Off-line Robustification of Multivariable Model Predictive Control

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- Introduction
- Multivariable MPC
- Robustness using the Youla parameter
- Robustified MIMO MPC
  - Robust stability (RS)
  - Nominal performance
- Application to a stirred tank reactor
- Conclusions

Introduction

- Off-line state-space methodology for enhancing the robustness of multivariable MPC

Starting point
- Initial stabilizing MIMO Model Predictive Controller

Goal
- Robustification of this initial controller by convex optimization of a multivariable Youla parameter

Means
- Off-line methodology to improve robust stability under unstructured uncertainties, while respecting nominal performance specifications ⇒ LMI tools

Content

- ✓ Introduction
- Multivariable MPC
  - *Model description*
  - *Cost function*
  - *Prediction equation*
  - *Control law synthesis*
- Robustness using the Youla parameter
- Robustified MIMO MPC
- Application to a stirred tank reactor
- Conclusions

Multivariable MPC

- Model description (MIMO system $m \times p$)

$$\begin{cases} \mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k) \\ \mathbf{y}(k) = \mathbf{C}\,\mathbf{x}(k) \end{cases}$$

with $\mathbf{A} \in \mathbf{R}^{n\times n}, \mathbf{B} \in \mathbf{R}^{n\times m}, \mathbf{C} \in \mathbf{R}^{p\times n}$

- Steady-state errors cancellation

$$\mathbf{u}(k) = \mathbf{u}(k-1) + \Delta\mathbf{u}(k)$$

$$\begin{cases} \mathbf{x}_e(k+1) = \mathbf{A}_e\,\mathbf{x}_e(k) + \mathbf{B}_e\,\Delta\mathbf{u}(k) \\ \mathbf{y}(k) = \mathbf{C}_e\,\mathbf{x}_e(k) \end{cases}$$

Extended state-space

$$\mathbf{x}_e(k) = \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{u}(k-1) \end{bmatrix}$$

- Predicted output vector

$$\hat{\mathbf{y}}(k+i) = \mathbf{C}\,\mathbf{A}^i\,\hat{\mathbf{x}}(k) + \sum_{j=0}^{i-1} \mathbf{C}\,\mathbf{A}^{i-j-1}\mathbf{B}\underbrace{\left[\mathbf{u}(k-1) + \sum_{l=0}^{j} \Delta\mathbf{u}(k+l)\right]}_{\mathbf{u}(k+j)}$$

- Observer

$$\hat{\mathbf{x}}_e(k+1) = \mathbf{A}_e\,\hat{\mathbf{x}}_e(k) + \mathbf{B}_e\,\Delta\mathbf{u}(k) + \mathbf{K}[\mathbf{y}(k) - \mathbf{C}_e\,\hat{\mathbf{x}}_e(k)]$$

Multivariable MPC

- Quadratic objective function minimization

$$J = \sum_{i=N_1}^{N_2} \left\| \hat{\mathbf{y}}(k+i) - \mathbf{y}_r(k+i) \right\|^2_{\tilde{\mathbf{Q}}_J(i)} + \sum_{i=0}^{N_u-1} \left\| \Delta\mathbf{u}(k+i) \right\|^2_{\tilde{\mathbf{R}}_J(i)}$$

Output prediction horizons

Weightings

Control horizon

with $\Delta\mathbf{u}(k+i) = 0, \forall i \geq N_u$

- Objective function in the matrix formalism

Future control actions

Extended state-space and future setpoints

$$J = \left\| \mathbf{Y}(k) - \mathbf{Y}_r(k) \right\|^2_{\mathbf{Q}_J} + \left\| \Delta\mathbf{U}(k) \right\|^2_{\mathbf{R}_J} = \left\| \mathbf{\Phi}_\Delta \Delta\mathbf{U}(k) - \mathbf{\Theta}(k) \right\|^2_{\mathbf{Q}_J} + \left\| \Delta\mathbf{U}(k) \right\|^2_{\mathbf{R}_J}$$

with

$$\mathbf{Y}(k) = \mathbf{\Psi}\,\hat{\mathbf{x}}(k) + \mathbf{\Phi}\,\mathbf{u}(k-1) + \mathbf{\Phi}_\Delta \Delta\mathbf{U}(k)$$

$$\mathbf{\Theta}(k) = \mathbf{Y}_r(k) - \mathbf{\Psi}\,\hat{\mathbf{x}}(k) - \mathbf{\Phi}\,\mathbf{u}(k-1)$$

$$\frac{\partial J}{\partial \Delta\mathbf{U}(k)} = 0$$

$$\Delta\mathbf{U}(k)$$

Multivariable MPC

- Future control laws sequence

$$\Delta \mathbf{U}(k) = (\mathbf{R}_J + \mathbf{\Phi}_\Delta^T \mathbf{Q}_J \mathbf{\Phi}_\Delta)^{-1} \mathbf{\Phi}_\Delta^T \mathbf{Q}_J \mathbf{\Theta}(k)$$

with

$$\mathbf{\Psi} = \begin{bmatrix} \mathbf{CA}^{N_1} \\ \vdots \\ \mathbf{CA}^{N_2} \end{bmatrix}, \mathbf{\Phi} = \begin{bmatrix} \mathbf{\Sigma}_{N_1-1} \\ \vdots \\ \mathbf{\Sigma}_{N_2-1} \end{bmatrix}, \mathbf{\Phi}_\Delta = \begin{bmatrix} \mathbf{\Sigma}_{N_1-1} & \cdots & \mathbf{\Sigma}_0 & 0 & \cdots & 0 \\ \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{\Sigma}_{N_2-1} & \cdots & \mathbf{\Sigma}_{N_2-N_1} & \mathbf{\Sigma}_{N_2-N_1-1} & \cdots & \mathbf{\Sigma}_{N_2-N_u} \end{bmatrix}$$

where $\mathbf{\Sigma}_i = \mathbf{C} \sum_{j=0}^{i} \mathbf{A}^{i-j} \mathbf{B}$

- The first component of each future control sequence

$$\Delta \mathbf{u}(k) = \boldsymbol{\mu} \mathbf{\Theta}(k)$$

Receding horizon principle

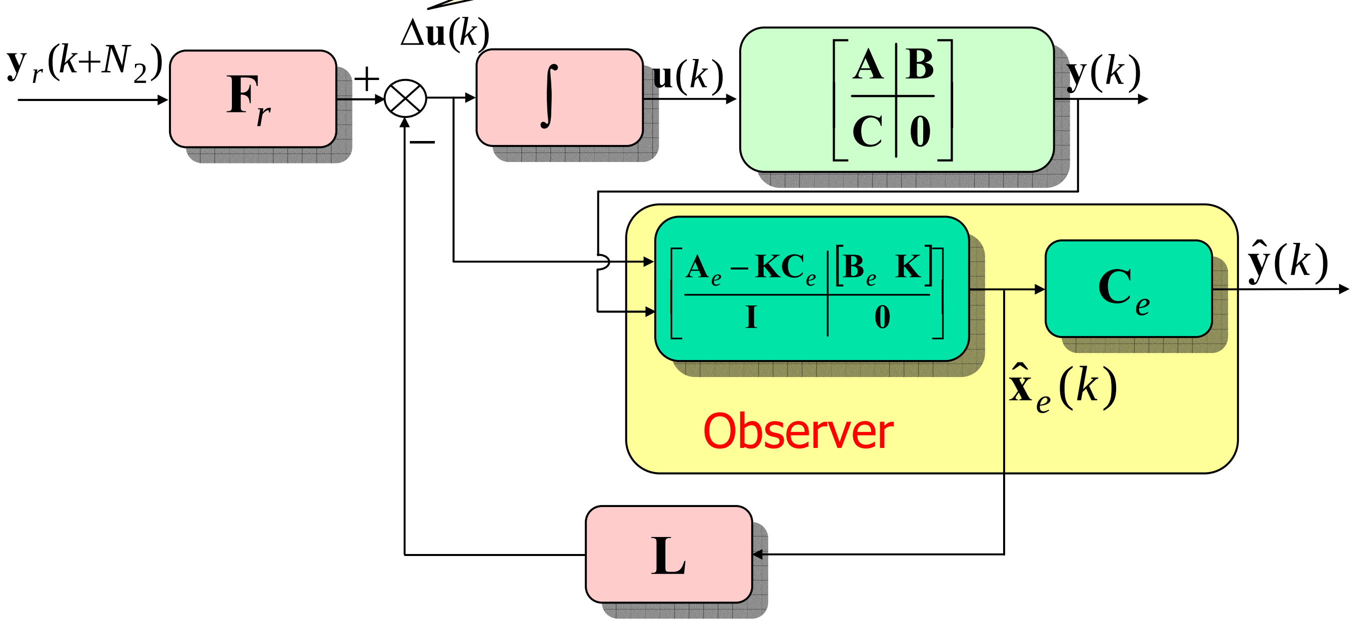
with $\boldsymbol{\mu} = \begin{bmatrix} \mathbf{I}_m & \mathbf{0}_{m,m(N_u-1)} \end{bmatrix} (\mathbf{R}_J + \mathbf{\Phi}_\Delta^T \mathbf{Q}_J \mathbf{\Phi}_\Delta)^{-1} \mathbf{\Phi}_\Delta^T \mathbf{Q}_J$

