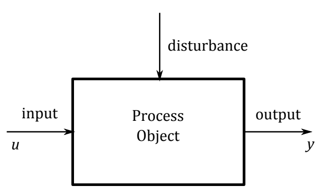
Chapter 2

Process control

1 Basic concepts

Management levels are: business management, production management, process control.

1.1 Purpose



Goals: to bring the object to the desired state

Meet the requirements:

1. Ensure the output values with certain conditions
   - Value y, deviations $\pm\Delta y$, conditions, etc.
   - Regulatory problem - reducing the impact of the disturbances;
   - Servo/tracking problem - track the changing set point;
   - Not to keep as close as possible, but within permitted limits.
2. The fight against disturbances and environment/ object changes
   - Operability, robustness, safety, etc.
3. Process information administration and communication

- Where: production management, quality monitoring and control, business administration, asset management.
- How: local area networks, databases.

The most common problem in industry is to keep steady operation around the setpoint when disturbances are happening. Role of the controller is to react and recover the desired plant operation in a smooth manner.

Setpoint tracking arises in processes where output variable (quality or quantity) varies. A smooth and rapid transition between changes of the setpoint is expected.

General guidelines [5]:

1. Keep control as simple as possible.

   Everyone involved should understand the system.

2. Use feedforward control to compensate for a large, frequent and measurable disturbance.

3. Use override control to avoid constraints.

4. Avoid lags and deadtimes in feedback loops.

   - Keep them inside loop as small as possible;
   - Sensors should be located close to manipulated variable.

5. Eliminate minor disturbances by using cascade control systems when it is possible.

6. Avoid control-loop interaction if possible, otherwise make sure the controllers are tuned to make entire system stable

   MIMO control.

7. Check control system for potential dynamic problems during abnormal conditions.

   - Flexibility: work well over a range of conditions;
   - Startup and shutdown situations.

8. Avoid saturation of the manipulated variable

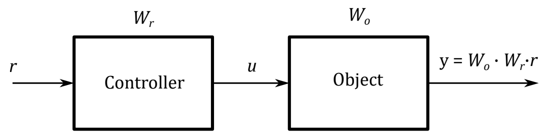
   - Use override control.

9. Avoid "nested" control loops if possible.

   - Operation of the external loop depends on the operation of the internal loop.

Two concepts: an open system, closed system.

1.2 Open-loop system



From the condition $y = r$ it follows

$$\begin{aligned} W_r &= W_o^{-1} \\ (K_r &= 1/K_o, \\ F_r() &= F_o^{-1}()) \end{aligned}$$

Is it realizable?

Feedforward control

If we could detect disturbance influencing the process, we will be able to correct it before it upsets the process. Feedforward control configuration measures the disturbance (load) directly and takes a preemptive control action to eliminate its impact on the process [3, 4].

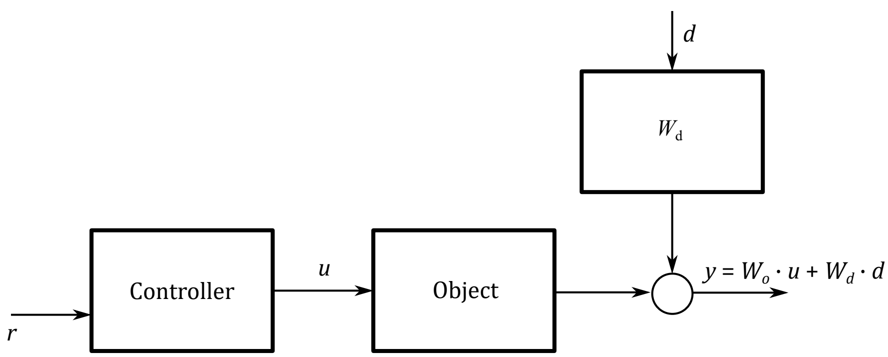


Figure 2.1: Feedforward System

Consider disturbances d, $y = r$, so it follows

$$W_r = W_o^{-1} \cdot (r - W_d \cdot d), \tag{2.1}$$

if the disturbance is measurable its impact can be compensated.

