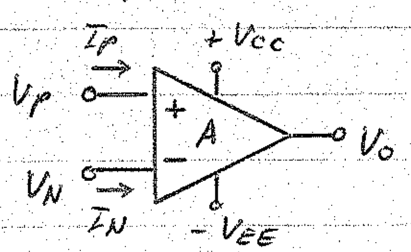
VIII Operational Amplifiers (Opamps)

8.1 The ideal Opamp

symbol



Voltage Gain:

$$\boxed{V_o = A \cdot (V_P - V_N)}$$

$$A \rightarrow \infty$$

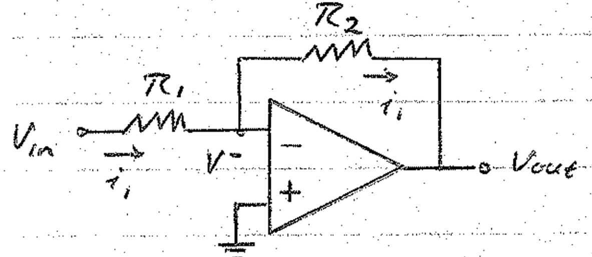
$$\therefore \boxed{V_P = V_N}$$

Currents:

$$\boxed{I_P = I_N = 0}$$

$$\therefore R_{in\,diff} \rightarrow \infty$$

Example 1: Inverting Amplifier



Since $A \rightarrow \infty$

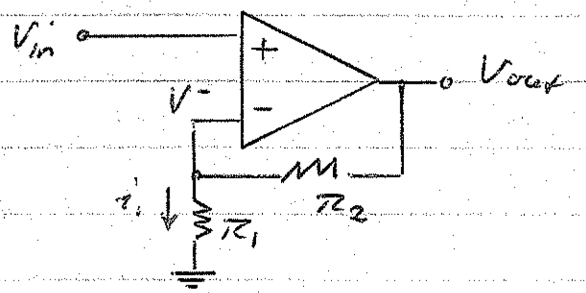
$$\boxed{V^- = 0}$$

$$\therefore \left| \begin{array}{l} V_{in} = i_1 R_1 \\ V_{out} = -i_1 R_2 \end{array} \right|$$

$$\therefore \boxed{T = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}}$$

$$\boxed{R_{in} = \frac{V_{in}}{i_1} = R_1}$$

Example 2: Noninverting Amplifier



Since $A \to \infty$

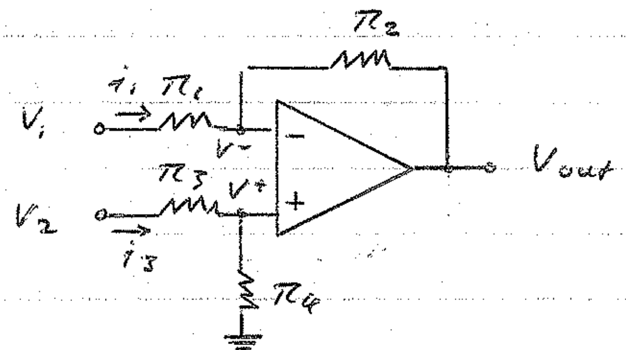
$\therefore \left\| V^- = V_{in} \right\|$

$$\therefore \left| \begin{array}{l} V_{out} = i_1 (R_1 + R_2) \\ V_{in} = i_1 R_1 \end{array} \right|$$

$$\therefore \left\| T = \frac{V_{out}}{V_{in}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} \right\|$$

$$\left\| R_{in} \to \infty \right\|$$

Example 3: Difference Amplifier



Since $A \to \infty$

$$\therefore \left\| \begin{array}{l} V^- = V^+ \\ V^+ = V_2 \dfrac{R_4}{R_3 + R_4} \end{array} \right\|$$

$$\therefore \quad V_{out} = V^+ - i_1 R_2 = V_2 \frac{R_4}{R_3 + R_4} - V_1 \frac{R_2}{R_1} + V_2 \frac{R_4}{R_3 + R_4} \frac{R_2}{R_1}$$

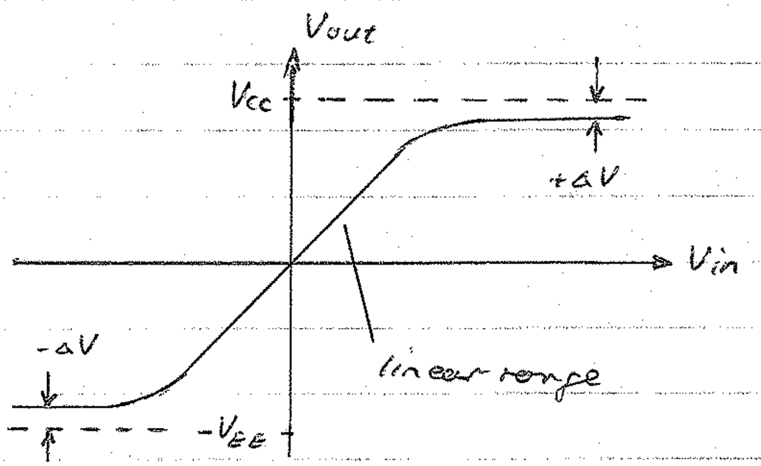
$$\left\| V_{out} = V_2 \frac{R_4}{(R_3 + R_4)} \frac{(R_1 + R_2)}{R_1} - V_1 \frac{R_2}{R_1} \right\|$$

$$\left\| R_{in_1} \Big|_{V_2 = 0} = R_1 \right\| \quad \left\| R_{in_2} = R_3 + R_4 \right\|$$

