Advances in PID Control

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Introduction

- Awareness of PID and need for automatic tuning:
  - KJs Telemetric Experience 79-80, Westrenius
  - Euroterm and Mike Sommerville
- The idea - Automatic generation of good input signals
- The patents Tore+KJ: Sweden 83, USA 85, ...
- Commercial exploitation
  - NAF Control, Sune Larsson, Ideon: Tore, Båth, SDM 20 (84), ECA 40 (86)
  - Ahlsell, Alfa Laval Automation, Satt Control, ABB
  - Fisher Controls, Advisory board 88-92, board of directors 90-92. Fisher Controls + Rosemount $\Rightarrow$ Emerson
- Product development - From 2kbytes to Mbytes
  - Gain scheduling, continuous adaptation
  - Research: papers, MS, Lic & PhD
- Research Goals

  Understand PID control and its use
  How good models are required?
  How to find tuning rules - computation dependent
- This lecture: What have we learned?

Tore – 40 Years of Collaboration

- Phd student 1978, PhD 1983; New Estimation Techniques for Adaptive Control
- Relay auto-tuning - patent 1983
- NAF 1985-89
- Back to the department at LTH 1999
- PID control

Recent PhD Students

- Kristian Soltesz 2013 On automation in Anesthesia
- Vanessa Romero 2014 CPU Resource Management and Noise Filtering for PID Control
- Olof Garpinger 2015 Analysis and Design of Software-Based Optimal PID Controllers
- Martin Hast 2015 Design of Low-Order Controllers using Optimization Techniques
- Josefin Berner 2017 Automatic Controller Tuning using Relay-based Model Identification
- Fredrik Bagge Carlson 201X Side projects: Optimization Julia programming






The Magic of Feedback

Feedback has some amazing properties, it can

- make good systems from bad components,
- make a system insensitive to disturbances and component variations,
- stabilize an unstable system,
- create desired behavior, for example linear behavior from nonlinear components.

The major drawbacks are that

- feedback can cause instabilities
- sensor noise is fed into the system

PID control is a simple way to enjoy the Magic!

The Amazing Property of Integral Action

Consider a PI controller

$$u = ke + k_i \int_0^t e(\tau)d\tau$$

Assume that all signals converge to constant values $e(t) \to e_0$, $u(t) \to u_0$ and that $\int_0^t (e(\tau) - e_0)d\tau$ converges, then e_0 must be zero.
Proof: Assume $e_0 \neq 0$, then

$$u(t) = ke_0 + k_i \int_0^t e(\tau)d\tau = ke_0 + k_i \int_0^t \big(e(\tau) - e_0\big)d\tau + k_i e_0 t$$

The left hand side converges to a constant and the left hand side does not converge to a constant unless $e_0 = 0$, furthermore

$$u(\infty) = k_i \int_0^\infty \big(e(\tau) - e_0\big)d\tau$$

A controller with integral action will always give the correct steady state provided that a steady state exists. Sometimes expressed as it *adapts* to changing disturbances.

Predictions about PID Control

- 1982: The ASEA Novatune Team 1982 (Novatune is a useful general digital control law with adaptation):

  PID Control will soon be obsolete
- 1989: Conference on Model Predictive Control:

  Using a PI controller is like driving a car only looking at the rear view mirror: It will soon be replaced by Model Predictive Control.
- 2002: Desborough and Miller (Honeywell):

  Based on a survey of over 11 000 controllers in the refining, chemicals and pulp and paper industries, 98% of regulatory controllers utilise PID feedback. The importance of PID controllers has not decreased with the adoption of advanced control, because advanced controllers act by changing the setpoints of PID controllers in a lower regulatory layer.The performance of the system depends critically on the behavior of the PID controllers.
- 2016: Sun Li

  A recent investigation of 100 boiler-turbine units in the Guangdong Province in China showed 94.4% PI, 3.7% PID and 1.9% advanced controllers

Entech Experience & Protuner Experiences

Bill Bialkowsk Entech - Canadian consulting company for pulp and paper industry *Average paper mill has 3000-5000 loops, 97% use PI the remaining 3% are PID, MPC, adaptive etc.*

- 50% works well, 25% ineffective, 25% dysfunctional

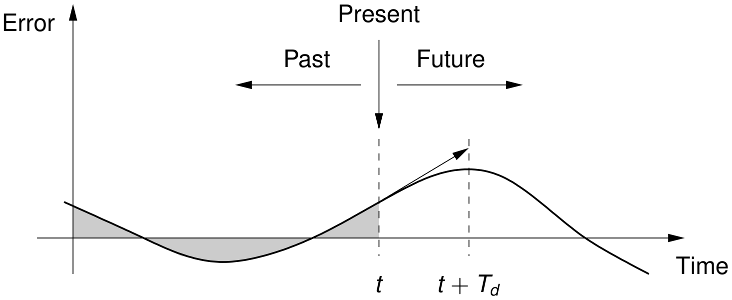
Major reasons why they don't work well

- Poor system design 20%
- Problems with valve, positioners, actuators 30%
- Bad tuning 30%

Process Performance is not as good as you think. D. Ender, Control Engineering 1993.

