MPC Monitoring: Detection and Diagnosis of Model Errors

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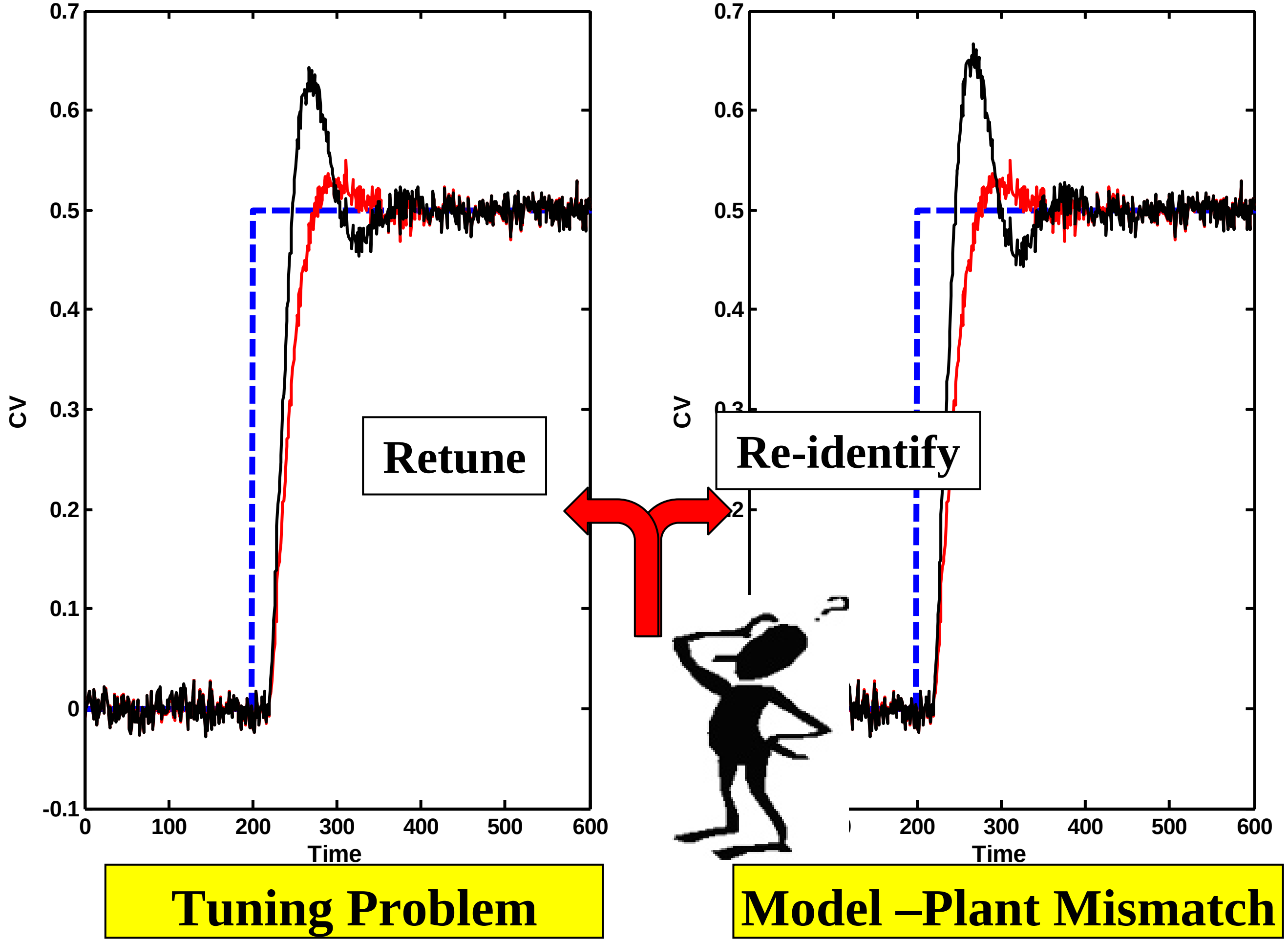
Outline

1. Introduction
2. Motivation
3. Assessing the need for re-identification
4. Detection and Isolation of Mismatch
5. Case Studies
6. Concluding Remarks

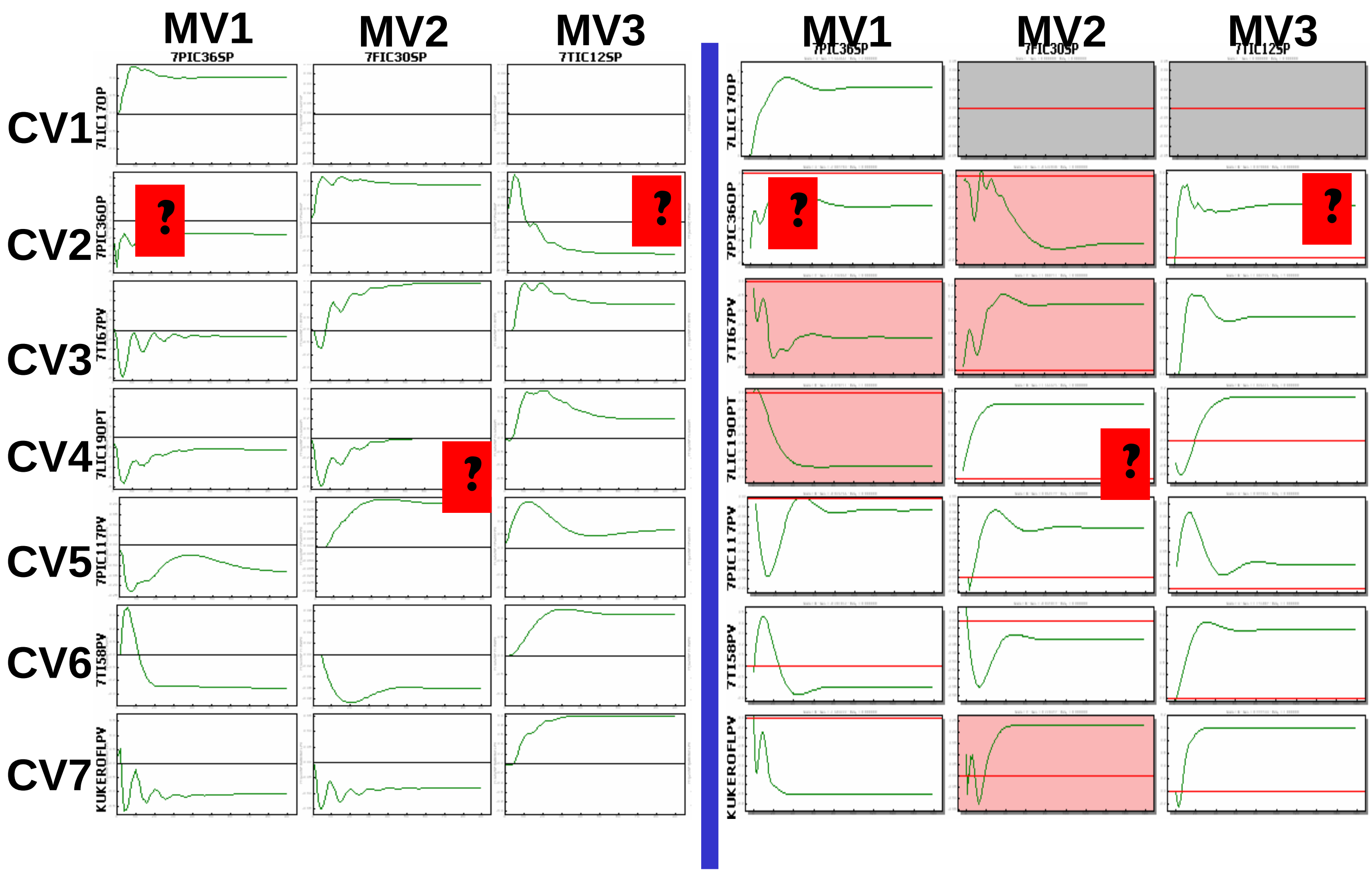
Introduction

- MPC performance is affected by model quality
- Model quality is influenced by changes in the plant and/or operating conditions
- Online model maintenance:
  - Monitoring of model quality
    - Mismatch detection and isolation
    - Assessment of need for re-identification
  - Only update the model if necessary
    - Identification under closed-loop
- Performance after maintenance

Motivation: Retune or Re-identify?



