System Identification for Process Control:
Recent Experiences and a Personal Outlook

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1. Introduction

- Model predictive control (MPC) has been applied extensively in the refining/petrochemical industry.
- MPC technology has huge benefits to refineries and petrochemical plants: M US$ (1 ~ 3)/controller.
- Other process industries (paper, power) are starting MPC trials.
- The key to MPC success is a good process model
- Model identification is the most time consuming and difficult task in MPC projects and maintenances.

2. Industrial MPC and MPC Identification

2.1 A Brief Introduction to MPC

- MPC technology started in 1980s and developed by industrial control engineers.
- MPC has become the standard tool of advanced process control (APC) in the refining/petrochemical industry.
- There are 7000 ~ 10000 applications (Qin and Badgwell, 2003).
- The academic control community became interested in MPC in the 1990s due to its success.

2.1 A Brief Introduction to MPC (cont.)

A Project Approach to Industrial MPC

- Functional design and benefit study (10%)
- Pre-test (10%)
- Identification test and model identification (40%)
- Controller simulation and tuning (15%)
- Controller commissioning and operator training (25%)
- Controller maintenance*

2.1 A Brief Introduction to MPC (cont.)

The Need of Process Identification in MPC

- A fact: Major MPC vendors own many rigorous (first principle) models, but most MPC modeling is done using identification.

- Rigorous models are not accurate enough for MPC; an industrial example shows that gains and time constants can differ by a factor of 3.

- Rigorous models cannot adapt to process changes.

- Model identification is needed in both new MPC projects and in MPC maintenances.

2.1 A Brief Introduction to MPC (cont.)

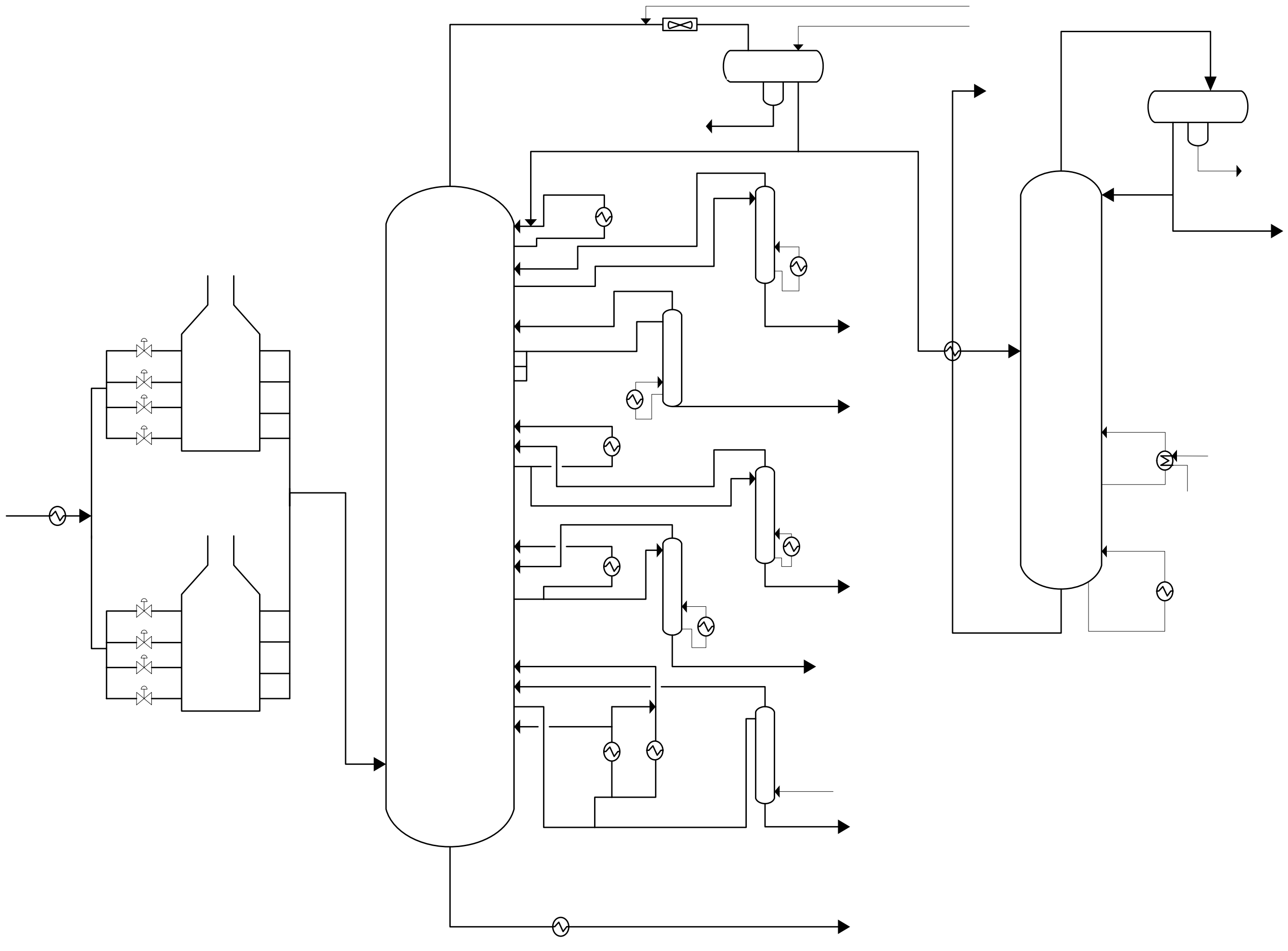
Inferential Model or Soft Sensor

- Many product qualities (compositions) cannot be measured fast enough using analyzers or laboratory data.
- Inferential models are used to provide prediction of product qualities.
- So far, only static inferential models are used.
- The use of dynamic inferential models can improve prediction accuracy.