- More than 30% of installed controllers operate in manual
- More than 30% of the loops increase short term variability
- About 25% of the loops use default settings
- About 30% of the loops have equipment problems

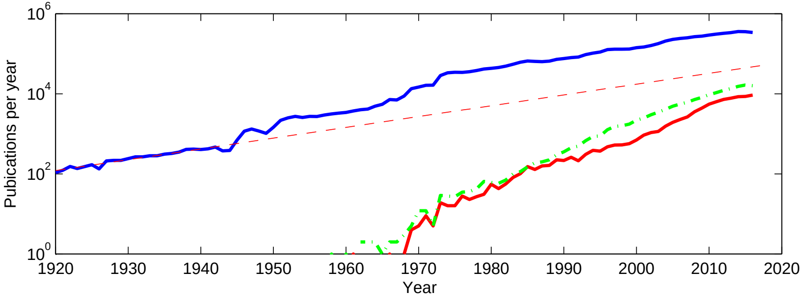
PID versus More Advanced Controllers



$$u(t) = k_p\big(\beta y_{sp}(t) - y_f(t)\big) + k_i \int_0^t \big(y_{sp}(\tau) - y_f(\tau)\big)\,d\tau + k_d\Big(\gamma \frac{dy_{sp}}{dt} - \frac{dy_f}{dt}\Big)$$

- PI does not predict
- PID predicts by linear extrapolation, T_d prediction horizon
- Advanced controllers predict using a mathematical model

Publications in Scopus

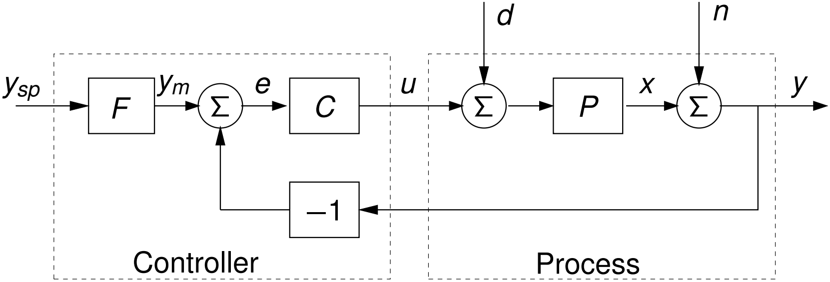


Number of publications by year for control (blue), PID (red) and model predictive control (green) from Scopus search for the words in title, abstract and keywords.

Outline

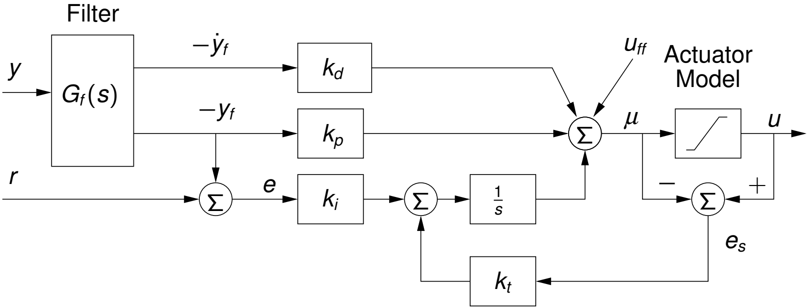
1. Introduction
2. Requirements
3. Tradeoffs
4. PI Control
5. PID Control
6. Relay Auto-tuners
7. Summary

Requirements



- Attenuate load disturbances d
- Do not inject too much measurement noise n
- Robustness to model uncertainty
- Setpoint response - Can be dealt with separately by feedforward F – (2 DOF, setpoint weighting, I-PD)

I–PD Controller with filtering and antiwindup



The filter (can be combined with antialias filter)

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -T_f^{-2} & -T_f^{-1} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ T_f^{-2} \end{bmatrix} y,$$

has the states $x_1 = y_f$ and $x_2 = dy_f/dt$. The filter thus gives filtered versions of the measured signal and its derivative. The second-order filter also provides good high-frequency roll-off.

Tune for Load Disturbances - Shinskey 1993

"The user should not test the loop using set-point changes if the set point is to remain constant most of the time. To tune for fast recovery from load changes, a load disturbance should be simulated by stepping the controller output in manual, and then transferring to auto. For lag-dominant processes, the two responses are markedly different."

Process control: Tune k_p, k_i, k_d and T_f for load disturbances, measurement noise and robustness, then tune β, and γ for setpoint response.

$$u(t) = k_p\big(\beta r(t) - y_f(t)\big) + k_i \int_0^t \big(r(\tau) - y_f(\tau)\big)d\tau + k_d\Big(\gamma \frac{dr}{dt} - \frac{dy_f}{dt}\Big)$$

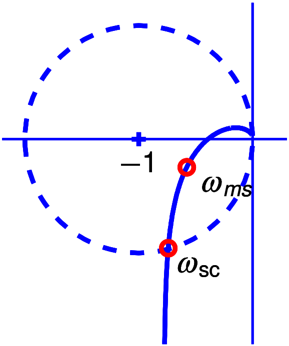
$$Y_f(s) = \frac{1}{1 + sT_f + s^2 T_f{}^2/2} Y(s)$$

Assessment of Disturbance Reduction

Compare open and closed loop systems!

$$\frac{Y_{cl}}{Y_{ol}} = \frac{1}{1+PC} = S$$

Geometric interpretation: Disturbances with frequencies outside are reduced. Disturbances with frequencies inside the circle are amplified by feedback, the maximum amplification is M_s.
Disturbances with frequencies less than sensitivity crossover frequency ω_{sc} are reduced by feedback.