Problems:

- Inaccurate model O: $W_o \pm \Delta W_o$;
- Non-measurable disturbances d;
- Non-realizable controller W_o^{-1}.

An open system is one possible solution, which has its own characteristics.

Feedforward control is widely used in industry processes that include boilers, evaporators, solids dryers, direct fired heaters and waste neutralization plants.

Example 1 *Liquid level control in a boiler drum*

The feedforward control can provide better control of the liquid level. If we measure the steam flow rate, feedforward controller will adjust the feed water flow rate so, that it balances the steam demand [7].

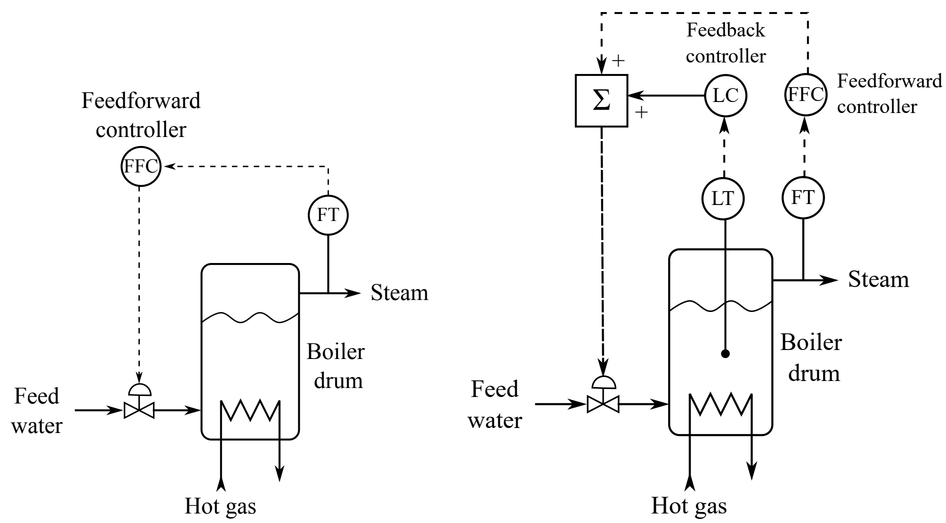


Figure 2.2: Feedforward and Feedforward-Feedback Control

Alternatively we can measure pressure instead of steam flow rate.

Ratio Control [7]

Ratio control is a special type of feefforward control that can be used in industry applications. Its objectives to maintain the ratio of two process variables at specified value for the mixture. The two variables are usually flow rates, a manipulated value (MV) u and disturbance d those are physical parameters not deviations.

$$R = \frac{u}{d} \tag{2.2}$$

Thus, the ratio is controlled rather than individual variables.

Typical applications of ratio control include

- Specifying the relative amounts of components in blending operations;
- Maintaining a stoichiometric ratio of reactants to reactor;
- Keeping a specified reflux ratio for a destination column;
- Holding the fuel-air ratio to a furnace at the optimum value.

Ratio control can be implemented by two basic methods, one of whicj is direct raio control, see Figure 2.3.

