Loop-Shaping Controller Design from Input-Output Data

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- **Control-Oriented ID:** Uncertainty description compatible with the controller design method. (Loop-Shaping for available insight & computations.)
- Linear-model estimation: Coprime factor uncertainty (forward and feedback)
- Controller Design: Loop-Shaping (S&T)
- **Final Result:** Quick design & implementation, Performance, Reliability

The Application: Control of Paper Machines

- Inputs:
  - Stock Flow
  - Dryer temperatures (set-points to the local PID's)
  - Machine speed set-point
- Outputs:
  - Dry weight
  - Moistures
  - Machine speed
- Disturbances:
  - Operators change set-points in other loops to maintain overall product quality.
  - Feed consistency, especially after paper breaks (re-circulation).
  - Other nonlinear effects

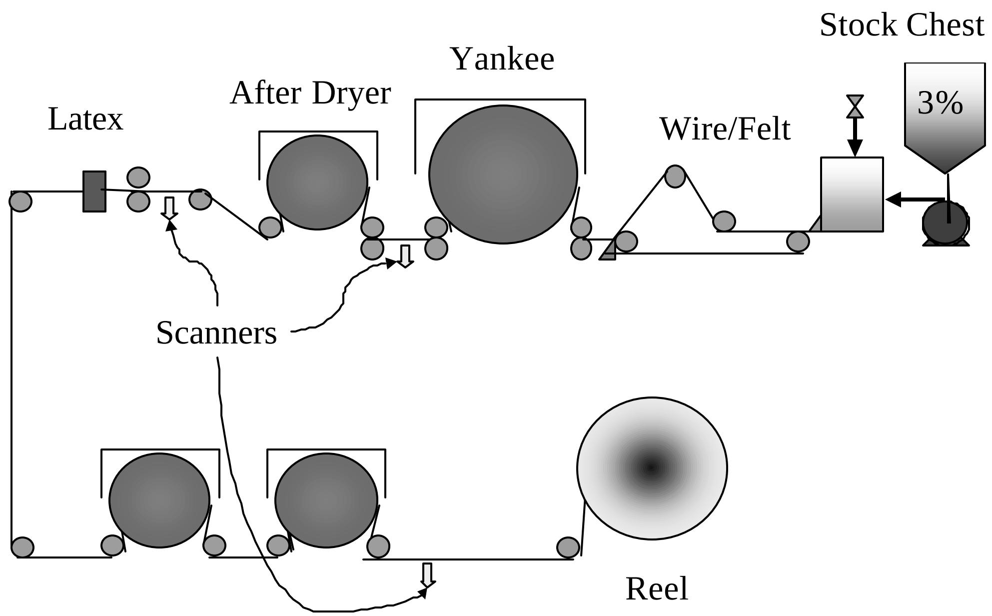


Figure 1. Paper Machine Schematic

Generalities: System ID

- System Identification: Nominal Model and Uncertainty Description
- Control-Oriented ID: Uncertainty description compatible with the controller design method.
- Our choice: Loop-Shaping (available insight, computations) based on sensitivity and complementary sensitivity targets.
- Nominal Model: MISO equation error, yielding a linear estimation model

$$y = N(\theta)[u] + D(\theta)[y] + e = w^T\theta$$

  - Estimated parameters include initial conditions; this is important to handle input-output sets that begin on a transient.

- Left factorization and a coprime factor description of uncertainty:
  - Handling of low frequency perturbations and changes in unstable modes.
  - Indicates required low-frequency sensitivity roll-off (disturbance attenuation)
  - “Easy” computation of target loop properties

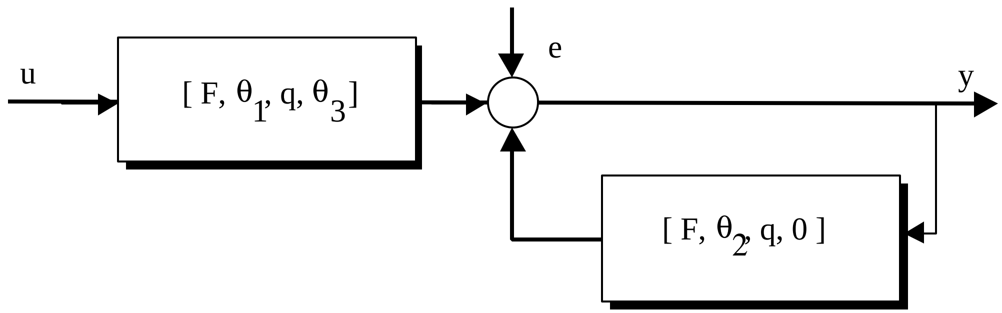


Figure 2. Structure of Parameter Estimator

Generalities: Uncertainty Description

- Error Sources: Plant Input and Plant Output processed by "perturbation" subsystems (uncertainty)
- Uncertainty bound computation and target loop selection: Minimization of a robust stability condition

$$\sigma [U_s C S M^{-1} W_E] \sigma [\Delta_N] + \sigma [Y_s S M^{-1} W_E] \sigma [\Delta_M] < 1$$

- Controller-independent approximations
- Input-output scaling and whitening to handle disparate channel-bandwidths and measurement units.