Multivariable MPC

- Block diagram of MIMO MPC

$$\Delta\mathbf{u}(k) = \mathbf{F}_r \mathbf{y}_r(k+N_2) - \mathbf{L}\hat{\mathbf{x}}_e(k)$$

with $\mathbf{L} = [\mathbf{L}_1 \;\; \mathbf{L}_2] = [\boldsymbol{\mu\Psi} \;\; \boldsymbol{\mu\Phi}]$



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- ✓ Multivariable MPC
- Robustness using the Youla parameter
  - *Initial stabilizing control law*
  - *Robust stability under frequency constraints*
  - *Nominal performance specifications*
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Robustness using the Youla parameter

- Initial stabilizing controller $\mathbf{K}_0$

Youla parametrization

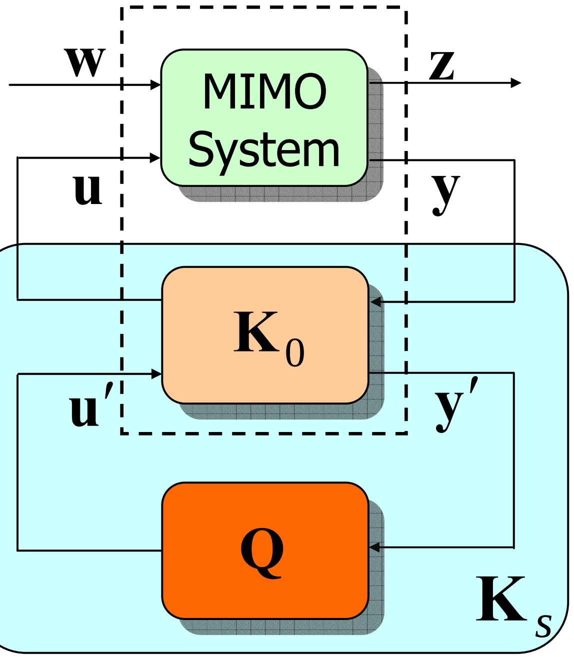
- Set of stabilizing controllers $\mathbf{K}_s$
- $\mathbf{Q} \in \Re H_\infty$

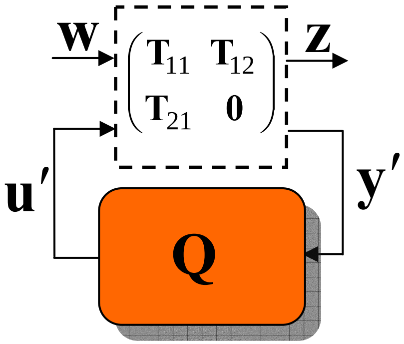
Affine dependence in $\mathbf{Q}$

$$\mathbf{T_{zw}} = \mathbf{T}_{11} + \mathbf{T}_{12}\mathbf{Q}\mathbf{T}_{21}$$

$\mathbf{Q} = ?$

Convex specifications in closed-loop





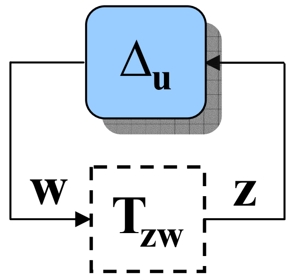
Robustness using the Youla parameter

Supélec

- Robustification under unstructured uncertainties $\Delta_{\mathbf{u}}$

$$\min_{\mathbf{Q} \in \Re H_\infty} \left\| \mathbf{T_{zw}} \right\|_\infty$$

Small gain theorem



- Theorem

A discrete-time system $(\mathbf{A}_{cl}, \mathbf{B}_{cl}, \mathbf{C}_{cl}, \mathbf{D}_{cl})$ *is stable and admits a* H_∞ *norm lower than* γ *if and only if*

$$\exists \mathbf{X}_1 = \mathbf{X}_1^{\mathrm{T}} \succ 0 \,/ \begin{bmatrix} -\mathbf{X}_1^{-1} & \mathbf{A}_{cl} & \mathbf{B}_{cl} & \mathbf{0} \\ \mathbf{A}_{cl}^{\mathrm{T}} & -\mathbf{X}_1 & \mathbf{0} & \mathbf{C}_{cl}^{\mathrm{T}} \\ \mathbf{B}_{cl}^{\mathrm{T}} & \mathbf{0} & -\gamma \mathbf{I} & \mathbf{D}_{cl}^{\mathrm{T}} \\ \mathbf{0} & \mathbf{C}_{cl} & \mathbf{D}_{cl} & -\gamma \mathbf{I} \end{bmatrix} \prec 0$$

Transformation

into LMI1

- New optimization problem $\min_{LMI_1} \gamma$

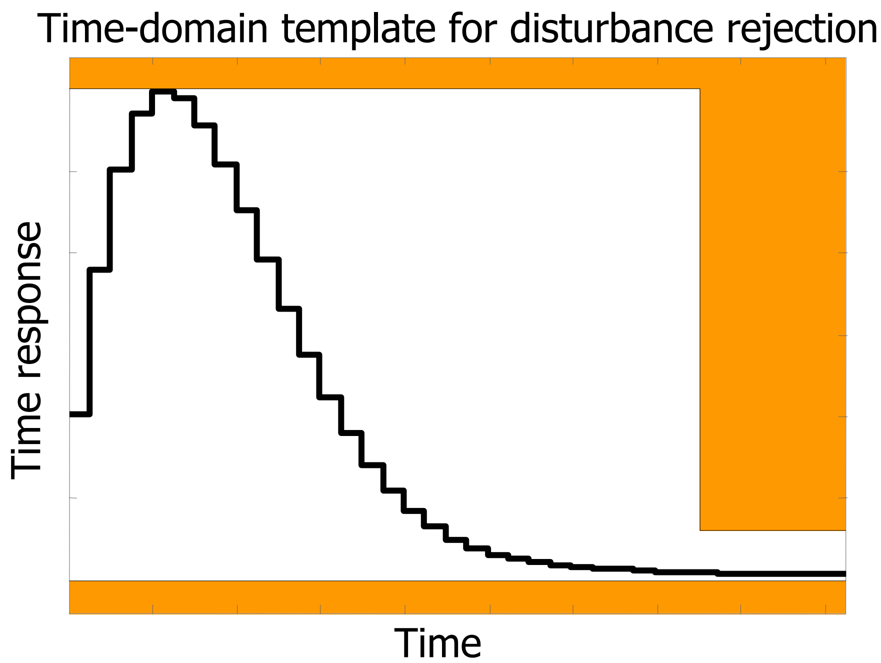
Robustness using the Youla parameter

- Nominal performance specifications as output time-domain templates for disturbances rejection

$$\mathbf{y}_{\min}(k) \le \mathbf{y}(k) \le \mathbf{y}_{\max}(k), \;\; \forall k \,/\, 0 \le k \le N_t$$

