TTK4210 Advanced Control of Industrial Systems, Exercise 6

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Contents

1 Abstract

In this project, a model of a distillation column is used to design a controller for the composition of two product streams consisting of n-butane and isobutane, respectively.

Legg til resultater

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.

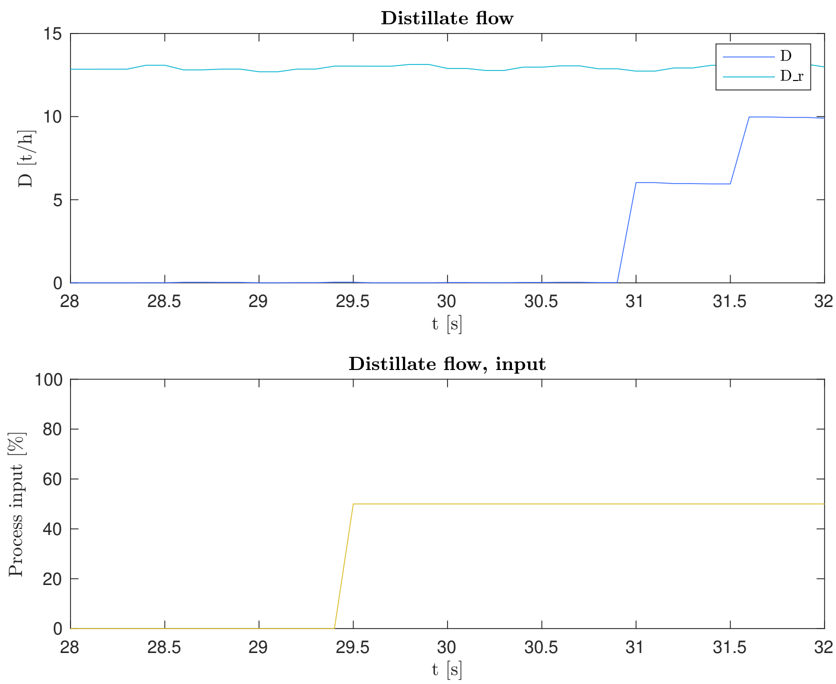

Fig. 1: Open-loop step response of D

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 [**?**])

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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 $K_p = \frac{1}{k'}\frac{1}{\tau+T_L}$, $T_i = \min(T_1, 4(\tau + T_L))$.

