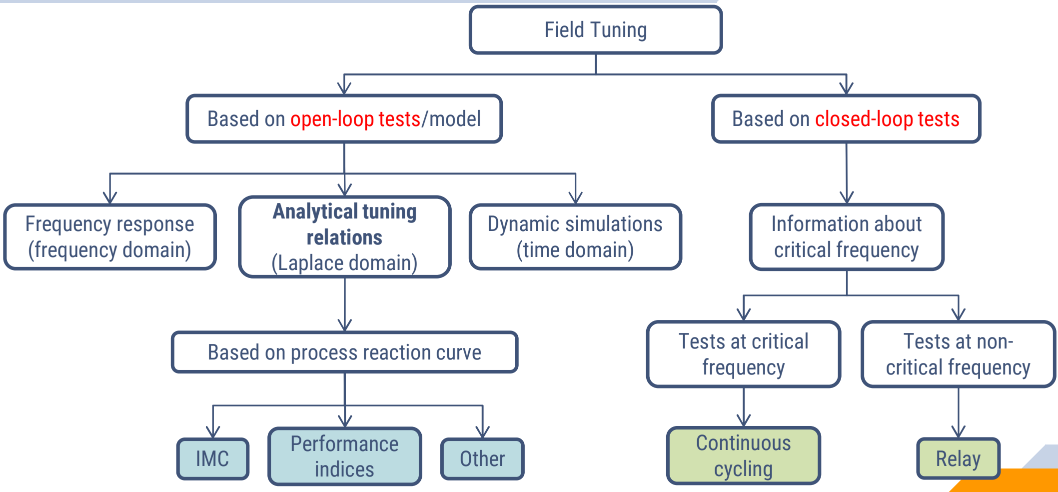
PID CONTROLLER TUNING



Adapted from Barolo M

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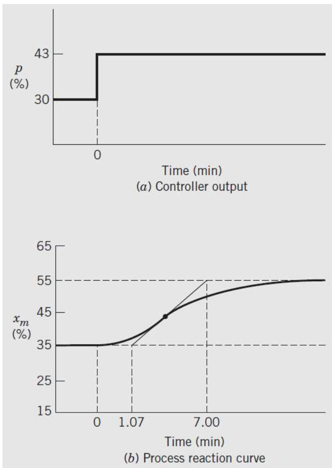
THE PROCESS REACTION CURVE

- All **analytical** tuning relations assume that an open-loop model of the process ($K_p; \tau_p; \theta_p$) is available, from which the tuning ($K_c; \tau_I; \tau_D$) is obtained
- The process reaction curve is a way to obtain this model (**system identification**)
- In principles, a single step test is sufficient (with the controller in manual mode)
  - The system TF is identified → ($K_p; \tau_p; \theta_p; \ldots$)
  - From the model parameters, the controller tuning is obtained using one set of analytical relations
  - Step amplitude: depends on signal-to-noise ratio
- Drawbacks
  - The test is carried out at **open-loop**
    - If a disturbance enters the process while the test is being done, the process dynamics is altered → the TF identified does not represent the true process dynamics
  - For a **nonlinear process**, the identification result depends both on the amplitude and on the direction of the step
    - It is convenient to step the manipulated input both above and below its nominal value
  - The reaction curve cannot be obtained for **open-loop unstable** processes
  - The open-loop response may be very slow



Seborg *et al.* (2016)

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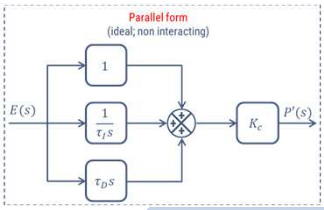
ANALYTICAL TUNING RELATIONS

- From a general viewpoint, **analytical** PID tuning **relations** can be obtained by following different rationales
  - Considering an IMC approach (or a DS one, typically not employed in industry)
    - The analytical relations are «automatically» derived from IMC controller synthesis
  - Requiring that, under PID control, some performance indices (CL response) are optimized ⟶ minimization of IAE, ISE or ITAE
    - The analytical relations are those allowing these indices to be minimized
  - Requiring that, under PID control, a given performance criterion is obtained
    - A given decay ratio ⟶ Ziegler-Nichols; Cohen-Coon
    - A good tradeoff between performance and robustness ⟶ Hägglund-Åström; Skogestad
- Analytical relations abound in the technical literature
  - Either directly or indirectly, they all rely on the fact that an open-loop model of the process to be controlled is available
  - Finding a tuning relation that is «universally optimal» is impossible
- Caution!
  - Always check for which implementation of the PID controller the analytical relation is valid
    - Paraller or serial? Interacting or non-interacting?
    - See SEMD, Table 12.2, p.208
  - The parallel form is always consider here



