Operational Amplifier Specifications

Gain, Frequency Response, and Dynamic Limitations

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Why Study Op-Amp Specifications?

Ideal vs. Real Op-Amps:

- **Ideal**: Simple analysis, perfect behavior
- **Real**: Practical limitations exist
- Ignoring specifications results in circuit failure

Key Questions:

- What gain can I actually achieve?
- How fast can my circuit respond?
- What frequencies can I amplify?
- What errors will appear in my output?

Real-World Applications:

- Audio amplifiers (20 Hz - 20 kHz)
- Active filters
- Analog sensor systems
- Control systems

Lecture Objectives

- Understand DC and AC specifications
- Analyze frequency response limitations
- Apply slew rate constraints
- Select appropriate op-amps for applications

Overview of Key Specifications

Category	Parameter	Typical Value (741)
DC Specs	Open-loop gain A_0	$200{,}000$ (106 dB)
	Input offset voltage V_{OS}	1–5 mV
	Input bias current I_B	80 nA
AC Specs	Gain-bandwidth product (GBW)	1 MHz
	Unity-gain frequency f_t	1 MHz
	Phase margin	60°
Dynamic	Slew rate (SR)	0.5 V/μs
	Full-power bandwidth	8 kHz
Other	CMRR	90 dB
	PSRR	80 dB

Note

These are **typical values for the 741 op-amp**. Modern op-amps offer better performance

Open-Loop Gain: Finite, Not Infinite

Open-Loop Gain A_0:

$$v_{out} = A_0(v_+ - v_-)$$

Real vs. Ideal:

- **Ideal**: $A_0 = \infty$
- **Real**: $A_0 = 10^5$ - 10^6 (100-120 dB)

Typical Values:

- 741: $A_0 \approx 200{,}000$ (106 dB)
- LM324: $A_0 \approx 100{,}000$ (100 dB)
- TL081: $A_0 \approx 200{,}000$ (106 dB)
- OP07: $A_0 \approx 1{,}000{,}000$ (120 dB)

Impact on Closed-Loop Gain:
For inverting amplifier with ideal gain:

$$G_{actual} = G_{ideal} \cdot \frac{A_0}{A_0 + 1 + |G_{ideal}|}$$

Example: $G_{ideal} = -100$, $A_0 = 100{,}000$

$$G_{actual} = -100 \cdot \frac{100{,}000}{100{,}101} \approx -99.9$$

Design Rule

For accurate gain, choose op-amp with:

$$A_0 \gg |G_{closed-loop}|$$

Rule of thumb: $A_0 > 100 \times |G|$

Input Referred Offset Voltage

Definition:
Input offset voltage V_{OS} is the **differential voltage** required at the inputs to force $v_{out} = 0$.

Physical Cause:

- ☹ Transistor mismatches inside IC
- ☹ Manufacturing variations

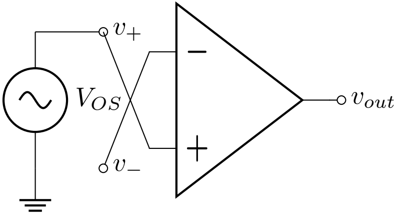

Figure 1: Offset voltage model

Key Characteristics:

- ☹ **Sample-to-sample variation**: Each IC has different V_{OS}
- ☹ **Not predictable**: Cannot know exact value without measurement
- ☺ **Datasheet specifies range**: Typical and maximum values given
- ☺ **Feedback helps**: Not critical when op-amp is in negative feedback

Effect in Non-Inverting Amplifier:

$$V_{out,offset} = V_{OS} \cdot G$$

Example: $V_{OS} = 2$ mV, $G = 100$

$$V_{out,offset} = 2 \text{ mV} \times 100 = 200 \text{ mV}$$

Open-Loop Frequency Response

Single-Pole Rolloff:
Most op-amps have internally compensated frequency response:

$$A(f) = \frac{A_0}{1 + jf/f_b}$$

where:

- A_0 = DC open-loop gain
- f_b = break frequency (3-dB point)

Magnitude Approximation:

- $f < f_b$: $|A| \approx A_0$ (flat)
- $f > f_b$: $|A| \approx A_0 f_b / f$ (-20 dB/decade)

Bode Plot - Open Loop:

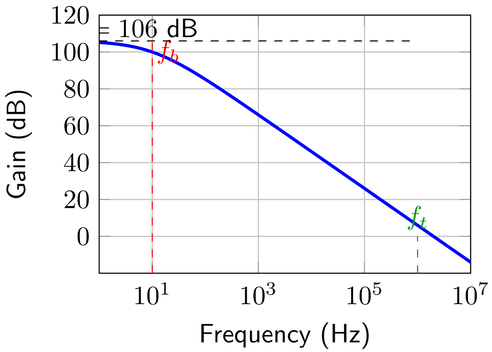

Figure 2: Typical 741 open-loop response

Gain-Bandwidth Product

Unity-Gain Frequency f_t:
Frequency where $|A(f_t)| = 1$ (0 dB):

$$f_t = A_0 \cdot f_b$$

Gain-Bandwidth Product (GBW):
For frequencies $f \gg f_b$:

$$|A(f)| \cdot f = A_0 \cdot f_b = f_t = \text{constant}$$

Example - 741:

- $A_0 = 200{,}000$ (106 dB)
- $f_b = 5$ Hz
- $f_t = 200{,}000 \times 5 = 1$ MHz
- GBW $= 1$ MHz