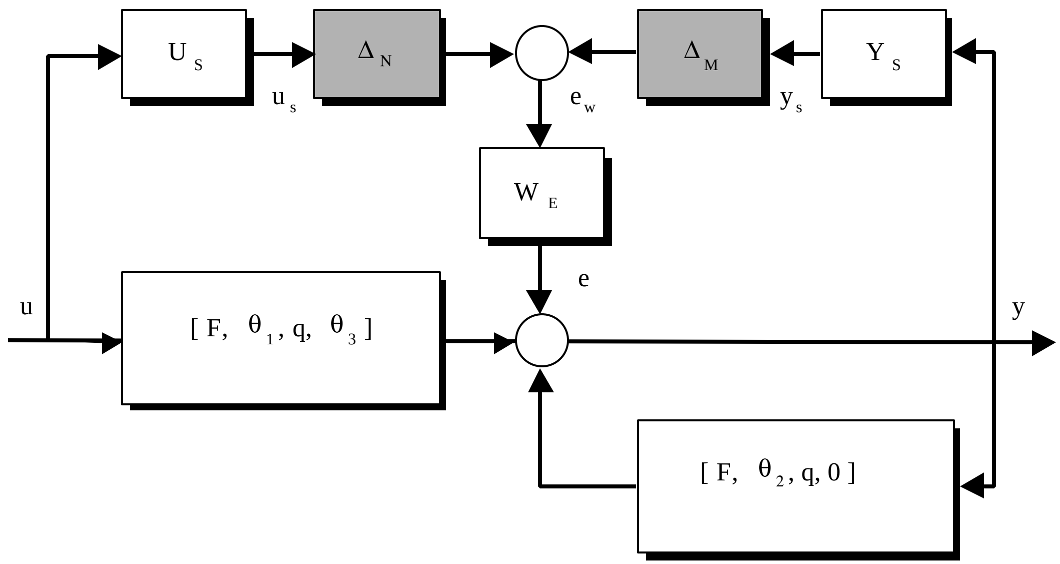


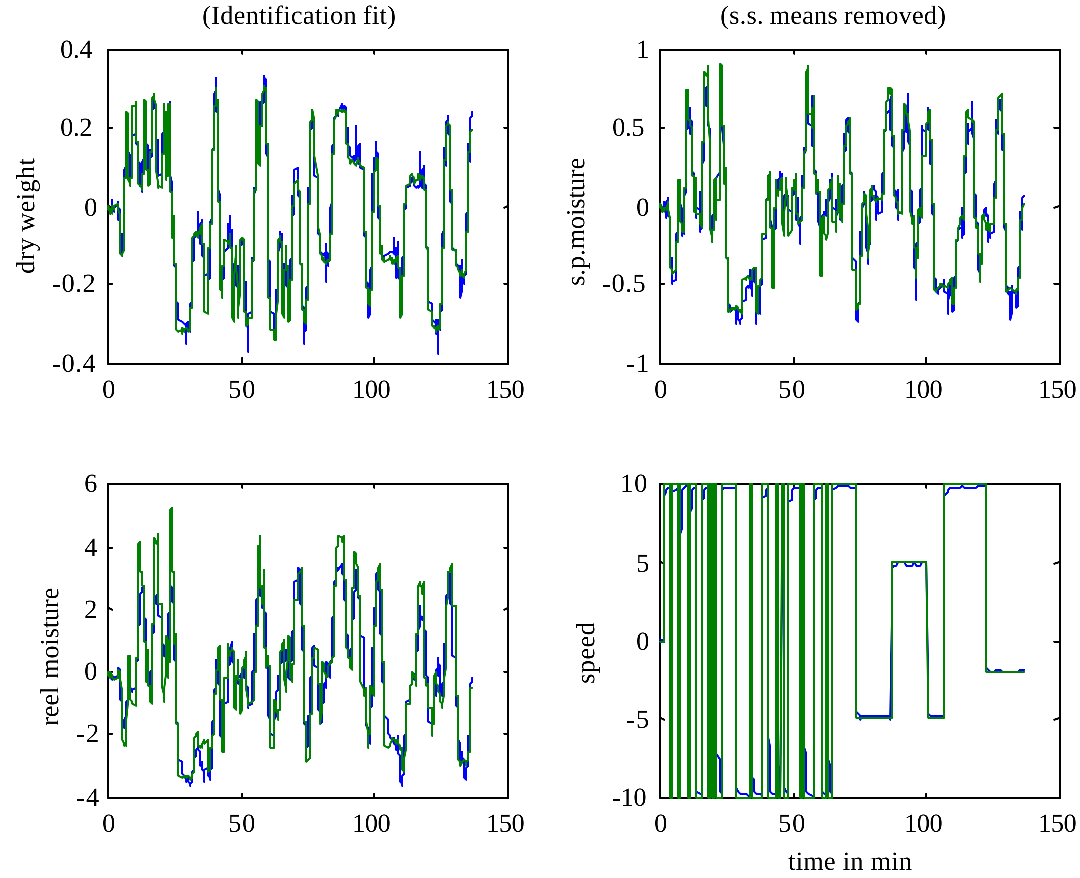
Figure 2. Structure of Identification Uncertainty