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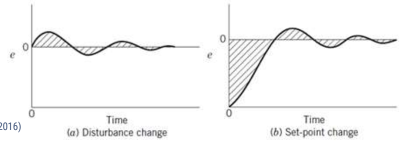
ANALYTICAL RELATIONS FROM PERFORMANCE INDICES

- The «quality» of a controlled system response can be quantified using performance indices
  - IAE, integral of the absolute value of the error $IAE = \int_0^\infty |e(t)|\,dt$



Seborg *et al.* (2016)

  - ISE, integral of the squared error: $ISE = \int_0^\infty [e(t)]^2\,dt$
    - Penalizes large errors; very aggressive
  - ITAE, integral of the time-weighted absolute error $ITAE = \int_0^\infty t|e(t)|\,dt$
    - Penalizes persisting errors; conservative and usually preferable
- There exist analytical tuning relations that minimize the performance indices
  - The tuning for regulatory control and for servo control are different
  - Usually, the tuning for servo control is more conservative

SEMD, Table 11.4 p.211

Adapted from Barolo M

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TUNING BASED ON CLOSED-LOOP TESTS

- The tuning parameters are determined from the tests performed **at closed-loop** on the real system (i.e., on field)
- The tests are aimed at extracting information on the process **critical behavior** $(\omega_u; P_u; K_{cu})$
  - This information is related to the **onset of instability** (marginal stability)
  - From this information, reasonable values for the PID controller settings can be obtained (using analytical relations)
- Afterwards, the response may be improved by fine-tuning the controller on field

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CLOSED-LOOP TESTS

- The values of ω_u, P_u and K_{cu} may be obtained:
  - by actually bringing the system on the verge of instability, i.e. at the marginal stability condition
    - Continuous cycling method (i.e., method of Ziegler-Nichols or «metodo della perturbazione continua»)
  - Or by testing the system away from the marginal stability
    - Relay method
- Once the values of ω_u, P_u and K_{cu} are known, the controller settings are obtained from **analytical relations** according to a desired objective
  - 1/4 (QAD; Quarter-Amplitude Decay) ⟶ Ziegler-Nichols (1942), Z-N
  - Performance + robustness ⟶ Tyreus-Luyben (1997), T-L
- The Ziegler-Nichols tuning relations are **not recommended**
  - A QAD ressesponds to 50% overshoot (see SEMD, Chapter 5, p.77)
  - But for most <u>**process**</u> control applications, a QAD response is too oscillatory
  - For loops that behave «normally», decay ratios of **1/6 – 1/8** are more reasonable
    - Overshoots between 35% and 40%

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TUNING ACCORDING TO ZIEGLER-NICHOLS AND LUYBEN

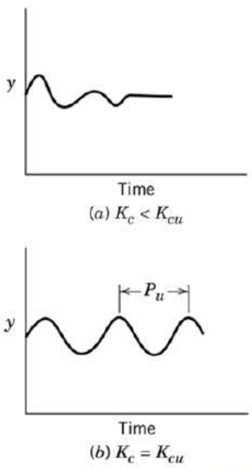
- Ziegler-Nichols (not recommended)
  - When the I action is switched on in addition to the P one, the Z-N gain must be decreased (~-10%)
  - If the D action is then included, Kc can be increased to a value larger than that used when the P-only action is used
    - Kc increases by ~33% with respect to PI
    - Additionally, the integral time can be decreased
- Tyreus-Luyben
  - It exists only for PI and PID controllers
  - It is more conservative than Z-N
  - When the D action is switched on, Kc increases by ~45% with respect to PI
    - The integral time does not change

Ziegler-Nichols	K_c	τ_I	τ_D
P	$0.5K_{cu}$	-	-
PI	$0.45K_{cu}$	$P_u/1.2$	-
PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$
Tyreus-Luyben	K_c	τ_I	τ_D
PI	$0.31K_{cu}$	$2.2P_u$	-
PID	$0.45K_{cu}$	$2.2P_u$	$P_{cu}/6.3$

Adapted from Barolo M

FINDING THE CRITICAL PARAMETERS – CONTINUOUS CYCLING METHOD

- Proposed by Ziegler and Nichols, it is based on a trial-and-error procedure
  1. Manually bring the process at **steady-state**
  2. Activate **only the P action** in the controller, and assign K_c a «small» value; set the controller to the automatic mode
  3. Introduce a «small» set-point change (step). **Gradually** increase K_c until a sustained oscillation (constant amplitude) occurs in the controlled variable → **marginal stability**
  4. The value of K_c that produces **continuous cycling** is equal to K_{cu} (ultimate gain). The period of oscillation is equal to P_u (ultimate period)
  5. Calculate the PID controller settings using the Z-N of the **T-L relations**
  6. Evaluate the loop **performance** by introducing a small set-point change
  7. Fine-tune if necessary
- Notice.
  - If by accidents, $K_c > K_{cu}$ is selected, valve saturation makes the cycling appear as continuous, even if it is not in reality (undamped response)