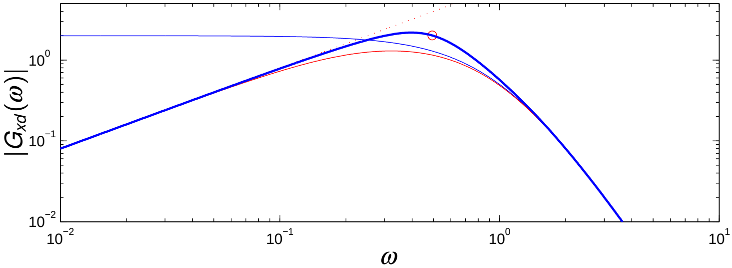


Load Disturbance Attenuation

Transfer function from load disturbance d to process outpur y ($P(0) = K$)

$$G_{yd} = \frac{P}{1+PC} = SP \approx \frac{sP(s)}{s+Kki} \approx \frac{s}{s+Kki} \times K \approx \frac{s}{k_i}$$

$$P = 2(s+1)^{-4} \text{ PI: } k_p = 0.5,\ k_i = 0.25$$



Criteria and FOTD Model

Traditionally the criteria

$$IE = \int_0^\infty e(t)dt, \qquad IAE = \int_0^\infty |e(t)|dt, \qquad IE2 = \int_0^\infty e^2(t)dt$$

$$ITAE = \int_0^\infty t\,|e(t)|dt, \qquad QE = \int_0^\infty (e^2(t) + \rho u^2(t))dt$$

Notice that for a step u_0 in the load disturbance we have

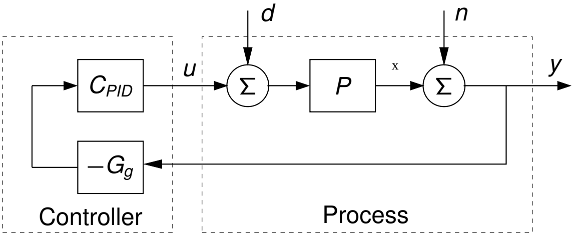
$$u(\infty) = k_i \int_0^\infty e(t)dt, \qquad IE = \frac{1}{k_i}$$

The FOTD model

$$P(s) = \frac{K}{1+sT}e^{-sL}, \qquad \tau = \frac{L}{L+T}, \qquad 0 \le \tau \le 1$$

Lag dominant τ small ($\tau < 0.3$) and delay dominant dynamics τ close to 1

Measurement Noise Injection



Controller transfer function

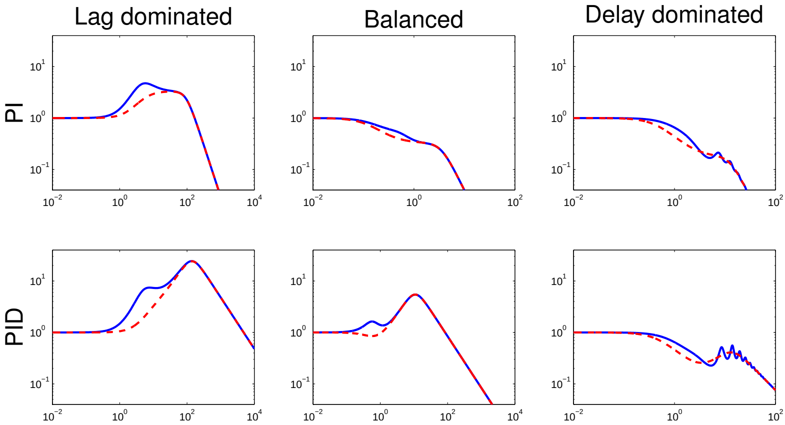
$$G_f = \frac{1}{1 + sT_f + s^2T_f^2/2} \qquad C_{PID}(s) = k_p + \frac{k_i}{s} + k_d s, \qquad C = C_{PID}G_f$$

Transfer function from measurement noise n to control signal u

$$-G_{un}(s) = -\frac{C}{1+PC} = -SC \approx -\frac{s}{s+Kk_i} \times \frac{k_i + k_p s + k_d s^2}{s(1 + sT_f + (sT_f)^2/2)}$$

Only controller parameters and $K = P(0)$

Bode Plots of Noise Transfer Function G_{un}



- Validity of approximation (error in mid frequency range M_s peak)
- Differences PI/PID lag dominated/delay dominated

Stochastic Modeling of Measurement Noise

Measurement noise stationary with spectral density $\Phi(\omega)$

$$\sigma_u^2 = \int_{-\infty}^{\infty} |G_{un}(i\omega)|^2 \Phi(\omega) d\omega, \quad \sigma_{y_f}^2 = \int_{-\infty}^{\infty} |G_f(i\omega)|^2 \Phi(\omega) d\omega$$

$$G_{un}(s) \approx -\frac{k_i + k_p s + k_d s^2}{(s + Kk_i)(1 + sT_f + (sT_f)^2/2)}$$

$$\sigma_u^2 \approx \pi \left(\frac{k_i}{K} + \frac{k_p^2 - 2k_i k_d}{T_f} + 2\frac{k_d^2}{T_f^3} \right) \Phi_0, \quad \sigma_{y_f}^2 = \frac{\pi}{T_f} \Phi_0$$