Transformation into LMI2

$$\min_{LMI_1, LMI_2} \gamma$$



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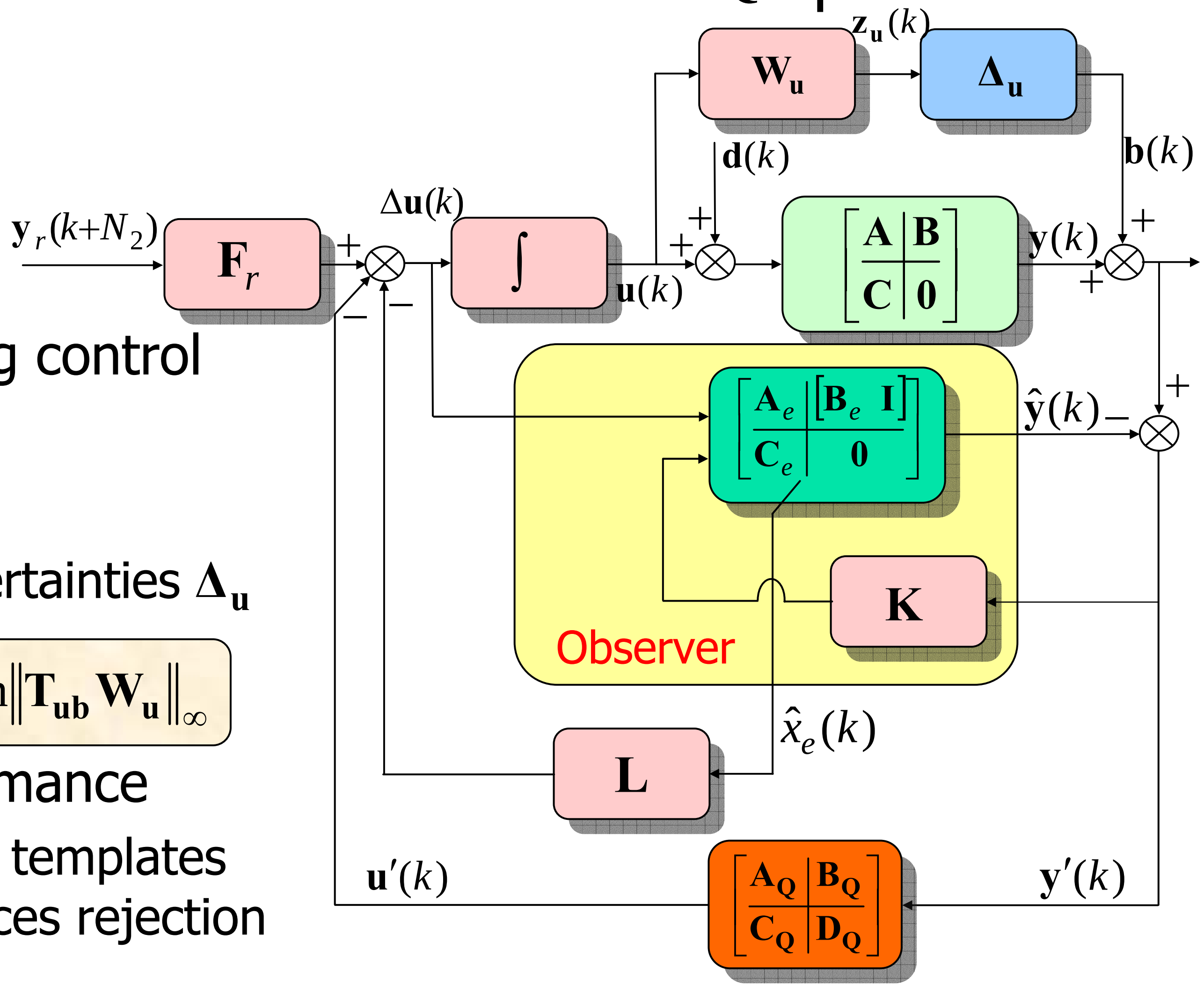
Robustified MIMO MPC

- Block diagram of MIMO MPC with the $\mathbf{Q}$ parameter



- Initial stabilizing control
  - MIMO MPC
- Robust stability
  - Additive uncertainties $\mathbf{\Delta_u}$

$$\min\left\|\mathbf{T_{z_u b}}\right\|_\infty = \min\left\|\mathbf{T_{ub}}\,\mathbf{W_u}\right\|_\infty$$

- Nominal performance
  - Time-domain templates for disturbances rejection

$\mathbf{d}(k) \rightarrow \mathbf{y}(k)$

Robustified MIMO MPC

Supélec

- Goal $\mathbf{b}(k) \rightarrow \mathbf{z_u}(k)$
- Multivariable Model Predictive Control law

$$\Delta\mathbf{u}(k) = \mathbf{F}_r \mathbf{y}_r(k + N_2) - \mathbf{L}\,\hat{\mathbf{x}}_e(k) - \mathbf{u}'(k)$$

with the observer

$$\hat{\mathbf{x}}_e(k+1) = \mathbf{A}_e\,\hat{\mathbf{x}}_e(k) + \mathbf{B}_e\,\Delta\mathbf{u}(k) + \mathbf{K}[\mathbf{y}(k) - \mathbf{C}_e\,\hat{\mathbf{x}}_e(k) + \mathbf{b}(k)]$$

- Error $\boldsymbol{\varepsilon}(k) = \mathbf{x}_e(k) - \hat{\mathbf{x}}_e(k)$
- Weighting $\mathbf{W_u} : \left[\begin{array}{c|c} \mathbf{A}_w & \mathbf{B}_w \\ \hline \mathbf{C}_w & \mathbf{D}_w \end{array}\right]$
- Youla parameter $\mathbf{u}'(k) = \mathbf{Q}\mathbf{y}'(k)$

Extended state-space of MIMO system

Robustified MIMO MPC

- Aim: find the Youla parameter $\mathbf{Q} \in \Re H_\infty$ which minimizes the norm $\left\| \mathbf{T_{z_u b}} \right\|_\infty$ ⇒ *convex optimization problem*
- Sub-optimal solution
  - for each pair (i, j) ⇒ a polynomial or a FIR filter Q^{ij}

unknown parameters

$$Q^{ij} = \sum_{l=0}^{n_Q} q_l^{ij} q^{-l}, i = \overline{1, m}, j = \overline{1, p}$$

order of Youla parameter

- State-space representation

fixed

$$\left[\begin{array}{c|c} \mathbf{A}_Q & \mathbf{B}_Q \\ \hline \mathbf{C}_Q & \mathbf{D}_Q \end{array}\right] = \left[\begin{array}{ccc|ccc} \mathbf{a}_Q & & \mathbf{0} & \mathbf{b}_Q & & \mathbf{0} \\ & \ddots & & & \ddots & \\ \mathbf{0} & & \mathbf{a}_Q & \mathbf{0} & & \mathbf{b}_Q \\ \hline \mathbf{c}_Q^{11} & \cdots & \mathbf{c}_Q^{1p} & d_Q^{11} & \cdots & d_Q^{1p} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{c}_Q^{m1} & \cdots & \mathbf{c}_Q^{mp} & d_Q^{m1} & \cdots & d_Q^{mp} \end{array}\right]$$

variable

$$\mathbf{a}_Q = \begin{bmatrix} \mathbf{0}_{1,n_Q-1} & 0 \\ \mathbf{I}_{n_Q-1} & \mathbf{0}_{n_Q-1,1} \end{bmatrix}, \mathbf{b}_Q = \begin{bmatrix} 1 \\ \mathbf{0}_{n_Q-1,1} \end{bmatrix}, \mathbf{c}_Q^{ij} = \begin{bmatrix} q_1^{ij} & \cdots & q_{n_Q}^{ij} \end{bmatrix}, d_Q^{ij} = q_0^{ij}$$