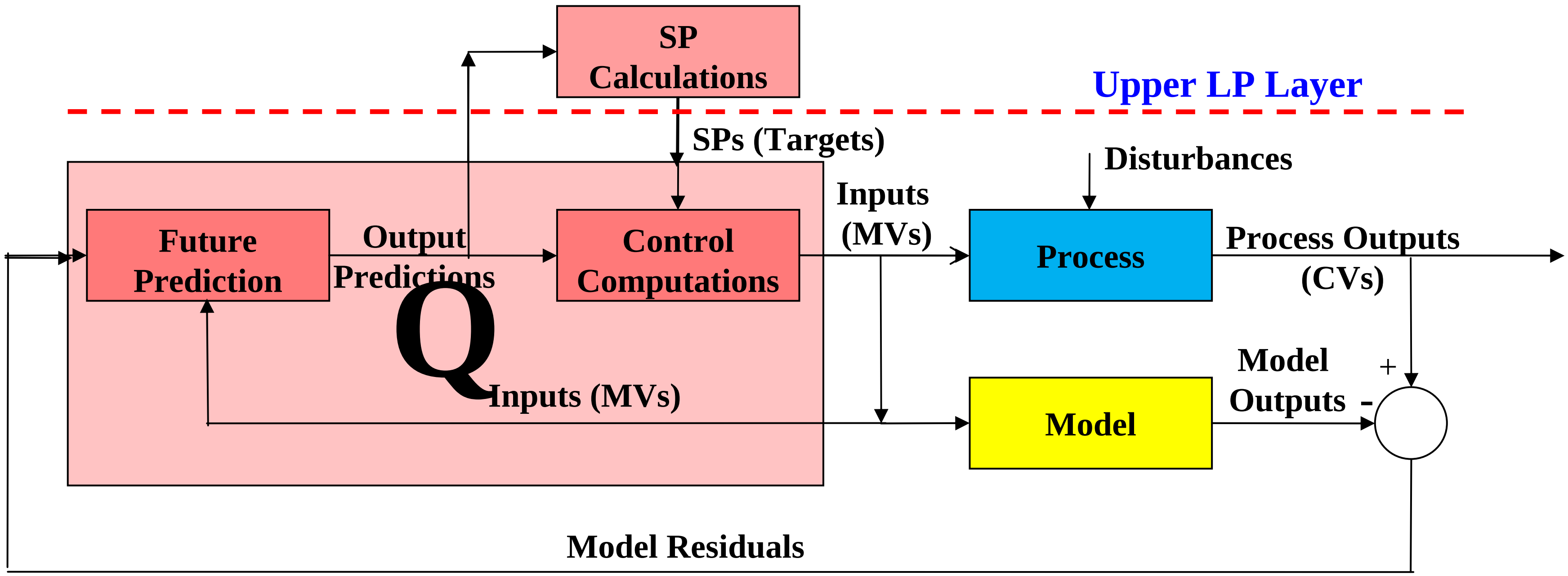
Motivation: Locate Significant MPM



MPM – Effect on controller performance

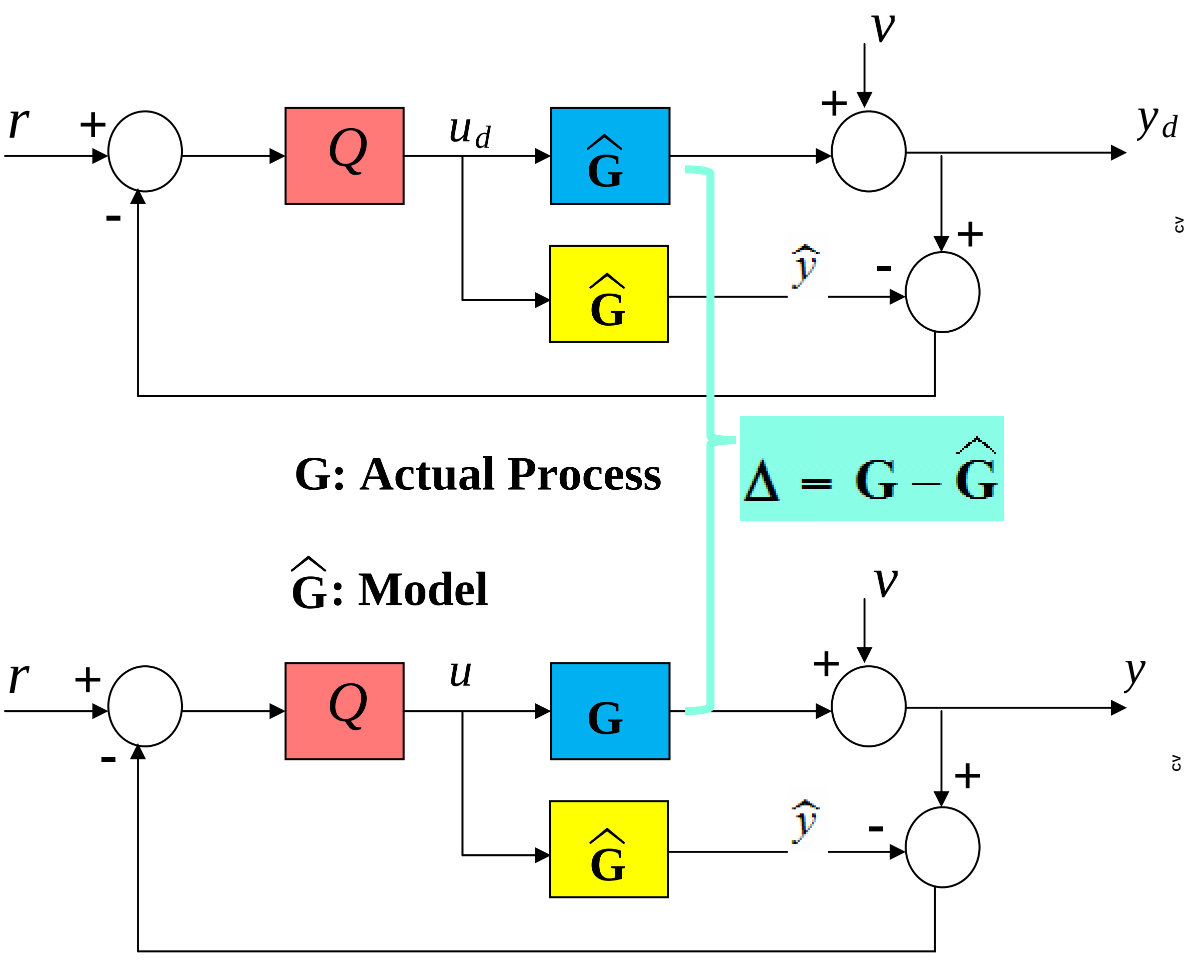
- Do we need to worry about MPM?
- If yes, when?
- Can we quantify the effect of MPM on performance?
- A measure of degradation in controller performance – How far is the achieved performance from the designed performance?
- **Relate MPM and this measure**

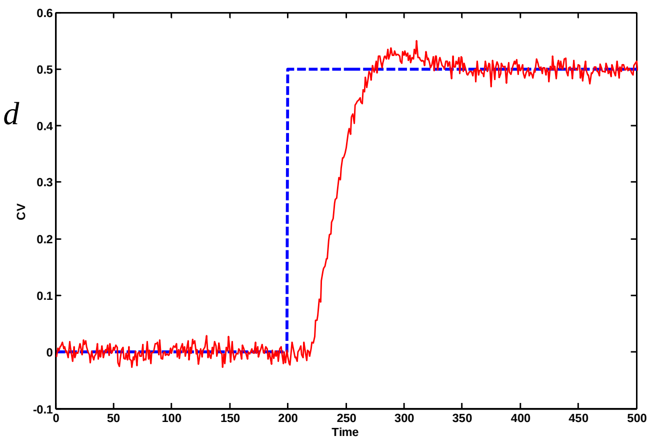
Model Predictive Control



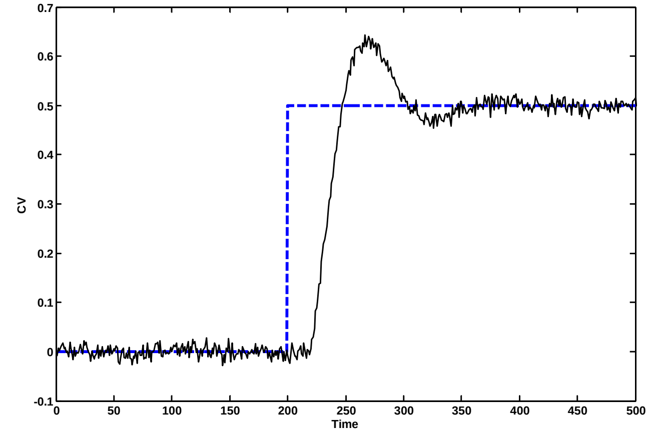
Internal Model Control (IMC) Structure

Designed and Achieved Performances





Designed Performance

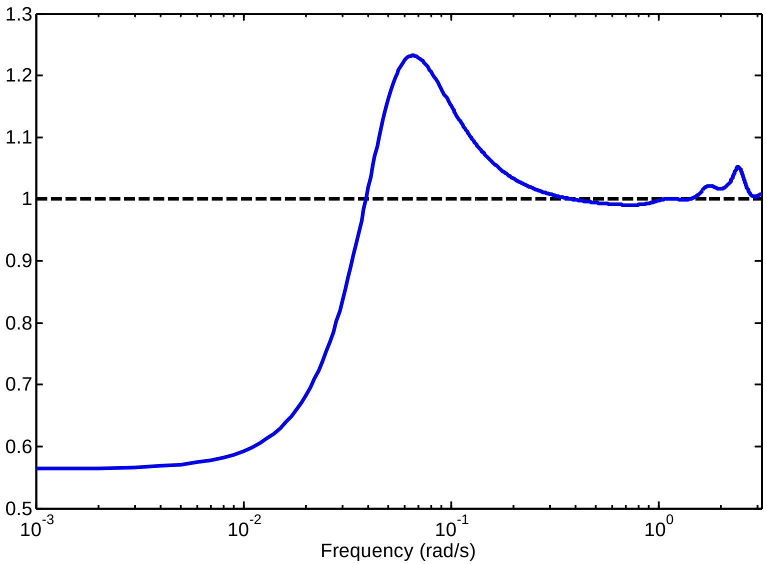


Achieved Performance

Important Closed-loop Term - 1

Achieved Performance $= \left[\frac{1}{1+\Delta Q} \right]$ **Designed Performance**

Achieved	Designed
$r - y_{achieved}$	$r - y_{designed}$
$(MV)_{achieved}$	$(MV)_{designed}$
$(Sensitivity)_{achieved}$	$(Sensitivity)_{designed}$



$\left\| \frac{1}{1+\Delta Q} \right\|_{\infty} > 1 \Rightarrow$ **Achieved is worse than designed**

