Chapter 3: Time-Domain Performance of Control Systems

1 - Time response of control systems

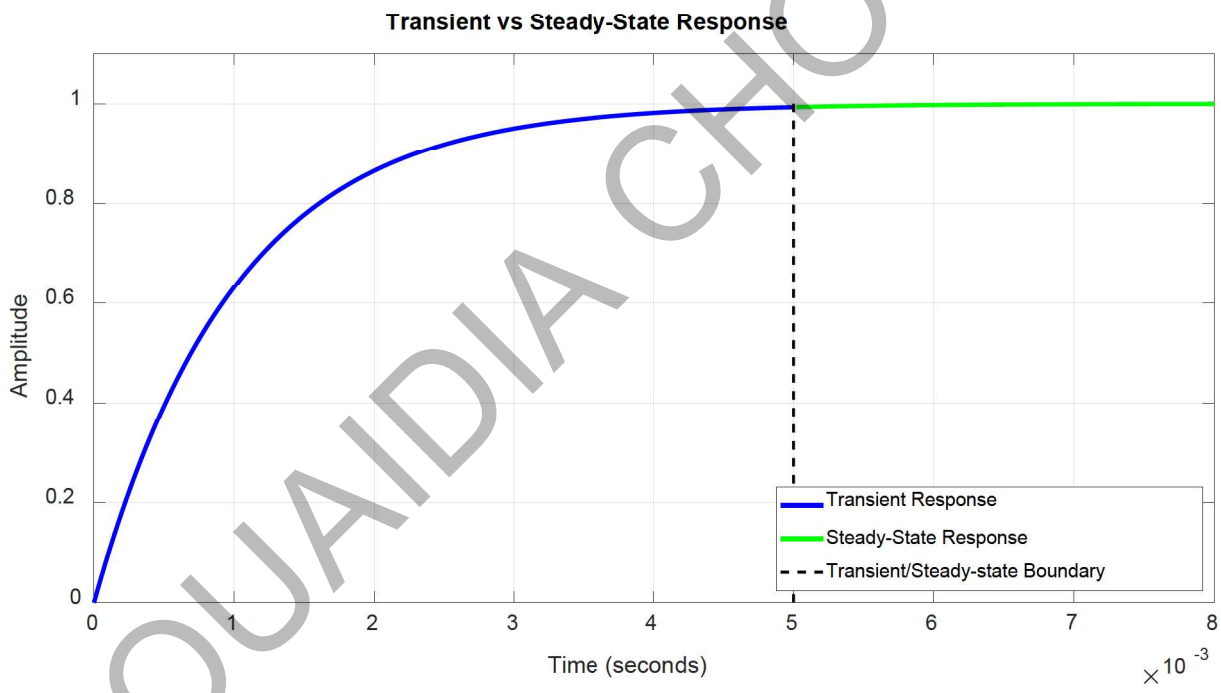
1.1 Introduction

In control systems, the objective is to understand how a system behaves when subjected to a particular input.

The *time response* of a system is the variation of its output with respect to time when it is subjected to a specific input signal.

It consists of two main parts:

$$Total\ Response = Transient\ Response + Steady\text{-}State\ Response$$



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1.2 Transient and Steady-State Response

Transient Response

- The transient response is the part of the total response that **decays with time**.
- It depends on the system's **initial conditions** and the **nature of the poles**.
- It determines how quickly and smoothly the system reaches its final value.
- It usually contains oscillations, overshoot, or exponential decay terms.

Example: For a first-order system:

$$y(t) = K(1 - e^{-t/\tau})$$

The term $e^{-t/\tau}$ is the transient part - it decays with time.

Steady-State Response

- The steady-state response is the behavior of the system **after the transient effects have died out**.
- It represents the **final value** reached as $t \to \infty$.

For the same example:

$$\lim_{t\to\infty} y(t) = K$$

This is the **steady-state value**.

1.3 Time Response to Standard Inputs

The most commonly used test inputs in control systems are:

1. **Unit Step Input:** $r(t) = 1(t)$
2. **Unit Ramp Input:** $r(t) = t$
3. **Unit Parabolic Input:** $r(t) = \frac{t^2}{2}$
4. **Unit Impulse Input:** $r(t) = \delta(t)$

These help analyze different aspects of the system's behavior.

1.4 Concepts of Stability, Speed, and Static Accuracy

(a) Stability

- A system is **stable** if its output remains bounded for a bounded input.
- In terms of the Laplace transform, a linear system is stable if **all poles of its transfer function have negative real parts** (lie in the left-half s-plane).

$$G(s) = \frac{N(s)}{D(s)} \quad \text{is stable if Re(roots of } D(s)) < 0$$

(b) Speed of Response

Speed describes how fast the system responds to a change in input. Key performance measures for speed include:

- **Rise Time (t_r)**: Time to go from 10% to 90% of the final value.
- **Peak Time (t_p)**: Time to reach the first maximum peak.
- **Settling Time (t_s)**: Time to remain within a specific error band (usually ±2% or ±5%) of the final value.

