Robust Model Predictive Control of Distillation Columns

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Abstract

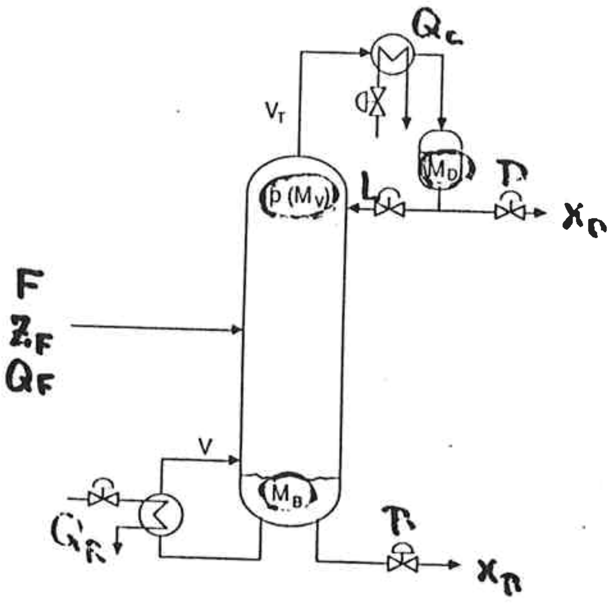
The paper addresses how to obtain good control performance, in the Model Predictive Control (MPC) framework, for an ill-conditioned distillation column despite imperfect knowledge about the plant and physical constraints on plant inputs.

In industry most columns are controlled by five single-input-single-output (SISO) loops. Pairing outputs to specific inputs may limit the performance of the system since each separate controller can utilize information from one measurement only. Another problem with decentralized controllers is that the control structure may have to be reconfigured if the system hit some constraints.

In this paper we do not assume any specific pairing of inputs and outputs. Instead we design a full 5×5 multivariable controller, using a state observer MPC algorithm. We divide the controller design into two subproblems:
1) A *linear* part dealing with Robust Performance (RP).
2) A *non-linear* part dealing with constraint handling.

First the linear RP problem is formulated and solved in the structured singular value (μ) framework. This step includes deriving frequency dependent weights to define model uncertainty and performance requirements. Thereafter we shift to the MPC framework in order to deal with the constraints (non-linear control). We utilize the weights obtained from the RP problem to define MPC control objectives. In particular, the 'D-scales' from the μ computation provide guidelines for how to mimic the uncertainty by adding noise to the MPC problem.

Distillation



5x5 open-loop unstable system

Control objectives:

- Stabilize the system
- Reject disturbances
- Track set-points

Control Problems

- Strong interactions
- Constraints
- Non-linear process
- Delayed and uncertain measurements
- Plant-model mismatch
- Input uncertainty

Conventional Control

3 SISO loops for level and pressure control

2 SISO loops for composition control ("configuration")

Requires "pairing" of variables

May require reconfiguration if manipulator hits constraint

Model Predictive Control

Possibly better performance

No pairing

Constraint handling

Robustness ?

Robust MPC

Goal:
A ***robust*** controller which can handle ***constraints***.

Use ***all*** available information (plant model, measurements etc.) to compute ***all*** inputs.

Divide the controller design into two sub-problems:

1 A ***linear*** part dealing with Robust Performance (RP).

2 A ***non-linear*** part dealing with constraint handling.

Part 1 is solved in the μ framework.
Part 2 is solved using an observer in the MPC framework.

Design Approach

1 Obtain a plant model

Derive a non-linear plant model

Linearize the model and reduce its order

2 Formulate and solve a RP problem (μ)

Check for intrinsic performance limitations

Define performance requirements

Define uncertainty limits

Apply μ-synthesis (DK-iteration)

3 MPC design

Transform the μ weights into MPC tuning parameters

Tune the MPC controller using μ, linear and non-linea ulations

Distillation Model

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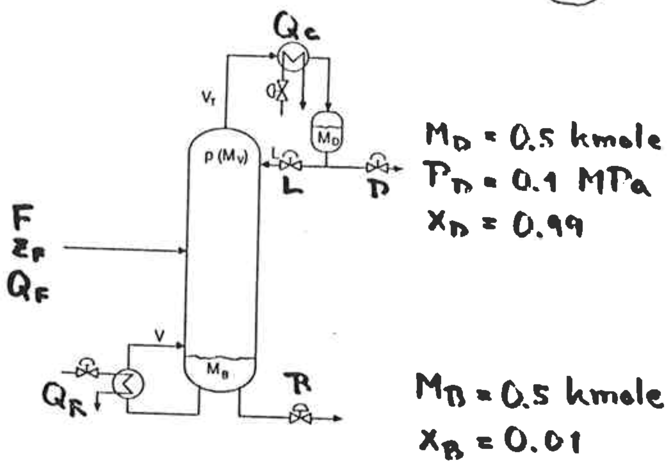

