Adaptive/Self-Tuning PID Control by Frequency Loop-Shaping

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Outline

• Problem Description: PID Tuning from Input-Output data
• Frequency Loop Shaping
  – Off-line tuning
  – Target loop selection, 1st-2nd order targets
• Direct Adaptation of the PID parameters
  – Cost functional
  – Regressor generation via filter banks
  – Adaptation
  – Performance Monitoring Implications
• Simulation Results
• Conclusions
Problem Description

• Industrial Applications
  – Large number of PID loops, often poorly tuned
  – Reliability and expediency requirements

• A Variety of PID Tuning Strategies
  – Complete or partial models. (System identification-based vs. crossover properties)
  – Control objectives (Time-Frequency domain)
  – Direct and indirect approaches to adaptation

• Frequency Loop Shaping
  – Accounting for uncertainty, several successful applications
FLS PID Tuning (batch/off-line)

- System ID-modeling from I/O data
- Nominal model & uncertainty bounds
- Control Objective
  - Loop-shaping (sensitivity targets)
  - Disturbance attenuation subject to bandwidth constraints
  - Guide: “Robust Stability Condition”
- On-line version via indirect adaptation
  - Update plant model, re-tune controller
  - Complete solutions can be computationally demanding
  - Simple models => off-line construction of look-up table for the PID gains
Target Loop Selection and FLS PID Tuning

- Typical Targets: \( \frac{\lambda}{s}, \frac{\lambda(s+a)}{s^2}, \frac{\lambda(s+a)}{s(s+\varepsilon)}, \ldots \)
  - Target order depends on open-loop/closed-loop bandwidth ratio (for input disturbance attenuation)
  - Uncertainty constraints and RHP pole-zero limitations
  - More difficult cases via LQ or full-order controller design methods e.g., K=lqr(A,B,Q,R), target: [A,B,K,0]

- FLS Tuning: convex optimization in the frequency domain

\[
\begin{align*}
\min_{\theta_{\text{pid}}} & \| S(GC(\theta_{\text{pid}}) - L) \|_{L_2} \\
\text{s.t.} & \quad \theta_{\text{pid}} \text{ constr.}
\end{align*}
\]

\(
\begin{align*}
\min_{\theta_{\text{pid}}} & \| S(GC(\theta_{\text{pid}}) - L) \|_{L_\infty} \\
\text{s.t.} & \quad \theta_{\text{pid}} \text{ constr.}
\end{align*}
\)

- L=loop gain, S=sensitivity, T=complementary sensitivity
Direct Adaptation with an FLS objective

- Construction of the estimation error (at the plant input)

\[ e_e = S(CG - L)[u] = SC[y] - T[u] \]

\[ \|S(CG - L)\|_{L_\infty} = \sup_{u \neq 0} \frac{\|e_e\|_2}{\|u\|_2} \]

- Approximate sup by using a filter bank

\[ \|S(CG - L)\|_{L_\infty} \equiv \max_i \frac{\|SCF_i[y] - TF_i[u]\|_2}{\|F_i[u]\|_2} \leq \max_i \frac{\|SCF_i[y] - TF_i[u]\|_{2,\delta}}{\|F_i[u]\|_{2,\delta}} \]

- \( F_i \): band-pass filters, \( \|.\|_{2,\delta} \): exponentially weighted 2-norm
Direct Adaptation with an FLS objective (cont.)

- Optimization problem

\[
\min_{\theta \in \mathcal{M}} \max_i \frac{J_{i,k}(\theta)}{m_{i,k}}
\]

\[
J_{i,k}(\theta_k) = \sum_{n=0}^{k} \lambda^{k-n} \left| z_{i,n} - w_{i,n}^T \theta_k \right|^2
\]

\[
m_{i,k} = \lambda m_{i,k-1} + \left| F_i[u]_k \right|^2
\]

\[
z_{i,k} = TF_i[u]_k , \quad w_{i,k} = SC_\theta F_i[y]_k
\]

- Recursive computation of \( J_{i,k} \)
- Optimization: min-max of quadratics
Direct Adaptation details

- Recursive computation of $J_{i,k}$

$$J_{i,k+1}(\theta) = \hat{J}_{i,k+1} - S_{i,k+1}^T(\theta - \theta_k) + \frac{1}{2}(\theta - \theta_k)^T P_{i,k+1}(\theta - \theta_k)$$

$$\hat{J}_{i,k+1} = \lambda J_{i,k}(\theta_k) + |z_{i,k+1} - w_{i,k+1}^T \theta_k|^2$$

$$P_{i,k+1} = \lambda P_{i,k} + 2w_{i,k}w_{i,k}^T, \quad S_{i,k+1} = R_{i,k+1} - P_{i,k+1} \theta_k, \quad R_{i,k+1} = \lambda R_{i,k} + 2z_{i,k}w_{i,k}^T$$

- Each $J_{i,k+1}$ is quadratic in the parameters: minimize the maximum by, e.g., computing a descent direction and performing a line search
Adaptive FLS Properties

- Excitation requirements
- Effects of disturbances and unmodeled dynamics (SNR)
- A dead-zone condition: update when

\[ S_{i,k}^T P_{i,k}^{-1} S_{i,k} - 2d_0^2 m_k > 0 \]

- Update when the error operator gain drops by at least \( d_0 \)
- Input Saturation does not affect updates
- Linearization offsets (estimation or high-pass filtering)
- The cost functional provides a measure of tuning confidence
  - Feasibility of performance monitoring
Example

- Simulation Results for the following plant and target loop:
  \[ G(s) = \frac{1}{(s + 1)^3}, \quad L(s) = \frac{1}{s} \]

- Square-wave reference input.
  - Excitation injected at the plant input for t<75.

- PID gains converge approximately to the off-line tuning.

- Cost functional has a maximum of 0.3^2, same as the off-line fitting error.
Simulation Results

- Left: Parameters, output, reference, excitation.
- Right: Square-root of cost functional.
Conclusions

- Direct adaptation of PID parameters with an FLS objective
  - FLS: Operator gain interpretation of fitting error
- Recursive implementation for on-line tuning
- Use of a filter bank to approximate the min-max objective
- Quantitative measures of tuning confidence
  - Gain of the error system

Future work:
- On-line monitoring of performance
- On-line adaptation of objective (target loop) based on the cost functional values