- **Indicates presence of MPM**

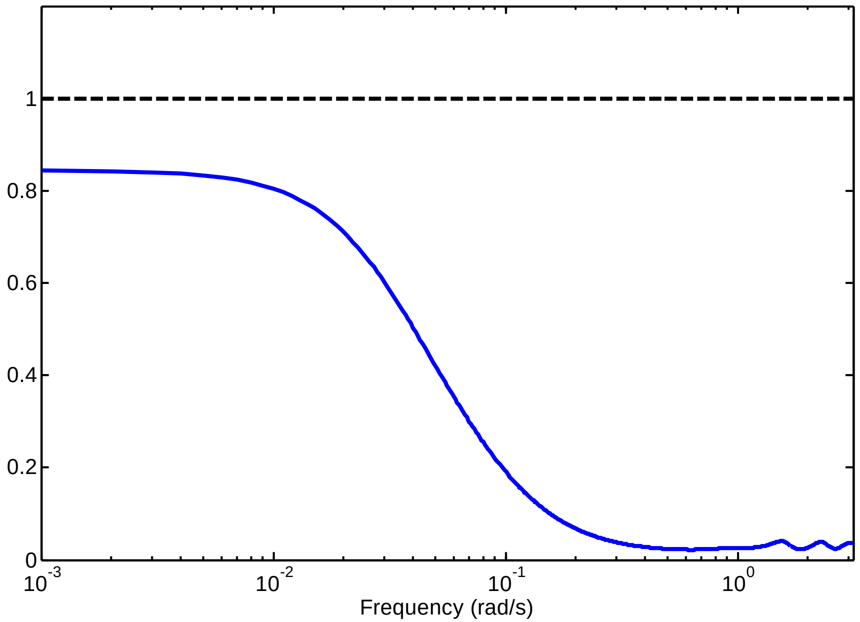
OR

- **MPM 'mishandled' by controller**

Important Closed-loop Term - 2

$$\|\Delta Q\|_\infty < 1$$

$\|\Delta Q\|_\infty \Longrightarrow$ **Measure of Robustness**



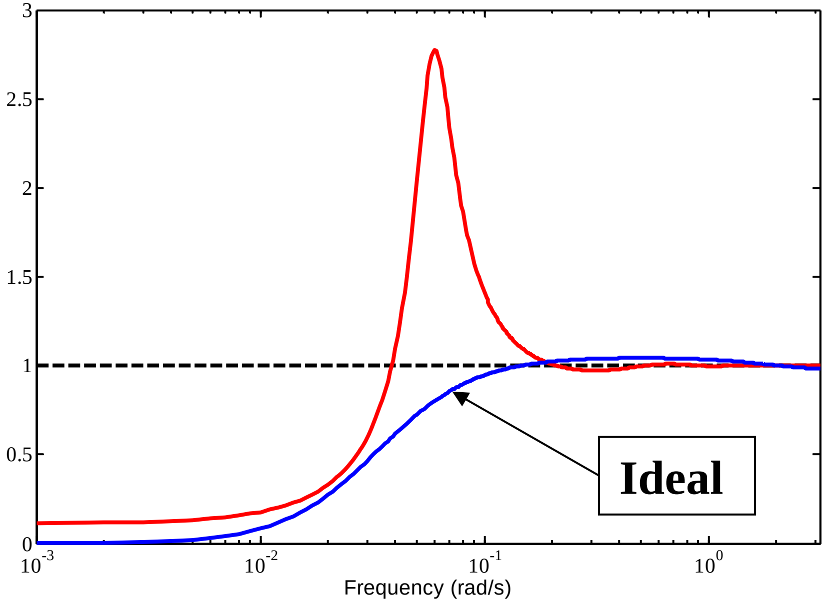
- **Sufficient condition for stability**
- **Smaller the value, the more robust is the closed-loop to the current MPM**

Important Closed-loop Term - 3

$$S_{designed} = \left[1 - \hat{G}Q\right]$$

Designed Sensitivity

Sensitivity: Closed-loop relationship between the CV and the disturbance



- **A measure of the designed performance**
- **Depends on controller tuning**
- **A large peak (> 2) indicates poor designed performance – Issues with tuning**

Key Observations

- All terms can be estimated from routine operating data – SPs, CVs and model residuals are required.

- Variability: $\frac{var(e_{ach})}{var(e_{des})} \leq \left\| \frac{1}{1+\Delta Q} \right\|_{\infty}^{2}$
- Degraded performance:

$\left\| \frac{1}{1+\Delta Q} \right\|_{\infty}$	$\|\Delta Q\|_{\infty}$	$\|S_{designed}\|_{\infty}$	**Diagnosis**	**Recommendation**
≈ 1	≈ 0	> 2	Tuning problem	Retune
> 1	≥ 1	> 2	Severe MPM	Retuning may help
> 1	≥ 1	< 2	Severe MPM	Re-identify
≈ 1	≈ 0	< 2	Disturbances	

Illustrative Example: SISO MPC

Plant:

$$G = \frac{4e^{-25s}}{50s+1}$$

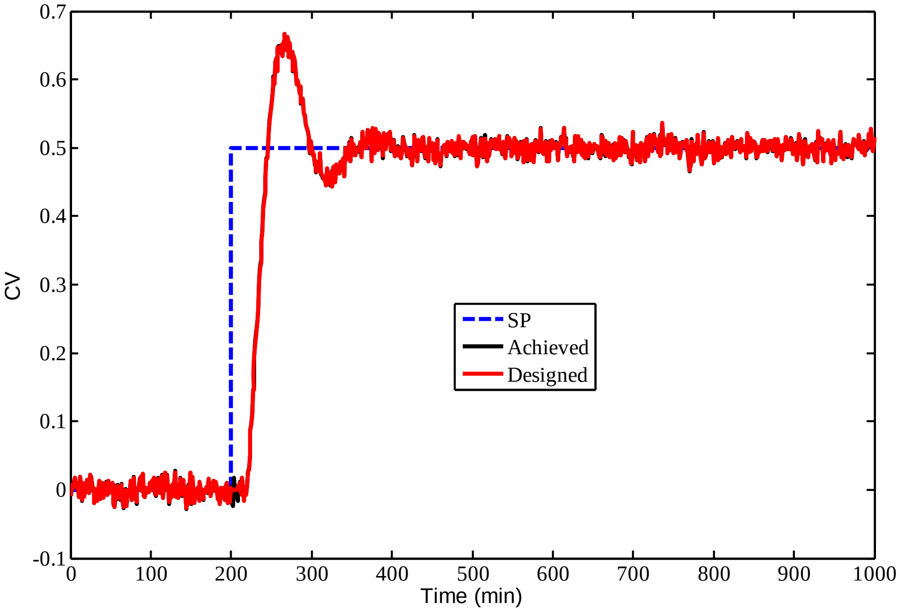
Controller:

MPC : Design based on the model G

Prediction Horizon	40
Control Horizon	3
Error Weight	1

Disturbance: Integrated white noise of std. deviation 0.005

Case-1: Tuning Problem, Perfect Model

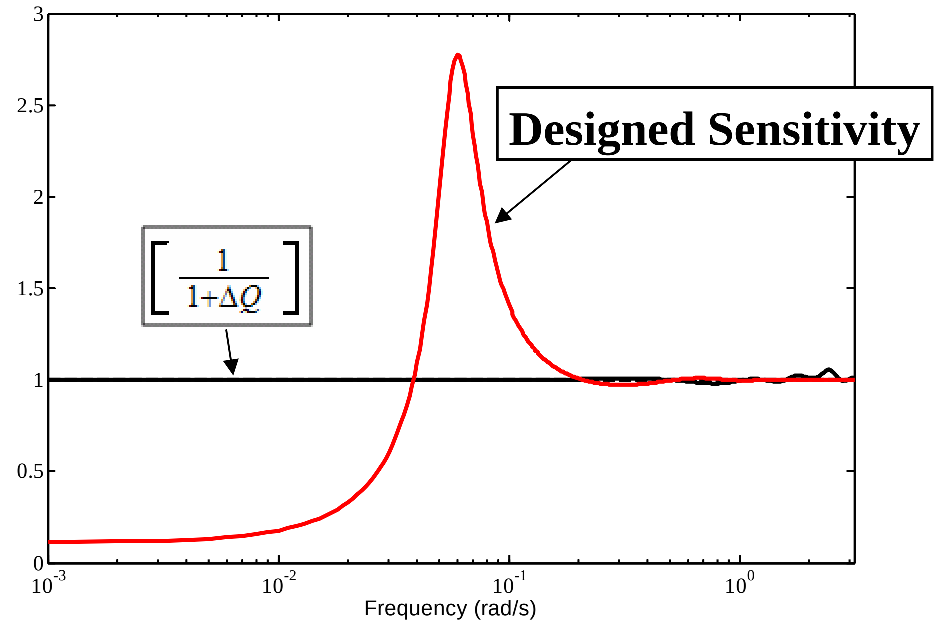


Simulation

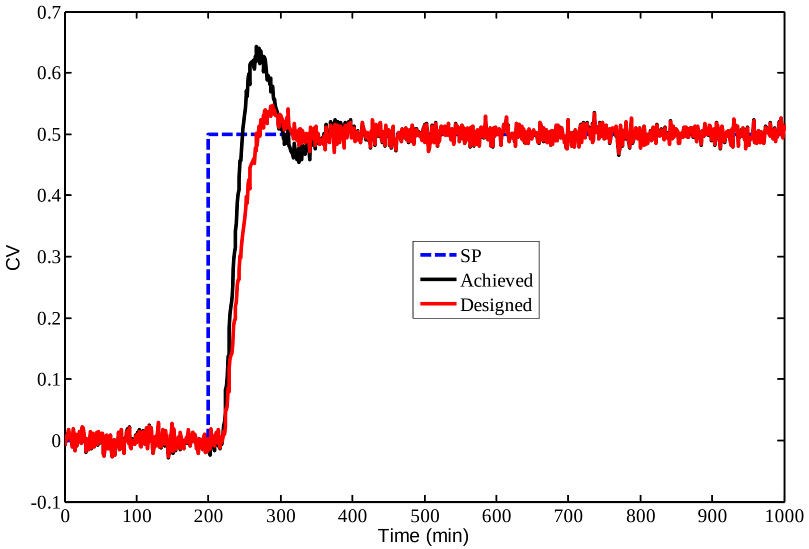
- **Aggressively tuned controller**
- **Model is perfect**