Robustified MIMO MPC

- Closed-loop system in state-space formulation

$\mathbf{b}(k) \rightarrow \mathbf{z_u}(k)$

$$\left[\begin{array}{c|c} \mathbf{A}_{cl} & \mathbf{B}_{cl} \\ \hline \mathbf{C}_{cl} & \mathbf{D}_{cl} \end{array}\right] = \left[\begin{array}{ccc|c} \overline{\mathbf{A}}_1 & \overline{\mathbf{A}}_3 - \overline{\mathbf{B}}_{u_1'}\mathbf{D}_Q\mathbf{C}_e & -\overline{\mathbf{B}}_{u_1'}\mathbf{C}_Q & -\overline{\mathbf{B}}_{u_1'}\mathbf{D}_Q \\ \mathbf{0} & \mathbf{A}_2 & \mathbf{0} & -\mathbf{K} \\ \mathbf{0} & \mathbf{B}_Q\mathbf{C}_e & \mathbf{A}_Q & \mathbf{B}_Q \\ \hline \overline{\mathbf{C}}_1 & \overline{\mathbf{C}}_2 - \mathbf{D}_w\mathbf{D}_Q\mathbf{C}_e & -\mathbf{D}_w\mathbf{C}_Q & -\mathbf{D}_w\mathbf{D}_Q \end{array}\right]$$

- Maximization of robust stability under $\Delta_{\mathbf{u}}$:

$\min \left\| \mathbf{T}_{\mathbf{z_u b}} \right\|_\infty$

$\min \gamma$
LMI_1

LMI_1

$$\left[\begin{array}{ccc|ccc|c|c} -\mathbf{R}_1 & \mathbf{0} & \mathbf{0} & \overline{\mathbf{A}}_1\mathbf{R}_1 & \overline{\mathbf{A}}_1\mathbf{S}_{11} - \mathbf{S}_{11}\mathbf{A}_2 - \mathbf{S}_{12}\mathbf{B}_Q\mathbf{C}_e + \overline{\mathbf{A}}_3 - \overline{\mathbf{B}}_{u_1'}\mathbf{D}_Q\mathbf{C}_e & \overline{\mathbf{A}}_1\mathbf{S}_{12} - \mathbf{S}_{12}\mathbf{A}_Q - \overline{\mathbf{B}}_{u_1'}\mathbf{C}_Q & -\overline{\mathbf{B}}_{u_1'}\mathbf{D}_Q + \mathbf{S}_{11}\mathbf{K} - \mathbf{S}_{12}\mathbf{B}_Q & \mathbf{0} \\ * & -\mathbf{T}_{11} & -\mathbf{T}_{12} & \mathbf{0} & \mathbf{T}_{11}\mathbf{A}_2 + \mathbf{T}_{12}\mathbf{B}_Q\mathbf{C}_e & \mathbf{T}_{12}\mathbf{A}_Q & -\mathbf{T}_{11}\mathbf{K} + \mathbf{T}_{12}\mathbf{B}_Q & \mathbf{0} \\ * & * & -\mathbf{T}_{22} & \mathbf{0} & \mathbf{T}_{12}^T\mathbf{A}_2 + \mathbf{T}_{22}\mathbf{B}_Q\mathbf{C}_e & \mathbf{T}_{22}\mathbf{A}_Q & -\mathbf{T}_{12}^T\mathbf{K} + \mathbf{T}_{22}\mathbf{B}_Q & \mathbf{0} \\ \hline * & * & * & -\mathbf{R}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{R}_1\overline{\mathbf{C}}_1^T \\ * & * & * & * & -\mathbf{T}_{11} & -\mathbf{T}_{12} & \mathbf{0} & \mathbf{S}_{11}^T\overline{\mathbf{C}}_1^T + \overline{\mathbf{C}}_2^T - \mathbf{C}_e^T\mathbf{D}_Q^T\mathbf{D}_w^T \\ * & * & * & * & * & -\mathbf{T}_{22} & \mathbf{0} & \mathbf{S}_{12}^T\overline{\mathbf{C}}_1^T - \mathbf{C}_Q^T\mathbf{D}_w^T \\ \hline * & * & * & * & * & * & -\gamma\mathbf{I} & -\mathbf{D}_Q^T\mathbf{D}_w^T \\ \hline * & * & * & * & * & * & * & -\gamma\mathbf{I} \end{array}\right] \prec 0$$

Robustified MIMO MPC

Supélec

- Nominal performance for disturbances rejection
  - Transfer $\mathbf{d}(k) \rightarrow \mathbf{y}(k)$ for $k = \overline{0, N_t}$

$$\begin{cases} \begin{bmatrix} \mathbf{y} \\ \mathbf{y}' \end{bmatrix} = \begin{bmatrix} \mathbf{T}_{11_{\mathbf{yd}}} & \mathbf{T}_{12_{\mathbf{yd}}} \\ \mathbf{T}_{21_{\mathbf{yd}}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{d} \\ \mathbf{u}' \end{bmatrix} \\ \mathbf{u}' = \mathbf{Q}\mathbf{y}' \end{cases} \Rightarrow \mathbf{y}(k) = \mathbf{T}_{11_{\mathbf{yd}}}\mathbf{d}(k) + \mathbf{T}_{12_{\mathbf{yd}}}\mathbf{Q}\mathbf{T}_{21_{\mathbf{yd}}}\mathbf{d}(k)$$

Affine in $\mathbf{Q}$

  - Time domain templates

$$\mathbf{y}_{\min}(k) \le \mathbf{y}(k) \le \mathbf{y}_{\max}(k)$$

$$\begin{aligned} &\mathbf{T}_{11_{\mathbf{yd}}}\mathbf{d}(k) + \mathbf{T}_{12_{\mathbf{yd}}}\mathbf{Q}\mathbf{T}_{21_{\mathbf{yd}}}\mathbf{d}(k) - \mathbf{y}_{\max}(k) \le 0 \\ &\mathbf{T}_{11_{\mathbf{yd}}}\mathbf{d}(k) + \mathbf{T}_{12_{\mathbf{yd}}}\mathbf{Q}\mathbf{T}_{21_{\mathbf{yd}}}\mathbf{d}(k) + \mathbf{y}_{\min}(k) \le 0 \end{aligned}$$

Manipulations $\Rightarrow LMI_2 \Rightarrow \min_{LMI_1, LMI_2} \gamma$

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- Application to a stirred tank reactor
  - *System description & MPC parameters*
  - *Robust stability under frequency constraints*
  - *Nominal performance specifications*
    - *Decoupled system(2 templates)*
    - *Coupled system(4 templates)*
- Conclusions

Application to a stirred tank reactor

- Simplified MIMO model of reactor

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{1}{1+0.7s} & \frac{5}{1+0.3s} \\ \frac{1}{1+0.5s} & \frac{2}{1+0.4s} \end{bmatrix} \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix}$$