(c) Static Accuracy

Static accuracy measures how close the system output stays to the desired input in the steady state. It is quantified by the **steady-state error (e_{ss})**.

$$e_{ss} = \lim_{t\to\infty}[r(t) - y(t)]$$

Where : $r(t)$: is the reference signal
$y(t)$: is the actual output

Type error constants:

- Position error constant K_p
- Velocity error constant K_v
- Acceleration error constant K_a

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2. First-order systems

2.1 Introduction

Many real-world control systems can be approximated by **first-order dynamics**, especially when they have a single dominant energy-storage element (like capacitance, inductance, inertia, or thermal mass).

A **first-order system** is one whose governing differential equation contains **only one energy-storage term** (one first derivative).

Typical examples:

- RC (resistor-capacitor) or RL (resistor-inductor) electrical circuits
- Thermal systems (temperature vs. heating power)
- Hydraulic or pneumatic level systems
- Speed control of a motor with viscous friction

2.2 General Form

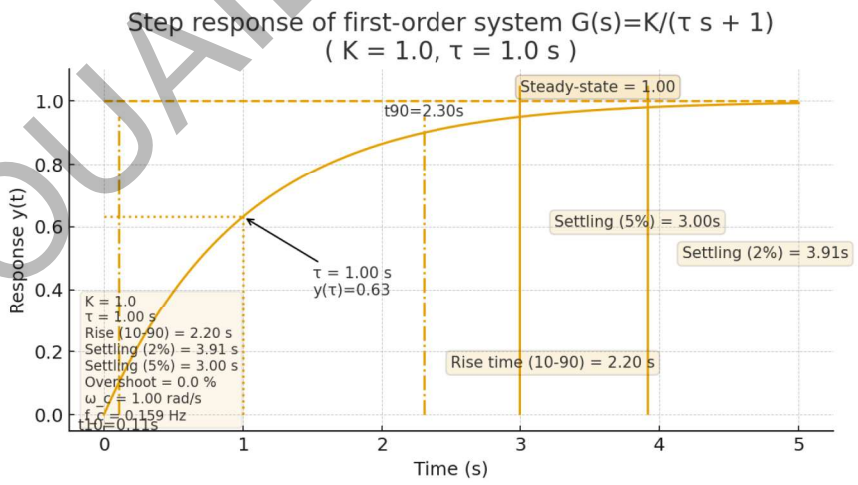
The general **first-order transfer function** is:

$$G(s) = \frac{K}{\tau s + 1}$$

Where:

- K: system gain (steady-state gain)
- τ: time constant (in seconds)
- s: Laplace variable

This function describes the ratio of output to input in the Laplace domain.



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2.3 Time-Domain Differential Equation

By taking the inverse Laplace form:

$$(\tau s + 1)Y(s) = KX(s)$$

Applying the inverse Laplace transform:

$$\tau \frac{dy(t)}{dt} + y(t) = Kx(t)$$

This is the **first-order linear differential equation** describing the system.

2.4 Step Response Analysis

Let the input be a **unit step**: $x(t) = 1(t)$, hence $X(s) = \frac{1}{s}$.

$$Y(s) = \frac{K}{s(\tau s + 1)}$$

Using partial fractions:

$$Y(s) = \frac{K}{s} - \frac{K}{s + \frac{1}{\tau}}$$

Taking the inverse Laplace transform:

$$\boxed{y(t) = K\left(1 - e^{-t/\tau}\right)}, \quad t \geq 0$$

2.5 Transient and Steady-State Components

- **Transient response:** $-Ke^{-t/\tau}$
- **Steady-state response:** K

The exponential term vanishes over time, leaving the steady-state value. $y_{ss} = K$.

2.6 System Parameters and Their Meaning

Parameter	Symbol	Meaning	Unit
Gain	K	Final ratio of output to input	Dimensionless
Time constant	τ	Time to reach 63.2% of the final value	seconds

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2.7 Performance Indices

5. **Rise Time (t_r):**
   Time for output to go from 10% to 90% of the final value.

$$t_r \approx 2.2\tau$$

6. **Settling Time (t_s):**
   Time for output to remain within ±2% of the final value.

$$t_s = 4\tau$$

7. **Steady-State Value (y_{ss}):**

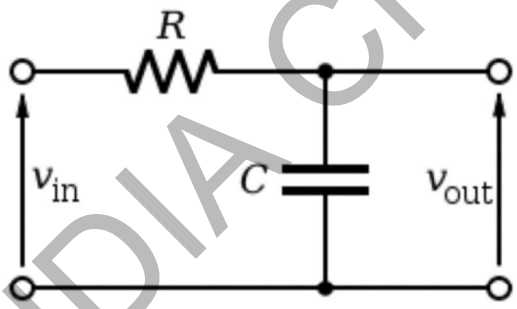
$$y_{ss} = K$$

8. **Initial Slope:**

$$\left.\frac{dy(t)}{dt}\right|_{t=0} = \frac{K}{\tau}$$

These quantities define the **speed** and **responsiveness** of a first-order system.