Identification 1

- Honeywell's high-fidelity simulator (TDC3000)
- Perform Identification
  - $y = N(\theta)[u] + D(\theta)[y] + e$
- Simulate Id'd system

  clockwise from top left:
  - dry weight
  - size-press moisture
  - reel moisture
  - machine speed
- Nominal plant: $M^{-1}N$,

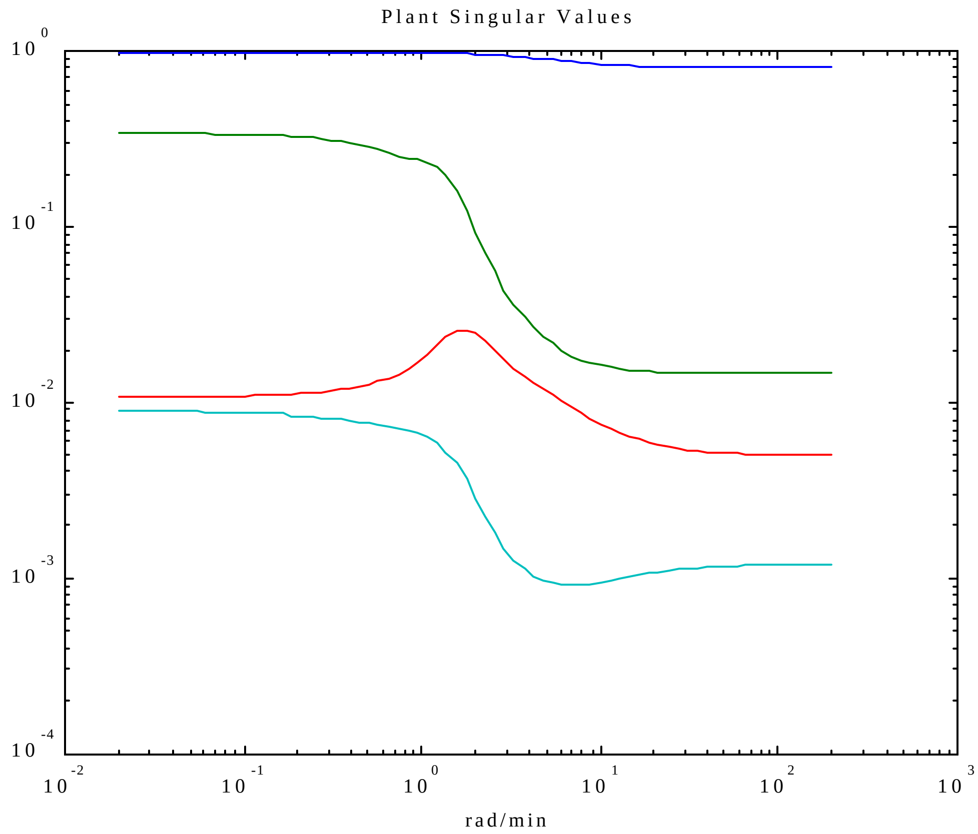
  (M=I-D)