- Discretized for $T_e = 0.03\,\text{min}$

State-space representation

$n = 4, m = 2, p = 2$

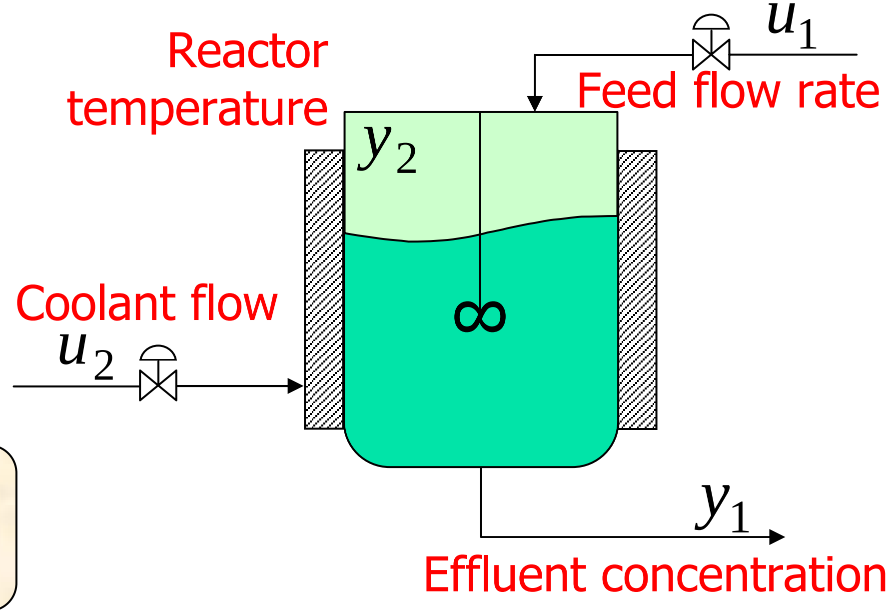
$$\left[\begin{array}{c|c} \mathbf{A} & \mathbf{B} \\ \hline \mathbf{C} & \mathbf{0} \end{array}\right]$$

- MPC parameters

$$N_1 = 1, N_2 = 3, N_u = 2$$
$$\tilde{\mathbf{R}}_J = 0.05\mathbf{I}_{N_u}, \tilde{\mathbf{Q}}_J = \mathbf{I}_{N_2-N_1+1}$$

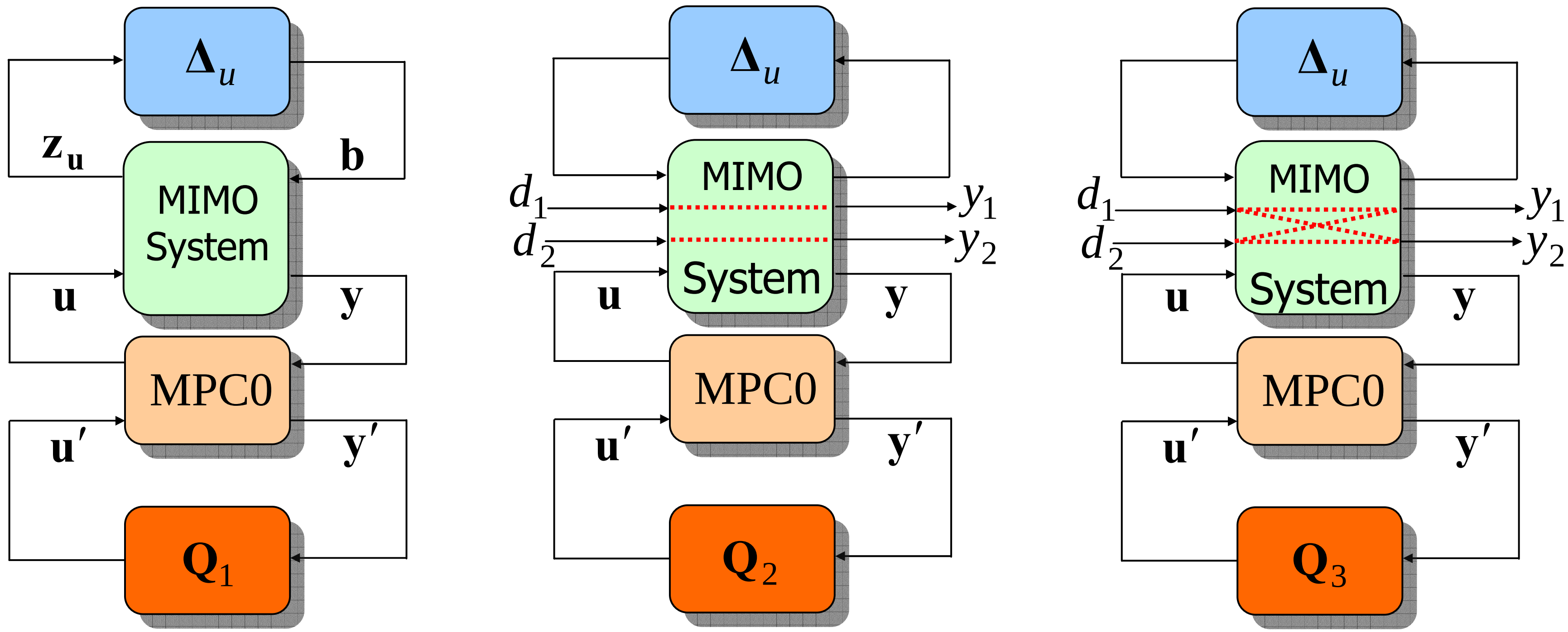
- Weightings

$$\mathbf{W_u} = \mathbf{I}_2\,(1-0.7q^{-1})/0.3 \Rightarrow \left[\begin{array}{c|c} \mathbf{A}_w & \mathbf{B}_w \\ \hline \mathbf{C}_w & \mathbf{D}_w \end{array}\right]$$



Application to a stirred tank reactor

- MPC0 : initial MPC controller (before robustification)



- MPC1 : robustness under frequency constraints only
- MPC2 : robustness under frequency and time-domain constraints – 2 templates
- MPC3 : robustness under frequency and time-domain constraints – 4 templates

Application to a stirred tank reactor

- Robustification using a Youla parameter of order $n_Q = 40$
- Decreasing H_∞ norm
- Increasing stability robustness

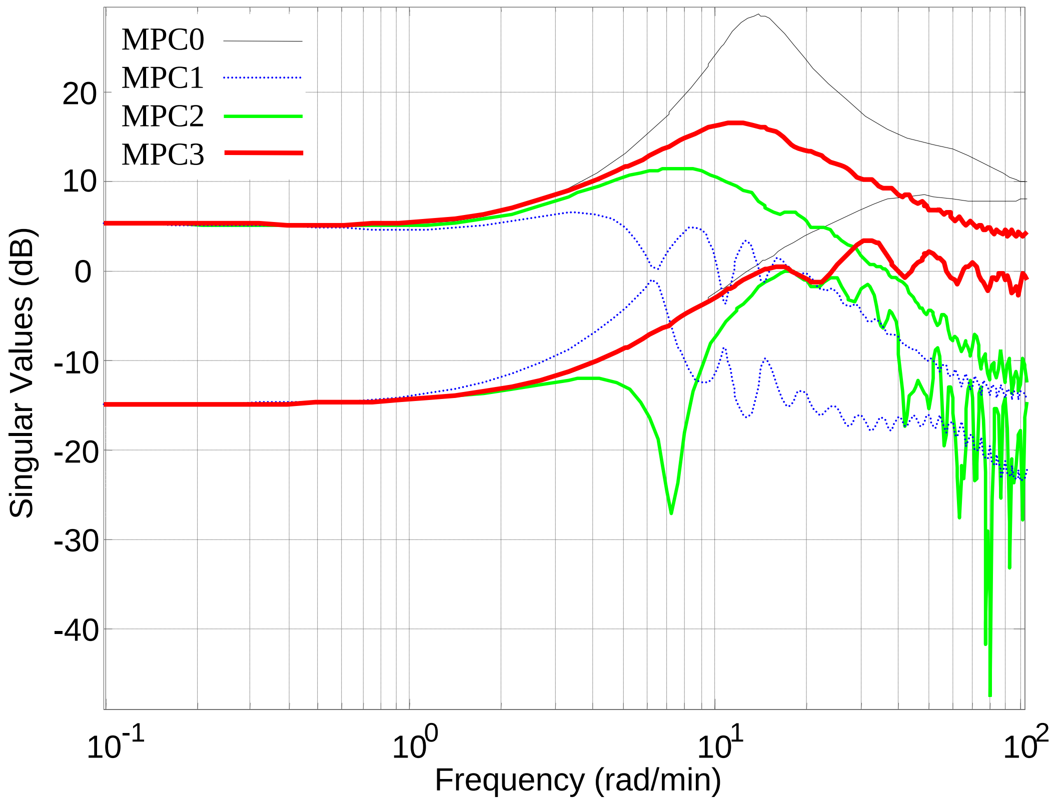
MPC0 = initial MPC

MPC1 = MPC0+LMI1

MPC2 = MPC0+LMI1+LMI2 (2 templates)