8.2 Non-Ideal Opamp

Parameter		ideal	actual (e.g. LF 353)
Open-loop Gain	A_o	∞	$10^5 = 100\,dB$
Bandwidth	BW	∞	5×10^6 Hz
Input Res.	R_{in}	∞	$> 10^{12}\ \Omega$
Output Res.	R_{out}	0	$50\ \Omega$
Offset Volt.	V_{os}	0	$1 \div 3$ mV
Slew Rate	SR	∞	$8\ V/\mu s$
Eq. Input Noise	V_n	0	$10\ nV/\sqrt{Hz}$

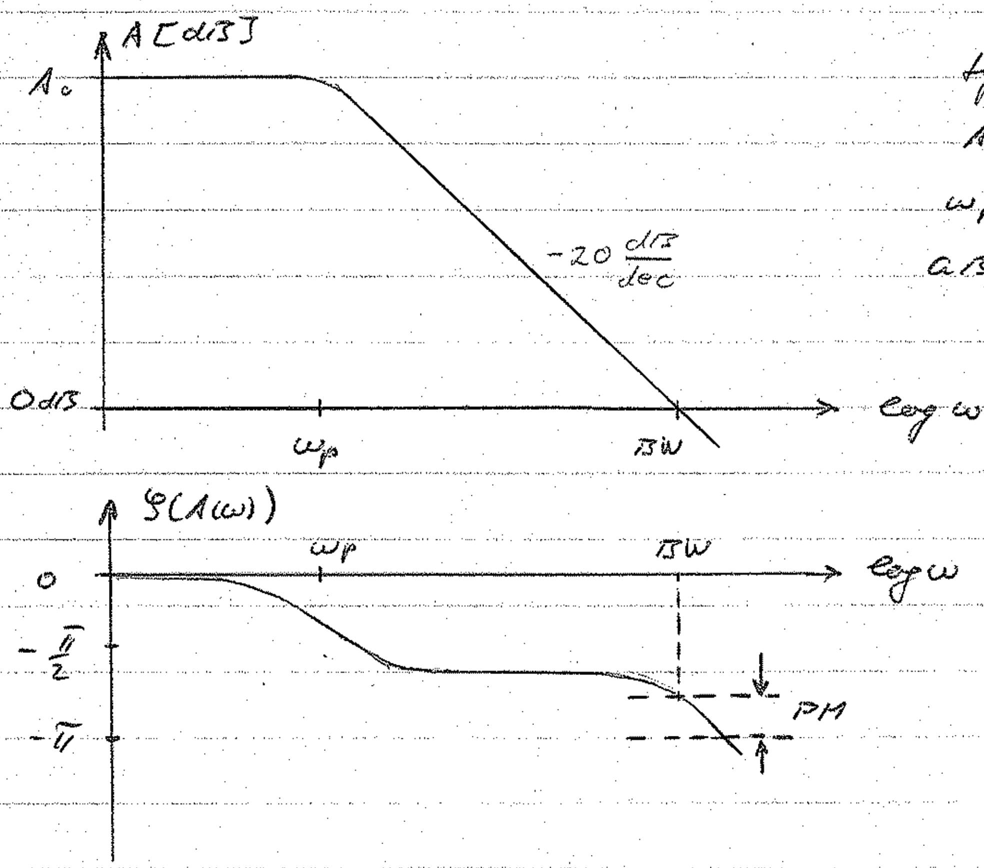
Voltage Transfer Characteristic



$$A_o = \frac{dV_{out}}{dV_{in}}$$

The output voltage of a typical Opamp is a few tenth of a volt less than the supply rails. In order to maximize the linear range, the input voltage should swing around the center of the two supply voltages.