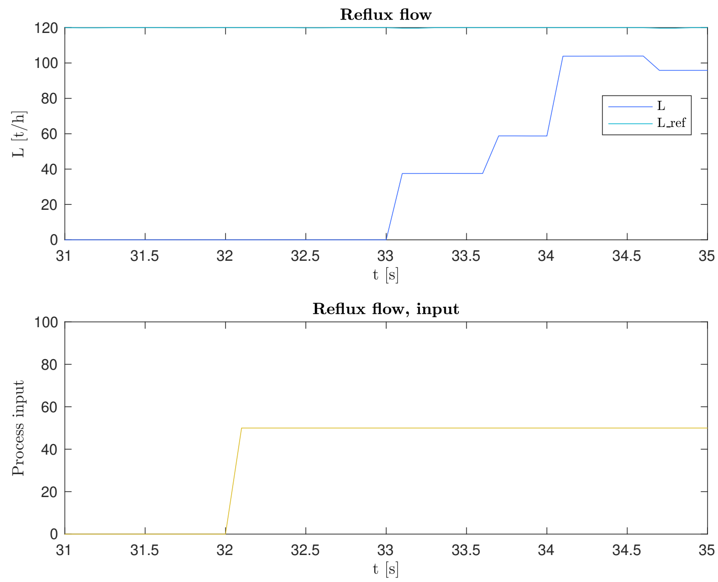

Fig. 2: Open-loop step response of L

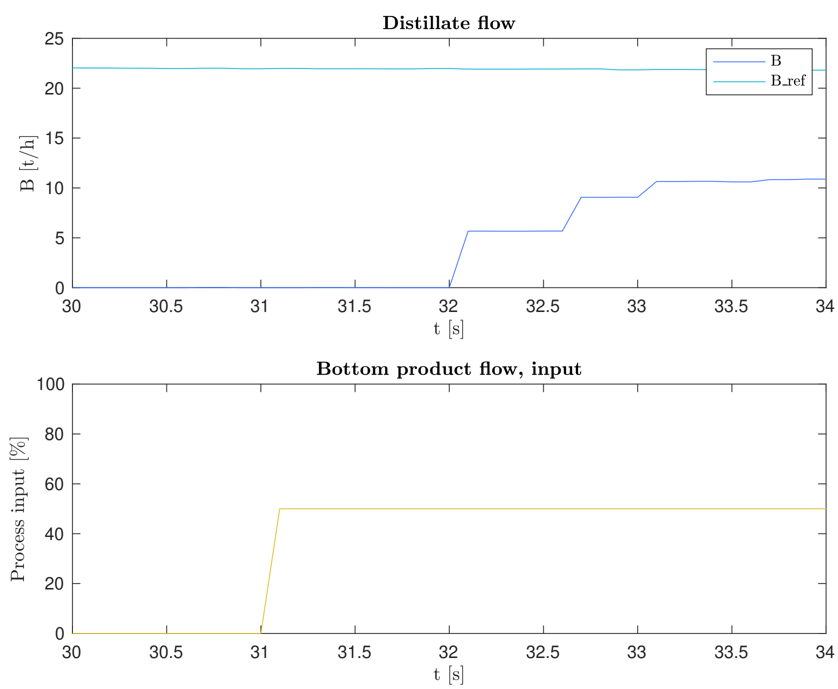

Fig. 3: Open-loop step response of B

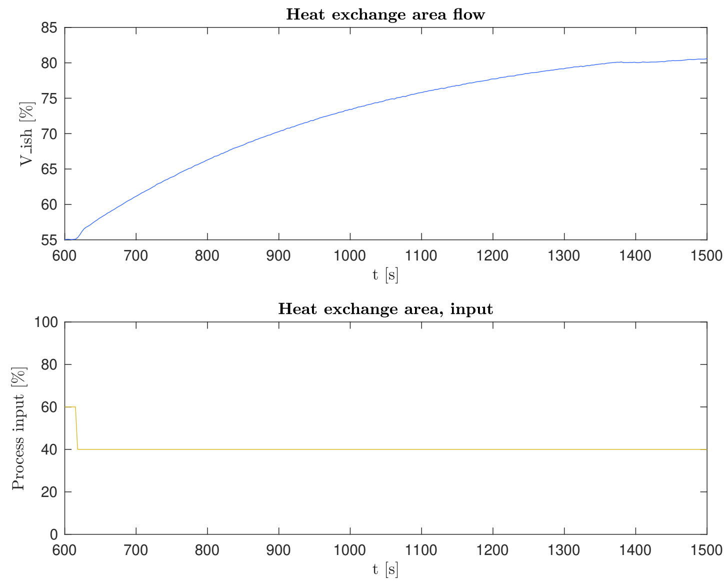

Fig. 4: Open-loop step response of heat exchanger area, related to V

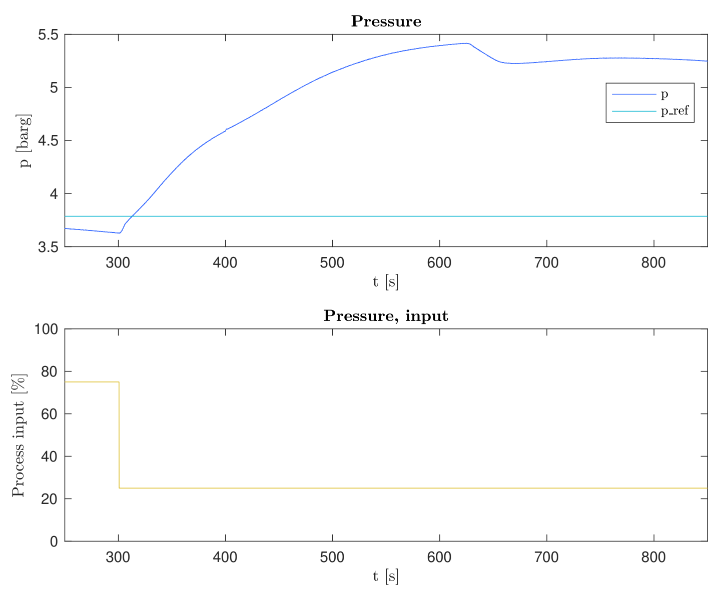

Fig. 5: Open-loop step response of p

The data from these experiments can be seen in figures 1, 2, 3, 4 and 5. 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 interpolation 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 $T_L = 10s$ 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. Here, the integral times (which could be read decently well from the open-loop step response plots) were kept fixed. The resulting one degree of freedom made tuning easier, and the results of this tuning is shown in table 3, together with the values from the SIMC method (which served as the starting point for this tuning). A column showing the scaled gain $G = K_p \frac{(y_{\max} - y_{\min})}{(u_{\max} - u_{\min})}$, which is the value implemented in K-spice, is also shown. The final controller gains are also given in this variable, since the parameters were changed directly in the K-spice panel. The two slowest control loops were showing slow responses, and the controller parameters were adjusted to be more aggressive. T_i in the p control loop was changed from 40s to 20s in the final tuning, and T_i was