Achieved is as good as designed :
No model-plant mismatch

Peak in the designed sensitivity:
Tuning Problem

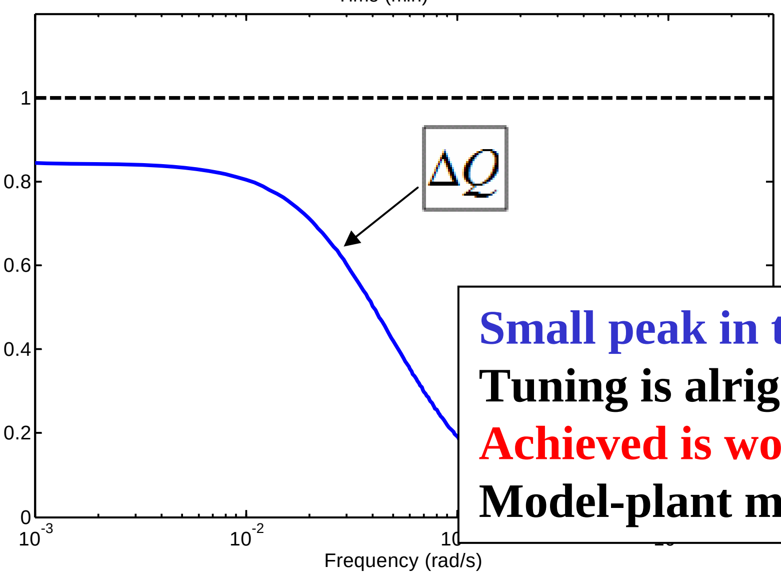


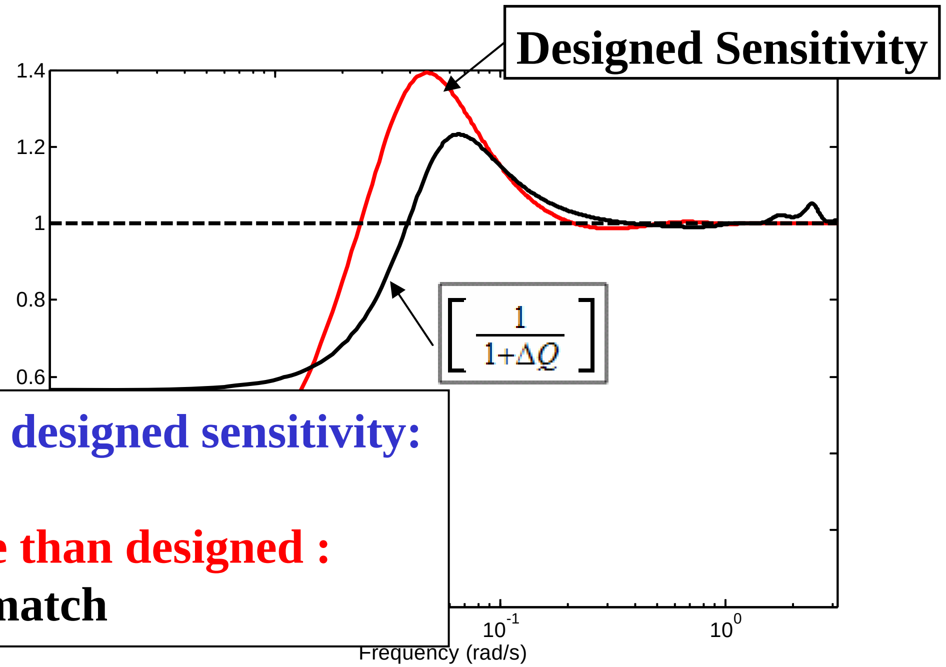
Case-2: Good Tuning, Model-Plant Mismatch



Simulation

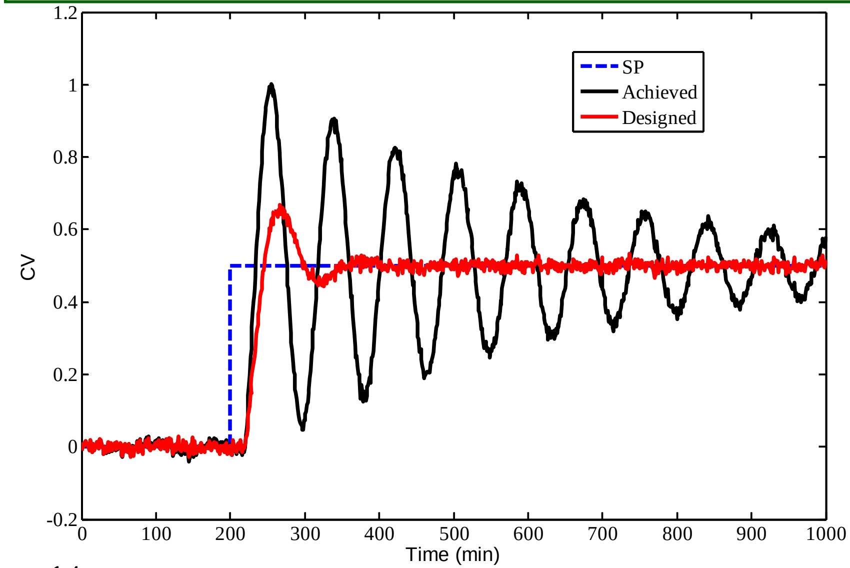
- **Well-tuned controller**
- **Model-plant mismatch: *Gain is Underestimated by 50%***





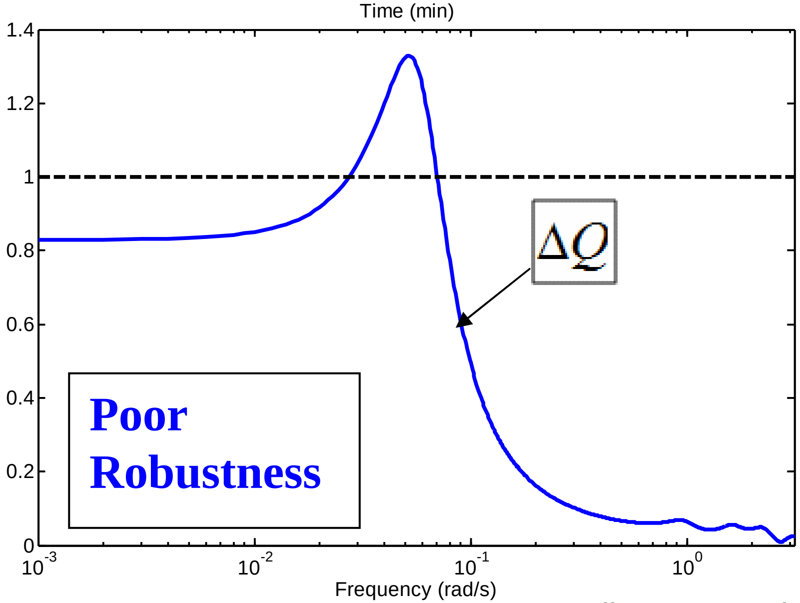
Small peak in the designed sensitivity:
Tuning is alright!
Achieved is worse than designed :
Model-plant mismatch

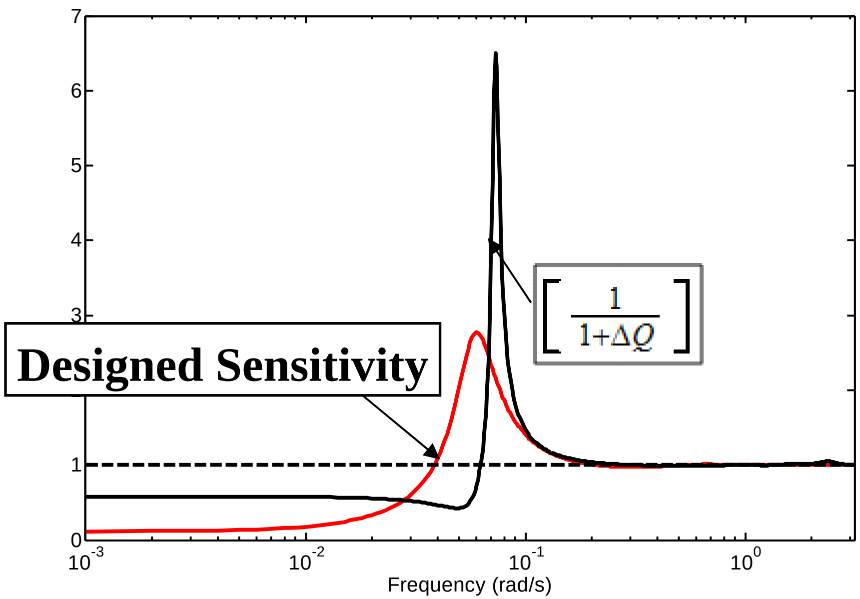
Case-3: Bad Tuning, Model-Plant Mismatch



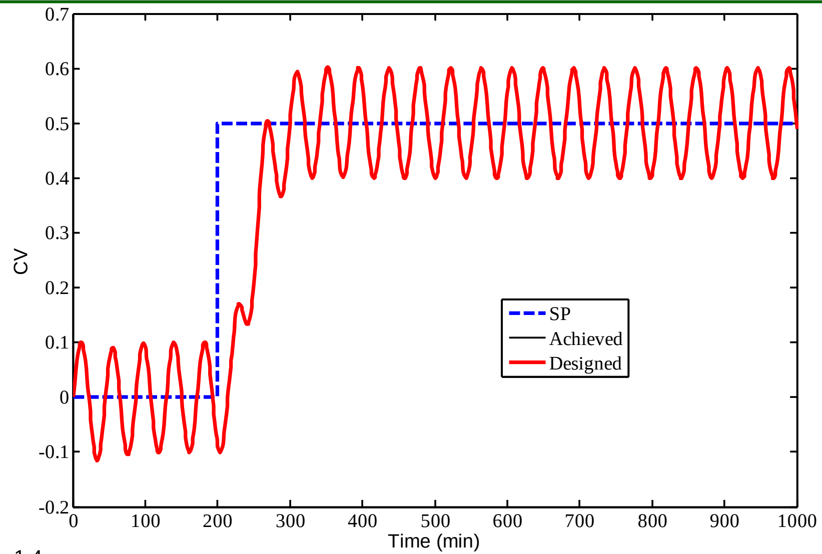
Simulation

- **Aggressive controller**
- **Model-plant mismatch: *Gain is Underestimated by 50%***



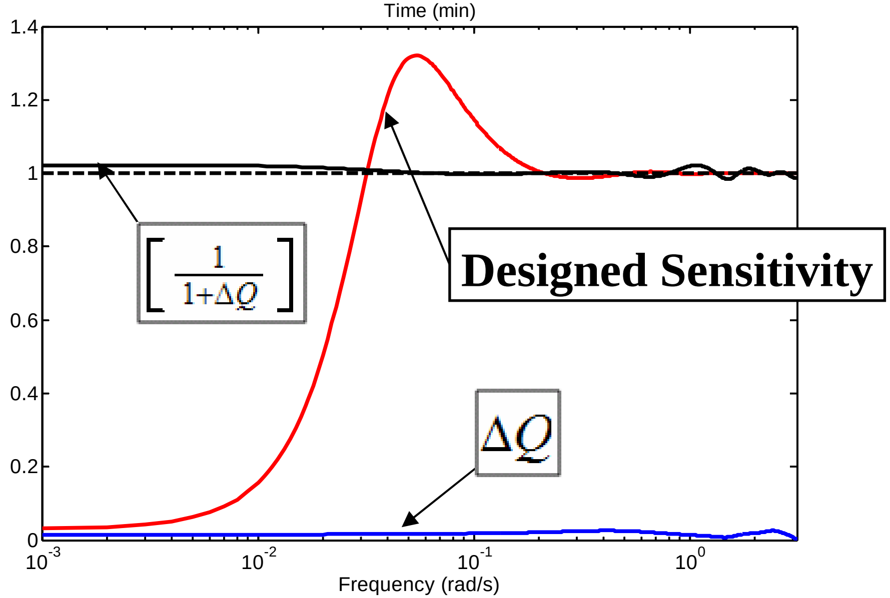


Case-4: Degradation due to disturbance



Simulation

- **Well tuned controller**
- **Perfect Model**
- **Oscillatory disturbance in the process**