Identification 2

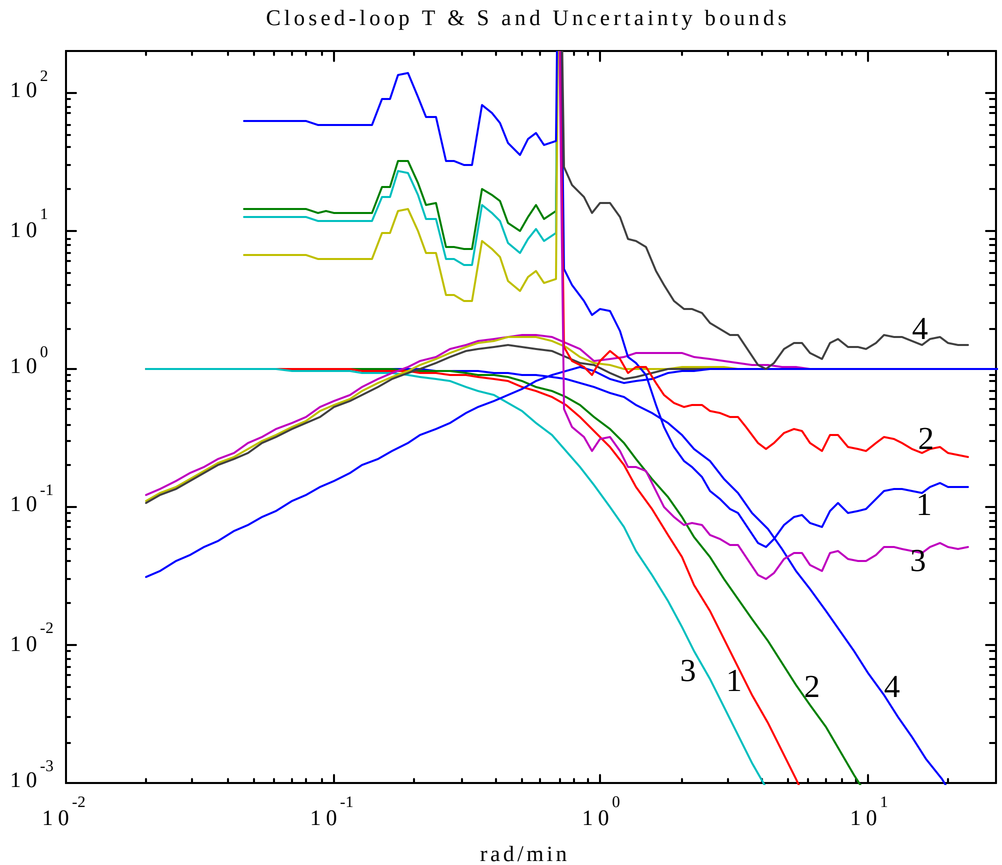
- Identified plant singular values
  - Eigenvalue spread: 0.57 - 5
  - RHP transmission zeros:
    0.95, 2.1, 2.4, 1.7+/-2j, 4.3

- Main interactions
  - Stock flow - moisture
  - Machine speed - moisture and dry weight



Controller Design 1

- Target selection (T & S)
  - approx. per-channel contributions
- Uncertainty constraints (more critical in moisture channels)
- RHP zeros constraints (more critical in dry-weight)
- Final check through robust stability condition
- Achievable specs determined within a few iterations.



Controller Design 2

- Weighted sensitivity minimization (standard software)
- A computational alternative: Glover-McFarlane

$$\min_K \left\| \begin{matrix} KSM^{-1} \\ SM^{-1} \end{matrix} \right\|_{H_\infty}$$

$$M, N = ncf(G)$$

- Plant-Controller augmentation
  - S&T approximate loop-shaping
  - Avoids g-iteration but increases dimensionality
  - Fairly efficient with scalar targets

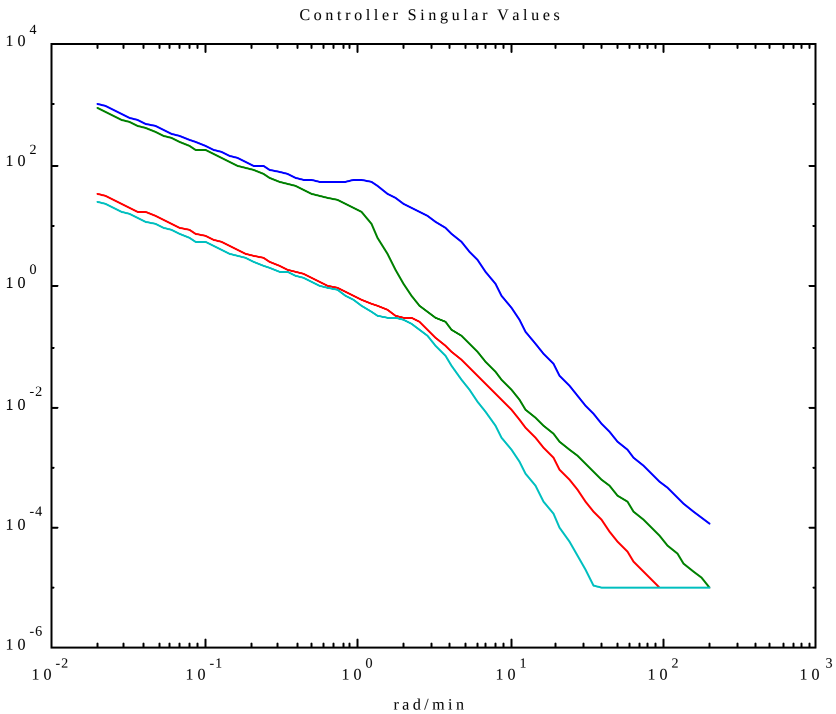
$$\min_K \left\| \begin{matrix} W_T^{-1}\Theta_n^{-1}\Theta_m M_o T M_o^{-1} \\ W_S^{-1} M_o S M_o^{-1} \end{matrix} \right\|_{H_\infty}$$