	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	T_i	G_{SIMC}	G_{final}
D	0,0035	0,4s	0,42	0,42
L	0,0018	1,0s	0,22	0,22
B	0,0083	1,0s	1,0	0,30
V	0,71	10s	86	200
p	0,57	20s	68	30

Table 3: PI controller parameters for inner loop

chosen to be 10s in the V control loop.

Legg til noe om at resten av systemet bare var i tilfeldige tilstander med tilfeldige regulatorer.

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4 Level controllers

4.1 System identification and analysis

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 experiments are shown in figures 7 and ??. The identified model was, not surprisingly, chosen to have order 2, decided from figure 8, showing the minimum singular value and condition number of $G(s)$ as a function of system dimension. Another non-surprise is shown in figure 9. 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 $\omega = 0,01$) and confirms that the model is at least not completely clueless of what is going on.

The most important information is however shown in figures 10 and 11. 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 $\omega \rightarrow \infty$. Likewise, the gain margin of $l_{22}(s) = \frac{M_B}{M_{B,ref}}(s)$ is read to be 10,7dB as $\omega \rightarrow \infty$. 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 12 and 13. Both systems has (in theory) 6dB gain margin and a bit under 60° phase margin.

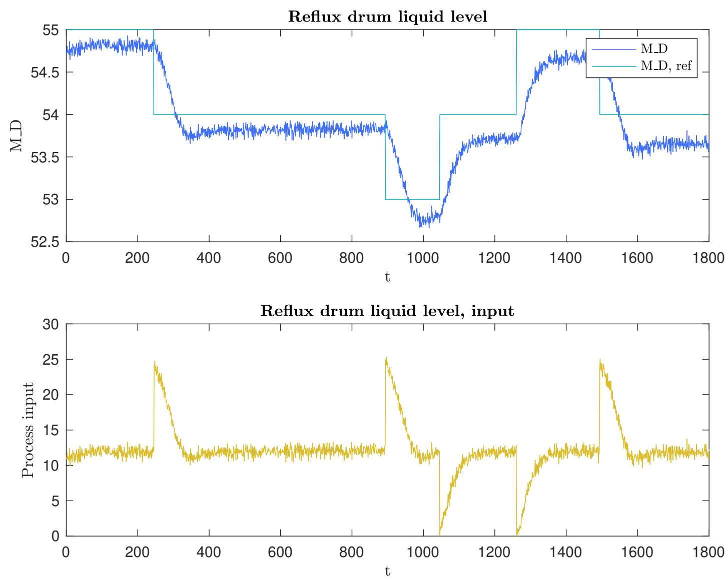

Fig. 6: System identification experiment for M_D controller

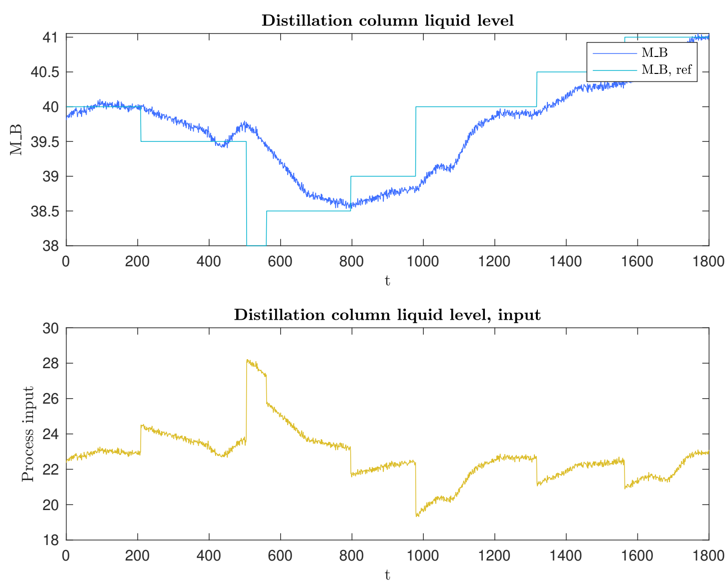

Fig. 7: System identification experiment for M_B controller

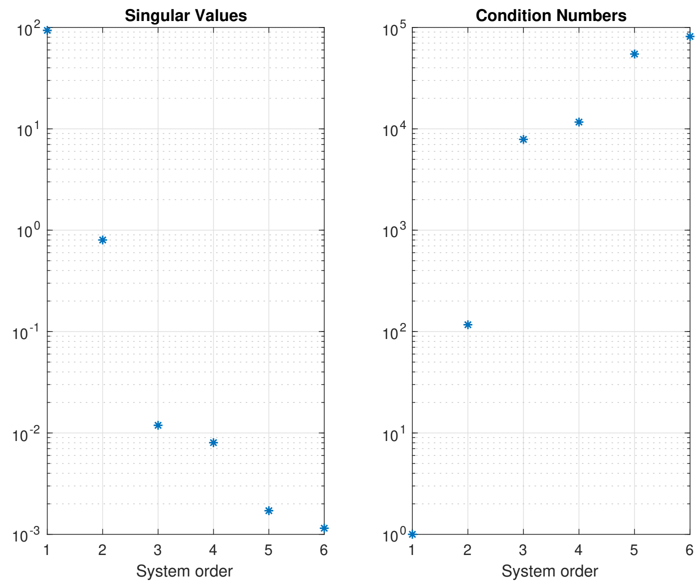

Fig. 8: Minimal singular value and condition number

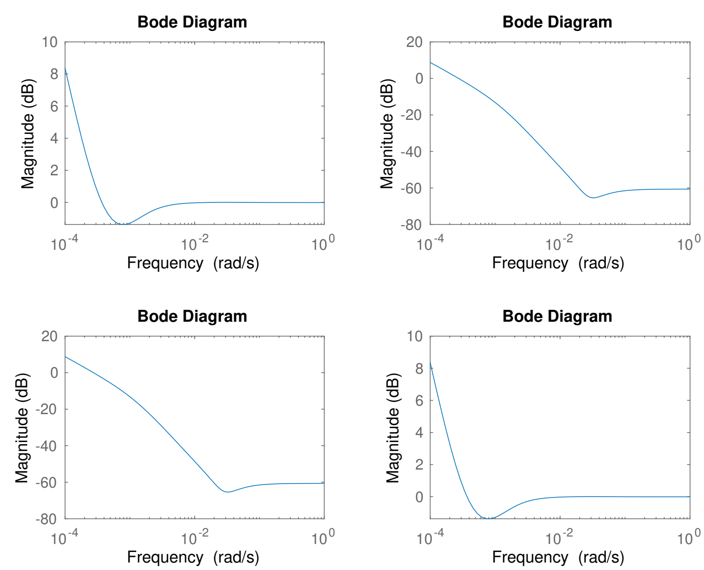

Fig. 9: Magnitude of RGA of identified system

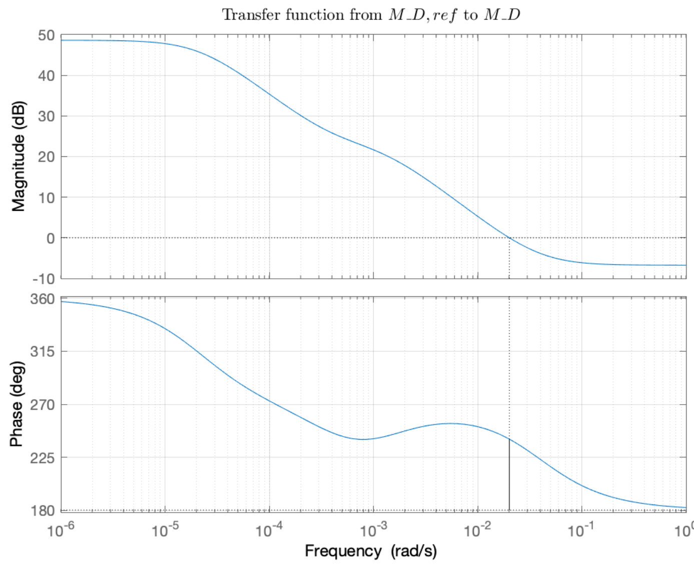

Fig. 10: Magnitude and phase response of reflux drum level from reflux drum level reference

