Temperature Control of Diffusion/CVD Furnaces Using Robust Multivariable Loop-Shaping Techniques

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• Issues:
  – Tight temperature control
  – Quick design turnaround (for retrofitting apps)
Introduction I

- Temperature uniformity, fast stabilization, disturbance attenuation,...
- Quick design, minimal iterations (furnace down-time)
- Low expertise requirements
Introduction II

- **Standard Practice:**
  - Spike PID, Profile table look-up
  - Periodic Profiling, Disturbances, Stabilization, Uniformity

- **Model-based multivariable control**
  - Modeling (nominal+uncertainty)
  - Controller design (loop-shaping)
  - Implementation
  - Multiple operating points
Modeling I

• System Identification

• 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 short input-output sets that begin on a transient.
  - Continuous time model.
  - Regularization of estimates
Modeling II

• **Coprime Factor Description of the Uncertainty**

• Robust Stability Condition: \( \sigma [C S D^{-1}] \sigma [\Delta_N] + \sigma [S D^{-1}] \sigma [\Delta_D] < 1 \)

• CS~P^{-1}T: Relates uncertainty to target loop properties (controller independent).

• **Uncertainty estimate + Target selection: Minimize RSC**

• Effective closed loop uncertainty estimate: (for outer loop design)

\[
\delta_{M,e} < \{ \sigma [S D^{-1}] \sigma [C S] \sigma [T^{-1}] \sigma [\Delta_N] + \sigma [S D^{-1}] \sigma [\Delta_D] \} \alpha
\]

\[
\alpha = (1 - \sigma [C S D^{-1}] \sigma [\Delta_N] + \sigma [S D^{-1}] \sigma [\Delta_D] )^{-1}
\]

**Interpretation:**

\( \Delta_N \Rightarrow \) compl. sensitivity constraints
(high frequencies)

\( \Delta_D \Rightarrow \) sensitivity constraints
(low frequencies)

\[ CDC, \text{December 1999} \]
Modeling III

- **Identification Experiment:**
  - ~20 min test (net time at the operating conditions)
  - Target bandwidth ~5 rad/min

![Graphs showing input and output data](image-url)
Inner Loop (Spike Subsystem) Modeling

- Power to spike temperature. Very high and uncertain low frequency gain. (but good model around the intended crossover)

- “Raw” uncertainty data expressed as inverse S&T bounds ($|\text{fft}(e)|/|\text{fft}(u)|$, $|\text{fft}(e)|/|\text{fft}(y)|$) show asymptotic behavior.
Spike Model Uncertainty

- After the split, the high frequency uncertainty is expressed as an inverse T constraint and the low frequency as an inverse S constraint.

- Rare limitations from RHP zeros
- Small RSC => Confidence in the design
Spike Controller Design

- Target loop $\Rightarrow$ weighted H-infinity sensitivity optimization
- The approach yields excellent matching properties with minimal iterations in the weight selection.
- Simple weights $\Rightarrow$ Automation, Low expertise requirements.
Outer Loop (Profile Subsystem)

- The profile subsystem (spike to profile temperatures) is identified in a similar manner.
- Target loop constraints: profile subsystem uncertainty, nominal inner closed-loop, effective inner closed-loop uncertainty.
- The profile controller is designed for the combined profile/inner-loop system. Typically a straightforward design.
Controller Implementation and Testing

- After reduction, the controller is discretized and augmented with anti-windup mechanisms.
- Excellent and predictable performance in the typical ramp-up/ramp-down operations.
More Results

• “Temperature no longer variable of concern”
  Source: M. Yelverton, et. al., AEC/APC XI, 1999. (AMD)

• Process Results:
  – Decreased cycle time (faster controlled ramps, faster stabilization). Time-to-process reduced by as much as 50%
  – Increased process indices (Cp, Cpk by as much as 250%)
  – Increased tool utilization (no need for profiling)

• >300 controllers in operation

• Semiconductor Intl, Best Product Award, 1988
Controller Scheduling

- Handling multiple operating conditions
- Modeling and controller design at different steady-states
- Scheduling with bumpless transfer techniques
  - In general, models and controllers will have different order; simple interpolation is not enough.
Scheduled Controller Tests

- Higher -but manageable- complexity
  - 3 controllers covering the range 500-1000 deg.C
- Scheduled controller has good performance in the entire range and transfers are fairly smooth

Overshoot due to saturation
Concluding Remarks

- Integrated method to design high-performance temperature controllers
- Quick and reliable designs; low expertise requirements
- Excellent success record
- Controller scheduling to handle wide-range operations
- Future work:
  - Tech-transfer to other processes
  - Nonlinear modeling and uncertainty descriptions