Gain vs Frequency



typical

$A_0 \approx 100\,dB$

$\omega_p = 2\pi \times 50\,Hz$

$GB = 2\pi \times 5\,MHz$

typical

$PM \geq 45°$

First-order Gain Model

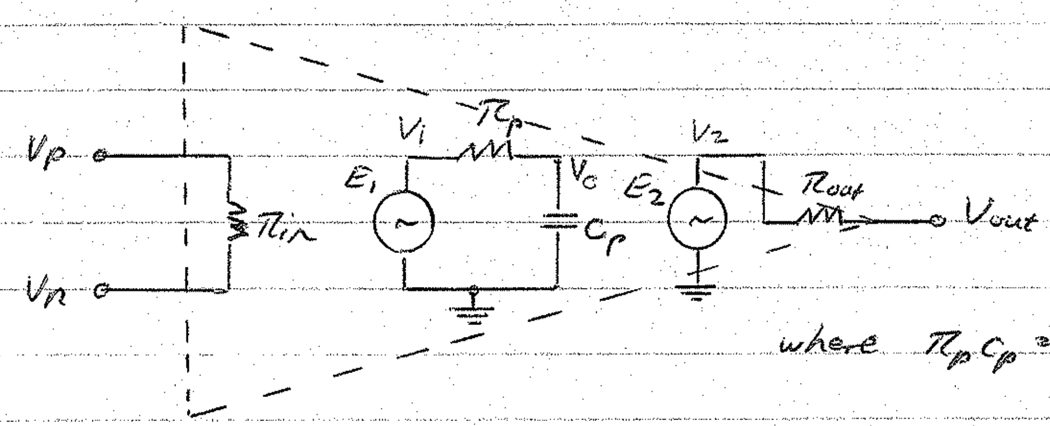
$$\left\| A(s) = \frac{A_0\,\omega_p}{\omega_p + s} = \frac{A_0}{1 + s/\omega_p} \right\|$$

A_0: Open-loop Gain

$A_0\omega_p$: Gain Bandwidth Product GBW

Note: Along the constant slope of the Gain vs. Frequency function, the Gain Bandwidth Product remains constant (GBW = BW)

Macromodel for finite Gain Bandwidth



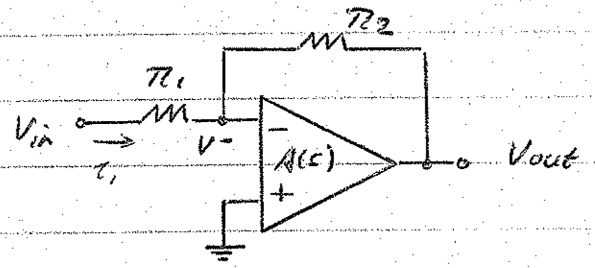
where $R_p C_p = \frac{1}{\omega_p}$

SPICE description ($\omega_p = 2\pi \times 50Hz$)

```
.subckt opamp Vp Vn Vout
Rin Vp Vn 1T
E1 V1 0 Vp Vn 100k
Rp V1 Vc 1
Cp Vc 0 3.3m
E2 V2 0 Vc 0 1
Rout V2 Vout 50
.ends opamp
```

<u>Note:</u> The above model is strictly linear and does not mimic any nonlinear behavior such as slewing or saturation close to either supply rail.

Example 4 Inverting Amplifier with non-ideal Opamp



Note: We assume the Opamp input resistance to be infinite

Equations:

$$\begin{aligned} i_1 &= \frac{1}{R_1}(V_{in} - V^-) & (1)\\ V_{out} &= -A(s)\cdot V^- & (2)\\ V^- &= V_{out} + i_1 R_2 & (3) \end{aligned}$$

Solution

$$V_{out} = -V_{in}\frac{R_2}{R_1}\frac{A(s)}{1+\frac{R_2}{R_1}+A(s)} \qquad \text{where } A(s) = \frac{A_0}{1+s/\omega_p}$$

Inserting the first-order gain expression yields

$$V_{out} = -V_{in}\frac{R_2}{R_1}\frac{A_0}{\left[1+\frac{R_2}{R_1}+A_0+s/\omega_p\left(1+\frac{R_2}{R_1}\right)\right]}$$

Replace $\frac{R_2}{R_1}$ by β and divide numerator and denominator by A_0

$$\therefore \quad V_{out} = -V_{in}\,\beta\,\frac{1}{\left[1+\frac{1+\beta}{A_0}+s\,\frac{1+\beta}{A_0\omega_p}\right]}$$

$$\omega_\beta = \left(1+\frac{1+\beta}{A_0}\right)\frac{A_0\omega_p}{(1+\beta)}$$

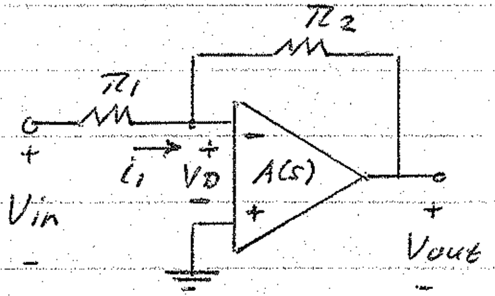
$$\text{dc Gain: } A_\beta = \frac{\beta}{1+\frac{1+\beta}{A_0}}$$