2.8 Example 1 - RC Circuit



Consider a simple **RC charging circuit**:

$$V_{in}(t) = RC\frac{dV_C(t)}{dt} + V_C(t)$$

Comparing with the general form:

- $\tau = RC$
- $K = 1$

Step response:

$$V_C(t) = V_{in}\left(1 - e^{-t/(RC)}\right)$$

Interpretation:
The capacitor voltage gradually increases from 0 to V_{in} With a rate determined by the time constant RC.

If $R = 1\,\text{k}\Omega, C = 1\,\mu\text{F} \Rightarrow \tau = 1\,\text{ms}$.
The output reaches 63.2% of V_{in} After 1 ms.

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2.9 Impulse Response of a First-Order System

Impulse input $x(t) = \delta(t) \Rightarrow X(s) = 1$:

$$Y(s) = G(s)X(s) = \frac{K}{\tau s + 1}$$

Taking inverse Laplace:

$$h(t) = \frac{K}{\tau} e^{-t/\tau}, \quad t \geq 0$$

This decaying exponential describes how the system reacts to an instantaneous disturbance.

2.10 Frequency Response (Brief Overview)

For a sinusoidal input $x(t) = \sin(\omega t)$, the steady-state output is:

$$|G(j\omega)| = \frac{K}{\sqrt{1 + (\omega\tau)^2}}$$

$$\phi(\omega) = -\tan^{-1}(\omega\tau)$$

This shows that:

- At low frequencies: $|G| \approx K$ (no attenuation)
- At high frequencies: $|G| \to 0$ (acts as a low-pass filter)

2.11 Identification of a First-Order System from Step Response

From the step response curve:

9. Measure the **steady-state value** $y_{ss} = K$.
10. Find the **time constant** τ at 63.2% of y_{ss}.
11. Write the transfer function:

$$G(s) = \frac{K}{\tau s + 1}$$

Example:
If $y_{ss} = 5$ V and at $t = 2$ s, $y(t) = 0.632 \times 5 = 3.16$ V,
Then $\tau = 2$ s, so:

$$G(s) = \frac{5}{2s + 1}$$

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2.12 Practical Observations

- Shorter $\tau \rightarrow$ faster response.
- Larger $\tau \rightarrow$ slower response.
- Increasing K increases the final value (steady-state gain).
- The transient is **monotonic** - no overshoot or oscillations (unlike second-order systems).

3. Second-order systems and higher-order cases

3.1 Introduction

Many physical control systems - such as mechanical mass-spring-damper systems, RLC electrical circuits, or position control loops - exhibit **second-order dynamics**.

They are characterized by **two energy-storage elements** (e.g., a capacitor + inductor, or mass + spring).

Second-order systems are particularly important because:

- They can **oscillate**, **overshoot**, or **ring**, unlike first-order systems.
- Their behavior depends on **two key parameters**: the **natural frequency** ω_n And **damping ratio** ξ.

3.2 General Form of a Second-Order System

$$G(s) = \frac{K\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

Where:

- K: DC gain
- ω_n: natural frequency (rad/s)
- ξ: damping ratio (dimensionless)

3.3 Standard Differential Equation

In the time domain:

$$\frac{d^2y}{dt^2} + 2\xi\omega_n\frac{dy}{dt} + \omega_n^2 y = K\omega_n^2 x(t)$$

This is the **standard second-order differential equation** describing most oscillatory systems.

3.4 Step Response Derivation (General Case)

For a **unit step input**, $X(s) = \frac{1}{s}$:

$$Y(s) = \frac{K\omega_n^2}{s(s^2 + 2\xi\omega_n s + \omega_n^2)}$$

To find $y(t)$, the analysis occurs based on the **damping ratio** ξ.

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3.5 Classification Based on Damping Ratio

Damping Ratio (ξ)	Nature of Response	Description
$\xi = 0$	Undamped	Pure oscillations, no decay
$0 < \xi < 1$	Underdamped	Oscillatory with decaying amplitude
$\xi = 1$	Critically damped	Fastest non-oscillatory response
$\xi > 1$	Overdamped	Slow, non-oscillatory, sluggish
$\xi < 0$	Unstable	Diverging oscillations

3.6 Underdamped Case ($0 < \xi < 1$)

Poles:

$$s_{1,2} = -\xi\omega_n \pm j\omega_d$$

Where:

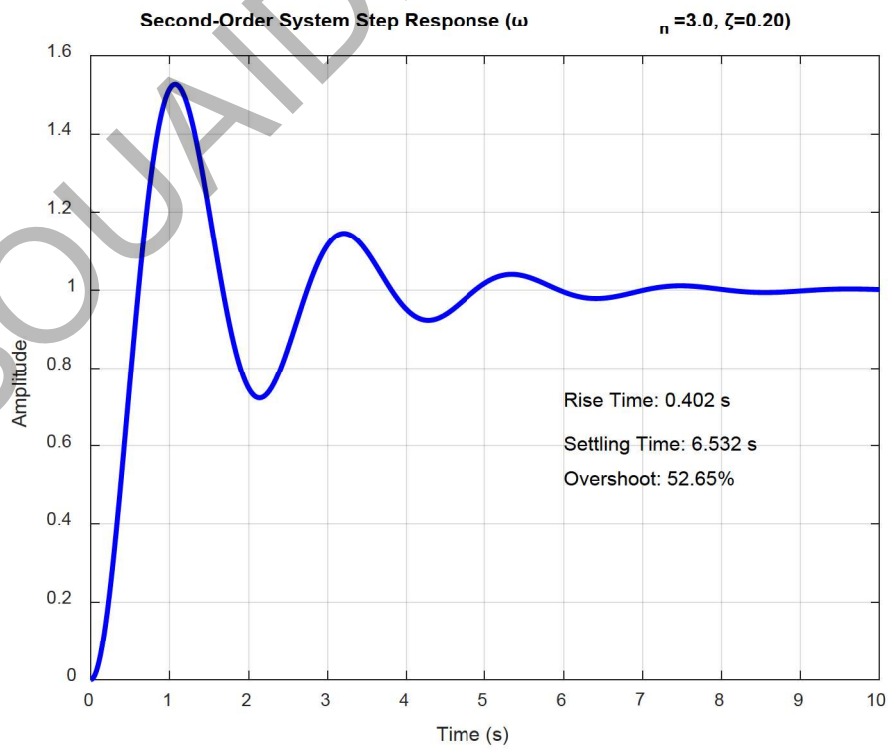
$$\omega_d = \omega_n\sqrt{1-\xi^2}$$

Step response:

$$\boxed{y(t) = K\left[1 - \frac{1}{\sqrt{1-\xi^2}}e^{-\xi\omega_n t}\sin(\omega_d t + \phi)\right]}$$

Where:

$$\phi = \tan^{-1}\left(\frac{\sqrt{1-\xi^2}}{\xi}\right)$$



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3.7 Performance Measures for Underdamped Systems

Parameter	Symbol	Formula	Meaning
Rise Time	t_r	$\frac{\pi - \phi}{\omega_d}$	Time to first reach steady-state value
Peak Time	t_p	$\frac{\pi}{\omega_d}$	Time of first peak (overshoot)
Maximum Overshoot	M_p	$e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \times 100\%$	Percentage above final value
Settling Time (2%)	t_s	$\frac{4}{\xi\omega_n}$	Time to stay within ±2% band
Steady-State Value	y_{ss}	K	Final value

3.8 Example 1 - Step Response Calculation

Given:

$$G(s) = \frac{25}{s^2 + 4s + 25}$$

Compare with standard form:

$$2\xi\omega_n = 4 \quad \text{and} \quad \omega_n^2 = 25$$

Thus:

$$\omega_n = 5, \quad \xi = 0.4, \quad K = 1$$

Now compute:

- $\omega_d = 5\sqrt{1 - 0.4^2} = 4.58$
- $\phi = \tan^{-1}\left(\frac{\sqrt{1-0.16}}{0.4}\right) = 1.159$ rad

The step response is:

$$y(t) = 1 - \frac{1}{\sqrt{1 - 0.4^2}} e^{-2t} \sin(4.58t + 1.159)$$

Performance:

- $M_p = e^{-\frac{0.4\pi}{\sqrt{1-0.16}}} \times 100\% = 25.4\%$
- $t_p = \frac{\pi}{4.58} = 0.685\ s$
- $t_s = \frac{4}{0.4(5)} = 2\ s$

The system oscillates lightly and settles around 2 seconds.

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3.9 Critically Damped Case (ξ = 1)

Poles: $s_{1,2} = -\omega_n$

Transfer function:

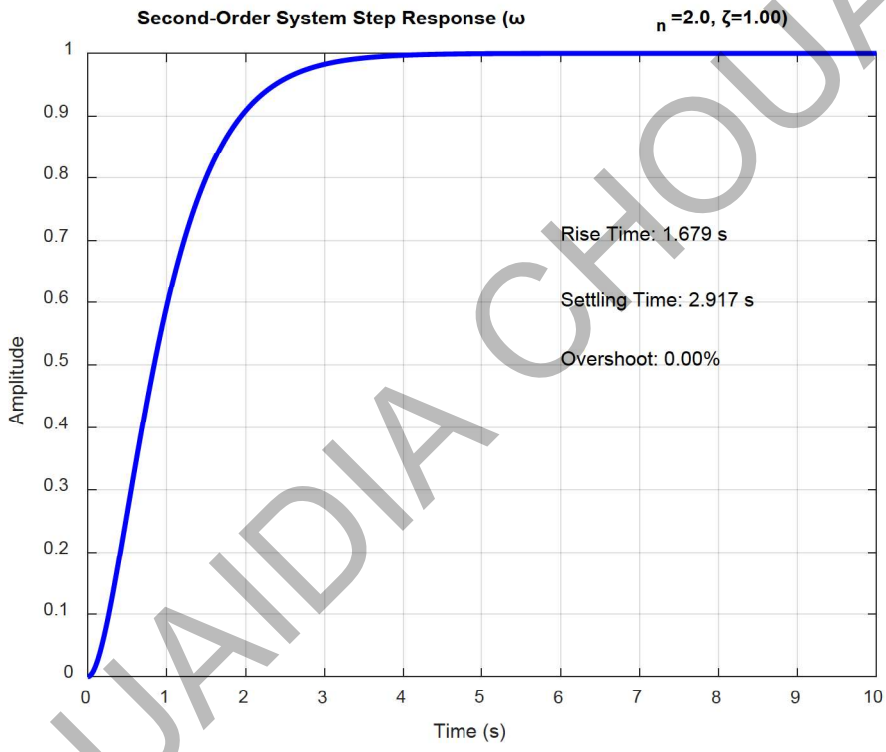
$$G(s) = \frac{K\omega_n^2}{(s+\omega_n)^2}$$

Step response:

$$y(t) = K[1 - (1+\omega_n t)e^{-\omega_n t}]$$

Characteristics:

- No oscillations
- Fastest possible response without overshoot
- Common in positioning systems (e.g., servo motors)



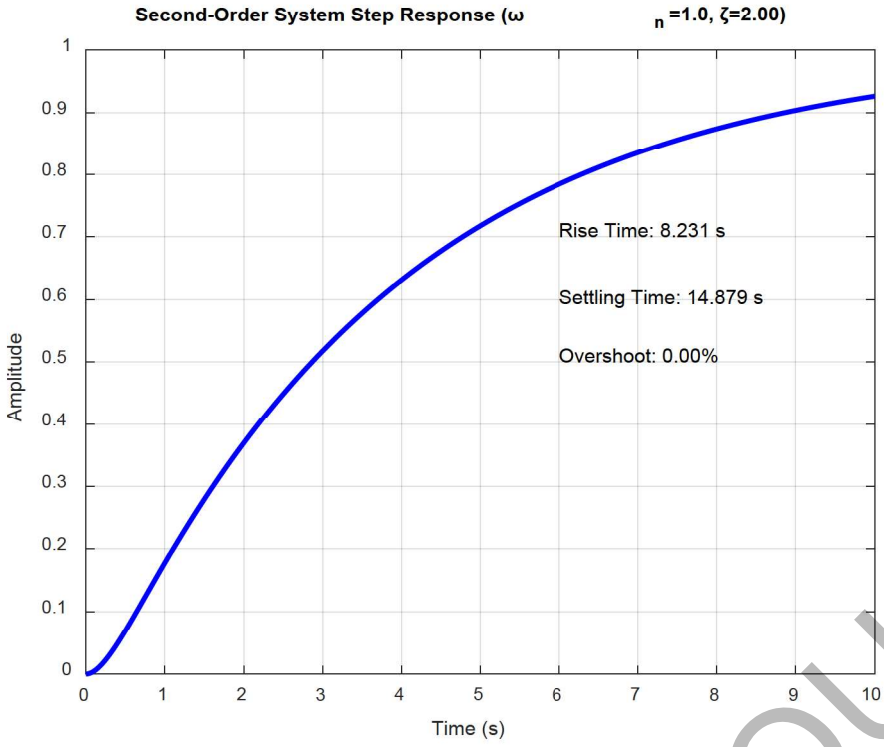
3.10 Overdamped Case (ξ > 1)

Poles: $s_{1,2} = -\omega_n(\xi \pm \sqrt{\xi^2 - 1})$

Step response:

$$y(t) = K[1 - Ae^{s_1 t} - Be^{s_2 t}]$$

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3.11 Undamped Case (ξ = 0)