Noise gain $k_n = \sigma_u / \sigma_{y_f}$ and SDU (standard deviation of u with white measurement noise $\Phi_0 = 1$)

$$k_{nw} = \frac{\sigma_u}{\sigma_{y_f}} \approx \sqrt{\frac{k_i T_f}{K} + k_p^2 - 2k_i k_d + 2\frac{k_d^2}{T_f^2}}$$

$$\pi\Phi_0 = 1 \Rightarrow SDU = \sqrt{\left(\frac{k_i}{K} + \frac{k_p^2 - 2k_i k_d}{T_f} + 2\frac{k_d^2}{T_f^3} \right)}$$

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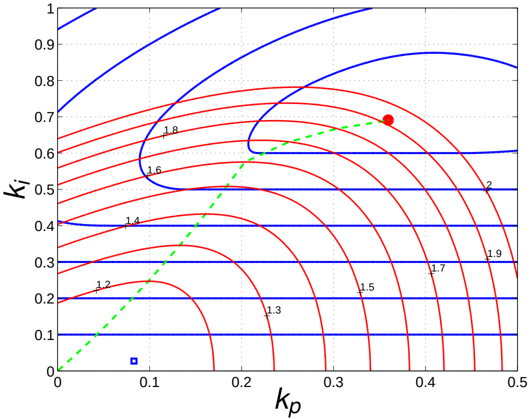
Load Disturbance Attenuation and Robustness

- Performance (IAE$= 1/k_i$ blue) and robustness (M_s, M_t red)
- IE level curves are horizontal lines ($P(s) = (s+1)^{-4}$



Little difference IE and IAE for $k_i < 0.4$ and robust systems $M_s < 1.6$
Approximately: k_i gives performance and k_p sets robustness

Load Disturbance Attenuation and Noise Injection

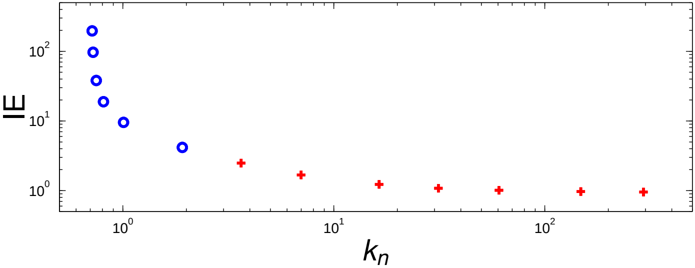
Process: $P(s) = \dfrac{1}{1+0.1s}e^{-s}$ $\tau = 0.09$ lag dominated!

Controller: $C = \left(k_p + \dfrac{k_i}{s} + k_d s\right) \times \dfrac{1}{1 + sT_f + (sT_f)^2/2}$

MIGO design without filtering: $k_p = 2.78$, $T_i = 47.2$, $T_d = 11.6$

Filter time constants:

$T_f = [0.01\ 0.02\ 0.05\ 0.1\ 0.2\ 0.5\ 1\ 2\ 5\ 10\ 20\ 50\ 100]$



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Design Process

Models - Essentially monotone step responses

Ziegler-Nichols - Two parameters

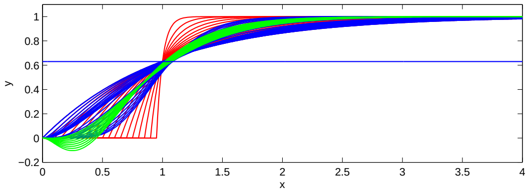
The FOTD model - Three parameters K, L, T

- $G(s) = \frac{K}{1+sT} e^{-sL}$
- Normalized time delay $\tau = \frac{L}{L+T}, 0 \leq \tau \leq 1$
- Lag (small τ) and delay dominated dynamics τ close to one

More complex models

The test batch - essentially monotone dynamics

- Heritage of Eurotherm and Mike Sommerville
- 123 processes



Design controllers and match to model parameters

Constrained Optimization

- Modeling & control design
- Criteria

  Load disturbance
  attenuation IE, IAE
  Robustness M_s M_t
  Measurement noise SDU
  Noise gain k_n

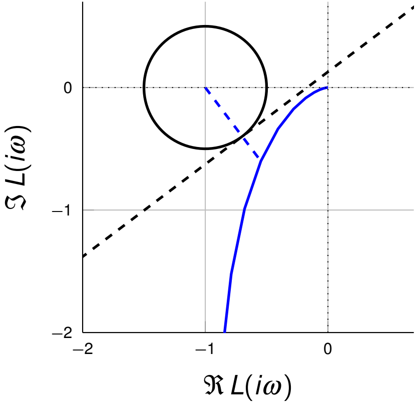
- Loop transfer function

$$G_l = PG_f\left(k_p + \frac{k_i}{s} + k_d s\right)$$

linear in parameters

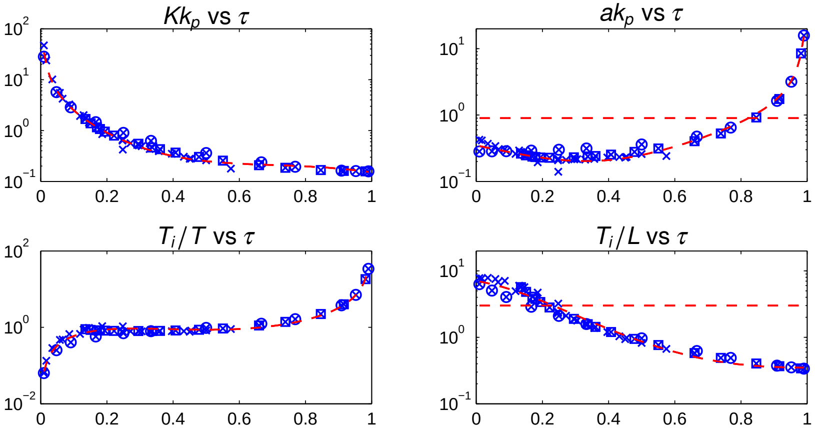
- Many algorithms

Convex-concave methods



github.com/JuliaControl/ControlSystems.jl/

PI Control: Minimize IAE, $M_s, M_t \leq 1.4$



- The two parameter Ziegler-Nichols does not work (red dashed right figures)!
- Tuning of PI controller can be done with a three parameter FOTD model model