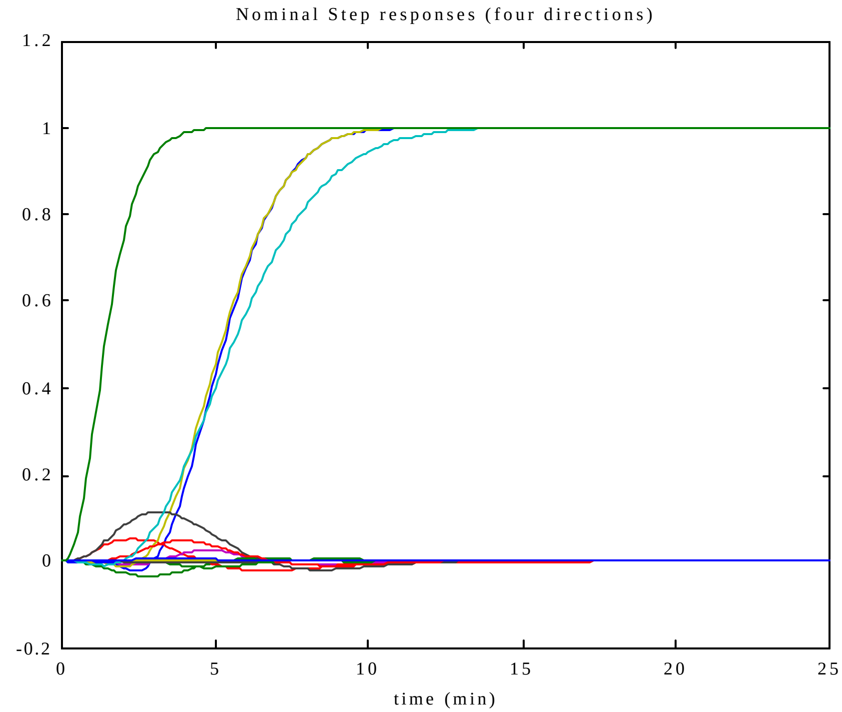
- Other alternatives, 2-DOF compensators (Open)

- Controller Implementation
  - Observers to substitute missing measurements
  - Anti-windup modifications

Controller Design 3

- Controller singular values
  - Reduction to remove unnecessary modes (low/high frequencies)
- Nominal Step responses in four directions.
  - Some coupling between channels remains due to RHP zeros