$$G(s) = \frac{K\omega_n^2}{s^2 + \omega_n^2}$$

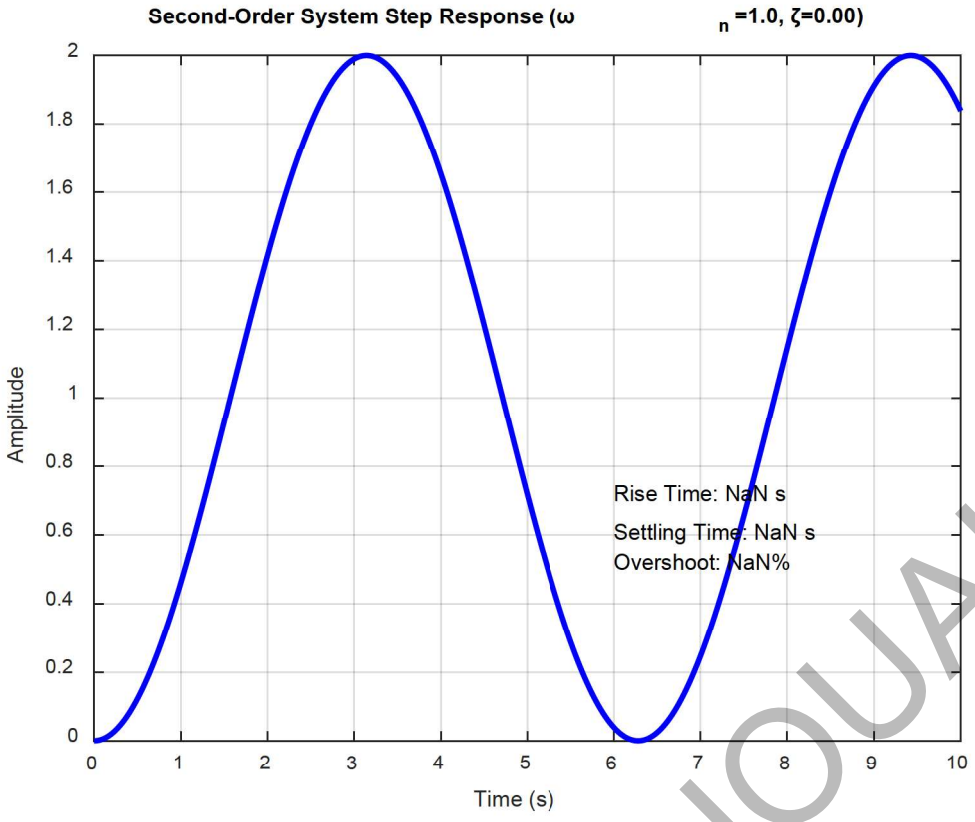
Step response:

$$y(t) = K(1 - \cos(\omega_n t))$$

Characteristics:

- Sustained oscillations forever
- The system is **marginally stable**
- Example: LC circuit with no resistance

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3.12 Impulse Response of a Second-Order System

For $G(s) = \frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2}$:

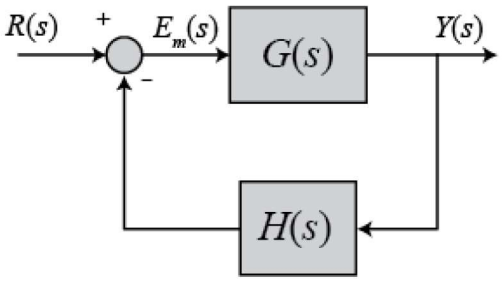
$$h(t) = \begin{cases} \frac{\omega_n}{\sqrt{1-\xi^2}} e^{-\xi\omega_n t}\sin(\omega_d t), & 0 < \xi < 1 \\ \omega_n^2 t e^{-\omega_n t}, & \xi = 1 \\ Ae^{s_1 t} + Be^{s_2 t}, & \xi > 1 \end{cases}$$

The impulse response directly shows damping, oscillation, and stability.

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4. Steady-State Response and Static Accuracy

4.1 Steady-State Error (e_{ss})



The **steady-state error** represents the **difference between the input and output** as time → ∞.

$$e_{ss} = \lim_{t\to\infty}[r(t) - y(t)]$$

In the **Laplace domain**, using the **Final Value Theorem**:

$$e_{ss} = \lim_{s\to 0} s.E(s)$$

and since $E(s) = R(s) - Y(s) = R(s)[1 - G(s)H(s)]$:

$$e_{ss} = \lim_{s\to 0} s.\frac{R(s)}{1 + G(s)H(s)}$$

Here, $H(s)$ is the feedback transfer function.

Where:

$r(t)$: Is the reference signal
$y(t)$: Is the output signal
E(s): The error transfer function
G(s): The Non-feedback transfer function
H(s): The feedback's transfer function

4.2 System Type and Error Constants

The **system type** is determined by the **number of pure integrators** (poles at the origin) in the open-loop transfer function $G(s)H(s)$.