2.2 An Example: A Crude Unit MPC

- The crude unit is located at one of the largest refineries in North America.
- The original MPC controller was commissioned in 1998.
- MPC main objectives:
    - Maximize crude charge.
    - Meet product specifications.
    - Maximize crude preheat train efficiency and balance heater passes.
    - Disturbance reduction during crude switches and product grade changes.

The Crude Unit



2.2 An Example: A Crude Unit MPC (cont.)

- The MPC had 33 MVs and 94 CVs that covers 2 heaters, the atmospheric tower and the naphtha stabilizer.
- The cost of model identification: 30 days (24x7) for plant test and 30 days (8x5) for model identification.
- Process models degraded after many years of operation and maintenance was needed for the MPC

Characteristics of Industrial Processing Units:

- Continuous process. Good character!
- Large scale and complex: 35 x 90
- Dominant slow dynamics: settling time in hours.
- High level disturbances (small test signals): 5 ~ 50% in power
- Nonlinearity: in composition CVs, in valves CVs, caused by product grade changes, …

Can we do a better job?

Than open loop 30 day test and 30 day model identification

2.3 Key Issues of MPC Identification

1) Plant Test

- Traditional test method: manual, single variable and open loop.
- Modern approach: automatic, multivariable and closed-loop (if possible).
- Advantages of automatic multivariable closed-loop test
  - Reduce disturbance to unit operation.
  - Shorter test, easy to carry out.
  - Better model for control.

2) Model Structure and Parameter Estimation

- Traditional methods use nonparametric FIR model.
- Modern method uses parametric models.
- Some models are suitable for closed-loop data and some are not.
- Nonparametric models and some parametric models are not suitable for closed-loop data.
- More advanced numerical optimization routines are needed for parametric models.

3) Model Validation/Selection

- Model validation has two objectives:
  1) to decide if the identified model is suitable for MPC control and, if not,
  2) to provide remedies.
- Traditional methods use knowledge on process gains and checks on model fit.
- Traditional methods cannot provide sufficient control-relevant information .
- Modern methods use model error bounds that are control relevant.
- Modern validation methods can provide advices on adjusting the ongoing test or on test redesign.

3. Asymptotic Method

The asymptotic theory (Ljung 1985, Zhu 1989)

Frequency responses of the process and of the model

$$T^o(e^{i\omega}) := col[G^o(e^{i\omega}), H^o(e^{i\omega})]$$
$$\hat{T}^n(e^{i\omega}) := col[\hat{G}^n(e^{i\omega}), \hat{H}^n(e^{i\omega})]$$

Asymptotic property of high order models

- $\hat{T}^n(e^{i\omega}) \rightarrow T^o(e^{i\omega}) \ as \ N \rightarrow \infty, n \rightarrow \infty$
- $\mathrm{cov}[\hat{T}^n(e^{iw})] \approx \frac{n}{N} \Phi^{-T}(\omega) \otimes \Phi_v(\omega)$

where $\Phi_v(\omega)$ is the power spectrum matrix of disturbances and $\Phi(\omega)$ is the spectrum matrix of inputs and prediction error residuals.

1) ASYM Identification Test

- Signals: normally GBN (PRBS), but can use others as well
- Closed-loop test with optimal test signal design (SISO)

$$\Phi_r^{opt}(\omega) \approx \mu \sqrt{\Phi_r(\omega)\Phi_v(\omega)}$$

- Test design only needs process settling time.
- Test time: For crude units, FCCUs or cokers with 30 to 40 MVs, test time is between 4 to 6 days.

2) ASYM parameter estimation

A) Estimate a high order ARX model

$$\hat{A}^n(z^{-1})y(t) = \hat{B}^n(z^{-1})u(t) + \hat{e}(t)$$

B) Frequency weighted model reduction by minimizing

$$\sum_{i=1}^{p}\sum_{j=1}^{m}\int_{\omega_1}^{\omega_2} |\,\hat{G}_{ij}^{\,n}(\omega) - \hat{G}_{ij}(\omega)\,|^2\,[\Phi^{-1}(\omega)]_{jj}^{-1}\,\Phi_{v_i}^{-1}(\omega)\,\mathrm{d}\,\omega$$

