



EE115 Analog Circuits Non-Ideal Op Amp

Prof. Haoyu Wang
Office: SIST Bldg. 3-530
wanghy@shanghaitech.edu.cn



Outline



- Non-Ideal Op Amp
 - DC Imperfections
 - Finite Open-Loop Gain and Bandwidth
 - Large-Signal Operation of Op Amps
- Reading: SEDTRA/SMITH book pages 97-116



Review: Ideal Op-Amp



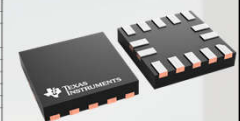
- Infinite input impedance
 - No current goes in, **virtual open circuit**
- Zero output impedance
- Infinite open-loop gain, A
 - **Virtual short circuit** between the inverting and non-inverting input ports
- Infinite bandwidth
- Infinite common-mode rejection
 - Common mode rejection ratio (CMRR)



Electrical Characteristics of a Real Op-Amp



PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
OFFSET VOLTAGE					
V_{OS}	Input offset voltage $V_S = 5\text{ V}$ $V_S = 5\text{ V}$, $T_A = -40^\circ\text{C}$ to 125°C		± 0.3	± 1.6	mV
dV_{OS}/dT	Drift $V_S = 5\text{ V}$, $T_A = -40^\circ\text{C}$ to 125°C		± 0.53		$\mu\text{V}/^\circ\text{C}$
PSRR	Power-supply rejection ratio $V_S = 1.8\text{ V} - 5.5\text{ V}$, $V_{OS} = (V_-)$ Channel separation, DC		± 7	± 80	$\mu\text{V/V}$
INPUT VOLTAGE RANGE					
V_{OS}	Common-mode voltage range $V_S = 1.8\text{ V}$ to 5.5 V $V_S = 5.5\text{ V}$, $(V_-) = 0.1\text{ V} + V_{OS} < (V_+) - 1.4\text{ V}$, $T_A = -40^\circ\text{C}$ to 125°C	$(V_-) - 0.1$		$(V_+) + 0.1$	V
CMRR	Common-mode rejection ratio $V_S = 1.8\text{ V}$, $(V_-) = 0.1\text{ V} + V_{OS} < (V_+) - 1.4\text{ V}$, $T_A = -40^\circ\text{C}$ to 125°C		80	103	dB
			57	87	
				88	
INPUT BIAS CURRENT	I_B Input bias current I_{OS} Input offset current $V_S = 1.8\text{ V}$, $V_{OS} = 0.1\text{ V}$ to 1.8 V , $T_A = -40^\circ\text{C}$ to 125°C		± 0.5		pA
			± 0.05		
NOISE					
E_n	Input voltage noise (peak-to-peak) $V_S = 5\text{ V}$, $f = 0.1\text{ Hz}$ to 10 Hz		4.77		μV_{rms}
e_n	Input voltage noise density $V_S = 5\text{ V}$, $f = 10\text{ kHz}$		10		nV/ $\sqrt{\text{Hz}}$
i_n	Input current noise density $V_S = 5\text{ V}$, $f = 1\text{ kHz}$		16		pA/ $\sqrt{\text{Hz}}$
INPUT CAPACITANCE					
C_{IP}	Differential $f = 1\text{ kHz}$		23		pF
C_{IC}	Common-mode		4		pF
OPEN-LOOP GAIN					
A_{OL}	Open-loop voltage gain $V_S = 1.8\text{ V}$, $(V_-) = 0.04\text{ V} + V_{OS} < (V_+) - 0.04\text{ V}$, $R_L = 10\text{ k}\Omega$ $V_S = 5.5\text{ V}$, $(V_-) = 0.05\text{ V} + V_{OS} < (V_+) - 0.05\text{ V}$, $R_L = 10\text{ k}\Omega$		100		dB
			104	130	
				100	
				130	