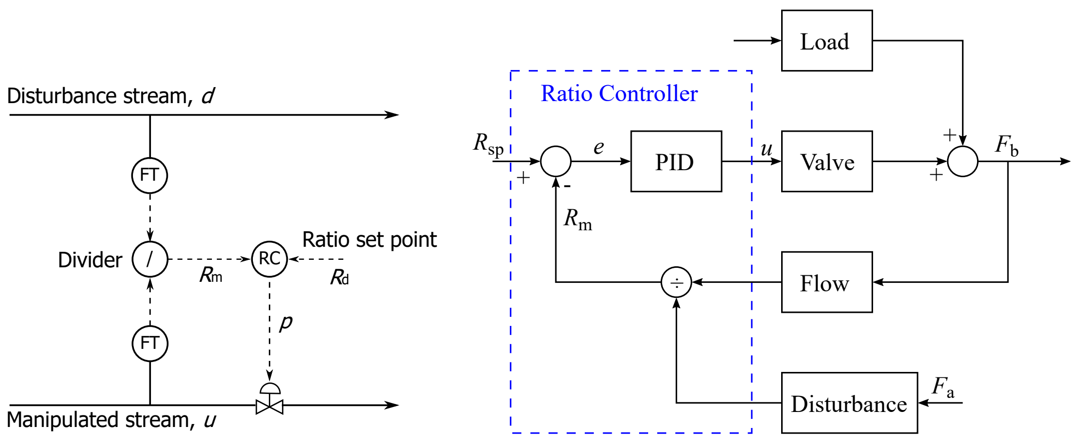


Figure 2.3: Ratio control: Direct Method

Advantage of the Method I is that measured ratio R_m is calculated. The main disadvantage is that divider element must be included in the loop and this element makes the process gain K_p vary in nonlinear way

$$K_p = (\frac{\partial R}{\partial u})_d = \frac{1}{d}.$$

The key advantage of the Method II is that process gain remains constant. Ratio station measures the desturbance flow rate and uses it to compute what should be the rate u to keep the ratio R constant, see Figure 2.4. The output is used as the set point for the controller $u_{\text{sp}} = d_m/R$.

A disadvantage of both methods that desired ration may not be achieved as a result of the dynamics associated with the flow control loop for u.

The design of the feedforward controller requires knowledge of how the controlled variable responds to changes in the control law (manipulated variable) and disturbance variables. This knowledge is usually represented as a process models.

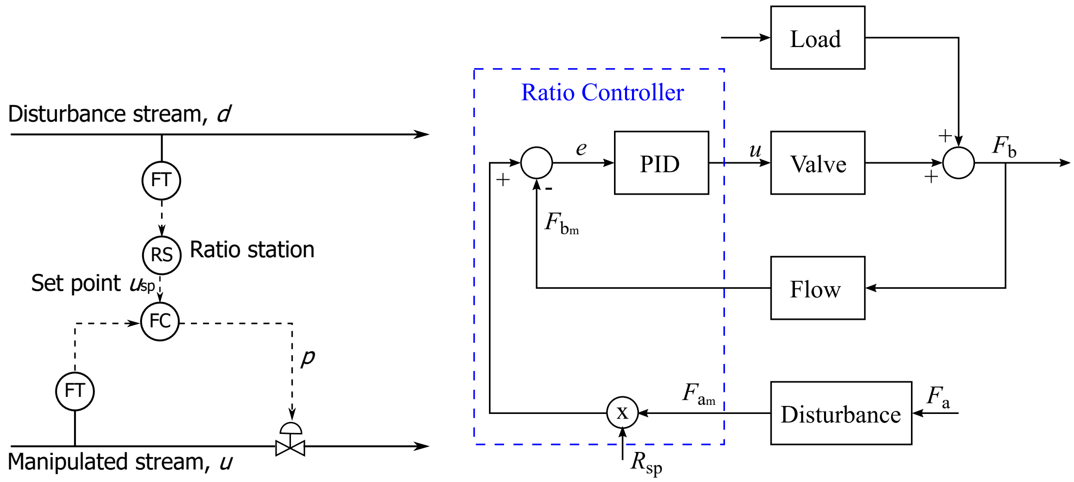


Figure 2.4: Ratio control: Indirect Method

Regardless of how ratio control is implemented, we must scale process variables. For that purpose spans of the two flow transmitters should be taken into account.

$$K_r = R_d \frac{S_d}{S_u},$$

where R_d is a desired ratio, and S_u, S_d are the spans of the flow transmitters for controlled and disturbance streams, respectively.

In practice, feedforward control is combined with feedback control. For these control configurations, the feedforward controller is usually tuned before the feedback controller.