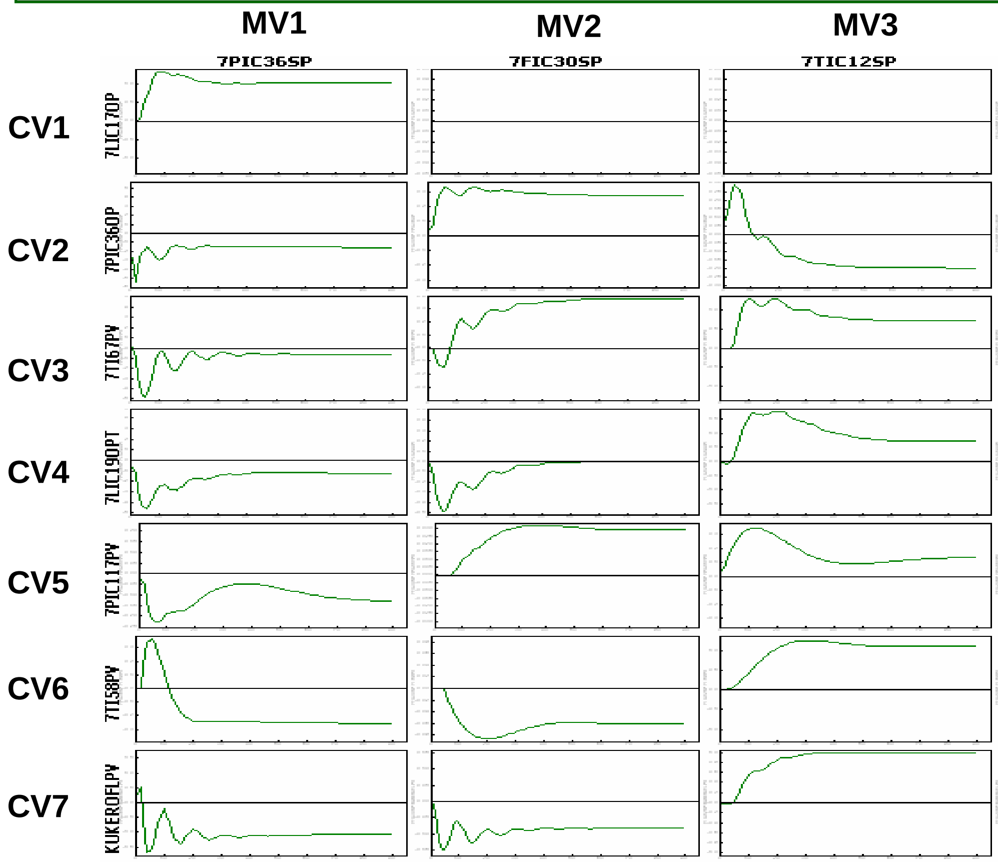


Small peak in the designed sensitivity:
Tuning is alright!
Achieved is as good as designed :
Model is perfect!
Degradation in performance is due to disturbance.

Summary

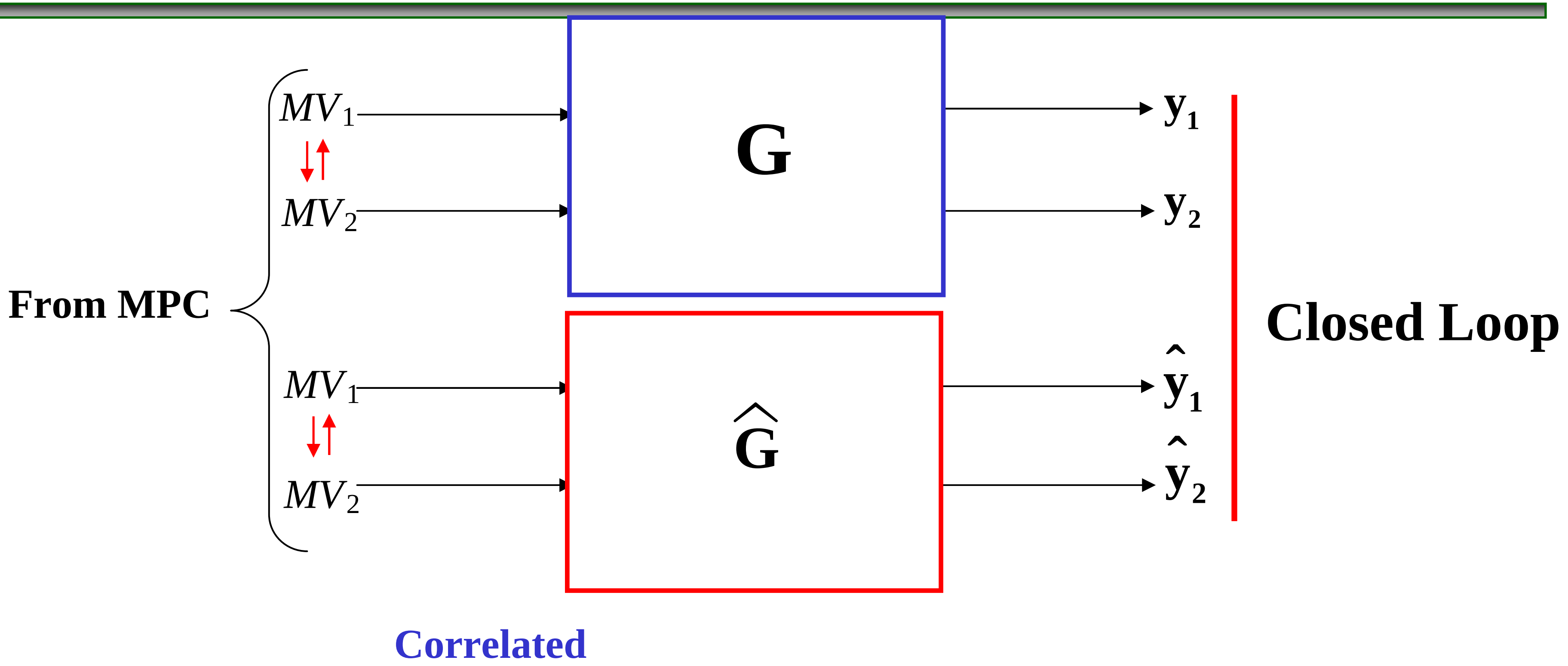
Case	$\frac{var(e_{ach})}{var(e_{des})}$	$\left\| \frac{1}{1+\Delta Q} \right\|_\infty$	$\|\Delta Q\|_\infty$	$\|S_{designed}\|_\infty$
Tuning problem	0.99	1.015	0.005	2.75
MPM	1.26	1.21	0.84	1.4
MPM + Tuning problem	6.10	6.46	1.32	2.77
Disturbances	1.03	1.02	0.002	1.36

MIMO Process - Location of MPM



Isolate that part/subsystem where model-plant mismatch is significant

MPM in MPC



$$e_1 = \Delta_{11} MV_1 + \Delta_{12} MV_2 + v_1$$
$$e_2 = \Delta_{21} MV_1 + \Delta_{22} MV_2 + v_2$$

$$G - \hat{G} = \begin{bmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{21} & \Delta_{22} \end{bmatrix}$$

MPM with MPC - Issues

- Correlations amongst the MVs
- Correlated MVs confound regular correlation analysis between model residuals and MVs – Misleading information regarding presence (or absence) of significant mismatch
- Absence of setpoint activity – $\mathbf{e} = -\mathbf{Q}^{-1}\mathbf{u}$
  - Detection of mismatch is not possible
  - In practice, setpoint activity is quite common

Problem and Approach

- Problem: A methodology for the detection and isolation of plant-model mismatch for MPC using closed-loop data.

- Approach: Analysis of partial correlations between the model residuals and the inputs.

Partial Correlations - Introduction

- Partial correlation analysis is a method used to describe the relationship between two variables whilst taking away the effects of other variables.
- Extensively used in social sciences.
- Generally linear regression is used to de-correlate variables.

Partial Correlation Analysis for Problem at hand

- We wish to analyze partial correlations in a dynamic sense because the variables under consideration (MVs and model residuals) are time series variables.
  - ✓ Use lagged variables
- Disturbances may confound the analysis of partial correlations
  - ✓ Replace linear regression by PEM based models

Methodology based on Partial Correlations

1. Choose data (model residuals and MVs) from the period where there is sufficient setpoint excitation in the process.
2. Identify relationship between MV_i and rest of the MVs and evaluate associated prediction error, E_{MVi}.
3. Identify relationship between residual, e_j and all MVs except MV_i and evaluate associated error, E_{ej}.
4. Evaluate correlation between E_{MVi} and E_{ej} – Large correlation indicates significant mismatch in channel MV_i-CV_j.