(Seborg et al., 2011)

Adapted from Barolo M

DRAWBACKS OF THE CONTINUOUS CYCLING METHOD

- Several trials are often needed before continuous cycling is attained
  - If the process dynamics is slow, the process operation is perturbated and the product quality remains poor for a long time
- The process is pushed to its stability limits
  - If an external disturbance enters the process, or if the process undergoes internal change, unstable operation may result
- The tuning procedure cannot be applied to **integrating** or **open-loop unstable** systems
  - Their control loops are unstable both high and low values of K_c, whereas they are stable for intermediate values
- Purely FO or SO systems (no dead time) cannot be made unstable (hence marginally stable) for any choice of K_c (provided that the sign of K_c is correct)
  - However, this is more a theoretical issue than a practical one

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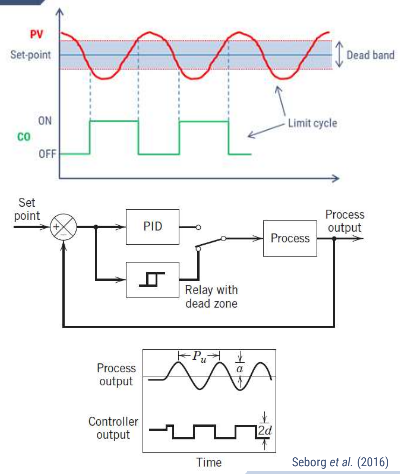
FINDING THE CRITICAL PARAMETERS – RELAY METHOD (ATV-Auto-Tune Variation)

- Proposed by Hägglund and Åström (1984)
- A **single test** is sufficient, from which information is extracted that enables one to determine the values of K_{cu} and P_u, without bringing the system on the verge of instability
- It uses an **on-off controller** (relay) with hysteresis (dead band)
  - After closing the control loop, a limit cycle appears, and the oscillation period is equal to P_u
  - The ultimate gain is calculated as: $K_{cu} = \dfrac{4d}{\pi a}$
  - 2 to 4 complete cycles are required
    - For slow processes this may not be acceptable



Seborg et al. (2016)

- **Advantages with respect to continuous cycling**
  - The process is not pushed to the instability limit
  - A single test is enough, no trial-and-error procedure
  - The response amplitude a can be adjusted by adjusting the relay amplitude d
  - The experimental test can be easily automated
    - Most commercial electronic controllers include a built-in «autotuning» or «autotaratura» feature

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GENERAL TUNING RECOMMENDATIONS

- If an open-loop process model is available, it is convenient to **tune** the PID controller using that **model** (analytical relations)
  - The model may be obtained by step testing (at open-loop)
  - **The IMC relations** are usually a very good starting point
  - Other good relations: Hägglund-Åström (2002) and Skogestad (2003)
- Tuning based on **performance indices** (error integrals) provide a good quantitative term of comparison, but usually are not enough robust
  - When different tunings exist for regulatory control and servo control, the regulatory control tuning is usually preferable
  - However, the resulting tuning may be too aggressive → to reduce the oscillations for set-point changes, the set-point profile should be filtered
- QAD criteria (Ziegler-Nichols; Cohen-Coon) are **not** recommended
- For closed-loop tuning, use the **relay method** whenever possible

Adapted from Barolo M

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GENERAL REMARKS ON TUNING

- The controller gain K_c should be inversely related to the product of the other loop gains
  - Not strange at all: recall the stability condition
- τ_D is usually **smaller** than τ_I
  - In most well-tuned controllers, $\tau_D/\tau_I = 0.1 - 0.3$
  - A good starting point is setting $\tau_D/\tau_I = 0.25$
- The larger the ratio θ_p/τ_p, the smaller should K_c be
  - Usually, the control performance worsens when θ_p/τ_p increases
    - Both the settling time and the overshoot increase
- The larger the ratio θ_p/τ_p, the larger should τ_I and τ_D be
- When the **I action** is activated on a P-only controller, **K_c should be decreased**
  - A subsequent activation of the D action allows one to increase K_c to a value larger than that used with P-only control

Adapted from Barolo M

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TYPICAL PID CONTROLLER SETTING IN COMMON LOOPS

Control variable	PB [%]	K_c [%/%]	τ_I [s]	τ_D [s]
Flow	100-500	0.2-1.0	0.2-2.0	0
Pressure (gas)	1-15	7-100	5-100	0
Pressure (liquid)	100-500	0.2-1.0	0.2-2.0	0
Level	5-50	2.0-20	5-60	0
Temperature	10-50	2.0-10	40-4000	30-2000*
Composition	100-1000	0.1-1.0	100-5000	30-4000*

(Riggs and Karim, 2008)

* τ_D should be always smaller than τ_I

Ch.12 independent study
- SEMD, Example 12.1 p.203

Adapted from Barolo M

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