Some Tuning Rules

- Ziegler-Nichols step

$$k_p = \frac{0.9}{K_v L}, \qquad k_i = \frac{0.27}{K_v L^3}, \qquad T_i = L/0.3$$

- Ziegler-Nichols frequency

$$k_p = 0.45 k_u, \qquad k_i = 0.54 \frac{k_u}{T_u}, \qquad T_i = T_u/1.2$$

- Lambda Tuning - $T_{cl} = T, 2T, 3T$

$$k_p = \frac{T}{K(T_{cl} + L)}, \qquad k_i = \frac{1}{K(T_{cl} + L)}, \qquad T_i = T$$

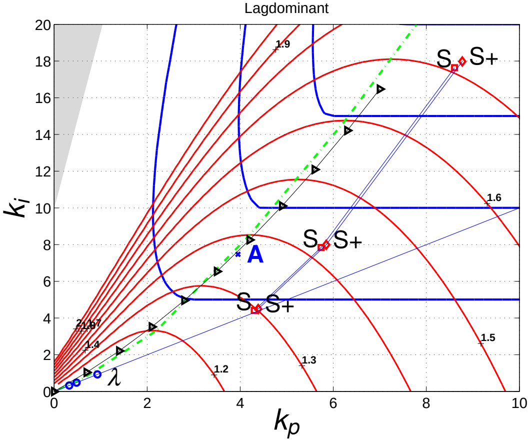
- Skogestad SIMC Like Lambda but $T_i = min(T, 4(T_{cl} + L))$
- Skogestad SIMC+

$$k_p = \frac{T + L/3}{K(T_{cl} + L)}, \qquad T_i = min(T + L/3, 4(T_{cl} + L))$$

- AMIG0 ($M_s, M_t = 1.4$)

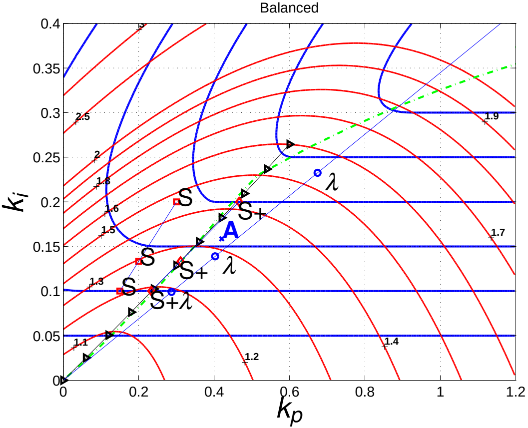
$$k_p = \frac{0.15}{K} + \left(0.35 - \frac{LT}{(L+T)^2}\right)\frac{T}{KL}, \qquad T_i = 0.35L + \frac{13LT^2}{T^2 + 12LT + 7L^2}$$

Tuning – Lag-Dominated Dynamics



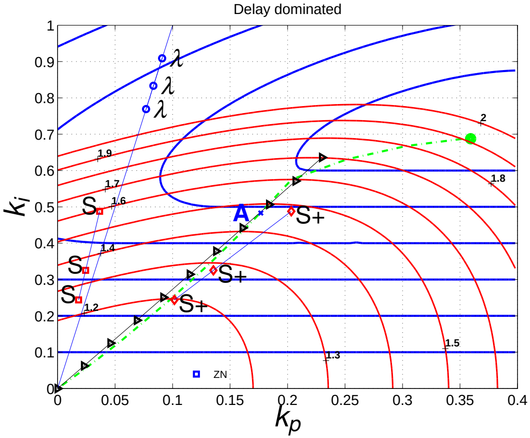
- Lambda tuning has very low gains
- S and S+ give similar tuning
- Lambda tuning gives constant integral time $T_i = k_p/k_i$

Tuning – Balanced Dynamics



- Tuning methods S+, A and λ gives similar results
- All controllers have constant integral time $T_i = k_p/k_i$

