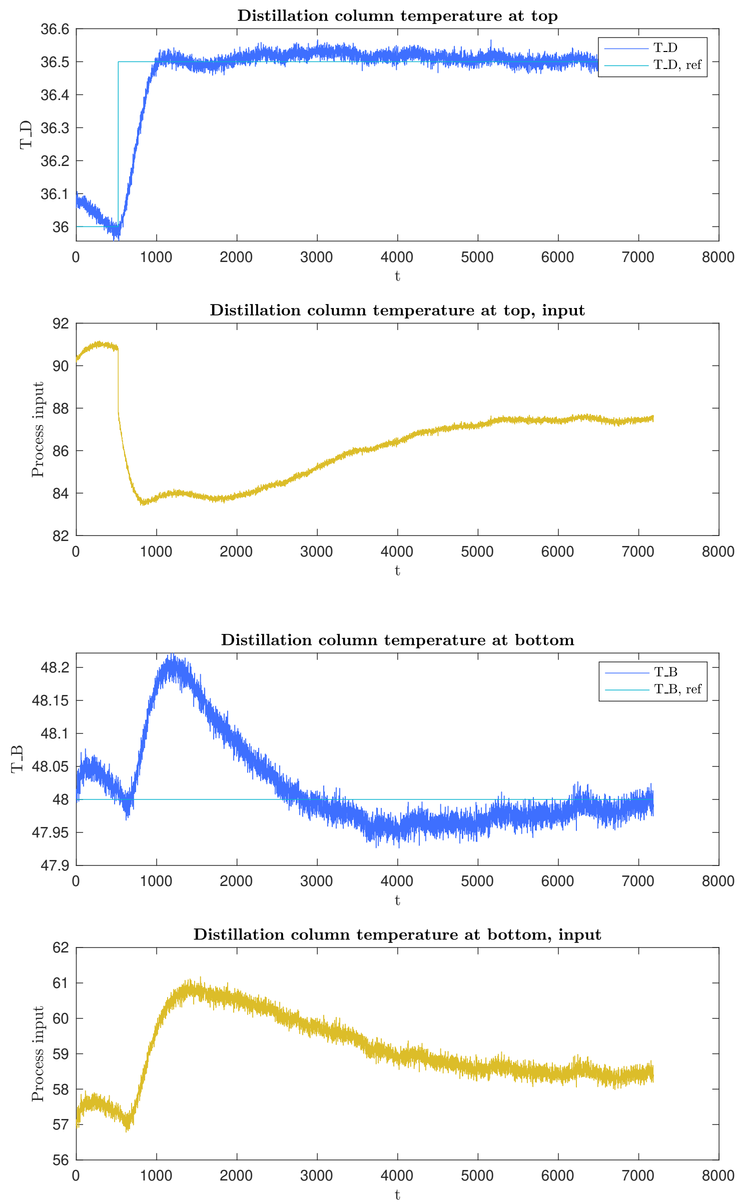

Fig. 21: Response of T_D and T_B to step change in $T_{D,\mathrm{ref}}$

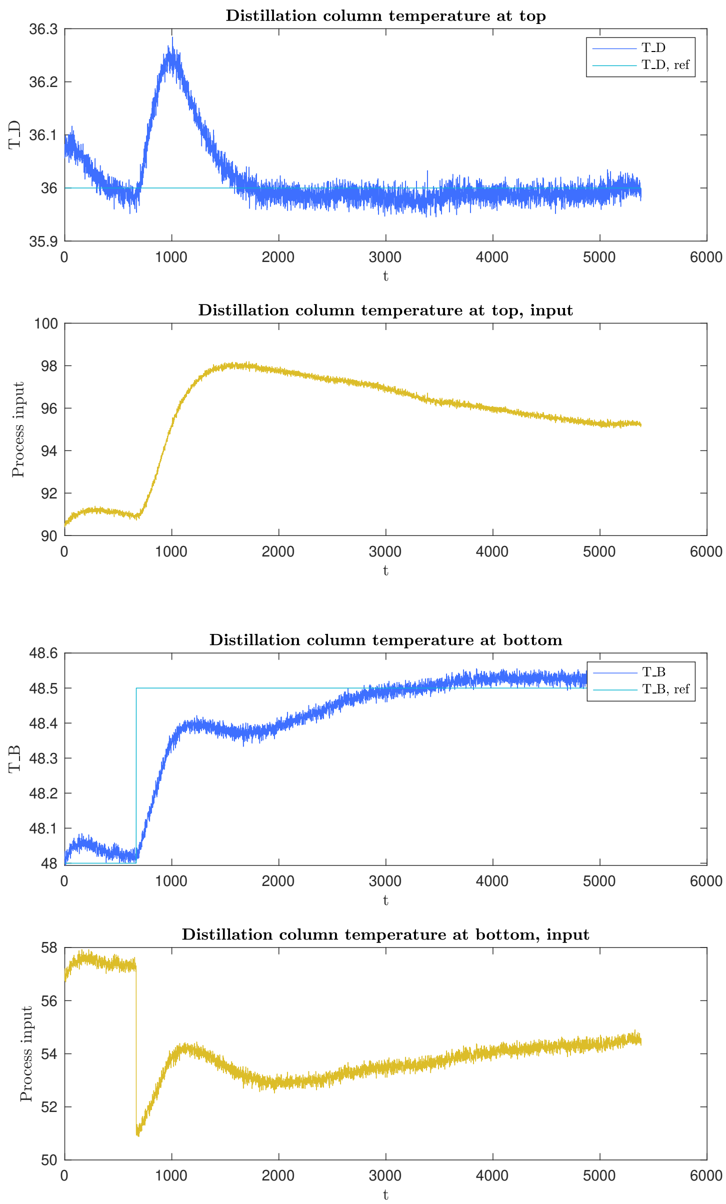

Fig. 22: Response of T_D and T_B to step change in $T_{B,\mathrm{ref}}$