If $A_0 \gg \beta$ then

$$\omega_\beta \cong \frac{A_0\omega_p}{1+\beta}$$

$$A_\beta = \beta$$

Inverting Amplifier with Op-amp



where

$$\boxed{A(s) = \frac{A_0}{1 + s/\omega_0}}$$

3 unknowns $\therefore$ 3 equations needed

$$i_1 = \frac{1}{R_1}[V_{in} - V_D] \quad (1) \text{ Ohm}$$

$$V_D = V_{out} + i_1 \cdot R_2 \quad (2) \text{ KVL}$$

$$V_{out} = -V_D \cdot A(s) \quad (3) \text{ device}$$

Solution:

$$\boxed{V_{out} = -V_{in} \frac{R_2}{R_1} \frac{1}{\left(1 + \frac{1}{A(s)} \frac{R_1 + R_2}{R_1}\right)}}$$

Inserting $A(s) = \frac{A_0}{1 + s/\omega_0}$ yields

$$\boxed{T(s) = \frac{V_{out}(s)}{V_{in}(s)} = -\frac{R_2}{R_1} \frac{1}{\left(1 + \frac{1}{A_0}\left[1 + \frac{R_2}{R_1}\right] + s\frac{1}{A_0 \omega_0}\left[1 + \frac{R_2}{R_1}\right]\right)}}$$

This complex function has a pole ω_p of

$$\boxed{\omega_p = -\omega_0 \left[\frac{A_0}{1 + \frac{R_2}{R_1}} + 1\right]}$$

The DC gain G_o of this function $T(s)$ is

$$G_o = -\frac{R_2}{R_1}\frac{1}{\left(1+\frac{1}{A_o}\left[1+\frac{R_2}{R_1}\right]\right)}$$

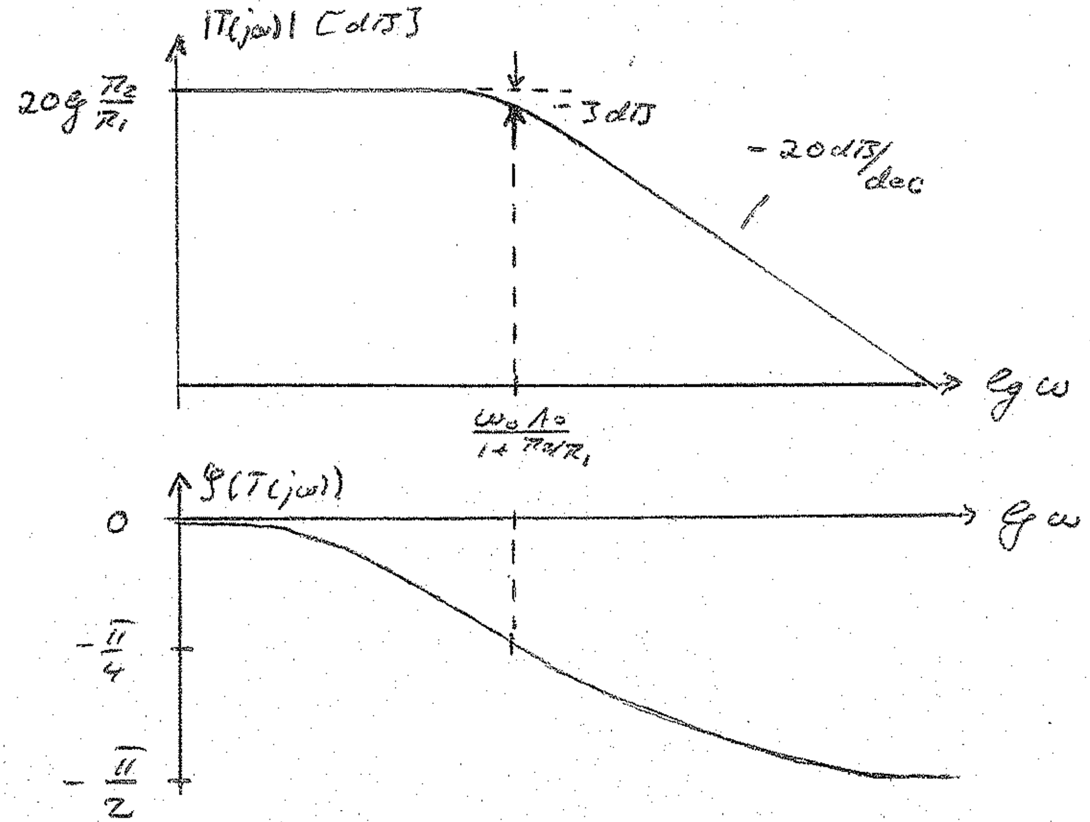
Since $A_o \gg 1$ we can approximate the pole location and the DC gain by

$$\omega_p \cong -\frac{\omega_o A_o}{1+\frac{R_2}{R_1}}$$

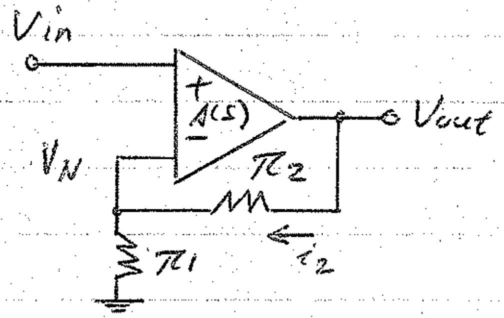
and

$$G_o \cong -\frac{R_2}{R_1}\frac{1}{1+\frac{1}{A_o}\frac{R_2}{R_1}} \approx -\frac{R_2}{R_1}$$