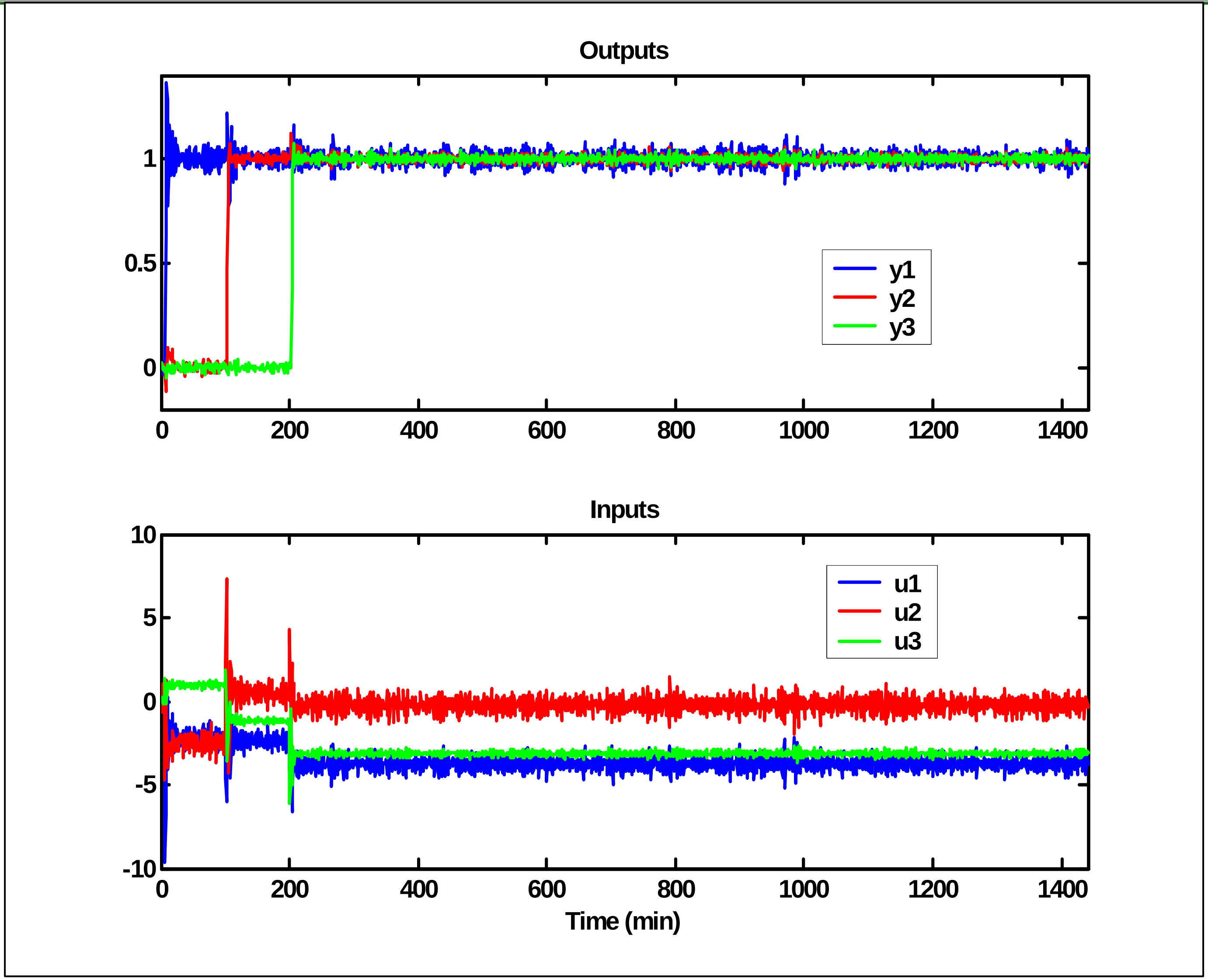
Case Study 1: Simulations on a 3x3 system

- Simulation of 3 CVs X 4 MVs example
- MPC controller parameters:
  - Prediction Horizon = 30
  - Control Horizon = 10
  - Sampling Time = 1 min
  - All CVs are equally weighted
  - All MVs are equally weighted with move supression factor = 0 or 1
  - MV4 is constrained at its lower limit – 3CVs X 4MVs controller
- Each MV is a setpoint to a PID loop

Case Study 1 – Gain mismatch

- MV1- CV1,CV2 gains underestimated by 50%
- Full and partial correlations analyzed
- Channels corresponding to residual-MV pairs with significant partial correlations contain mismatch

Input-Output Data



Case Study-1: Gain Mismatch – Full and partial correlation coefficients

Correlation coefficients between residuals and inputs

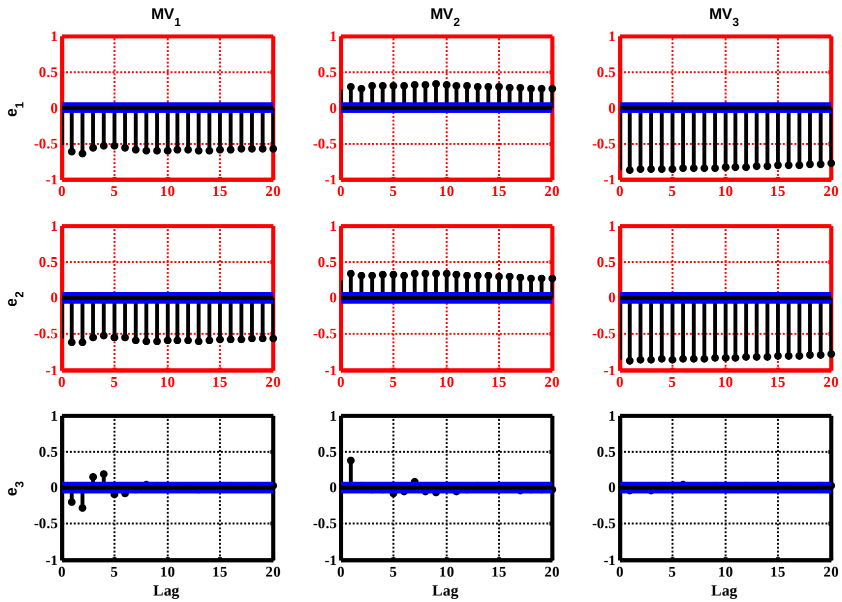
	u1	u2	u3
e1	-0.62 (0)	0.28 (0)	-0.88(0)
e2	-0.62 (0)	0.28 (0)	-0.88(0)
e3	-0.006 (0.81)	-0.02 (0.42)	0.002 (0.92)

Partial correlation coefficients between residuals and inputs

	u1	u2	u3
e1	0.15 (0)	-0.01 (0.57)	0.08 (0.16)
e2	0.38 (0)	-0.02 (0.33)	-0.04 (0.13)
e3	0.001 (0.97)	-0.01 (0.61)	-0.02 (0.48)

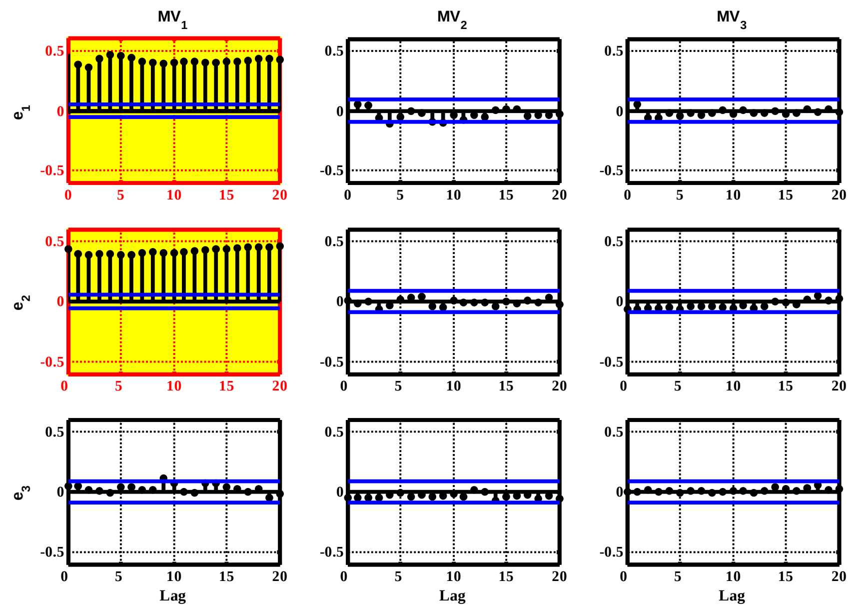
Mismatch correctly located in channels u1-y1,y2