System Type	Open-Loop $G(s)H(s)$	Steady-State Error Constants
Type 0	No integrator	Position constant $K_p = \lim_{s\to 0} G(s)H(s)$
Type 1	One integrator	Velocity constant $K_v = \lim_{s\to 0} sG(s)H(s)$
Type 2	Two integrators	Acceleration constant $K_a = \lim_{s\to 0} s^2G(s)H(s)$

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4.3 Steady-State Errors for Standard Inputs

Input Type	$R(s)$	Type 0	Type 1	Type 2
Step	$1/s$	$e_{ss} = 1/(1+K_p)$	0	0
Ramp	$1/s^2$	∞	$e_{ss} = 1/K_v$	0
Parabolic	$1/s^3$	∞	∞	$e_{ss} = 1/K_a$

4.4 Example

Given an open-loop transfer function:

$$G(s)H(s) = \frac{10}{s(s+2)}$$

- The system has **one pole at the origin → Type 1 system**.
- Compute error constants:

$$K_v = \lim_{s\to 0} s.G(s).H(s) = \lim_{s\to 0} \frac{10s}{s(s+2)} = \frac{10}{2} = 5$$

For a **ramp input**, $e_{ss} = 1/K_v = 0.2$.

4.5 Influence of Feedback Gain

Increasing the loop gain K improves accuracy:

- Higher $K_p, K_v, K_a \Rightarrow$ smaller e_{ss}
- But it can **reduce stability margins** and cause overshoot or oscillations. Hence, there is a trade-off between **accuracy and stability**.

4.6 Stability, Speed, and Accuracy - The Fundamental Trade-Off

12. **Speed vs. Stability:**
    - Increasing natural frequency ω_n Improves speed but can destabilize the system.
13. **Accuracy vs. Stability:**
    - Increasing gain reduces steady-state error but can make the system oscillatory.
14. **Speed vs. Accuracy:**
    - A faster system (high ω_n) responds quickly but may overshoot more, reducing precision.

4.7 Example: Step and Ramp Accuracy

Given:

$$G(s)H(s) = \frac{K}{s(s+3)}$$

15. **System type:** One integrator → **Type 1**

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16. **Error constants:**

$$K_v = \lim_{s\to 0} s.G(s)H(s) = \frac{K}{3}$$

17. **For a ramp input:**

$$e_{ss} = \frac{1}{K_v} = \frac{3}{K}$$

If $K = 30 \rightarrow e_{ss} = 0.1$.

Observation:
Increasing K tenfold reduces e_{ss} tenfold but may cause oscillations - thus, gain tuning is essential.

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5. Impulse response and system characterization

5.1 Introduction

The **impulse response** forms the mathematical foundation for understanding **how any LTI system behaves**.

5.2 The Unit Impulse Function δ(t)

The **unit impulse function** (Dirac delta) is a mathematical idealization used to model a very short, intense input applied at time $t = 0$.

It is defined by two key properties:

$$\delta(t) = 0, \quad \text{for } t \neq 0$$

$$\int_{-\infty}^{+\infty} \delta(t)\, dt = 1$$

In practice, it represents a **very short pulse** of unit area.

The impulse is useful because:

- It contains **all frequency components**,
- It allows us to study the **intrinsic dynamic behavior** of the system independent of the input shape.

5.3 Impulse Response Definition

For a **Linear Time-Invariant (LTI)** system with transfer function $G(s)$:

$$H(s) = G(s)$$

If the input $x(t) = \delta(t)$, then the output $y(t) = h(t)$, where:

$$h(t) = \mathcal{L}^{-1}\{G(s)\}$$

This $h(t)$ is called the **impulse response** of the system.

It completely characterizes the system's time-domain behavior.

5.4 Relationship Between Input, Output, and Impulse Response

For any arbitrary input $x(t)$, the system output $y(t)$ can be determined by the **convolution integral**:

$$y(t) = \int_0^t h(\tau)x(t-\tau)\, d\tau$$

In Laplace form:

$$Y(s) = H(s)X(s)$$

Thus, the impulse response acts as a **kernel** or **weighting function** that describes how the system reacts to each instant of the input.

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5.5 Example 1 - Impulse Response of a First-Order System

Given:

$$G(s) = \frac{K}{\tau s + 1}$$

Impulse input: $X(s) = 1$

Output:

$$Y(s) = G(s)X(s) = \frac{K}{\tau s + 1}$$

$$h(t) = \frac{K}{\tau} e^{-t/\tau}, \quad t \geq 0$$

Interpretation:

- The output starts at a maximum value K/τ and decays exponentially to zero.
- The **time constant** τ determines how fast the system "forgets" the impulse.

5.6 Example 2 - Impulse Response of a Second-Order System

Given:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

Using Laplace inversion:

$$h(t) = \frac{\omega_n}{\sqrt{1-\xi^2}} e^{-\xi\omega_n t} \sin(\omega_d t)$$

where $\omega_d = \omega_n\sqrt{1-\xi^2}$.

Key Observations:

- $e^{-\xi\omega_n t}$: exponential envelope that controls damping.
- $\sin(\omega_d t)$: oscillatory part of response.
- ω_n and ξ directly shape the amplitude and oscillation decay.