1.3 Closed-loop System

The feedback control problem starts with measurement of the manipulated variable y_m. Then measured value of the controlled variable is compared with desired setpoint variabley_{sp} to generate tracking error$e$. The role of the feedback controller is to produce a control action based on setpoint tracking error, which applied though the manipulated variable on the process, helps the controlled variable to achieve desired setpoint. The control action is implemented through an actuator, for example some valve that regulates the flow rate of a process [6].

$$\begin{aligned} y &= \frac{W_o \cdot W_{ac} \cdot W_r}{1 + W_s \cdot W_o \cdot W_{ac} \cdot W_r} \cdot r + \frac{W_d}{1 + W_s \cdot W_o \cdot W_{ac} \cdot W_r} \cdot d \\ &= \frac{W_o \cdot W_{ac} \cdot W_r}{1 + W_p \cdot W_r} \cdot r + \frac{W_d}{1 + W_p \cdot W_r} \cdot d \end{aligned}$$

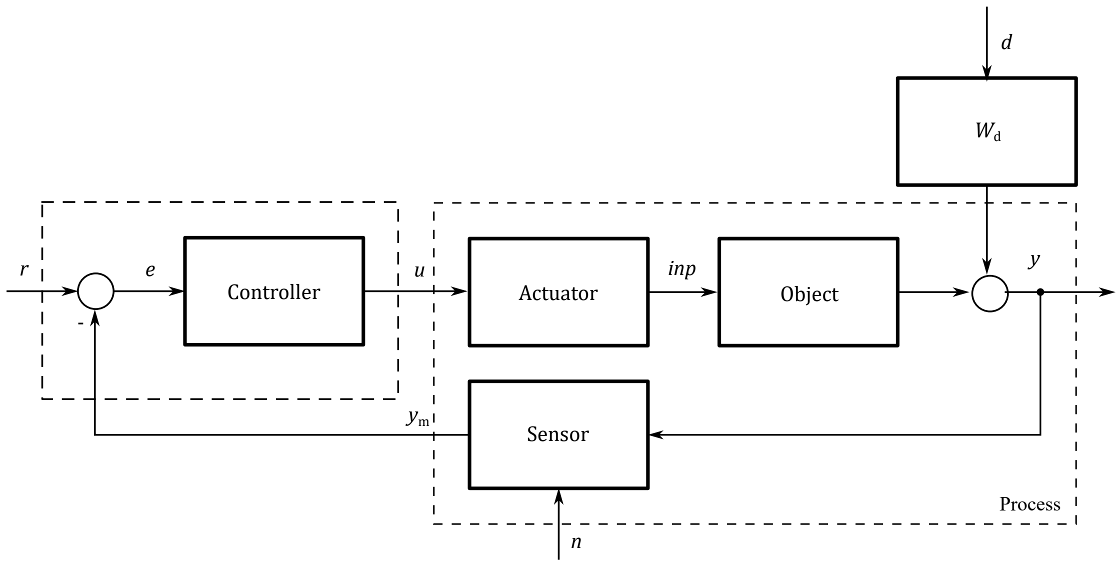


Figure 2.5: Feedback system

$$\text{out} = \frac{\text{direct}}{1 + \text{loop}} \cdot \text{inp} \tag{2.3}$$

The most important feature of the feedback control system, that it learns the process behavior through continuous measurement of the output and feed information back to controller that commands a certain change in the manipulated variable.

Table 2.1: Feedforward Control [6]

Advantages	Disadvantages
- Acts before the disturbance hits the process	- Must identify and measure all disturbances
- Cannot cause instability	- Fails for unmeasured disturbances
- Good for slow process dynamics	- Depends on the availability of process models
	- Fails if process behavior varies
	- No indication of control quality

The feedback loop is influenced by three external signals: the reference r, the load disturbance d and the measurement noise n. The control mechanism acts using the information fed back from the measurements.