MPC3 = MPC0+LMI1+LMI2 (4 templates)

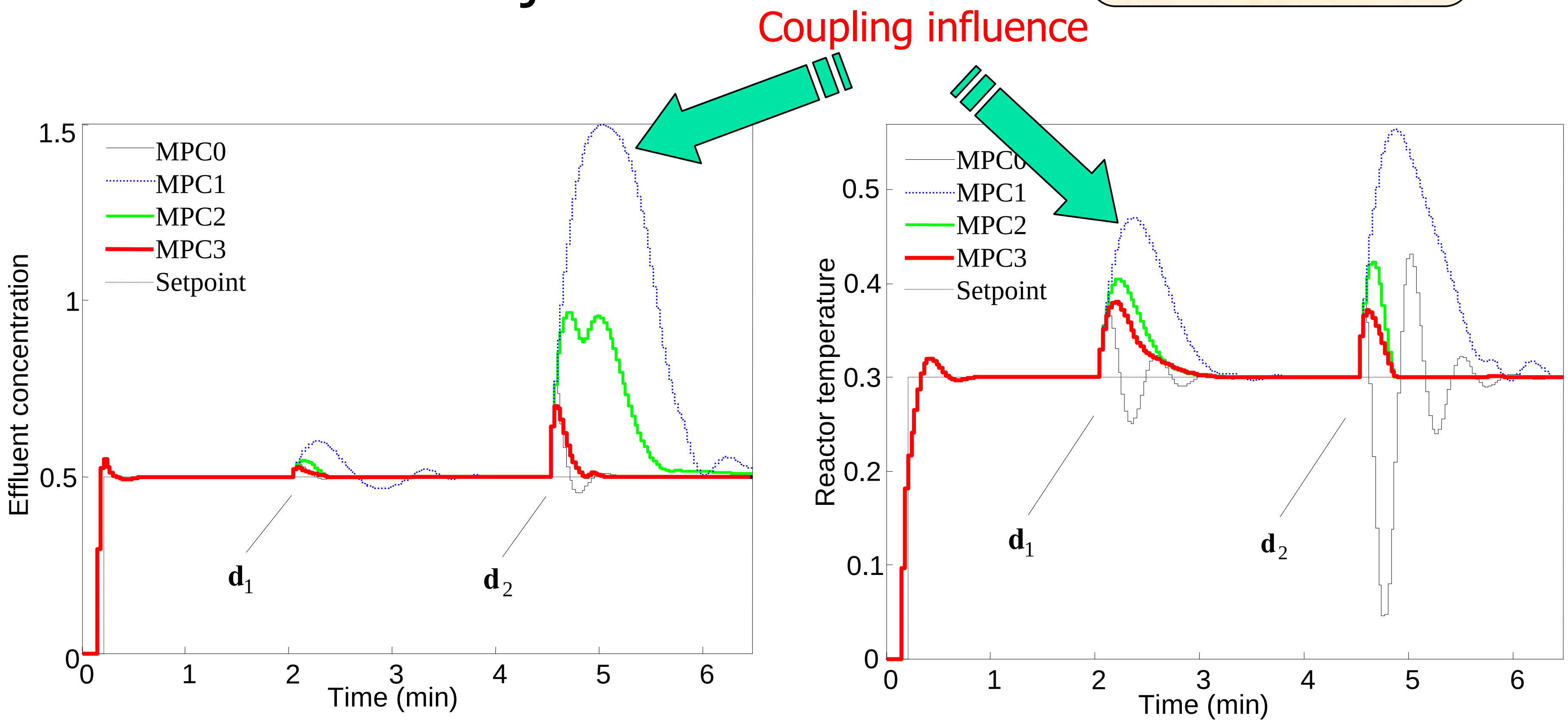
Singular values of $\mathbf{T_{ub}}$



Application to a stirred tank reactor

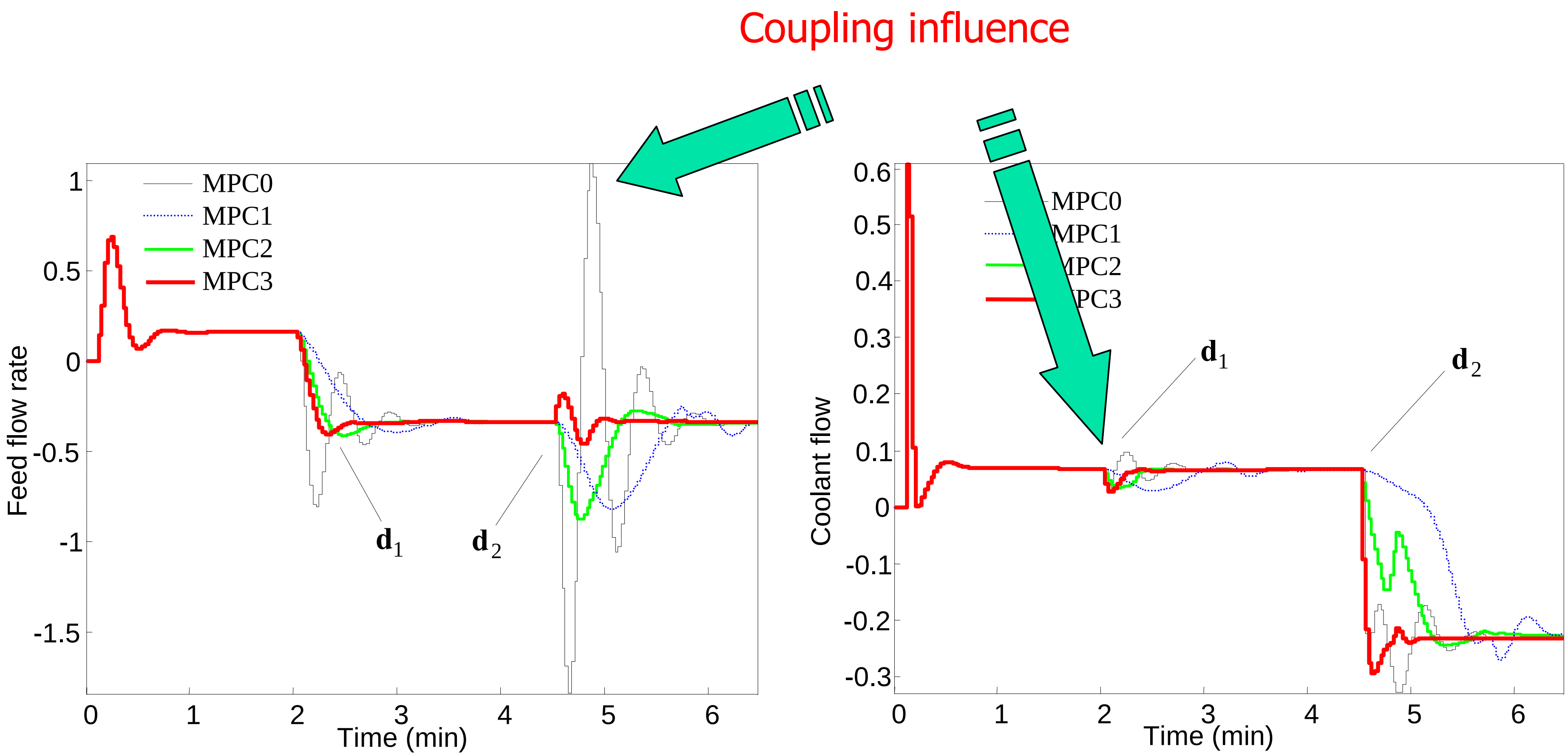
- Time-domain responses
- Disturbances rejection