For different damping ratios:

Damping Ratio	Type	Impulse Response Shape
$\xi = 0$	Undamped	Pure sine wave
$0 < \xi < 1$	Underdamped	Decaying sinusoid
$\xi = 1$	Critically damped	Aperiodic exponential
$\xi > 1$	Overdamped	Sum of decaying exponentials

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6. Identification of first- and second-order systems from the time response

6.1 Purpose of System Identification

System identification aims to:

- Determine a **mathematical model** of the system (transfer function)
- Predict system behavior under different inputs
- Design suitable controllers (P, PI, PID, etc.)

It's often done using:

18. **Time-response methods** (step, impulse, ramp responses)
19. **Frequency-response methods** (Bode plots, Nyquist plots)
20. **Analytical modeling** (from physical laws)

Here, we focus on **time-domain identification**.

6.2 Identifying a First-Order System

A first-order system's step response is:

$$y(t) = K\left(1 - e^{-t/\tau}\right)$$

The response is **monotonic**, **non-oscillatory**, and reaches a **steady-state value** asymptotically.

6.3 Graphical Method for First-Order Identification

Step 1: Measure the final steady-state value

$$y_{ss} = K \cdot x_{step}$$

For a unit step ($x_{step} = 1$), $K = y_{ss}$.

Step 2: Draw the tangent at the point of maximum slope

Extend this tangent line to intersect:

- The time axis → at $t = t_0$
- The final value line → at $t = t_1$

Then, the **time constant** τ is approximately:

$$\tau = t_1 - t_0$$

Step 3: Verify at the 63.2% point

The time at which the response reaches **63.2%** of y_{ss} is exactly τ:

$$y(t = \tau) = 0.632\, y_{ss}$$

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6.4 Example - First-Order Identification

Time (s)	Output (V)
0	0
1	1.8
2	3.2
3	4.0
4	4.6
5	4.9

From the data:

- $y_{ss} = 5.0$ V
- 63.2% of 5 = 3.16 V → occurs at $t = 2$ s

Hence:

$$K = 5, \quad \tau = 2\,s$$

$$G(s) = \frac{5}{2s+1}$$

Verification: step response $y(t) = 5(1 - e^{-t/2})$

6.5 Step Response Analysis for Second-Order Systems

Typical form:

$$y(t) = K\left[1 - \frac{1}{\sqrt{1-\xi^2}} e^{-\xi\omega_n t}\sin(\omega_d t + \phi)\right]$$

Key measurable quantities from the graph:

Quantity	Symbol	How to Measure	Formula
Peak time	t_p	Time of 1st peak	$t_p = \frac{\pi}{\omega_d}$
Overshoot	M_p	% above steady value	$M_p = e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \times 100\%$
Settling time	t_s	Time to stay within ±2%	$t_s = \frac{4}{\xi\omega_n}$

From measured M_p and t_p, ξ and ω_n Can be found.

6.6 Example - Second-Order System Identification

Measured from step response:

- $y_{ss} = 1.0$

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- $M_p = 16.3\%$
- $t_p = 0.5\,\text{s}$

Find ξ, ω_n, and $G(s)$.

Step 1: From overshoot:

$$M_p = e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \times 100 = 16.3$$

Convert:

$$0.163 = e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}}$$

$$\Rightarrow \xi = 0.5$$

Step 2: From peak time:

$$t_p = \frac{\pi}{\omega_d} = 0.5 \Rightarrow \omega_d = 6.283$$

$$\omega_n = \frac{\omega_d}{\sqrt{1-0.5^2}} = 7.25$$

Step 3: Write the transfer function

$$G(s) = \frac{K\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} = \frac{52.6K}{s^2 + 7.25s + 52.6}$$

For unit step, final value = 1 $\rightarrow K = 1$.

Final model:

$$G(s) = \frac{52.6}{s^2 + 7.25s + 52.6}$$

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6.7 Method Summary Table

System Type	Characteristic Response	Key Measurements	Identified Parameters
First-Order	Monotonic exponential rise	Final value, 63.2% time	K, τ
Second-Order Underdamped	Oscillatory with overshoot	M_p, t_p, t_s	ξ, ω_n, K
Second-Order Overdamped	Slow, no overshoot	Rise & settle time	$\omega_n, \xi > 1$
Critically Damped	Fast, no overshoot	Rise time	$\omega_n, \xi = 1$

6.8 Identifying Higher-Order Systems

If the response shows multiple slopes or oscillations, the system may be **third- or higher-order**.

To simplify:

- Identify **dominant poles** (slowest dynamics)
- Approximate with an equivalent first- or second-order model.

Example:

$$G(s) = \frac{10}{(s+1)(s+10)(s+20)} \approx \frac{10}{(s+1)(s+10)} \approx \frac{1}{s+1}$$

This approximation retains the main dynamic behavior.

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