Table 2.2: Feedback Control [2]

Advantages	Disadvantages
- Does not require identification and measurement of any disturbance for corrective action	- Control action not taken until the effect of disturbance has been felt by the system
- Does not require an explicit process model	- Unsatisfactory to the processes with large time constants and frequent disturbances
- It is possible to design controller to be robust to process/model errors	- May cause instability in the closed-loop response

Feedback changes open-loop system features.

1.4 Feedforward-feedback Control

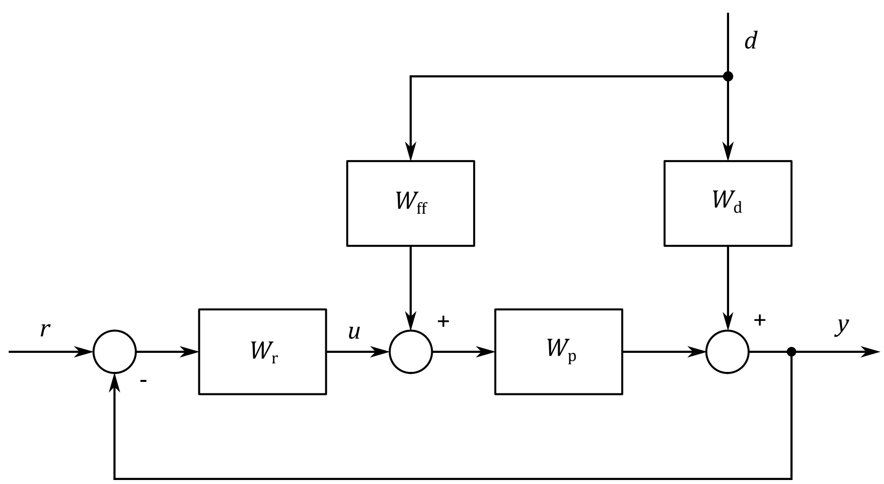


Figure 2.6: Feedforward-feedback Control

$$W_{ff} = -\frac{W_d}{W_p} \tag{2.4}$$

Models describe the relations between control signal and output of the system ($u \rightarrow y$) and effect of disturbances on the controlled variable ($d \rightarrow y$).

Performance of the feedforward controller depends on the accuracy of both models. However, since most mathematical models are only approximate and since not all disturbances are measurable, it is standard practice to utilize feedforward control in conjunction with feedback control.

Feedforward control therefore attempts to eliminate the effects of measurable disturbances, while feedback control would correct for unmeasurable disturbances and modeling errors.

$$
\begin{aligned}
y &= \frac{W_p(W_r r + W_{ff} d)}{1 + W_r W_p} + \frac{W_d}{1 + W_r W_p} d = \frac{W_p W_r r - \frac{W_p W_d}{W_p} d}{1 + W_r W_p} + \frac{W_d}{1 + W_r W_p} d \\
&= \frac{W_p W_r}{1 + W_r W_p} r
\end{aligned}
$$

1.5 Control limitations

Loop shaping [8, 1]

The main points for a feedback control are

1. Performance, good disturbance rejection needs large controller gains. That means open loop $L = W_p W_r$ transfer function magnitude is large.
2. Stabilization of unstable plant: L large.
3. Neglecting the noise of the sensor on the object output: L small.
4. Physical controller must be strictly proper: $W_r \to 0$ at high frequencies.
5. Nominal stability (stable plant): L small (because of RHZ and time delays).
6. Robust stability (stable object): L small (because of uncertain or neglected dynamics).

- If process W_p is unstable then closed system can be made stable, requires all four transfers to be stable
  - $S = \dfrac{1}{1 + W_r \cdot W_p}$ sensitivity function,
  - $W_d \cdot S = \dfrac{W_d}{1 + W_r \cdot W_p}$ load sensitivity ,
  - $T = \dfrac{-W_p W_r}{1 + W_r \cdot W_p}$ complementary sensitivity,
  - $W_r \cdot S = \dfrac{-W_r}{1 + W_r \cdot W_p}$ noise sensitivity.
- System is stable if bounded input signals (d, r, n) generate bounded outputs (y_m, u, y, e) (internal stability).
- If object W_p is stable then the only requirement is $W_r \cdot S = \dfrac{W_r}{1 + W_r \cdot W_p}$ should be stable;

- It is possible to use unstable controller W_r.