$$y_{r_1} = 0.5, y_{r_2} = 0.3$$
$$d_1 = 0.5, d_2 = 0.3$$



Application to a stirred tank reactor

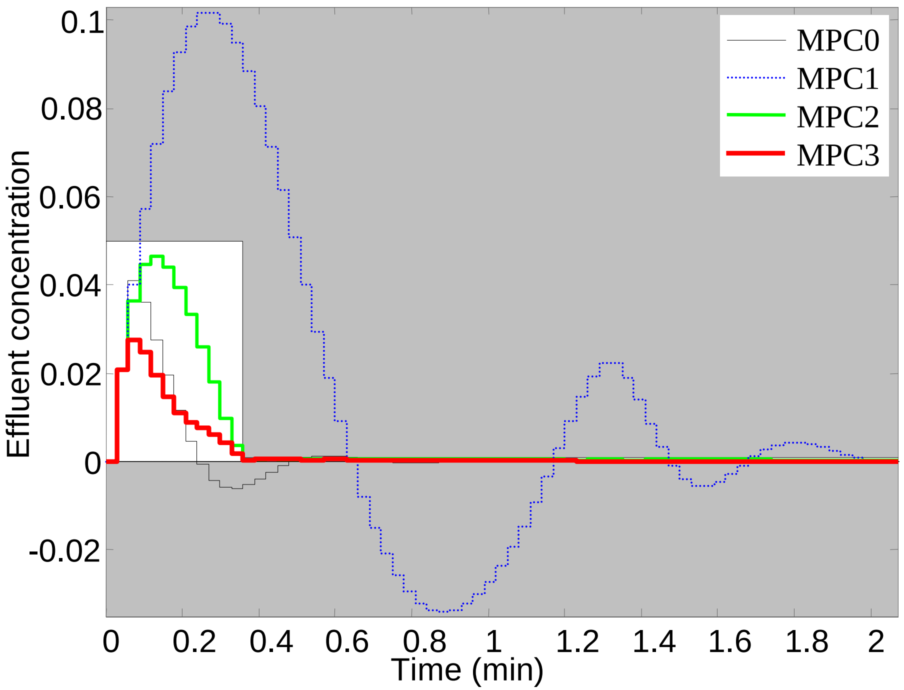
- Control signals



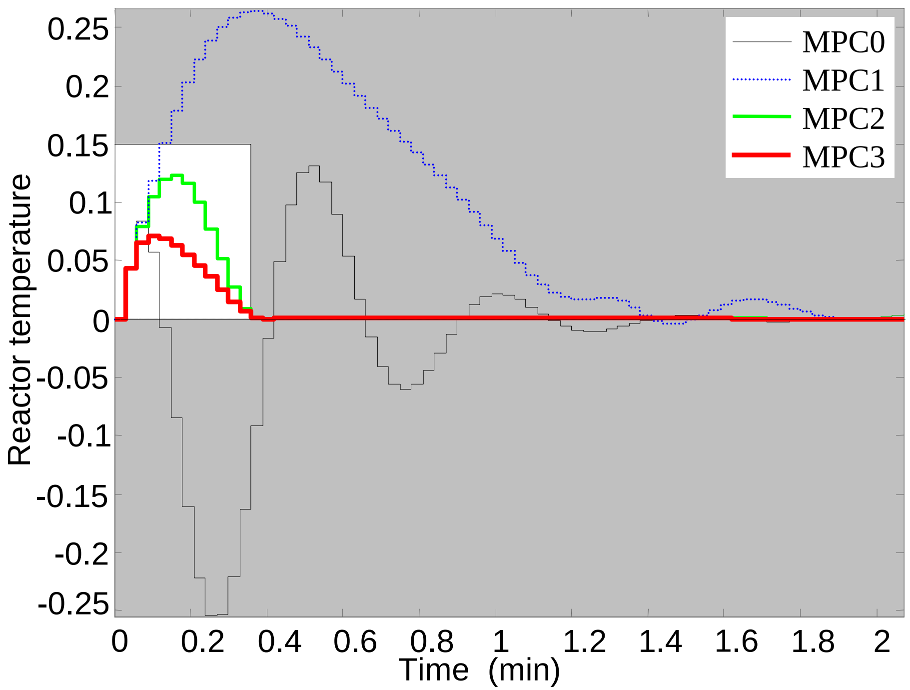
Application to a stirred tank reactor

- Time-domain templates for disturbances rejection

$$d_1 \rightarrow y_1$$



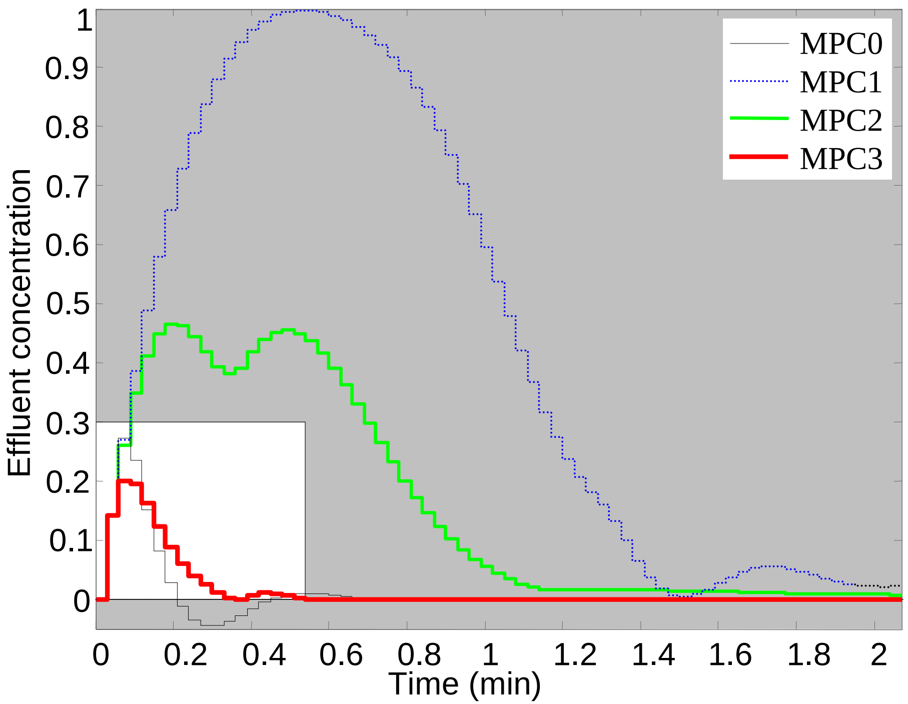
$$d_2 \rightarrow y_2$$



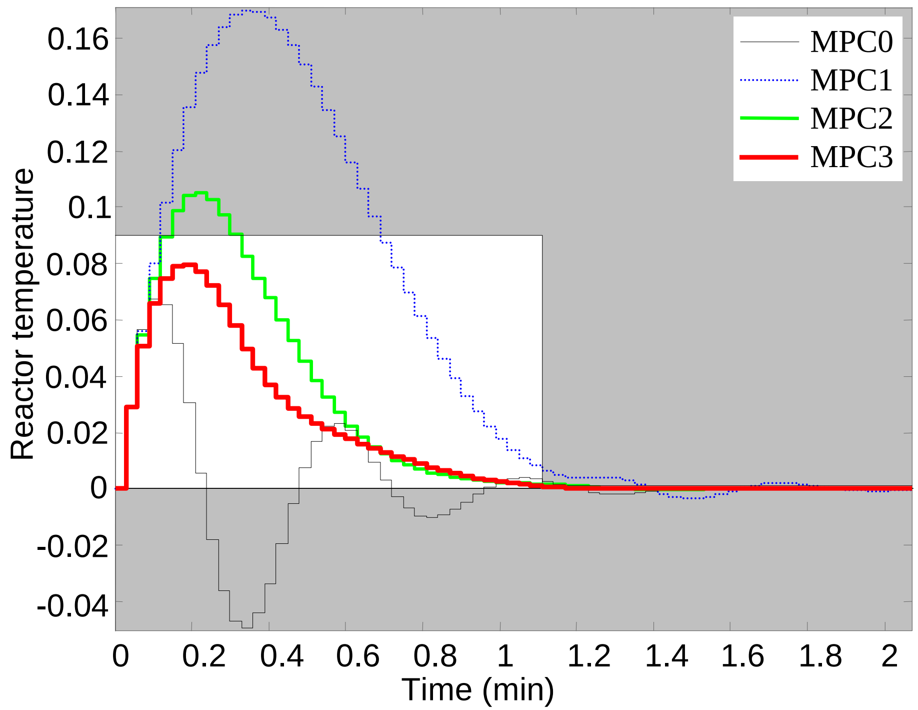
Application to a stirred tank reactor

- Time-domain templates for disturbances rejection

$d_2 \to y_1$



$d_1 \to y_2$

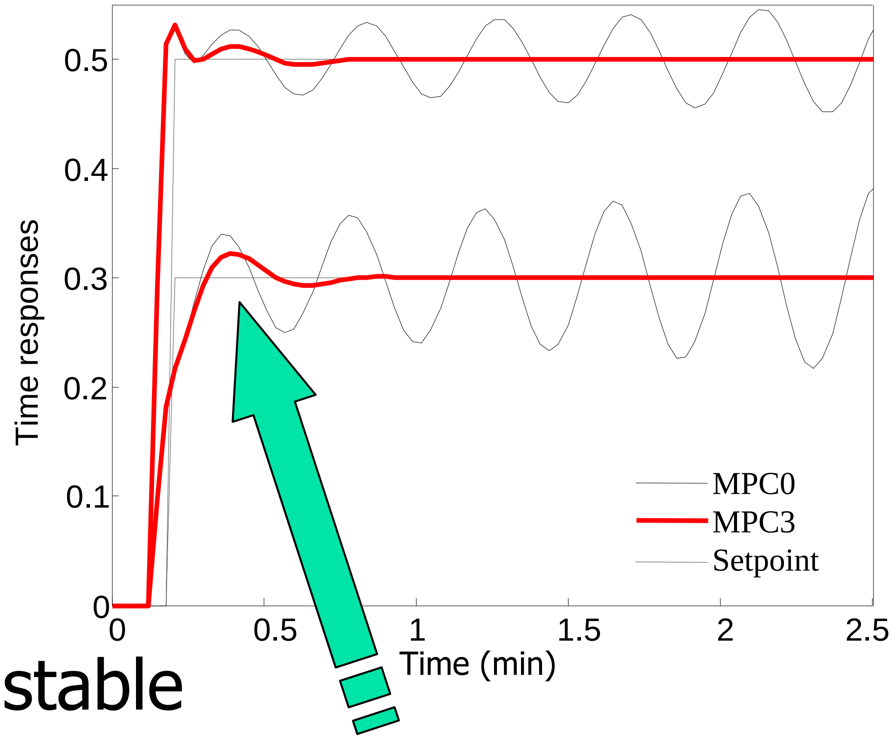


Application to a stirred tank reactor

- Validation of robust stability under a neglected dynamics of u_1 corresponding to the transfer

$$u_1 \rightarrow y_1$$

$$\frac{1}{(1+0.7s)(1+0.07s)}$$



Coupling influence

- Without robustification – unstable
- After robustification – stable

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Conclusions & current work