Closed-Loop Bandwidth:
For closed-loop gain G:

$$f_{-3dB} = \frac{f_t}{G}$$

Gain-Bandwidth Tradeoff

Higher gain $\rightarrow$ lower bandwidth!

$$G \times BW = f_t = \text{constant}$$

Examples (741, $f_t = 1$ MHz):

Gain	Bandwidth
1	1 MHz
10	100 kHz
100	10 kHz
1000	1 kHz

Closed-Loop Frequency Response

Non-Inverting Amplifier:

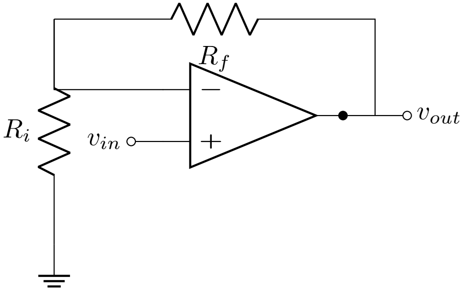

Figure 3: Non-inverting amplifier

$$G = 1 + \frac{R_f}{R_i}$$

$$f_{-3dB} = \frac{f_t}{G}$$

Frequency Response for Different Gains:

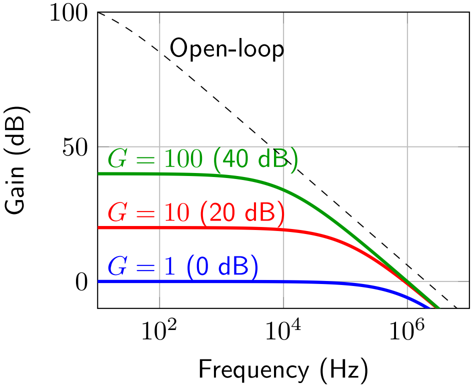

Figure 4: Closed-loop response for various gains

Phase Margin and Stability

Phase Margin (PM):
Amount of additional phase shift (beyond $-180°$) at unity-gain frequency before instability:

$$PM = 180° + \phi(f_t)$$

Stability Criteria:

- PM $> 45°$: stable, good damping
- PM $\approx 60°$: optimal (typical design)
- PM $< 30°$: marginal, may oscillate
- PM $\leq 0°$: unstable

Bode Plot - Phase Response:

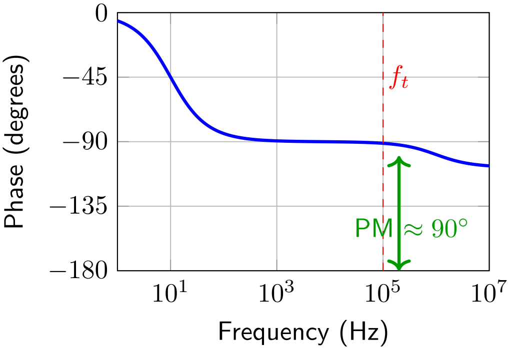

Figure 5: Phase response showing phase margin

Small Signal AC Model

Frequency-Dependent Model:

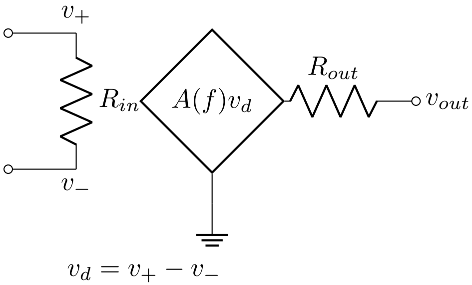

Figure 6: Small-signal AC model

Frequency-Dependent Gain:

$$A(f) = \frac{A_0}{1 + jf/f_b}$$

Typical Parameter Values:

Parameter	Typical (741)
R_{in}	2 MΩ
R_{out}	75 Ω
A_0	200,000 V/V
f_b	5 Hz
f_t	1 MHz

Analysis Steps:

1. Replace op-amp with AC model
2. Apply frequency-dependent $A(f)$
3. Solve for transfer function
4. Determine bandwidth from $|H(f)|$

Closed-Loop Gain Derivation

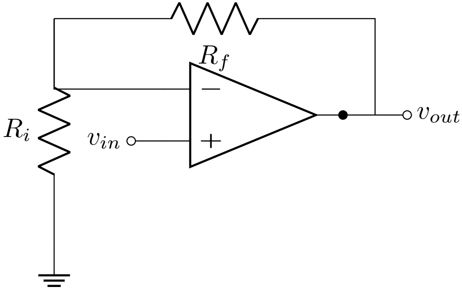

Figure 7: Non-inverting amplifier

$$\beta = \frac{R_i}{R_i + R_f}$$

$$G_{ideal} = \frac{1}{\beta} = 1 + \frac{R_f}{R_i}$$

Actual Closed-Loop Gain:
With finite open-loop gain $A(f)$:

$$G(f) = \frac{v_{out}}{v_{in}} = \frac{A(f)}{1 + A(f)\beta}$$

Substituting $A(f) = A_0/(1 + jf/f_b)$:

$$G(f) = \frac{G_{ideal}}{1 + jf/f_{-3dB}}$$

where the 3-dB frequency is:

$$f_{-3dB} = f_b(1 + A_0\beta) \approx A_0\beta f_b = \frac{f_t}{G_{ideal}}$$