Bode Plot of Gain function $T(s)$



Example 4a Noninverting amplifier with non-ideal opamp



$$\boxed{A(s) = \frac{A_0}{1+s/p_0}}$$

Op amp: $V_{out} = (V_{in} - V_N) \cdot A(s)$

KVL: $V_{out} = i_2 (R_1 + R_2)$

Ohm's Law: $i_2 = \frac{V_N}{R_1}$

$$\therefore \; V_{out} = \left(V_{in} - V_{out} \frac{R_1}{R_1+R_2}\right) A(s)$$

$$\frac{V_{out}}{V_{in}} = \frac{A(s)}{1 + \frac{R_1}{R_1+R_2} A(s)} = \frac{R_1+R_2}{R_1} \; \frac{A(s)}{\frac{R_1+R_2}{R_1} + A(s)}$$

$$\boxed{\beta = \frac{R_1+R_2}{R_1}}$$

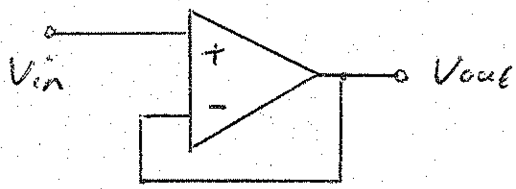
$$\therefore \; \boxed{\frac{V_{out}}{V_{in}} = \beta \, \frac{A_0}{A_0 + \beta(1+s/p_0)}}$$

DC Gain: $G_0 = \frac{\beta A_0}{A_0+\beta}$ $\qquad G_0 \approx \beta$

Pole: $\omega_p = (A_0+\beta) p_0 \frac{1}{\beta}$ $\qquad \omega_p \approx \frac{A_0 p_0}{\beta}$

$\therefore$ $\boxed{G_0 \cdot \omega_p = A_0 p_0}$ independent of β

Unity-Gain Amplifier with 2-pole Model



$$A(s) = \frac{A_0 p_1 p_2}{(s+p_1)(s+p_2)}$$

$$\frac{V_{out}}{V_{in}} = \frac{A(s)}{1+A(s)} = \frac{A_0 p_1 p_2}{(s+p_1)(s+p_2) + A_0 p_1 p_2}$$

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{A_0 p_1 p_2}{s^2 + s(p_1+p_2) + p_1 p_2 (1+A_0)}}$$

Poles:

$$\boxed{\begin{aligned} s &= -\frac{p_1+p_2}{2} \pm \frac{1}{2}\sqrt{(p_1+p_2)^2 - 4p_1p_2(1+A_0)} \\ &\cong -\frac{p_1+p_2}{2} \pm j\,\frac{1}{2}\sqrt{4p_1p_2A_0 - (p_1+p_2)^2} \end{aligned}}$$

If $p_2 = A_0 \cdot p_1$

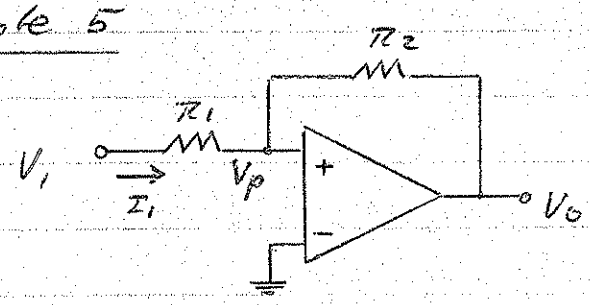
$$s \cong -p_1 \frac{1+A_0}{2} \pm j\,\frac{1}{2}\sqrt{4p_1^2 A_0^2 - p_1^2(1+A_0)^2}$$

$$\cong -p_1 \frac{A_0}{2} \pm j\, p_1 \frac{A_0}{2}\sqrt{4-1}$$

$$\boxed{s = -p_1 \frac{A_0}{2} \pm j\, p_1 \frac{A_0}{2}\sqrt{3}}$$

If $p_2 = h \cdot p_1$ $\quad h \gg 1$ $\quad$ then $\boxed{s = -p_1 \frac{h}{2} \pm j\, p_1 \frac{1}{2}\sqrt{4hA_0 - h^2}}$

Example 5 Schmitt Trigger



assume op-amp gain to be ideal, i.e. $A \to \infty$

Sketch the output voltage if the input signal V_1 is a bipolar triangular voltage with a peak value of 1V. and $R_2 = 10 \cdot R_1$. The op-amp possesses a ±5V supply.