If all control actions are based on feedback from the error only then the system is completely characterized by four transfer functions called Gang of Four [1].

The key idea of the loop shaping is to design the behavior of the closed loop system by focusing on the open loop transfer function.

If we specify the desired performance in terms of properties of open loop, we can directly see the impact of the changes in the controller [1].

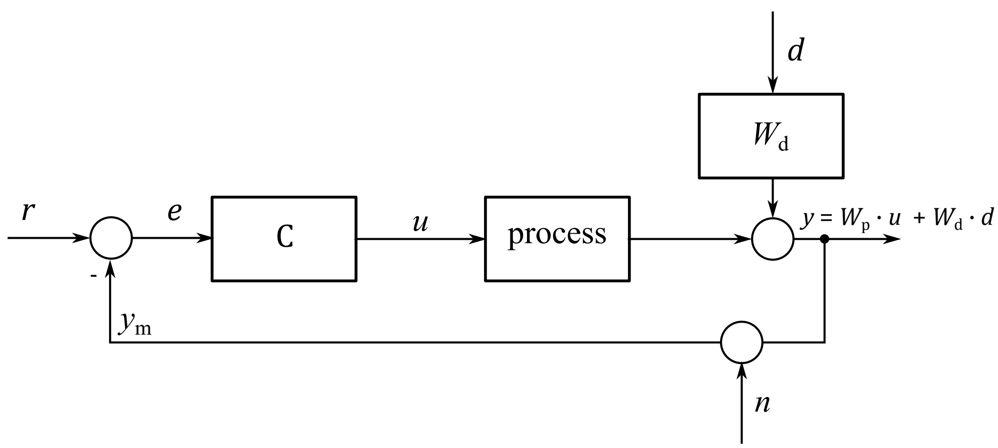


Figure 2.7: Block diagram of feedback control system

$$e = r - y_m = r - (y + n)$$

$$y = W_p W_r (r - y - n) + W_d d,$$

hence closed-loop response is

$$y = \underbrace{\frac{W_p W_r}{1 + W_p W_r}}_{T} r - \underbrace{\frac{W_p W_r}{1 + W_p W_r}}_{T} n + \underbrace{\frac{1}{1 + W_p W_r}}_{S} W_d d.$$

Lets take

$$T + S = \frac{L}{1+L} + \frac{1}{1+L} = \frac{L+1}{1+L} = 1,$$

thus we can use the fact $T = 1 - S$.

The manipulated value u will be the following

$$u = W_r e = W_r(r - Tr + Tn - SW_d d - n) = W_r(r - (1-S)r + (1-S)n - SW_d d - n) =$$
$$= W_r(r - r + Sr + n - n - Sn - SW_d d) = W_r(Sr - Sn - SW_d d)$$

or because $T = W_p W_r S$

$$u = W_p^{-1}Tr - W_p^{-1}Tn - W_p^{-1}TW_d d.$$

Perfect control requires the controller to generate an inverse of W_p.
There are principle limits (not all is possible).

Aim: stable closed loop.

Freedom: choose the controller gain, zeros and poles.

Problems:

- W_p contains RHZ leads to $W_p^{-1}$is unstable,
- $W_p$contains time delay leads to W_p^{-1}containing prediction,
- W_p has more poses than zeros leads to W_p^{-1} is unrealizable.
- MV has physical limitations, so perfect control cannot be achieved if
  - $\left|W_p^{-1}W_d\right|$ is large.

The process's with RHZ initial transient response always moves in opposite direction of steady-state value of the process response.