Case Study-1: Gain Mismatch – Correlation plots



Partial correlation plots

Full correlation plots



Case Study 1 – Delay mismatch in u1-y1,y2,y3

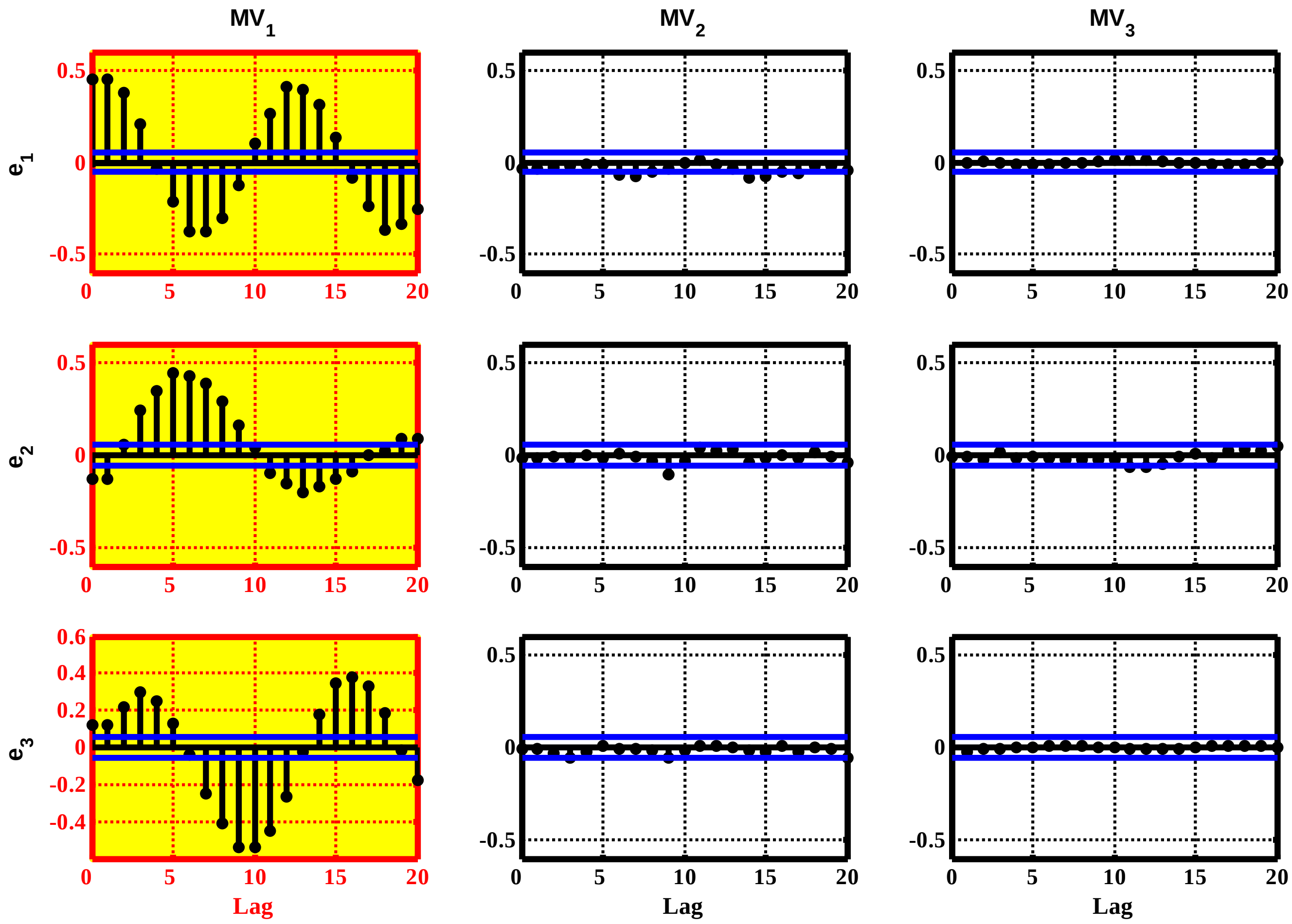
- Delay is underestimated by 2

Partial correlation coefficients between residuals and inputs

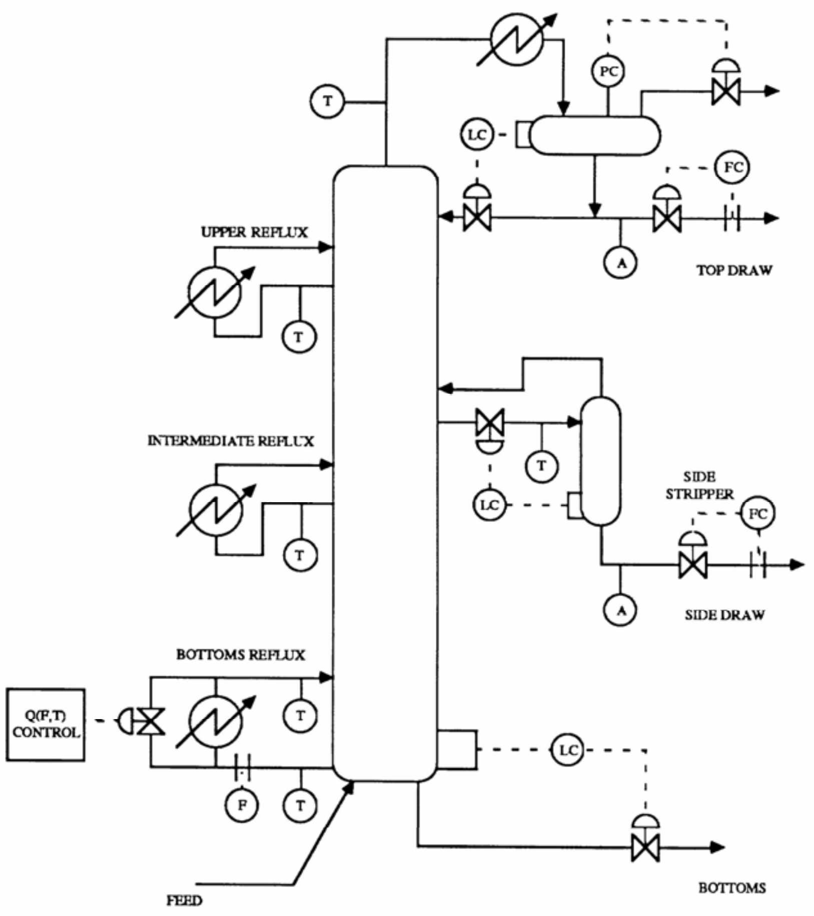
	MV1	MV2	MV3
e_1	**0.45 (0)**	-0.001 (0.45)	7.5e-4 (0.64)
e_2	**-0.2(0)**	-2e-4(0.43)	-2e-4(0.52)
e_3	**0.18 (0)**	-1.3e-4(0.61)	-1.4e-3(0.39)

Mismatch correctly located in channels u1-y1, y2, y3

Case Study 1 – Delay mismatch in u1-y1,y2,y3



Example: Shell Control Problem



Controlled Outputs :

(y_1) Top End Point

(y_2) Side Endpoint

(y_3) Bottom Reflux Temp.

Manipulated Inputs :

(u_1) Top Draw

(u_2) Side Draw

(u_3) Bottom Reflux Duty

Unmeasured Disturbances:

(d_1) Upper reflux

(d_2) Intermediate reflux

Process Dynamics

$$y(s) = G_u(s)u(s) + G_d(s)d(s)$$

$$G_u(s) = \begin{bmatrix} \frac{4.05e^{-27s}}{50s+1} & \frac{1.77e^{-28s}}{60s+1} & \frac{5.88e^{-27s}}{50s+1} \\ \frac{5.39e^{-18s}}{50s+1} & \frac{5.72e^{-14s}}{60s+1} & \frac{6.9e^{-15s}}{40s+1} \\ \frac{4.38e^{-20s}}{33s+1} & \frac{4.42e^{-22s}}{44s+1} & \frac{7.2e^{-19s}}{19s+1} \end{bmatrix}$$

- System with large time delays and significant multivariable interactions
- Time delay matrix is assumed to me known a-priori

Unmeasured Disturbance Dynamics

$$G_d(s) = \begin{bmatrix} \dfrac{1.2e^{-27s}}{45s+1} & \dfrac{1.44e^{-27s}}{40s+1} \\ \dfrac{1.52e^{-15s}}{25s+1} & \dfrac{1.83e^{-15s}}{20s+1} \\ \dfrac{1.14}{27s+1} & \dfrac{1.26}{32s+1} \end{bmatrix}`$$

All disturbance inputs assumed to be piecewise constant

$$\begin{bmatrix} d_1(z) \\ d_2(z) \end{bmatrix} = \begin{bmatrix} \dfrac{z}{z-0.95} I \end{bmatrix} \begin{bmatrix} w_1(z) \\ w_2(z) \end{bmatrix}$$

$$mean(w_i) = 0\ ;\ \sigma(w_i) = 0.0075\ \ for\ i = 1,2$$

Measurement Noise

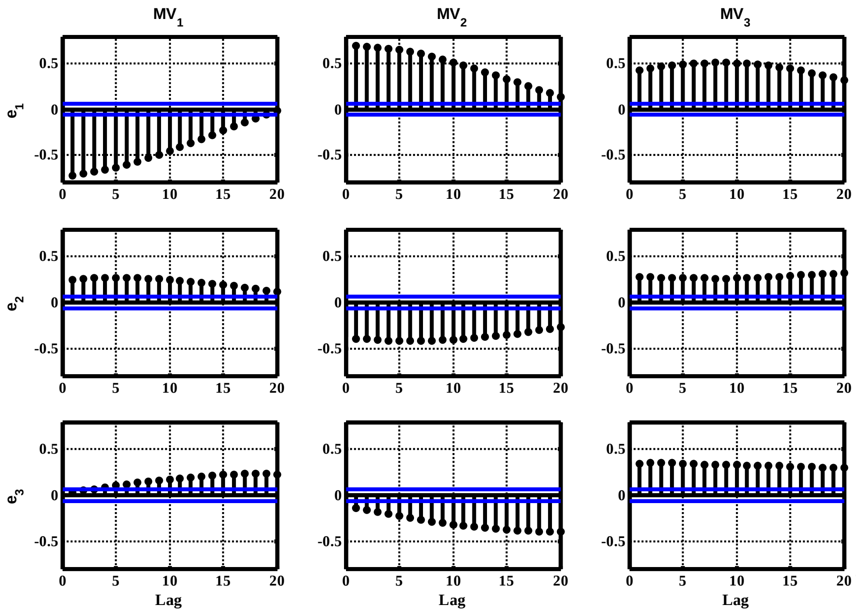
$$mean(v_i) = 0\ ;\ \sigma(v_i) = 0.005\ \ for\ i = 1,2,3$$

Shell Control Problem – Scenario-1

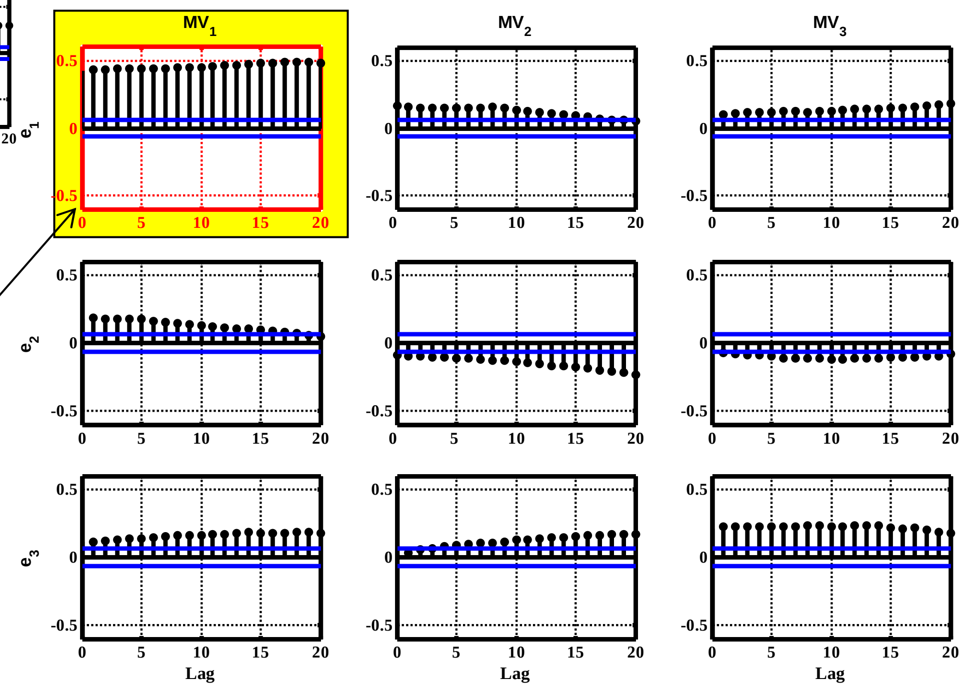
- 10 % gain mismatch and 10 % mismatch in time constant was added in all channels except channel u_1-y_1, where a larger mismatch of 50 % (underestimated gain) was added.

- Challenge is to identify the channel with significant mismatch.