Non-linear model (SPEEDUP)

- Binary mixture
- $\alpha \approx 1.5 \quad (\alpha = f(T, P))$
- 40 trays + Total condenser
- 3 states per tray
- Varying pressure
- No vapor holdup

Linear analysis

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Inputs: L, Q_B, D, B, Q_C

Outputs: $x_D(1), x_B(1), M_D, M_B, P_D$

Steady state RGA:

36.67	−61.99	0	0	26.31
−35.63	60.80	0	0	−24.17
0	0	1	0	0
0	0	0	1	0
−0.04	2.18	0	0	−1.14

Constraints would impose problems if decentralized control was used.

μ-Problem

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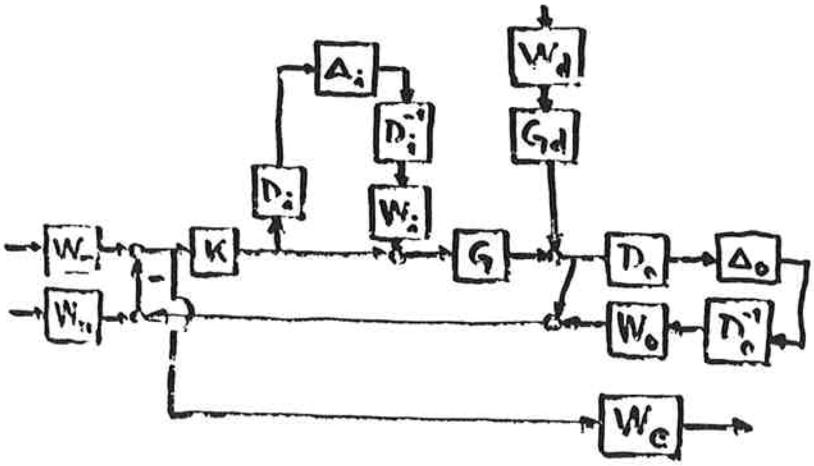
Unconstrained linear Robust Performance problem



W_i : ±10% input uncertainty
W_o : 30s delay in compositions
10s delay in levels and pressure
W_e : Closed-loop time constant for set-points
20 min compositions
50 min levels
5 min pressure

After some DK-iterations:

$$\mu_{RP}(K_{\mathcal{H}_\infty}) = 0.933$$
$$\mu_{RP}(K_{\mathcal{H}_2}) = 1.402$$

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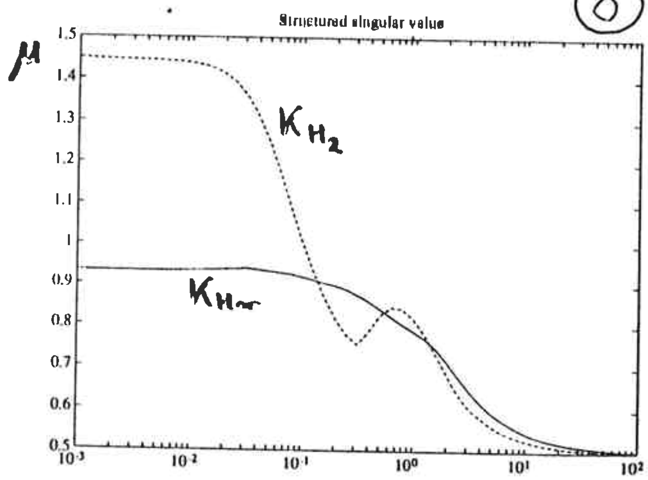
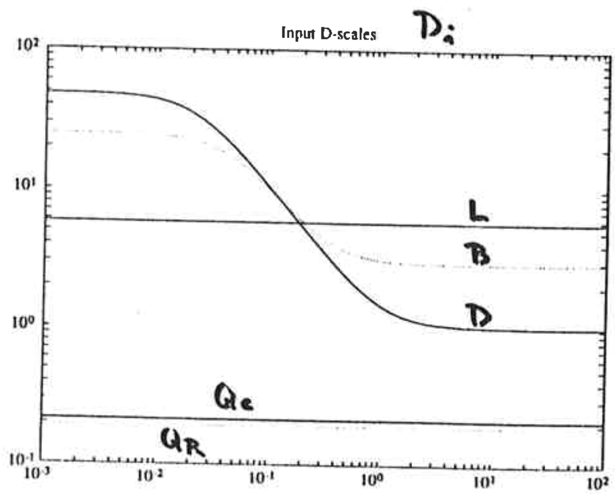
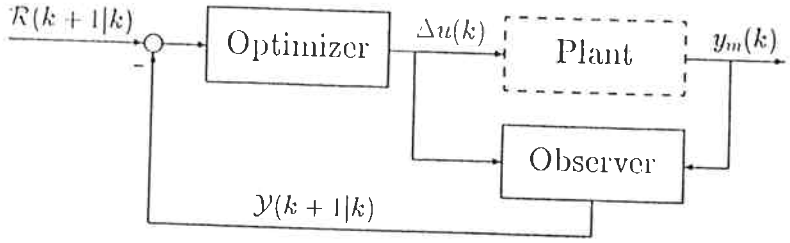