TLV90641, 5.5-V, 10-MHz, operational amplifier

Switching Characteristics of a Real Op-Amp

FREQUENCY RESPONSE

GBP	Gain bandwidth product	$V_S = 5\text{ V}, G = +1$	10	MHz
ϕ_m	Phase margin	$V_S = 5\text{ V}, G = +1$	55	°
SR	Slew rate	$V_S = 5\text{ V}, G = +1$	6.5	V/ μs
t_s	Settling time	To 0.1%, $V_S = 5\text{ V}, 2\text{-V step}, G = +1, C_L = 100\text{ pF}$	0.5	μs
t_{OR}	Overload recovery time	To 0.01%, $V_S = 5\text{ V}, 2\text{-V step}, G = +1, C_L = 100\text{ pF}$	1	μs
THD + N	Total harmonic distortion + noise ⁽¹⁾	$V_S = 5.5\text{ V}, V_{CM} = 2.5\text{ V}, V_O = 1\text{ V}_{RMS}, G = +1, f = 1\text{ kHz}$	0.0008%	

OUTPUT

V_O	Voltage output swing from supply rails	$V_S = 5.5\text{ V}, R_L = 10\text{ k}\Omega$	20	mV
		$V_S = 5.5\text{ V}, R_L = 2\text{ k}\Omega$	60	mV
I_{SC}	Short-circuit current	$V_S = 5\text{ V}$	± 50	mA
Z_O	Open-loop output impedance	$V_S = 5\text{ V}, f = 10\text{ MHz}$	100	Ω

Imperfections in Practical Op-Amps

- Finite open-loop gain ($A_o < \infty$)
- Finite input resistance ($R_i < \infty$)
- Non-zero output resistance ($R_o > 0$)
- Finite bandwidth
- Offset voltage
- Input bias and offset currents

Offset Voltage

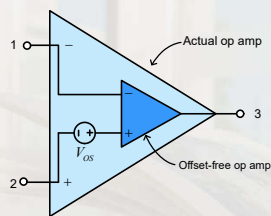


Fig. Circuit model for an op amp with input offset voltage V_{OS} .

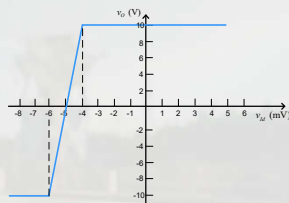


Fig. Transfer characteristic of an op amp with $V_{OS} = 5\text{ mV}$ and output saturation levels $\pm 10\text{ V}$.

Causes: mismatches in the input differential stage

Trimming of Offset Voltage

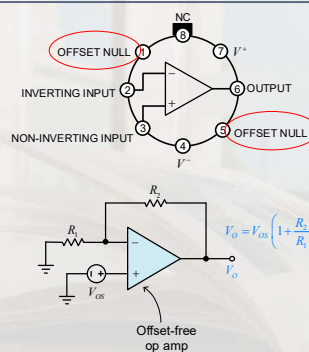


Fig. Evaluating the output dc offset voltage due to V_{OS} in a closed-loop amplifier.

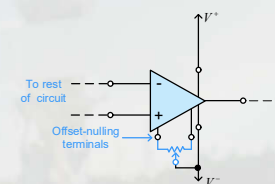
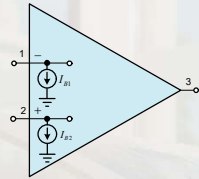


Fig. output dc offset voltage of an op amp can be trimmed to zero by connecting a potentiometer to the two offset-nulling terminals.

Input Bias Currents and Offset Currents*



Input bias current:

$$I_B = (I_{B1} + I_{B2})/2$$

Input offset current

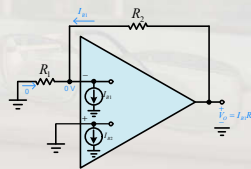
$$I_{OS} = |I_{B1} - I_{B2}|$$

Typical CMOS Op amps:

- > $I_B < 1 \text{ pA}$
- > $I_{OS} < 0.1 \text{ pA}$

How to measure I_B ?

$$V_O = I_{B1}R_2 \cong I_B R_2$$



9/18

Reducing the Effect of Input Bias Currents *

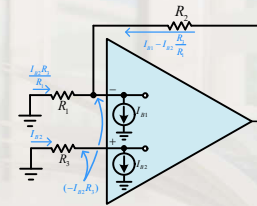


Fig. Reducing the effect of the input bias currents by introducing a resistor R_3 .