Tuning Delay-Dominated Dynamics

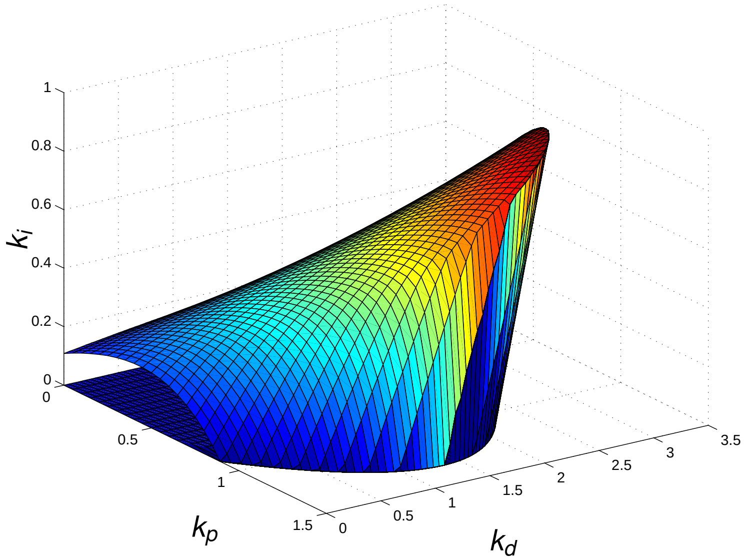


- Lambda tuning too high integral gain
- Obvious why Skogestad modified his method
- All controllers have constant integral time $T_i = k_p / k_i$

Outline

Difficulties with Derivative Action

- Shapes of stability region - don't fall off the cliff



- Filtering necessary

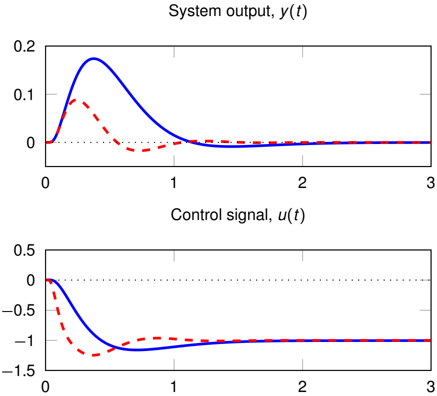
Temperature Control $P(s) = e^{-\sqrt{s}}$

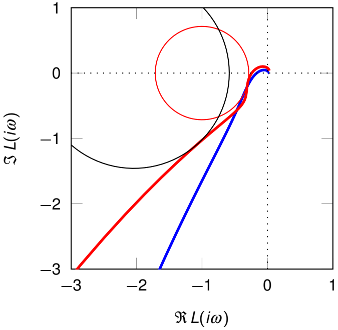
$$C_{\mathrm{PI}}(s) = 2.94 + \frac{11.54}{s}$$

$\mathrm{IE} = 0.086$, $\mathrm{IAE} = 0.10$

$$C_{\mathrm{PID}}(s) = 7.40 + \frac{48.25}{s} + 0.46s$$

$\mathrm{IE} = 0.021$, $\mathrm{IAE} = 0.031$





IE or IAE for $P = (s+1)^{-3}$

$$C_{IE} = 3.31 + \frac{6.62}{s} + 6.26s$$

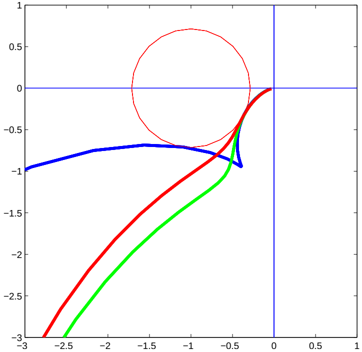
$$IAE = 0.74$$

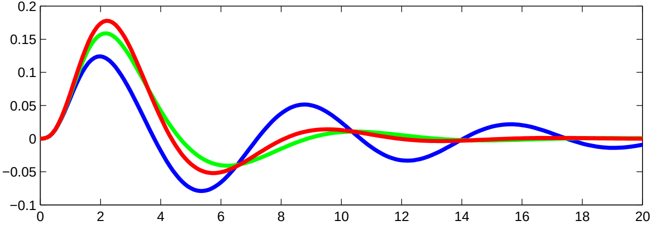
$$C_{\kappa} = 3.61 + \frac{3.20}{s} + 3.34s$$

$$IAE = 0.57$$

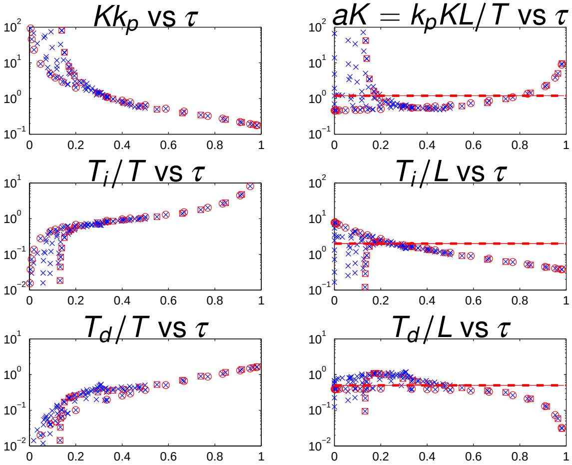
$$C_{IAE} = 3.81 + \frac{3.33}{s} + 4.25s$$

$$IAE = 0.53$$





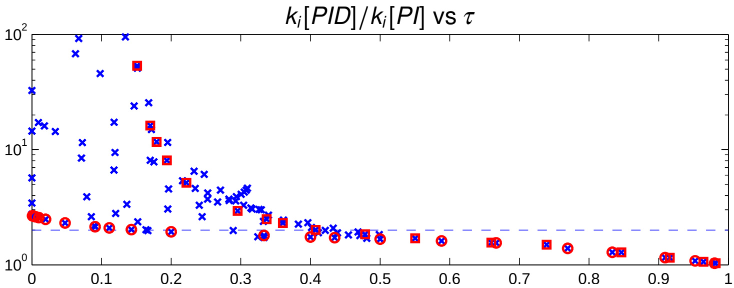
PID Control: Minimize IAE, $M_s, M_t \leq 1.4$