3) ASYM order selection using ASYC

$$\sum_{i=1}^{p}\sum_{j=1}^{m}\int_{\omega_1}^{\omega_2} |\{|\hat{G}_{ij}^{n}(\omega) - \hat{G}_{ij}(\omega)|^2 - \frac{n}{N}[\Phi^{-1}]_{jj}(\omega)\Phi_{v_i}(\omega)\}|\,\mathrm{d}\omega$$

4) ASYM model validation

Upper error bound

$$\left|G_{ij}^{o}(e^{i\omega})-\hat{G}_{ij}^{n}(e^{i\omega})\right|\leq 3\sqrt{\frac{n}{N}[\Phi^{-1}(\omega)]_{jj}\Phi_{v_i}(\omega)}\quad \text{w.p. } 99.9\%$$

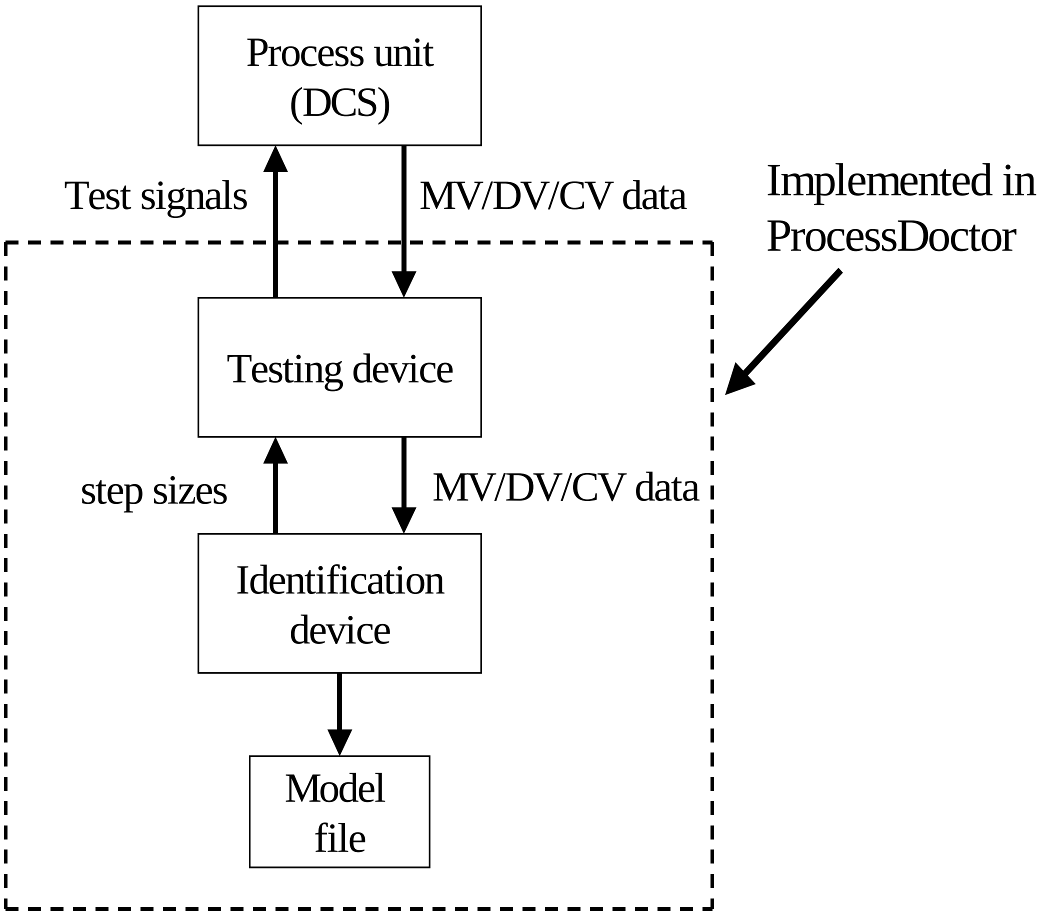
Grading the models

A, very good; B, good; C, marginal; D, poor or no model

Rules for test adjustment/redesign

- Doubling amplitude will halve the error
- Doubling test time will make the error 1.414 times smaller
- Doubling GBN switch time will halve the error at the low frequencies and double it in high frequencies