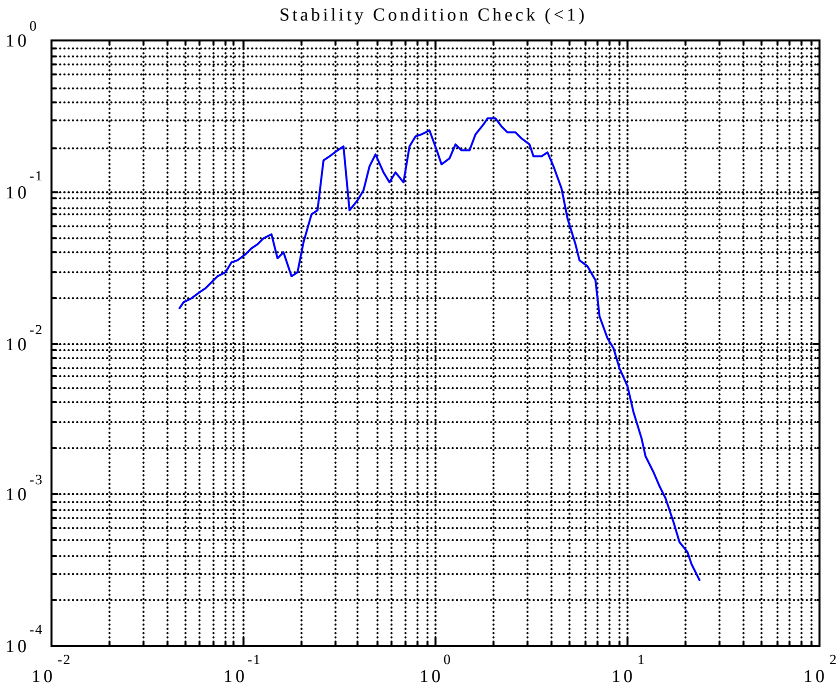
Controller Design 4

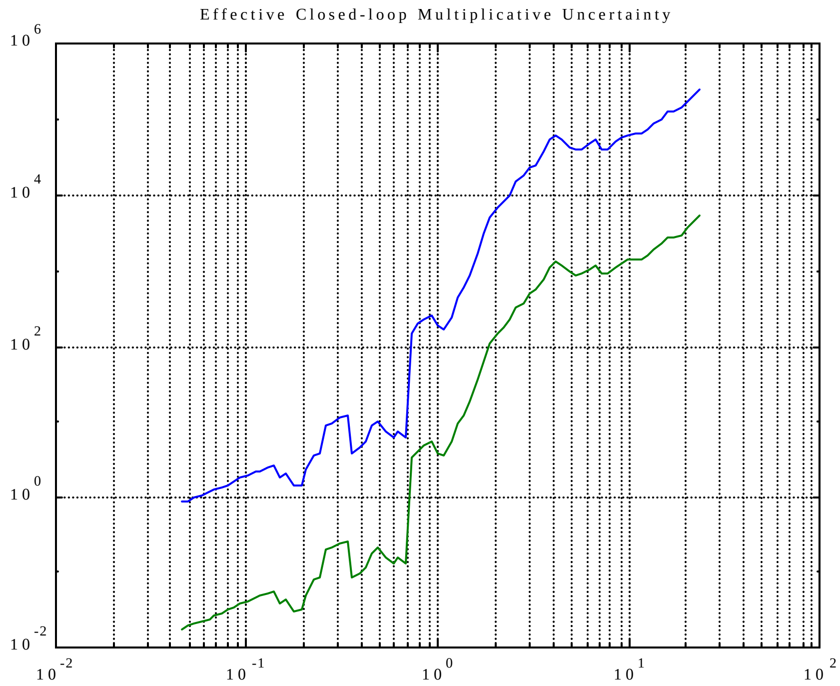
- Robust stability condition
- Tests with different controllers

- Closed-loop confidence: effective mult. uncertainty for scaled and un-scaled output

$$\delta_{CL,e} < \{\sigma[\, S\, M^{-1}\, W_E\,]\, \sigma[\, U_s\, C\, S\,]\, \sigma[\, T^{-1}\,]\, \sigma[\Delta_N] + \sigma[\, Y_s\, S\, M^{-1}\, W_E\,]\, \sigma[\Delta_M]\,\}\ \alpha\ \kappa(Y_s)$$

$$\alpha = (1 - \sigma[\, U_s\, C\, S\, M^{-1}\, W_E\,]\, \sigma[\Delta_N] - \sigma[\, Y_s\, S\, M^{-1}\, W_E\,]\, \sigma[\Delta_M]\,)^{-1};\ \kappa(Y_s) = \sigma(Y_s)\, \sigma(Y_s^{-1})$$