Solution

circuit exhibits positive feedback!
Behavior is likely to be non-linear!
If V_p becomes positive, the output saturates at $+V_{Max}$
If V_p becomes negative, the output saturates at $-V_{Max}$

A) Transition from $+V_{Max} \to -V_{Max}$

equation for V_p: $\left| \begin{array}{l} I_1 = \dfrac{V_1 - V_p}{R_1} \\ V_p = V_0 + I_1 R_2 \end{array} \right|$ $\begin{array}{l} (KCL) \\ (KVL) \end{array}$

$$\therefore \left\| V_p = V_0 \frac{R_1}{R_1 + R_2} + V_1 \frac{R_2}{R_1 + R_2} \right\|$$

1. For transition $+V_{Max} \to -V_{Max}$ $\therefore V_0 \hat{=} +V_{Max}$

2. At trip-point $V_p = 0$

Condition for $+V_{Max} \rightarrow -V_{Max}$ transition

$$\left| +V_{Max} \frac{R_1}{R_1+R_2} = -V_1^- \frac{R_2}{R_1+R_2} \right|$$

or

$$\left\| V_1^- = -V_{Max} \frac{R_1}{R_2} \right\|$$

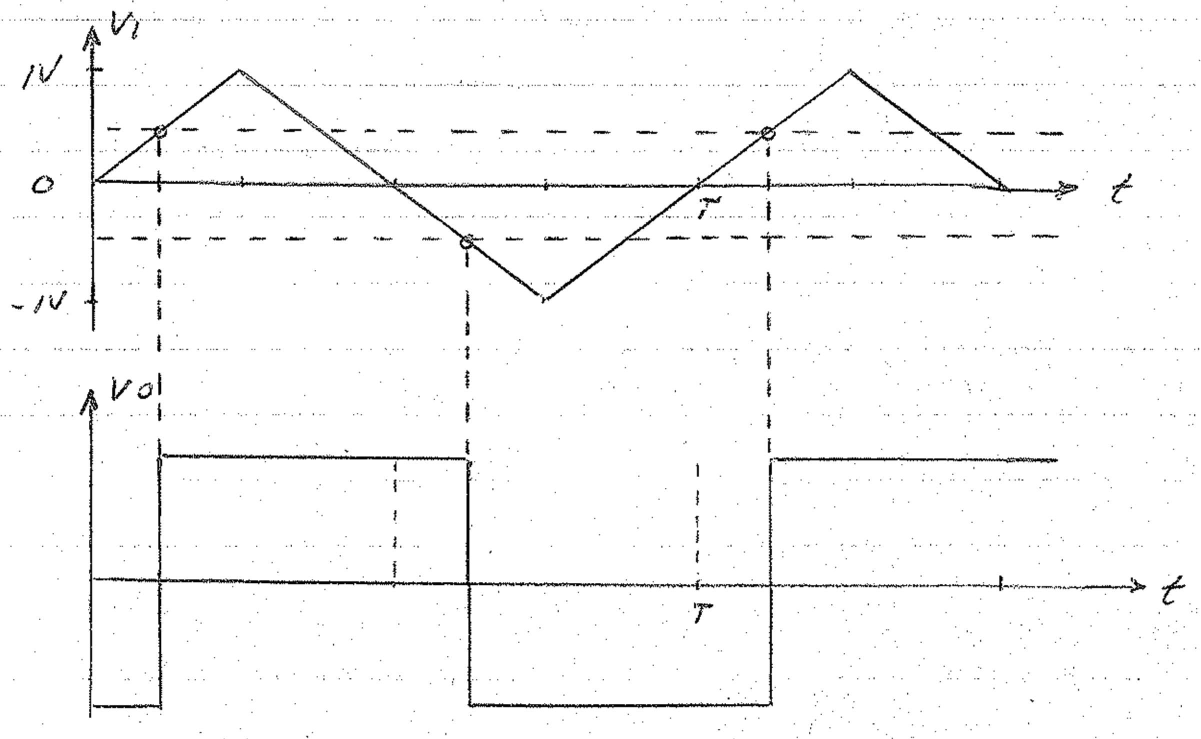
B) Transition from $-V_{Max} \longrightarrow +V_{Max}$

$$\left| -V_{Max} \frac{R_1}{R_1+R_2} = -V_1^+ \frac{R_2}{R_1+R_2} \right|$$

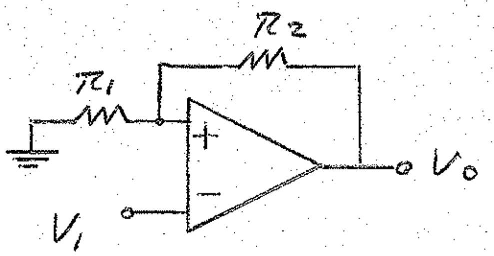
or

$$\left\| V_1^+ = +V_{Max} \frac{R_1}{R_2} \right\|$$

Thus, if $+V_{Max} = 5V$, $-V_{Max} = -5V$ and $\frac{R_1}{R_2} = \frac{1}{10}$ we have the following waveforms



Example 5a



Schmitt Trigger

Sketch the output voltage if the input signal represents a triangular voltage with a peak value of 1V. $R_2 = 10 \cdot R_1$; Op-amp saturation $\pm V_{Max}$