Tai-Ji Online Software



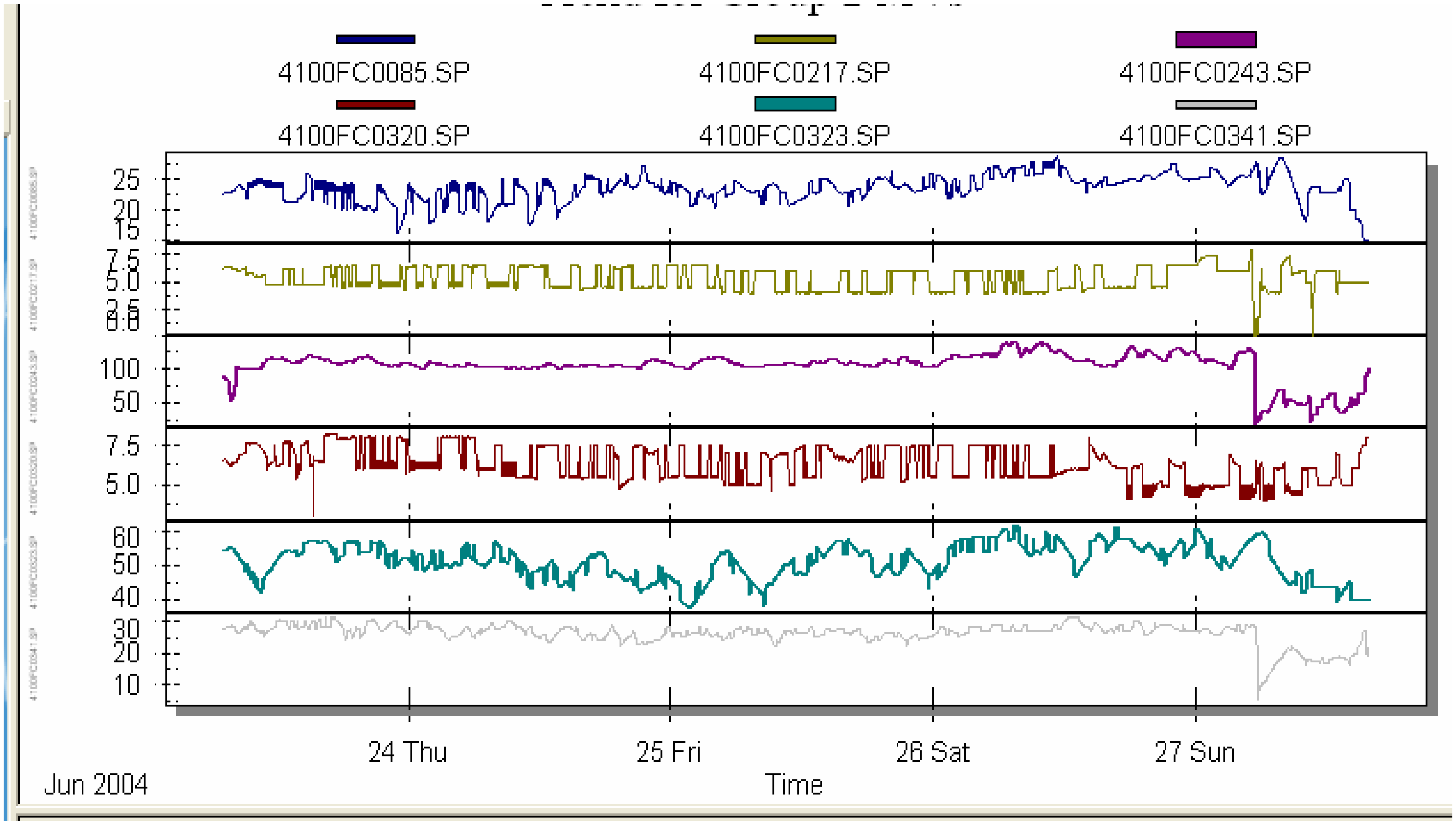
4. The Crude Unit Closed-Loop Identification

- After years of operation, the MPC controller needed maintenance.
- The revised MPC has 34 MVs, 7 DVs and 90 CVs.
- During the test, the test program moved all 34 MVs simultaneously with the current MPC controller ON
- Qualities remained on specification.
- The operator was able to focus on normal operational issues.
- The operator were very cooperative.