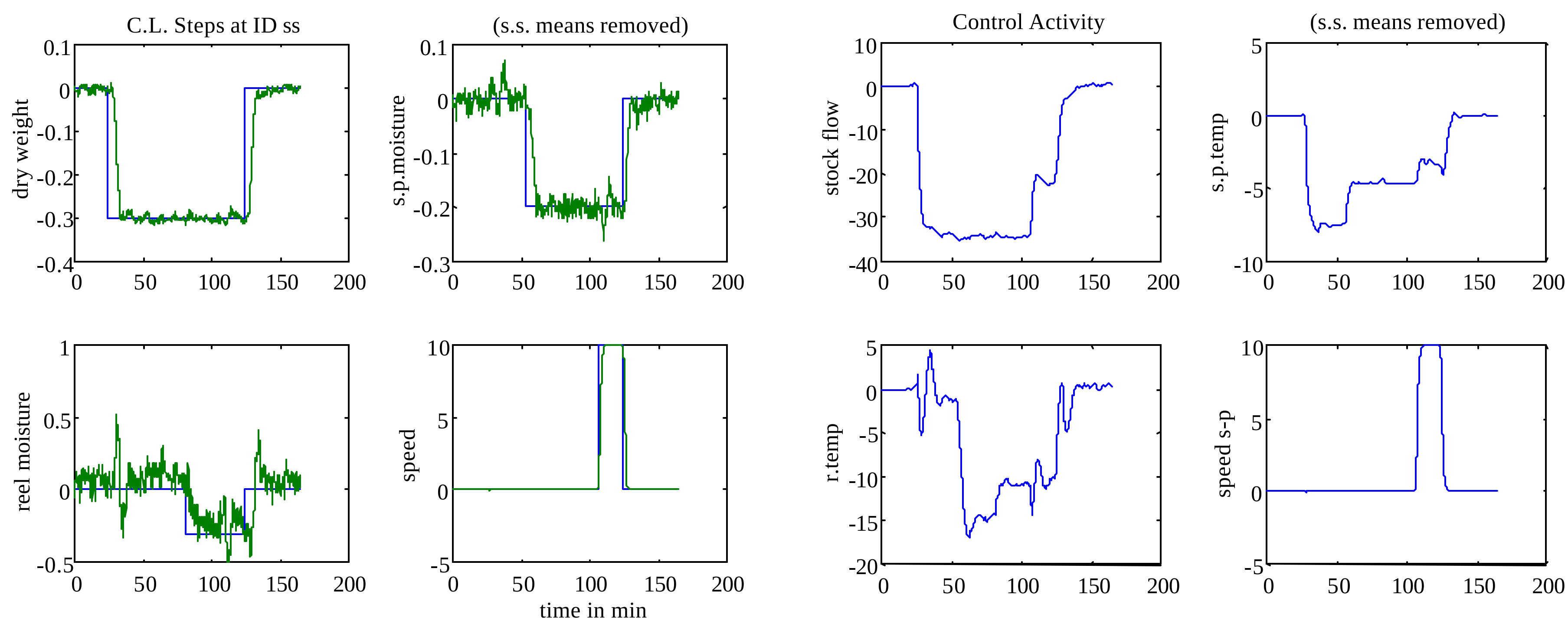




Controller Evaluation 1

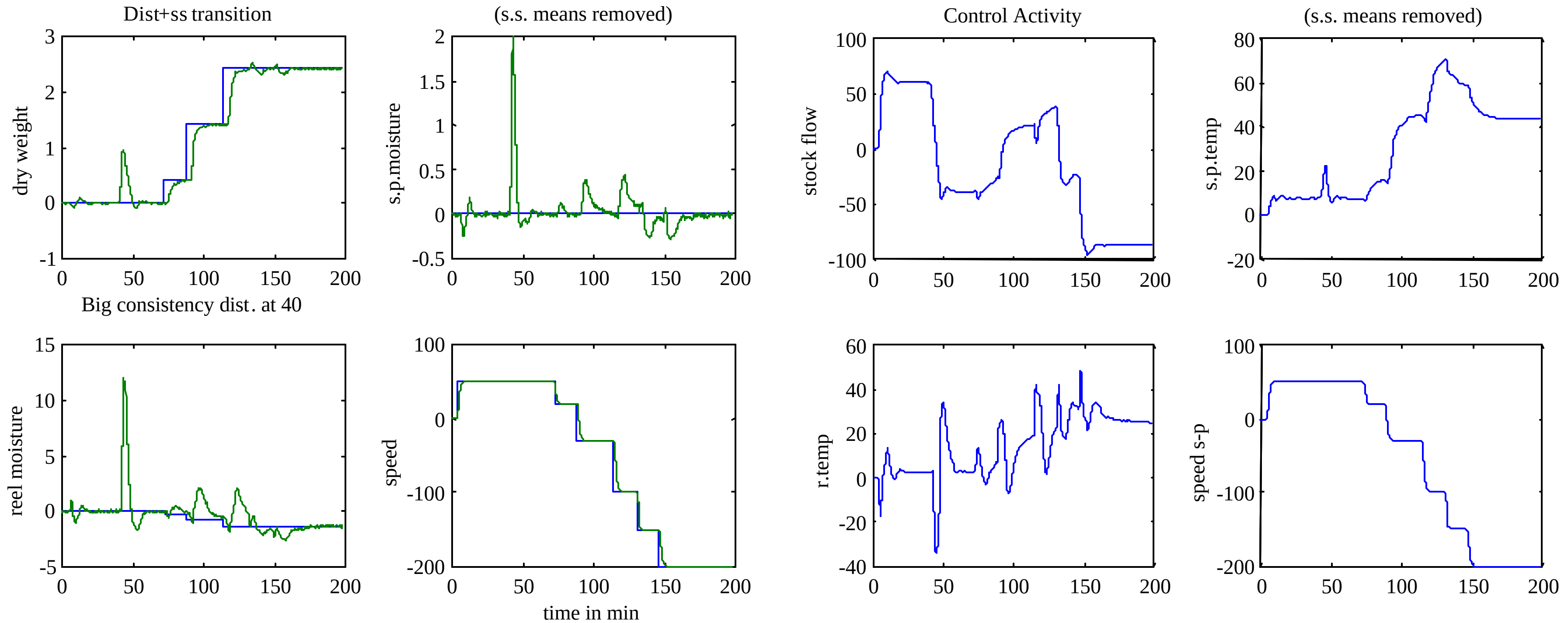
- Step responses at nominal steady-state (identified)
- Reasonably smooth control activity
- Overall behavior assessment: excellent