- Fundamental limitation
  - $S + T = 1$ (both cannot be small at the same time);
  - Cannot attenuate disturbances at all frequencies.
- Dynamics fundamental limitations of feedback control performance
  - RHZ at $z \Rightarrow \omega_c < (0.2 \ldots 0.5) \cdot z$,—upper bound to bandwidth;
  - RHP at $p \Rightarrow \omega_c > (5 \ldots 2) \cdot p$,—lower bound to bandwidth;
  - delay $\theta \Rightarrow \omega_c < (0.4 \ldots 0.7) \cdot \frac{1}{\theta}$—upper bound to bandwidth.

Due to time delays, RHZ, unmodeled high frequency dynamics and limitations on the allowed manipulated inputs the loop gain has to drop below one at and above some frequency which we call the crossover frequency ω_c.

Right half plane poles and zeros

- In order to get acceptable performance and robustness with single RHP and RHZ we must require $z > 4p$;
- In case of multi-components:
  - $z > (14 \dots 7) \cdot p$,
  - $p < (0.05 \dots 0.16) \cdot \theta$.

Example 2

We need high feedback gain ("fast control") in order to reject disturbances, to track setpoints and to stabilize the plant. On the other hand, we must low feedback gains in the frequency range where RHZ or delays have a lot of phase lag. If those are in conflict then the plant is not controllable.

1.6 Control Performance

- System Requirements (objective description),
- Performance evaluation.

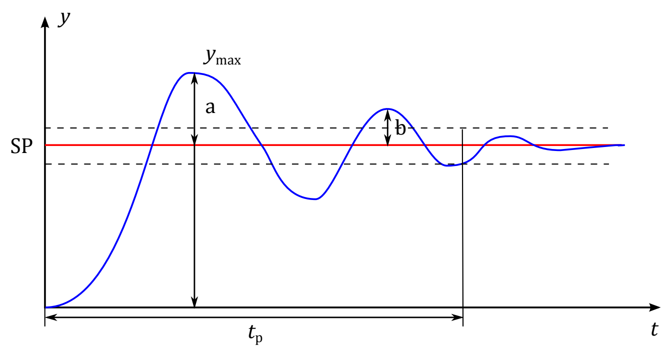
To choose a controller type your need:

1. Model of the object/process or test data;
2. System requirements.

How to describe the desired behavior of a closed loop system?
How comparable system is? What is numerical value of the system performance?
Requirements (goals)→ actual (results)

- What is changing? $r(t), d(t), W_o, \dots$ -reason
- How is changing? (step, random,...)
- What is observed? $y(t), e(t), \dots$ -conclusion
- How to evaluate the change by numeric value? (max, standard deviation, integral,...)

What system features are important?
Requirements must be: measurable, unambiguous, understandable.



Requirements in time domain

Step response analysis.

Overshoot the process makes a transition from one operating level to another

$$\sigma(\%) = \frac{y_{max} - y_{sp}}{y_{sp}} \cdot 100\% \tag{2.5}$$

Decay Ratio is the ratio of the second peak overshoot b to the first peak overshoot a

$$\psi = \frac{b}{a} \tag{2.6}$$

The term: "quarter - wave damping"

Settling time is the time required for y to reach and remain inside a quality band.

Rise time the time it takes for the output to reach 90% of its final value.

Offset the difference between the final value and the desired final value.

The integral criteria

An integral criterion is a performance measure that is based on the integral of some function of the control error and on possibly other variables (such as time).

The three most commonly used integral criteria are as follows:

1. Integral of the absolute error (IAE) → loses;

   Settings between next two.

2. Integral of the square error (ISE) → energy;

   Penalizes large errors, most aggressive

   - sensitive to large deviations,

- long and oscillating process.

3. Integral of time and absolute error (ITAE).

   Penalizes errors persisting for a long time

   - quick process ,
   - aperiodic process.

Requirements in frequency domain [8]

Main parameters:

- Poles placement, dominant pole;
- Magnitude and phase margins.