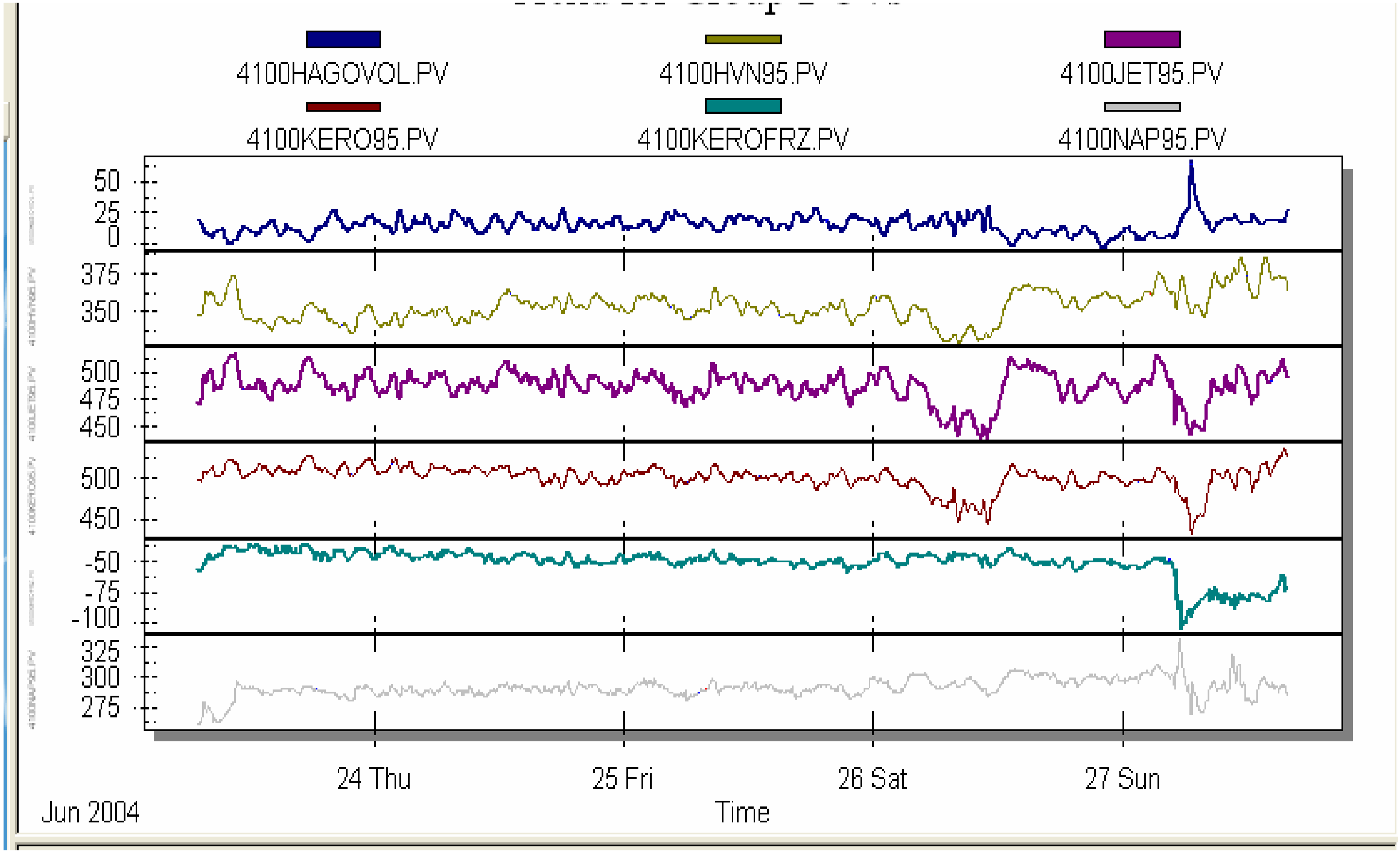
4. The Crude Unit Closed-loop Identification (cont.)

- Models were identified after the first 24 hours of testing.
- New models were generated every 24 hours thereafter.
- Model error bounds were used to adjust step sizes and signal patterns during the test in order to improve the data quality.
- The plant test was stopped after 4.5 days with most of expected models as A (very good) or B (good) grades.
- Several days were spent to double check the obtained models.
- The MPC with new models was commissioned successfully and improved performance has been achieved.
- The control engineers have done the same for an FCC unit and a delayed coker unit.