- Small error definitions:
  - dry weight ~0.1 (lb)
  - moisture ~0.1 - 0.2 (%)
  - higher for reel moisture



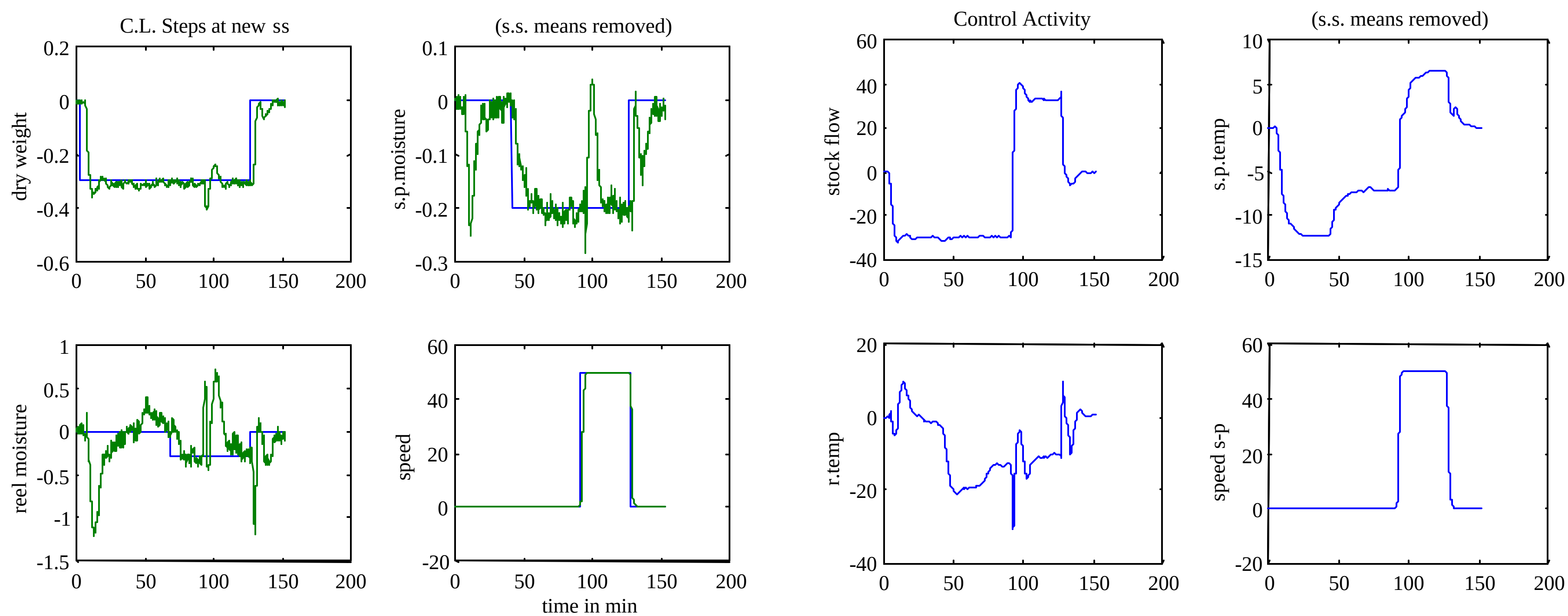
Controller Evaluation 2

- Consistency Disturbance (unreasonably large) at t=40. Quick recovery without excessive errors.
- Steady-state transition to a new operating point under closed-loop control. (Normally done in open loop)
- Overall behavior assessment: excellent



Controller Evaluation 3

- Step responses at new operating condition
- More coupling appears but still within acceptable limits
- Overall behavior assessment: very good



Conclusions

- Approach: "Coprime factor" uncertainty estimation
  - Flexible and reasonable framework (theoretically, computationally)
  - Compatible with established loop-shaping controller design
- Controller Performance
  - Excellent disturbance attenuation properties (sensitivity minimization)
  - Reliability (minimal iterations, work well the first time)
- Controller design
  - Quick design turn-around time
  - Very quick refinements!
  - Fast execution cycle
- Simulation results
  - Full first-principles, Nonlinear, High fidelity, but still a simulator
  - Preliminary results with real plant data support the same conclusions