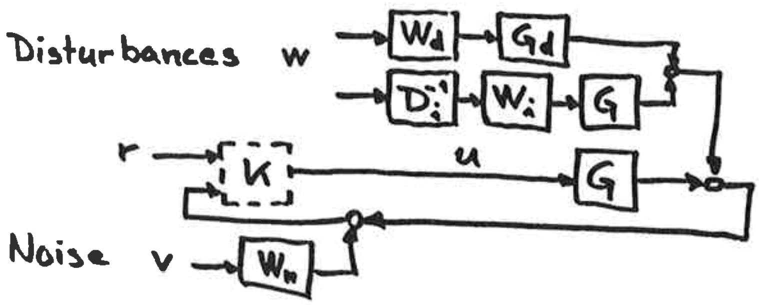


State Observer MPC

(9)



Observer filter design



MPC tuning

(10)

K_{filter}:

$G_{mod} = [G \;\; GW_iD_i^{-1} \;\; G_dW_d]$

Covariance of w: $W = I_{8\times 8}$

Covariance of v: $V = W_n^2$

K_{MPC}:

$\Delta T = 1$ min

$M = 3$ (input horizon)

$P = 60$ (prediction horizon)

$U_{wt} = 1$, 1/30 , 1/6 , 1/2 , 1/30

$Y_{wt} = 5$, 5 , 0.01 , 0.01 , 2

Input constraints:

	L	Q_R	D	B	Q_C
max	1	30	0.5	0.5	15
min	-1	-30	-0.5	-0.5	-15
Δ	0.5	5	0.5	0.5	5

Level constraints: $-0.5 <$ Level < 0.5

Simulations

(11)

Set-point change x_D : $0.99 \rightarrow 0.98$

Disturbance z_F : $0.50 \rightarrow 0.60$

Input uncertainty:

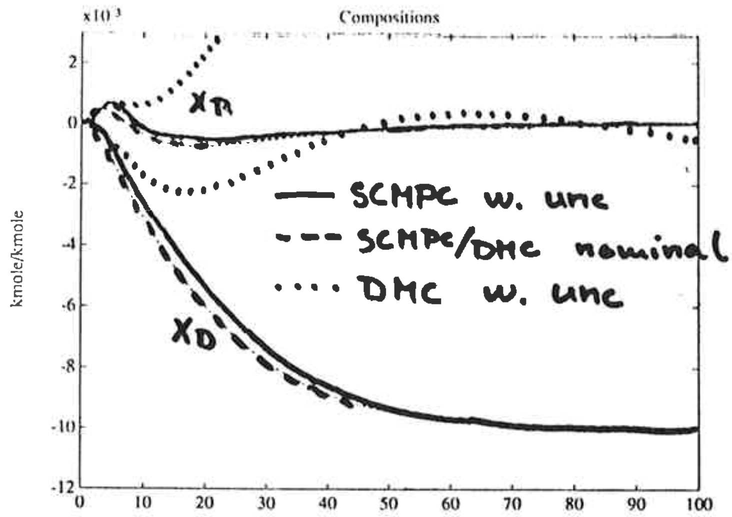
ΔL	-20%	1 min delay
ΔQ_R	+20%	- " -
ΔD	-20%	- " -
ΔB	-20%	- " -
ΔQ_C	-20%	- " -