Introduce R_3 in series with the non-inverting input

$$V_O = -I_{B2}R_3 + R_2(I_{B1} - I_{B2}R_3/R_1) *$$

If $I_{B1} = I_{B2} = I_B$,

$$V_O = I_B [R_2 - R_3(1 + R_2/R_1)]$$

Reduce V_O to 0 by designing R_3

$$R_3 = \frac{R_2}{1 + R_2/R_1} = \frac{R_1 R_2}{R_1 + R_2}$$

Insert into *,

$$V_O = I_{OS}R_2$$

10/18

Frequency Response of Open-Loop Op Amp

Single pole response with a dominant pole at ω_b

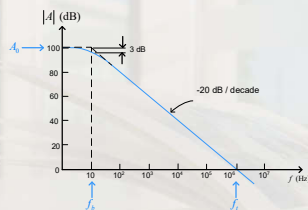


Fig. Open-loop gain of a typical general-purpose, internally compensated op amp.

Open-loop transfer function

$$A(j\omega) = \frac{A_o}{1 + j\omega/\omega_b}$$

At higher frequency

$$A(j\omega) \cong \frac{A_o \omega_b}{j\omega}$$

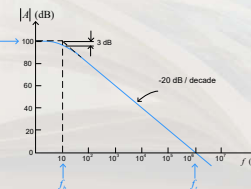
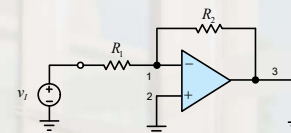
$$|A(j\omega)| = \frac{A_o \omega_b}{\omega}$$

Unity-gain bandwidth

$$\omega_t = A_o \omega_b$$

11/18

Frequency Response of Closed-Loop Op Amp (Inverting Amplifier Example)



Close-loop transfer function:

$$\frac{V_O}{V_i} = \frac{-R_2/R_1}{1 + (1 + R_2/R_1)/A}$$

Include the bandwidth-limited A:

$$A(s) = \frac{A_o}{1 + s/(\omega_t/A_o)} = \frac{A_o}{1 + A_o s/\omega_t}$$

$$\frac{V_O(s)}{V_i(s)} = \frac{-R_2/R_1}{1 + \frac{1}{A_o}(1 + R_2/R_1) + \frac{s}{\omega_t/(1 + R_2/R_1)}}$$

If: $A_o \gg 1 + R_2/R_1$,

$$\frac{V_O(s)}{V_i(s)} \cong \frac{-R_2/R_1}{1 + \frac{s}{\omega_t/(1 + R_2/R_1)}}$$

Close-loop corner frequency:

$$\omega_{3dB} = \frac{\omega_t}{1 + R_2/R_1}$$

GBW unchanged

12/18

Frequency Response of Closed-Loop (Noninverting Amplifier Example)

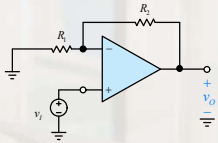
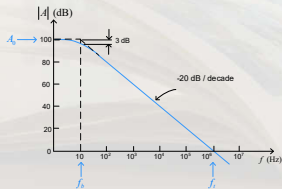


Figure 2.12 The noninverting configuration.