Shell Control Problem: Scenario - 1



Regular correlation plots



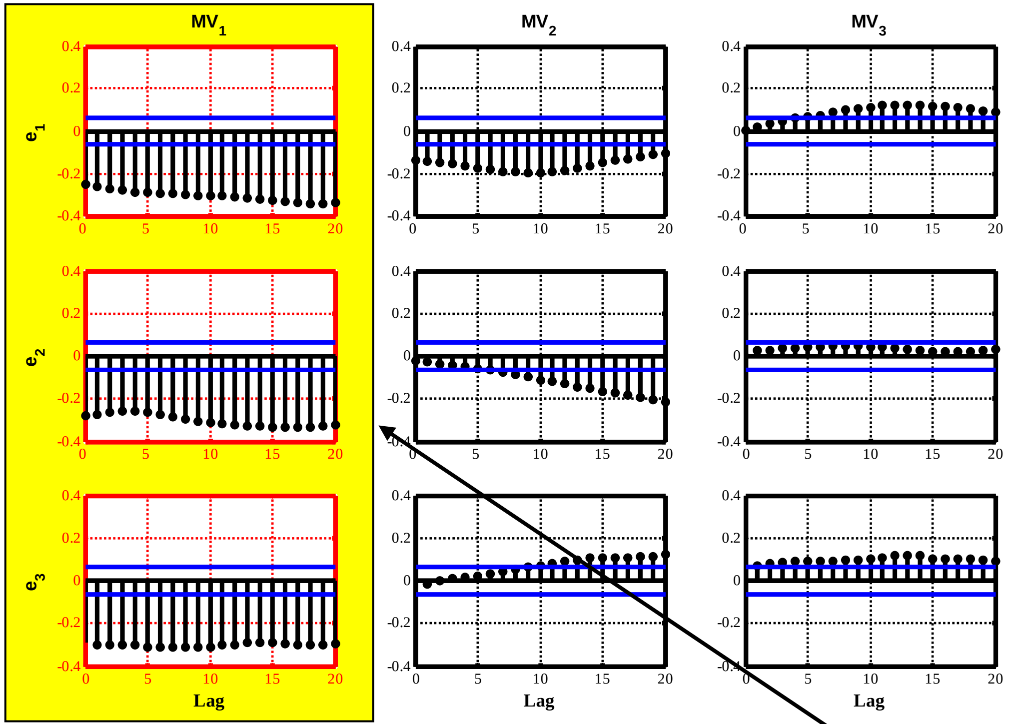
Significant partial correlation between e_1 and u_1 implies significant mismatch in channel MV_1-CV_1

Shell Control Problem: Scenario - 2

- A mismatch in delay (underestimate) of 5 samples was introduced in MV1-CV1,CV2,CV3

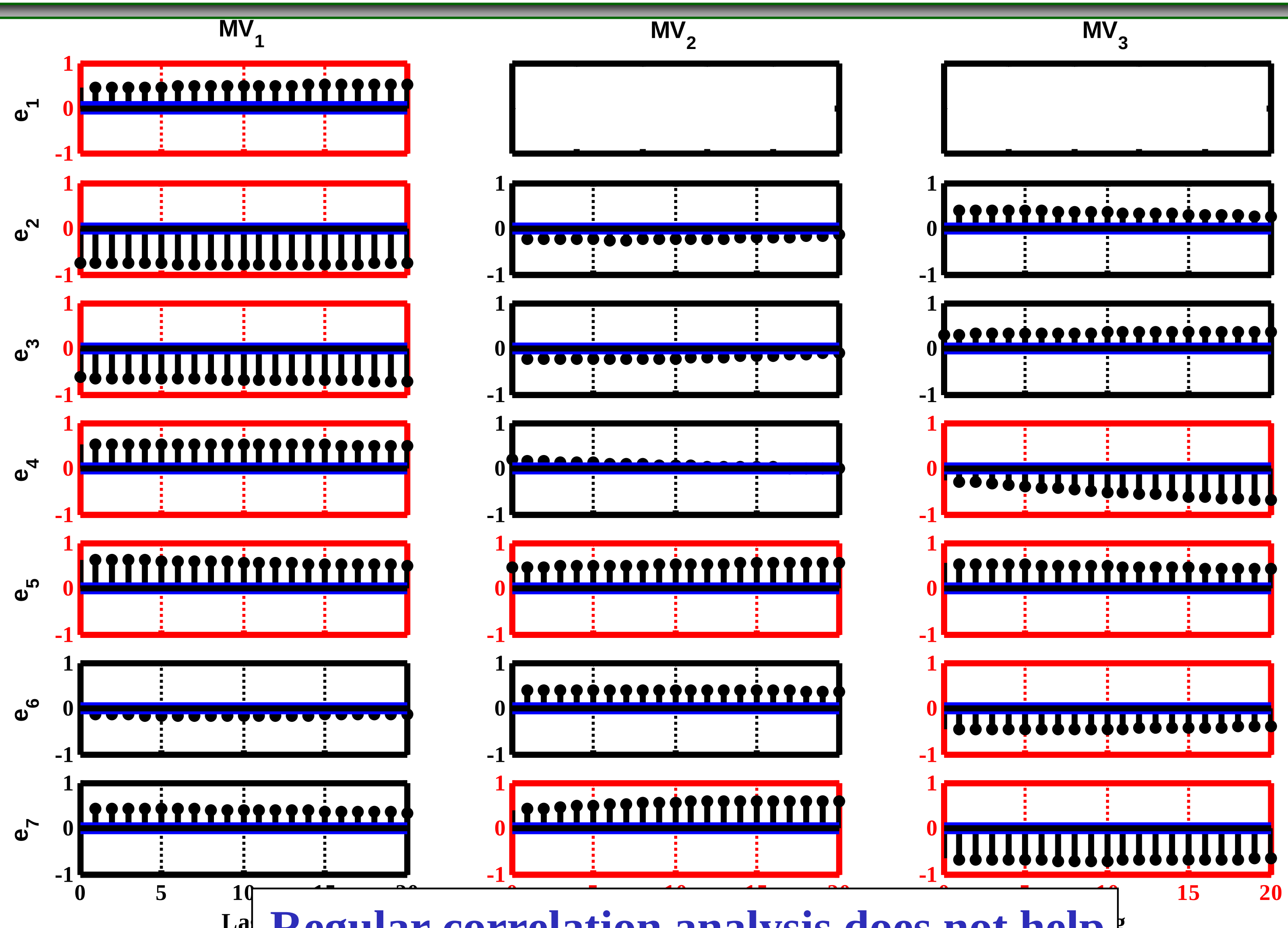
- 10 % gain mismatch in all channels

Shell Control Problem: Scenario - 2



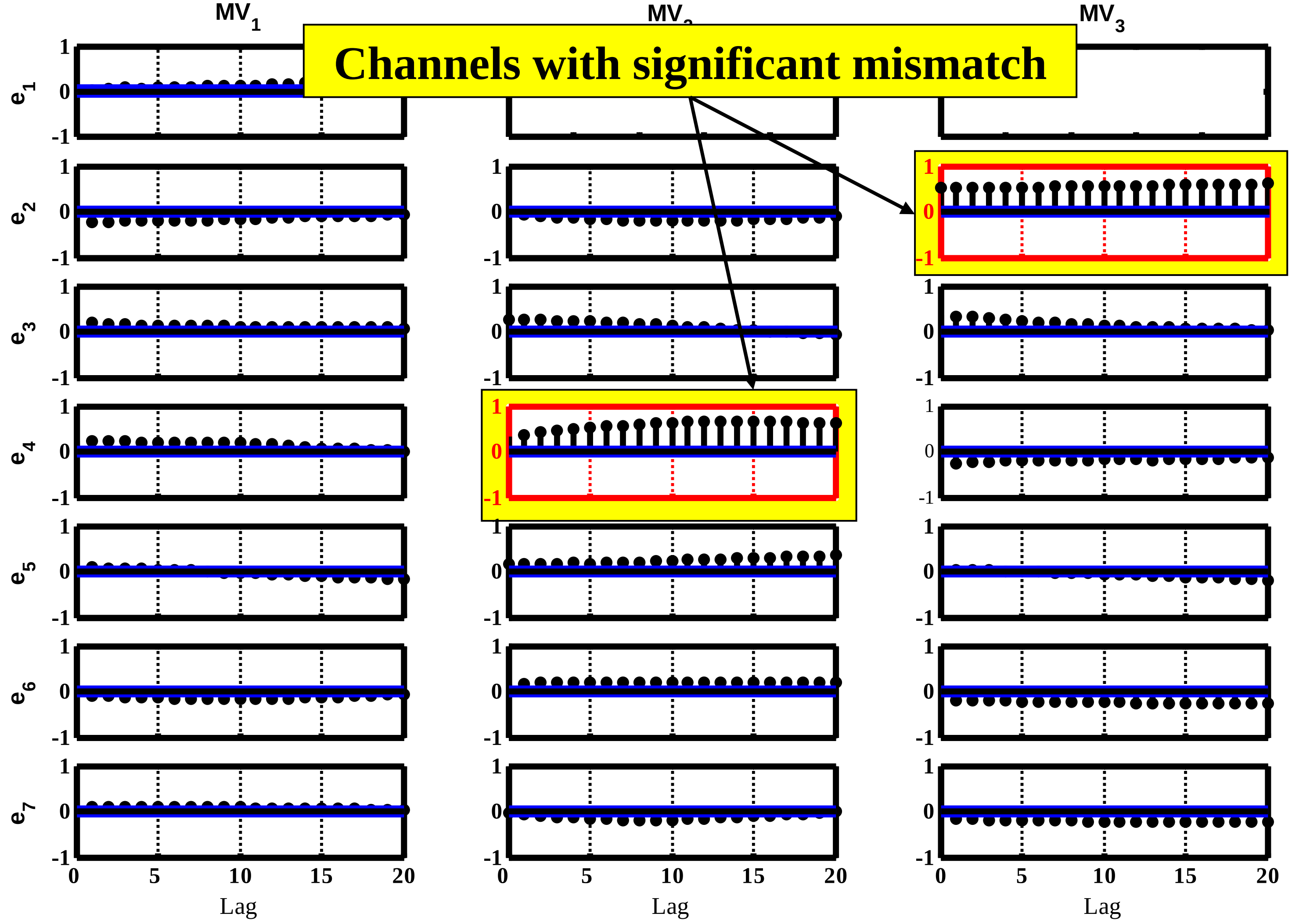
Significant partial correlations between e_1, e_2, e_3 and u_1 imply significant mismatches in channels MV_1-CV_1, CV_2, CV_3

Industrial Case Study – KHU Unit at Suncor Energy



Regular correlation analysis does not help

KHU – Partial correlations methodology



Concluding Remarks

1. Proposed a methodology for assessing the need for re-identification / re-tuning.
2. Demonstrated the efficacy on a SISO MPC simulation case study.
3. Proposed a technique based on partial correlations analysis for detection and isolation of mismatch.
4. Applied the technique successfully to simulated examples and industrial data.

Ongoing Work

- Assessing need for re-identification – Extension to the multivariable case

- Cancellation of effect of MPM – Re-tuning guidelines for MPC

Acknowledgements

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3. Prof. Sachin Patwardhan (IIT, Bombay)

4. CPC Group Members

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