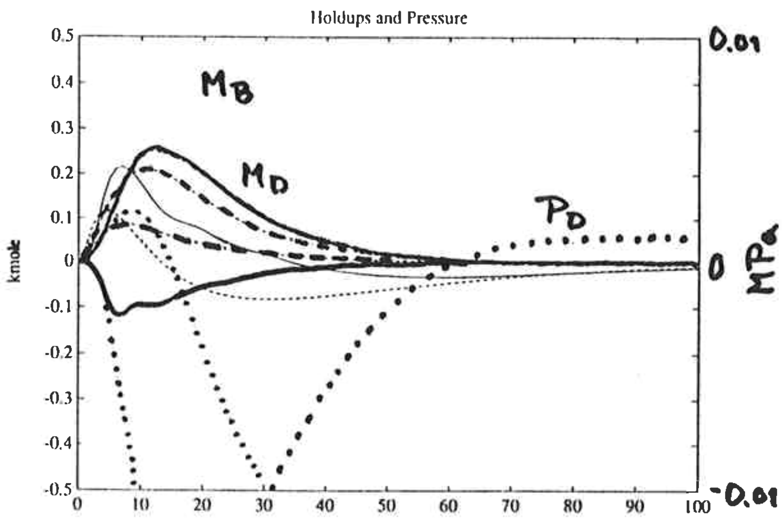
Measurement noise:

Compositions:	$\leq \pm 0.0001$ kmole/kmole
Levels:	$\leq \pm 0.005$ kmole
Pressure:	$\leq \pm 0.001$ MPa

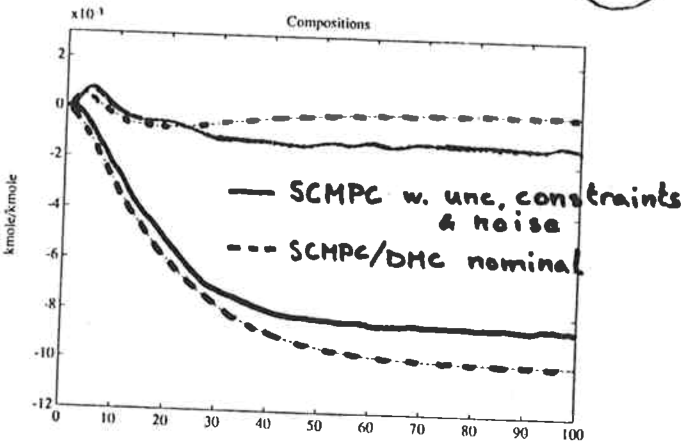
Set-point change in x_D

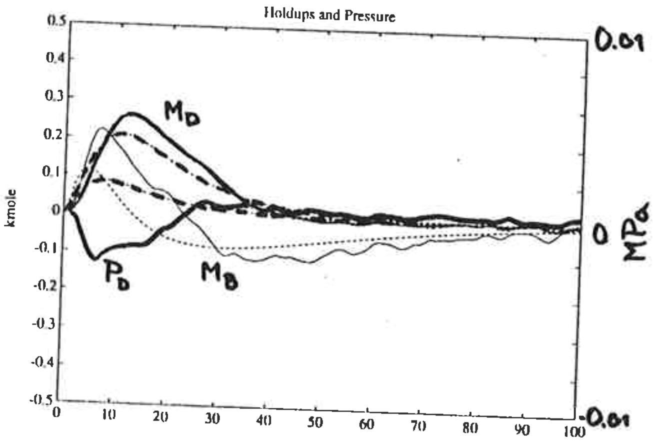
(12)



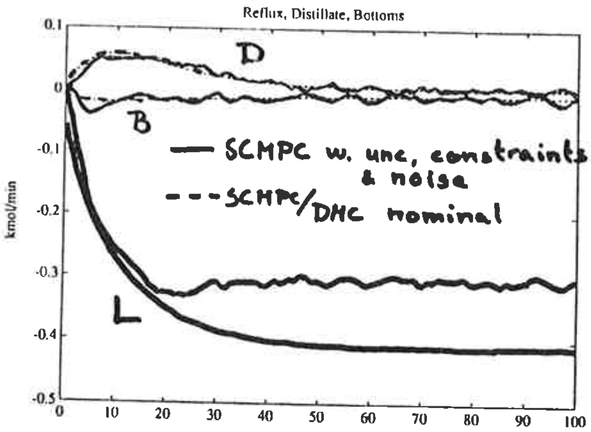


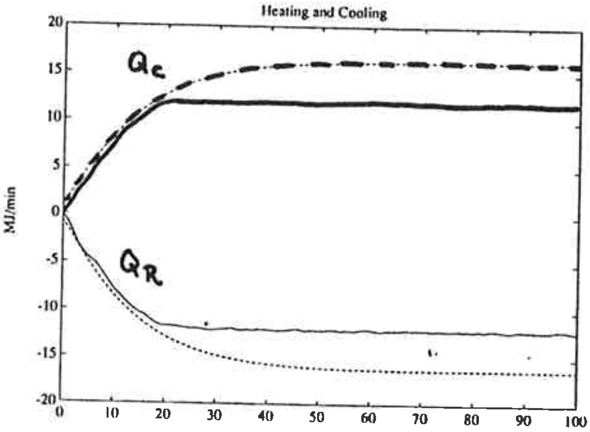
Set-point change x_D (13)