- Close-loop transfer function:

$$\frac{V_o}{V_i} = \frac{1 + R_2/R_1}{1 + (1 + R_2/R_1)/A}$$

- Include the bandwidth-limited A:

$$A(s) = \frac{A_o}{1 + s/(\omega_t/A_o)}$$

$$\frac{V_o(s)}{V_i(s)} \cong \frac{1 + R_2/R_1}{1 + \omega_t/(1 + R_2/R_1)}$$

- Close-loop corner frequency:

$$\omega_{3dB} = \frac{\omega_t}{1 + R_2/R_1}$$

- GBW** unchanged

Output Saturation

- The output voltage swing is limited by
 - 1. **Saturation voltage** (usually 1~2V lower than power supply voltage)
 - 2. **Maximum output current** (in case of small load resistance)
- Output waveform appears to be **"clipped"** when either condition happens

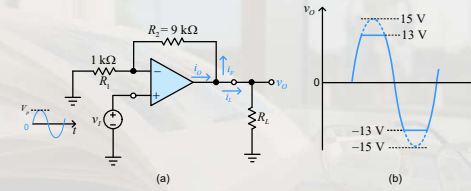


Fig. (a) A noninverting amplifier with a nominal gain of 10 V/V designed using an op amp that saturates at ± 15 -V output voltage and has ± 20 -mA output current limits. (b) When the input sine wave has a peak of 1.5 V, the output is clipped off at ± 13 V.

Slew Rate

- Amplifier output is limited by **"slew rate"**: maximum rate of change possible at output

$$SR = \left. \frac{dv_o}{dt} \right|_{\max}$$

- SR is specified in datasheet in V/ μ s.

- Note: SR limit is different from bandwidth limit:

- Limited **bandwidth** is a **linear** phenomenon, it does not result in changing the shape of an input sinusoid
- SR** limitation can cause **nonlinear** distortion to input sinusoidal signal.

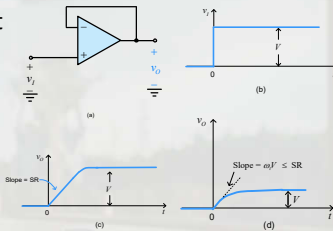
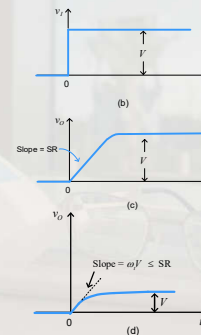


Fig. (a) Unity-gain follower. (b) Input step waveform. (c) Linearly rising output waveform obtained when the amplifier is slew-rate limited. (d) Exponentially rising output waveform obtained when $\omega_t V_i$ is sufficiently small so that the initial slope ($\omega_t V_i$) is smaller than or equal to SR.

Comparison of Slew Rate and Bandwidth Limits

- For a **step response**, both SR and bandwidth limits cause the output to rise with a finite slope, but there is an important difference:
- Slew rate limited output:
 - Slope = SR at all times
- Bandwidth limited output:
 - Slope = $\omega_t V_{exp}(-\omega_t t) < SR$
- (V: steady state output voltage)



Transfer function:

$$\frac{V_o(s)}{V_i(s)} = \frac{1}{1 + \frac{s}{\omega_t}}$$

Time domain:

$$v_o(t) = V(1 - e^{-\omega_t t})$$

Full-Power Bandwidth

- For sinusoidal input to unity-gain follower:

$$v_i = V_i \sin \omega t$$

- Rate of change:

$$\frac{dv_i}{dt} = V_i \omega \cos \omega t \leq SR$$

- **Full-power bandwidth:**

The frequency at which SR-limited distortion starts to occur for an output sinusoid with maximum rated output voltage, V_{omax} ,

$$\omega_M V_{omax} = SR$$

$$f_M = \frac{SR}{2\pi V_{omax}}$$

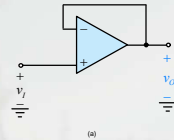


Fig. (a) Unity-gain follower.

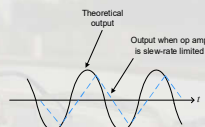


Fig. Effect of slew-rate limiting on output sinusoidal waveforms.

Summary

- Open loop gain
- Input impedance
- Output impedance
- Input offset & Bias
- CMRR
- Saturation
- Unity-gain bandwidth
- Slew rate
- Full-power bandwidth