- Complete off-line methodology which enables robustification of an initial MIMO MPC
- Input/output behaviour remains unchanged
- Improved robustness towards unstructured uncertainties through a convex optimization problem (LMI techniques)
- Use of four time-domain templates to manage the coupling effect in an efficient way
- Compromise between robust stability and nominal performance specifications
- Reduced computational effort due to state-space representation

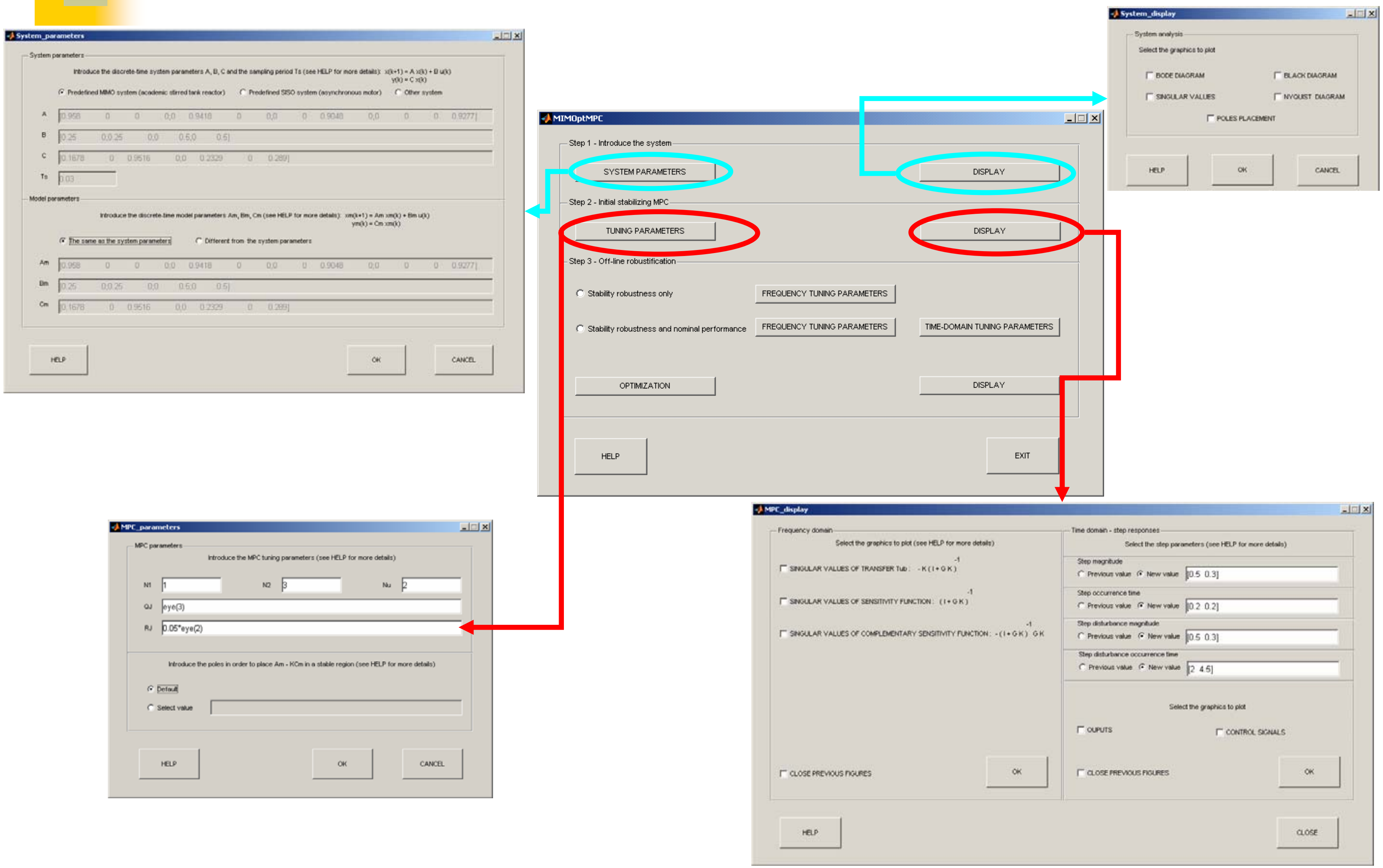
Conclusions & current work

- Developing a new MATLAB toolbox (MIMOptMPC) based on the theoretical feature of this off-line robustification procedure

- An user friendly and easily extensible toolbox
  - Choice of tuning parameters and robustification options
  - Visualization tools enabling performances evaluation

- A helpful solution for non-specialist users as well as researchers working in the field of robust MPC

Conclusions & current work



Conclusions & current work

Supélec