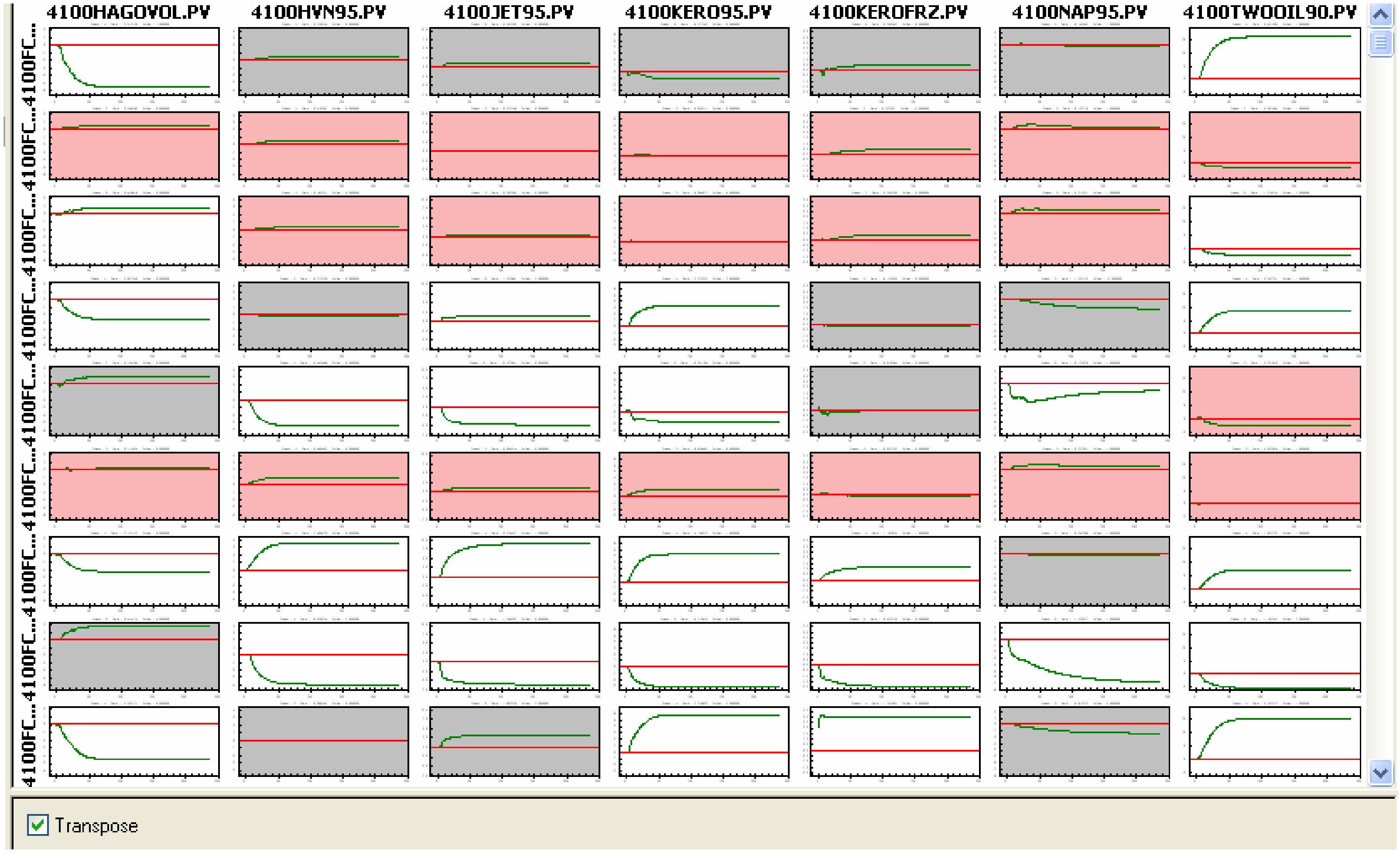
MV behavior during the test



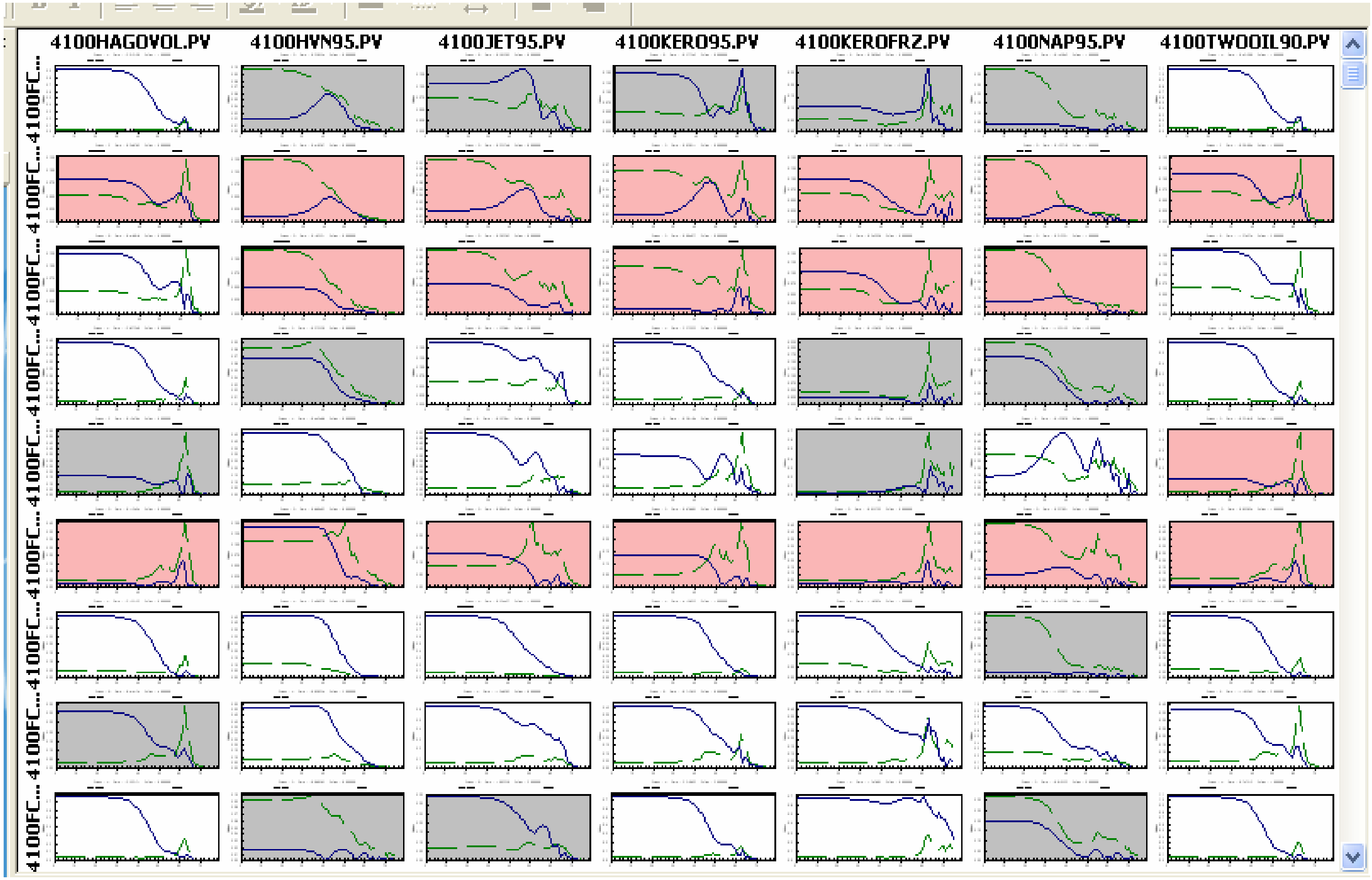
CV behavior during the test



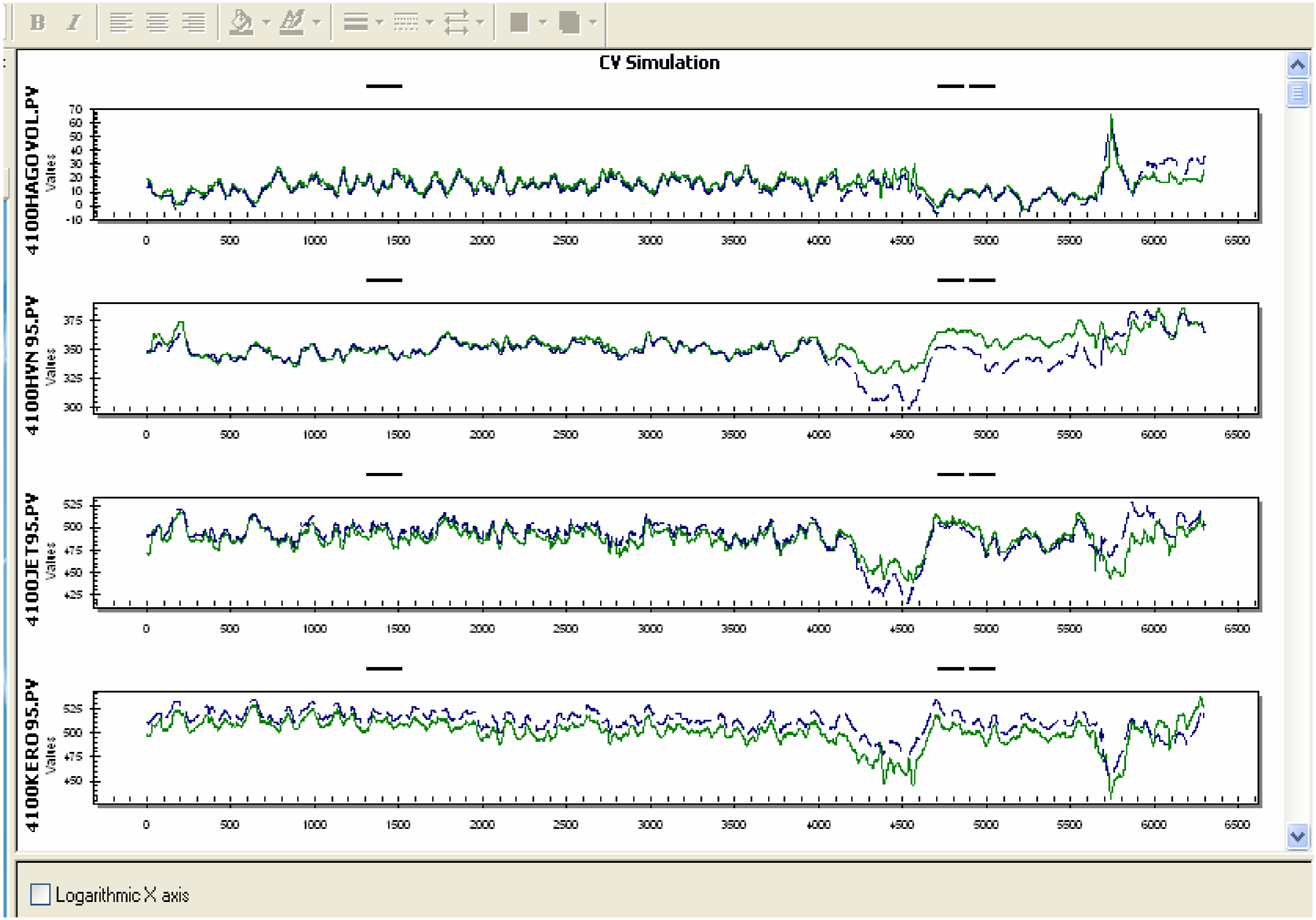
Model Step Responses



Model Frequency response and error bounds



Model Simulation



5. Conclusions and a Personal Outlook

5.1 Conclusions

- Model identification is the key to MPC technology.
- The ASYM method provides a solution to MPC identification:
  - More efficient: Saved over 70% time.
  - More accurate models for control.
  - User friendly: all procedures are automatic.
- Reasons that have made this development possible:
  - The drive in developing advanced control technology.
  - First hand knowledge of industrial process control.
  - The availability of the **asymptotic theory.** Thanks Lennat!

5.2 A Personal Outlook

Challenges in MPC and automation systems:

- The cost of MPC is too high, even for the refining/ petrochemical industry.
- Due to high cost, it is difficult to apply MPC in other process industries.
- Traditional automation (DCS/PLC) industry is in stagnation or even in decline. (Well, very recently, China and India…)
- The control community is not able to bring its scientific achievements (LQG, H-infinity, adaptive control, neural-fuzzy, identification, …) to process control.