Speed of response to reject disturbances We approximately require $\omega_c > \omega_d$ or $|S(j\omega)| \leq |1/W_d(j\omega)|\, \forall\omega$.

Speed of response to track reference changes We require $|S| \leq 1/R$ up to the frequency ω_r, where tracking is required.

$r(t) = R\sin(\omega t)$

Input constraints arising from disturbances
- Acceptable control $|e| < 1$ we require $|W_p| > |W_d| - 1$at frequencies where $|W_d| > 1$.
- Perfect control $e = 0$ we require $|W_p| > |W_d|$.

Input constraints arising from setpoints We require $|W_p| > R - 1$ up to the frequency ω_r, where tracking is required.

Time delay We approximately require $w_c < 1/\theta$.

Tight control at low frequencies with a RHZ z We require $\omega_c < z/2$ and for an imaginary RHZ we approximately require $\omega_c < |z|$.

Phase lag constraint We require in most practical cases (with PID control) $\omega_c < \omega_u$.

Real open-loop unstable pole in W_p at $s = p$. We need high feedback gains to stabilize the system and we approximately require $\omega_c > 2p$. Plus for unstable plants we need $|W_p| > |W_d|$ up to the frequency p (which may be larger than ω_d where $|W_d| = 1$). Otherwise, the input may saturate when there are disturbances, and the plant cannot be stabilized.

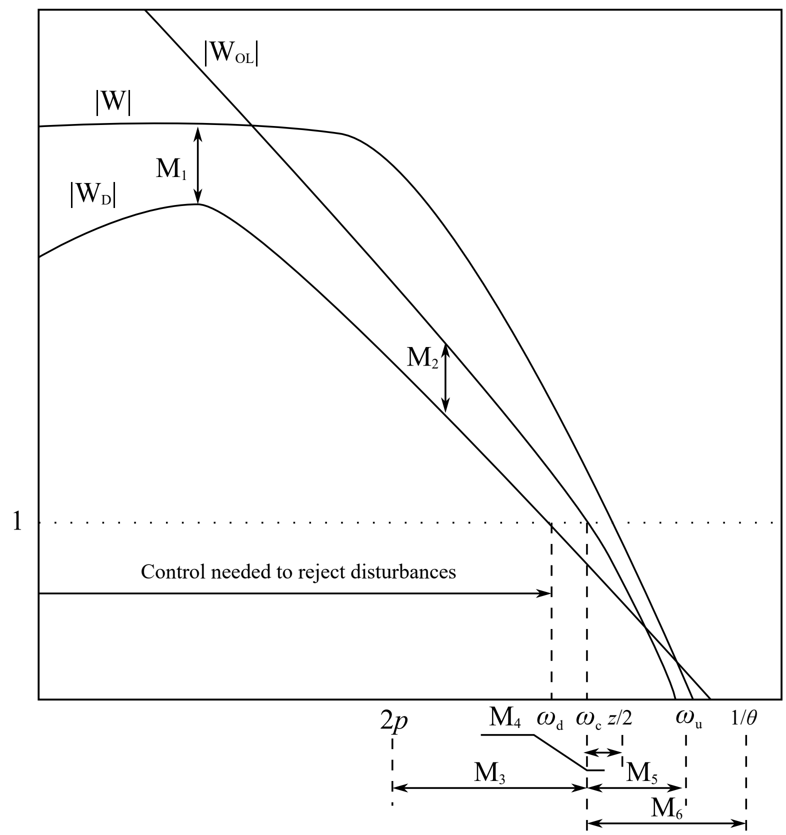


Figure 2.8: Controllability requirements

M_1 : Margin to stay within $|u| < 1$.
M_2 : Margin for performance $|e| < 1$.
M_3 : Margin because of RHP, p.
M_4 : Margin because of RHZ, z.
M_5 : Margin because of w_u, where plant has $-180°$ phase lag.
M_6 : Margin because of delay, θ.

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