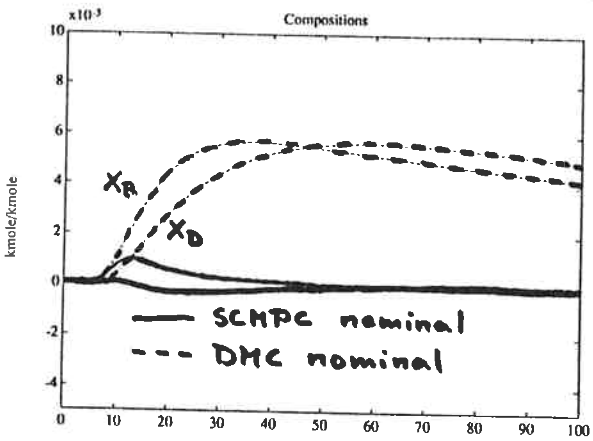


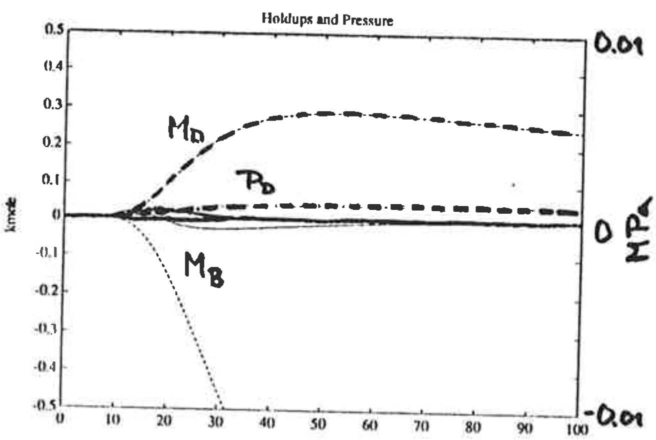
Inputs for Set point change in x_D (14)



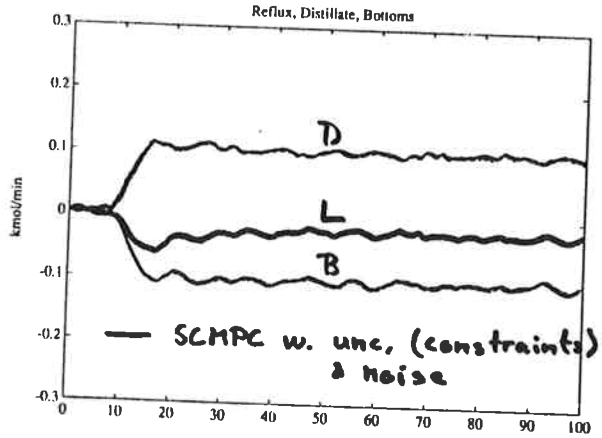


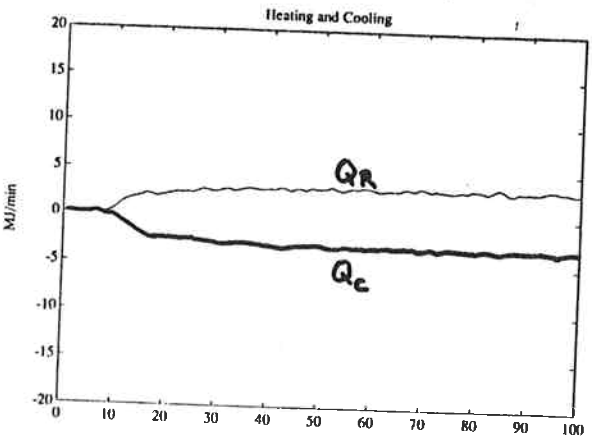
Disturbance z_F (15)





Inputs for Disturbance in z_F (16)





Conclusions

- May obtain Robust MPC by using a well designed state observer.
- D-scales from μ synthesis yield valuable information for observer tuning.