- Tuning rules based on FOTD can be found for $\tau > 0.3$
- More complex models for lag dominated dynamics
- Limiting cases $\frac{K}{1+sT}e^{-sL}$ and $\frac{K}{(1+sT/2)^2}e^{-sL}$

Modeling for PI & PID Control

AMIGO Tuning - complete testbatch

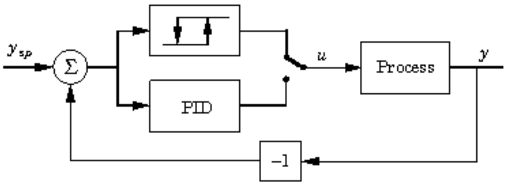


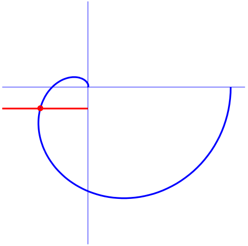
$$\text{circles: } P(s) = \frac{K}{1+sT}e^{-sL}, \quad \text{squares: } P(s) = \frac{K}{(1+sT)^2}e^{-sL}$$

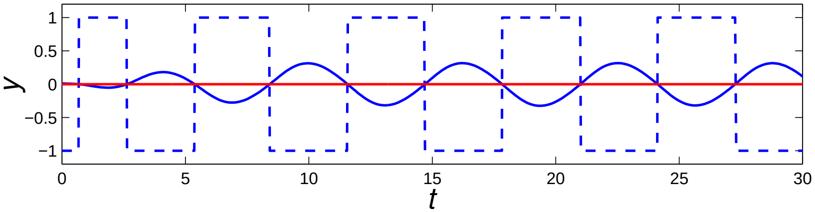
- FOTD OK for $\tau > 0.4$ better model required for smaller τ!
- Derivative action small improvement for $\tau > 0.8$

Outline

Relay Auto-tuning





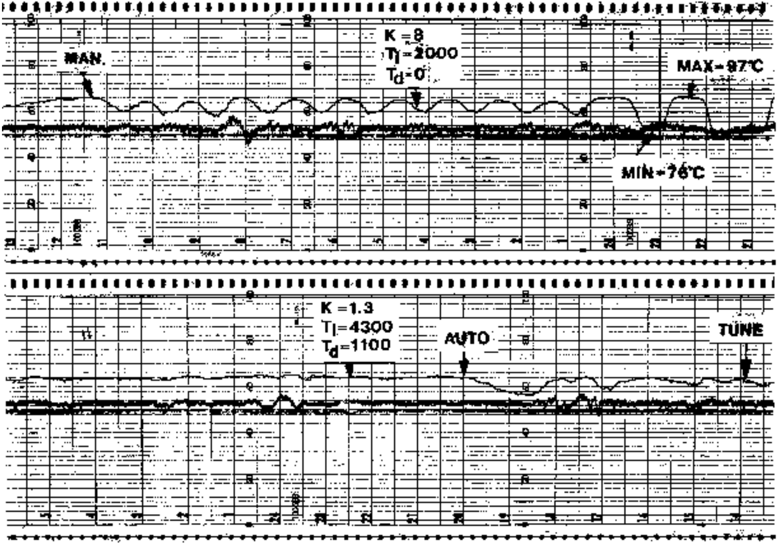


Relay feedback creats oscillation at ω_{180}!

Automation of ZN frequency response method modified ZN tuning rules

The First Industrial Test 1982

Temperature Control of Distillation Column



Commercial Autotuners

- One-button autotuning
- Three settings: fast, slow, delay dominated
- Automatic generation of gain schedules
- Adaptation of feedback gains
- Adaptation of feedforward gain
- Many versions

  Single loop controllers
  DCS systems
- Robust
- Excellent industrial experience
- Large numbers

Industrial Systems

Functions

- Automatic tuning AT
- Automatic generation of gain scheduling GC
- Adaptive feedback AFB and adaptive feedforward AFF

Sample of products

- NAF Controls SDM 20 - 1984 DCS AT, GS
- SattControl ECA 40 - 1986 SLC AT, GS
- Satt Control ECA 04 - 1988 SLC AT
- Alfa Laval Automation Alert 50 - 1988 DCS AT, GS
- Satt Control SattCon31 - 1988 PLC AT, GS
- Satt Control ECA 400 -1988 2LC AT, GS, AFB, AFF
- Fisher Control DPR 900 - 1988 SLC
- Satt Control SattLine - 1989 DCS AT, GS, AFB, AFF
- Emerson Delta V - 1999 DCS AT, GS, AFB, AF
- ABB 800xA - 2004 DCS AT, GS, AFB, AFF

Next Generation of Autotuners

Observations

- A sine-wave input permits estimation of only two parameters
- PI controllers can be designed based on an FOTD model
- Little difference between PI and PID for processes with delay dominated dynamics
- Improvement by derivative action a factor 2 for $\tau = 0.45$
- PID controllers require better modeling if $\tau < 0.4$
- Separate real delays from higher order dynamics
- Suitable model classes

Requirement on an auto-tuner

- Good excitation - modify relay and experiments
- Short experiment time - do not wait for steady state
- Other types of inputs - asymmetric relay additional inputs
- Trade-off buttons - performance & robustness related