The problem is

The high cost of modeling!

Model Intelligence

***Definition**: Model intelligence is a class of computer programs that can, for a given class of processes, <u>automatically</u> develop, maintain and use dynamic process models for control, prediction and monitoring/diagnosis.*

Comments

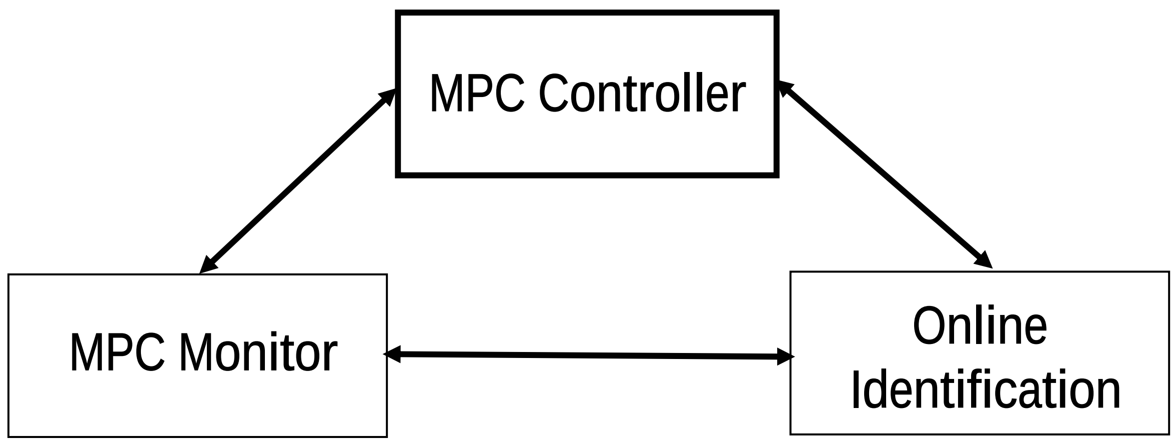
- Model intelligence consists of three modules
  1) Connectivity module: OPC, …
  2) Modeling module: online identification, …
  3) Model based application module: MPC tuning/control, PID tuning/control, H-inf design/control, monitor and diagnosis program, …
- Key differences: automatic model development and maintenance, online and real-time.
- Online identification plays the key role.
- Adaptation is included, though not sample-wise.

5.2 A Personal Outlook (cont.)

Next Generation MPC

- "*Get the design right, the rest is automatic*":

  A self-commissioning and self-maintaining MPC



- "MPC for dummies." -- Reduce cost by a factor of 5 to 10!
- All process industries can apply MPC technology.

5.2 A Personal Outlook (cont.)

Next Generation DCS/PLC

- All PID loops will have self-diagnosis, auto-tuning and decoupling functionalities.
- MPC, H-infinity control and other model based control will be embedded in DCS/PLC and can be used by operators.

5.2 A Personal Outlook (cont.)

Embedded MPC and H-infinity Control for Machines

- Using model intelligence, MPC and H-infinity control can be embedded in machines and equipments.
- Model based control can improve machine performance and reduce costs.

6. MPC Relevant Identification Problems

1) Multi-Linear Model Identification

- Most continuous processing units operate in one or multiple working points: Crude units, lubricate oil units, polymer plants, power plants, …
- Multi-model MPC can be used for these processes.
- Good transition control in addition to working point control.
- The three basic identification problems need to be addressed.

6. MPC Relevant Identification Problems (cont.)

2) Identification of Dynamic Inferential Model

- Static models are used (maybe) due to a misunderstanding.
- Dynamic models will be more accurate
- Nonlinear models can be useful.

6. MPC Relevant Identification Problems (cont.)

3) Model Reduction of Rigorous Models using Identification

- Many rigorous models exist in process industries.
- They are nonlinear PDEs and are too complex for MPC.
- Model reduction using *proper orthogonal decomposition* (POD) is popular, but reduced models are still to complex for MPC.
- Nonlinear identification techniques can be a good alternative.
- Identified models are simplest in use.
- This approach may lead to new nonlinear identification methods.

6. MPC Relevant Identification Problems (cont.)

4) Model Quality Assessment for MPC

- Needed in MPC monitoring module
- Data are from closed-loop operation.
- Questions:
  - How to quantify model accuracy for MPC?
  - What data length should be used in calculations?
  - Are test signals (excitation) needed?
- Fault detection and diagnosis techniques may be used.

6. MPC Relevant Identification Problems (cont.)

5) Time Delay Estimation for MIMO Processes

- Large delays exist in industrial processes.
- Compensating delays in identification can improve model quality.
- Accurate and efficient methods are desired.

6. MPC Relevant Identification Problems (cont.)

6) Closed-Loop Identification of Oscillating System

- Oscillation is caused by too aggressive (tight) control.
- Disturbance level is high.
- Many methods produce poor results.
- Can be very misleading: a poorer model can produce better simulation.

The future of identification and process control is …