Solution

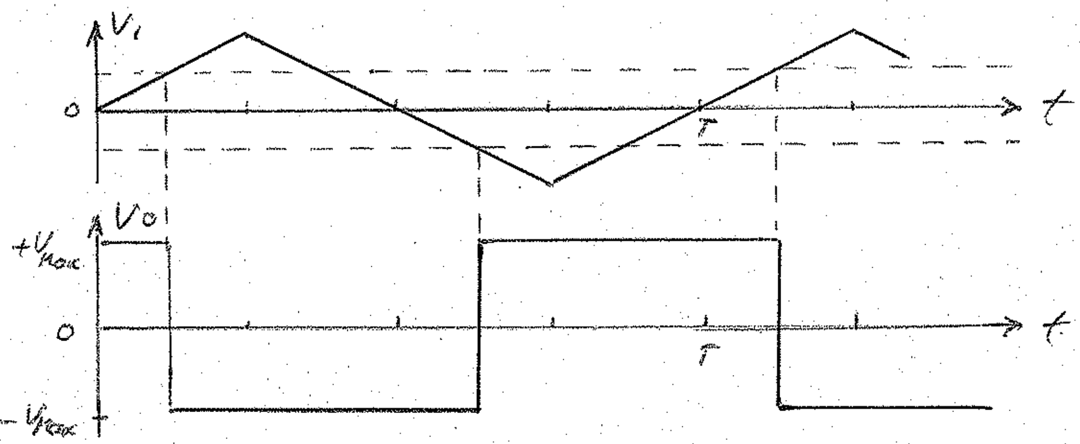
If the input is strongly negative, the output voltage will be equal to the pos. saturation voltage of the op-amp. On the other hand, if the input is strongly positive, the output will be equal to the neg. saturation voltage of the op-amp.

Trip-point neg. transition of output:

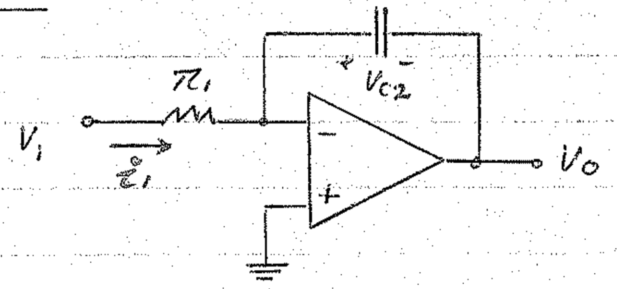
$$\boxed{V_1^- = V_{Max} \frac{R_1}{R_1 + R_2}}$$

Trip-point pos. transition of output

$$\boxed{V_1^+ = -V_{Max} \frac{R_1}{R_1 + R_2}}$$



Example 6



Ideal Integrator

assume op-amp ideal

Determine the voltage transfer function $T = \frac{V_o}{V_i}$ in the Laplace domain and in the time domain.

Solution

2 unknowns (I_1 and V_o) $\therefore$ 2 equations required

1. ohm's law $\quad i_1 = \frac{V_1}{R_1}$

2. Device eq. $\quad V_{C2} = -V_o = \begin{cases} \frac{1}{C_2} \int i_1(t)\,dt & \text{time domain} \\ \frac{1}{C_2}\,\frac{1}{s}\, i_1(s) & \text{Laplace domain} \end{cases}$

$$\therefore \quad \boxed{V_o = \begin{cases} -\frac{1}{R_1 C_2} \int V_1(t)\,dt & \text{time domain} \\ -\frac{1}{R_1 C_2}\,\frac{1}{s}\, V_1(s) & \text{Laplace domain} \end{cases}}$$

Note: This circuit is very susceptible to the presence of even minute dc components in V_1 since this quantity gets integrated and eventually will saturate the output voltage