Models

Two parameter models

$$P(s) = \frac{b}{s+a}, \quad P(s) = K\, e^{-sL}$$

Three parameter models

$$P(s) = \frac{b}{s^2 + a_1 s + a_2}, \quad P(s) = \frac{b}{s+a}\, e^{-sL}, \quad P(s) = \frac{K}{1+sT}\, e^{-sL}$$

$$P(s) = \frac{K}{(1+sT)^2}\, e^{-sL}$$

Four parameter models

$$P(s) = \frac{b_1 s + b_2}{s^2 + a_1 s + a_2}, \quad P(s) = \frac{b}{s^2 + a_1 s + a_2}\, e^{-sL}$$

Five parameter model

$$P(s) = \frac{b_1 s + b_2}{s^2 + a_1 s + a_2}\, e^{-sL}$$

Typical Experiments

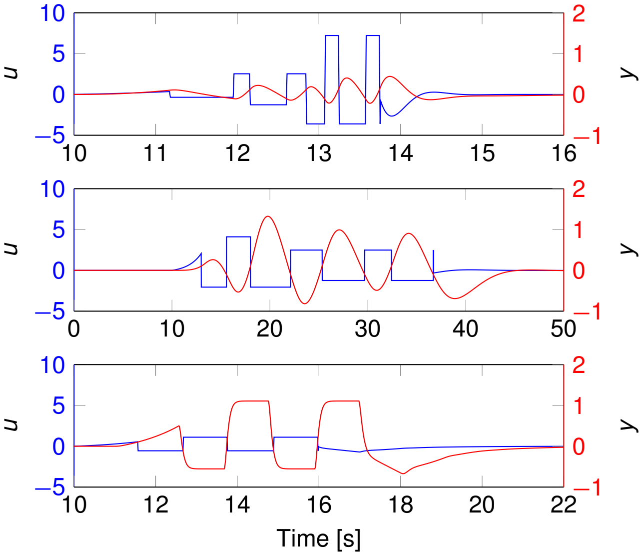
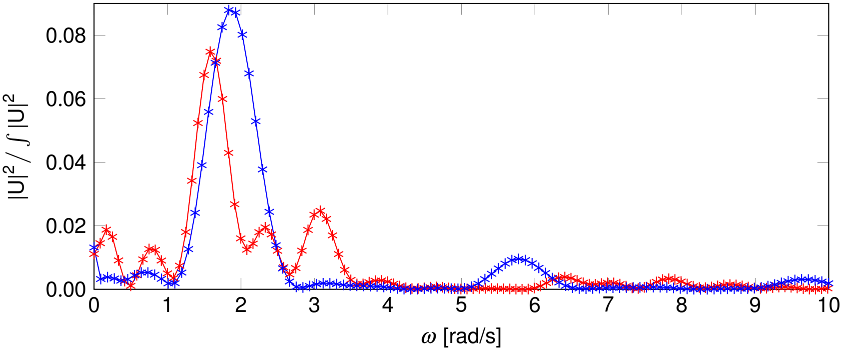


Figure from Josefin Berner

Better Excitation with Asymmetric Relay



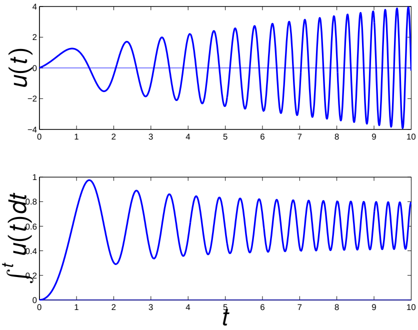
- Symmetric relay blue
- Asymmetric relay red

Figure from Josefin Berner

Chirp Signal – Broadband Excitation

$$u(t) = (a + b\,t)\sin(c + d\,t)t$$

Frequency varies between a and $c + d\,t_{max}$ amplitude between $a + b\,t_{max}$

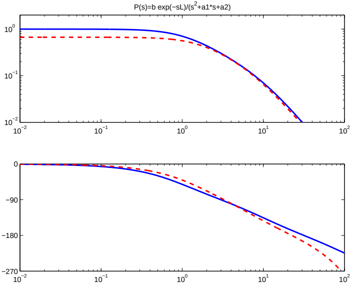


Notice both high and low frequency excitation

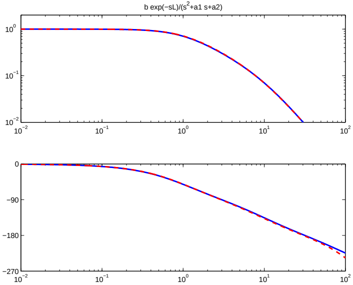
Asymmetric Relay and Chirp

- Asymmetrical relay experiment combined chirp signal experiment
- Double experiment time. Constant amplitude, $L = 0.01, w = 15 * (1 + 0.5 * t), t_{max} = 2.7$, $0.15 \leq \omega L \leq 0.35$

Relay only



Relay and Chirp



Outline

Summary

Insight into PID control

- PI control can be designed based on FOTD model
- Importance of lag and delay dominant dynamics and normalized time delay τ
- PI is sufficient for delay dominated processes $\tau > 0.8$
- Derivative action helps for $\tau \leq 0.8$
- Derivative action gives significant improvement for $\tau < 0.4$ but improved models are required

Next generation of relay auto-tuners

- Use system identification and model testing
- Use algorithms instead of simple tuning rules
- Admits tuning knob