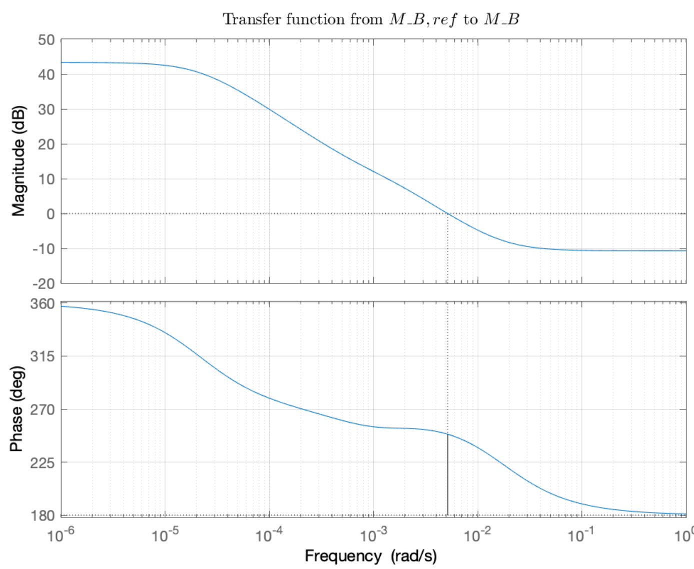

Fig. 11: Magnitude and phase response of distillation column level from distillation column level reference

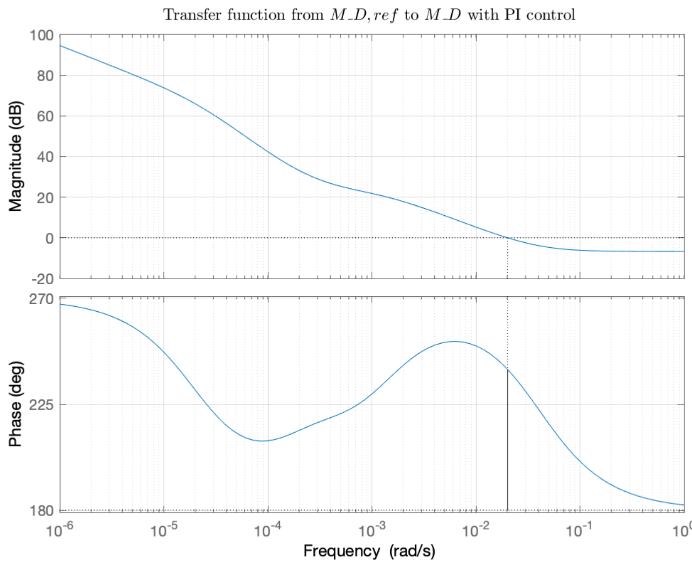

Fig. 12: Magnitude and phase response of reflux drum level from reflux drum level reference, using suggested PI controller

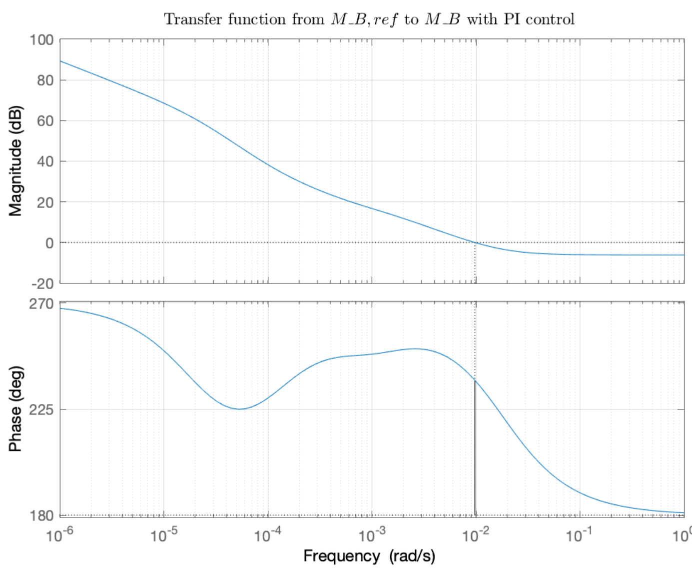

Fig. 13: Magnitude and phase response of distillation column level from distillation column level reference, using suggested PI controller

4.2 Controller tuning

The parameters are shown in table **??**, together with the parameters gained from a second round of tuning using K-spice simulations.

	$K_{p,\text{initial}}$	$T_{i,\text{initial}}$	$K_{p,\text{second}}$	$T_{i,\text{second}}$
D	1200	5000s	600	1000s
B	2000	5000s	120	10000s

Table 4: Parameters for level controllers

5 Composition controllers

5.1 System identification

Dette

5.2 Controller tuning

Dette