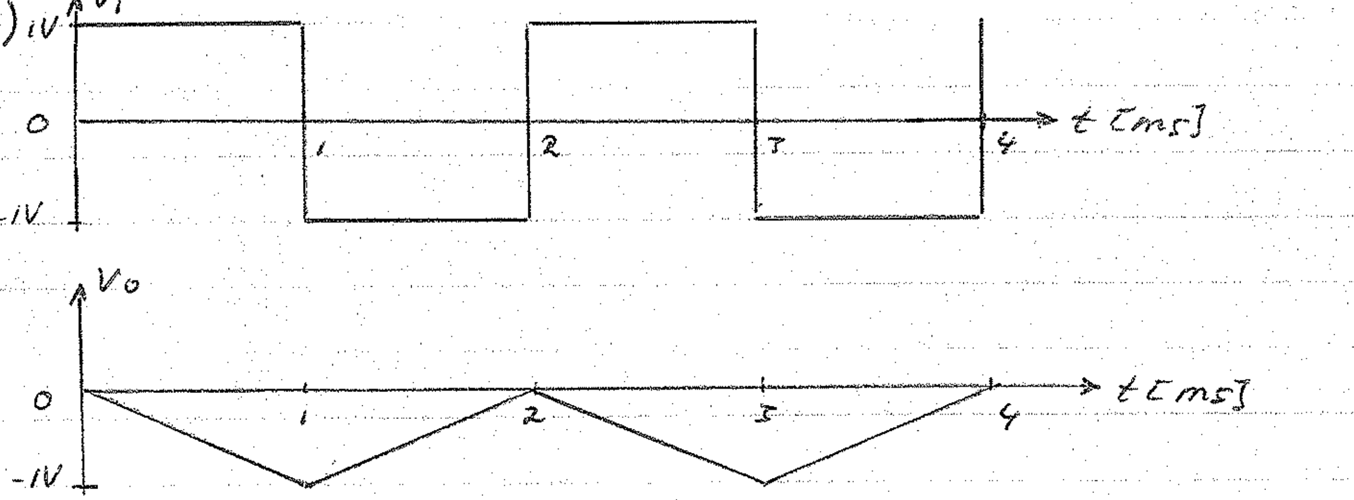
Sketch the output voltage of example 6 for $R_1 = 1k\Omega$, $C_2 = 1\mu F$ if $V_o(t=0) = 0$ and

a) The input is a square wave of 1V amplitude and 2ms period. (assume no dc component is present)

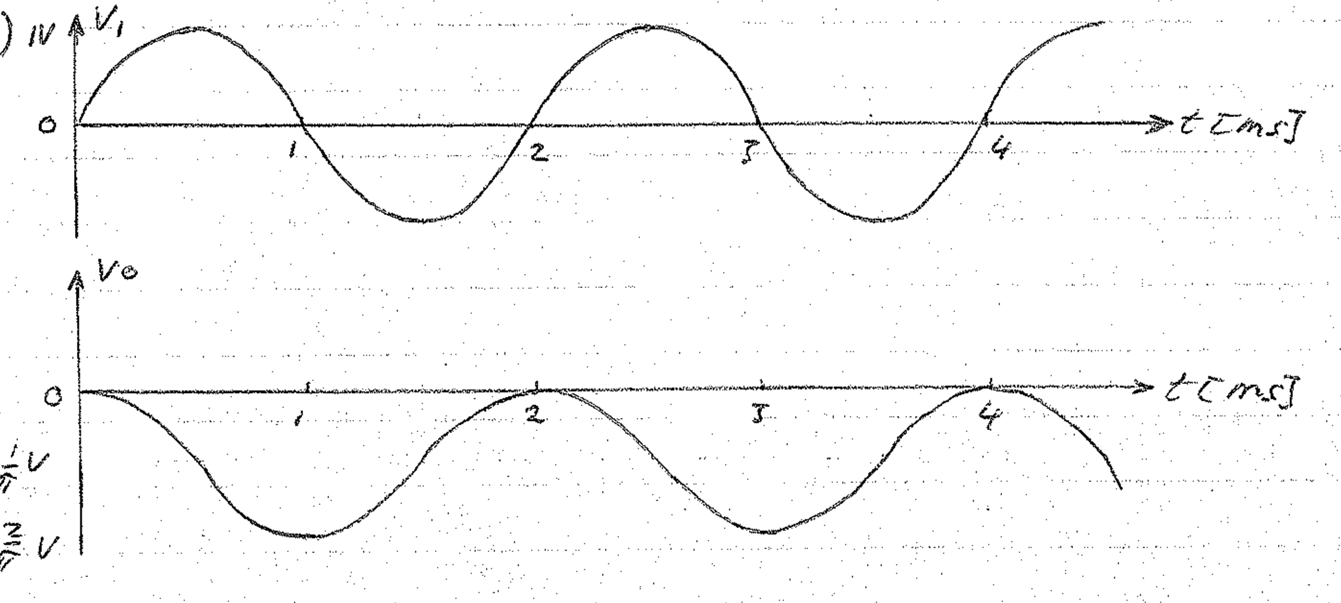
b) The input is a sine wave of 1V amplitude and 2ms period. (assume no dc component is present)

Solution

a)

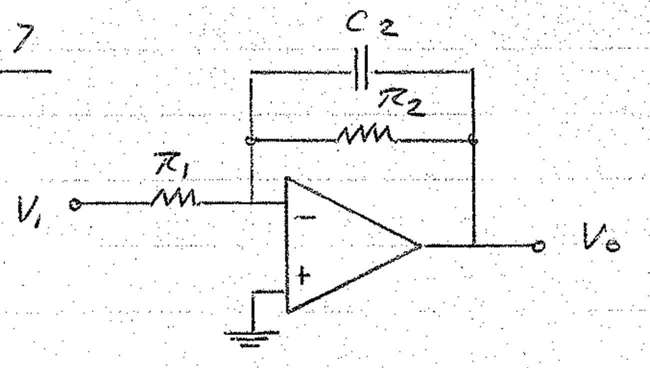


b)



Example 7

Lossy Integrator

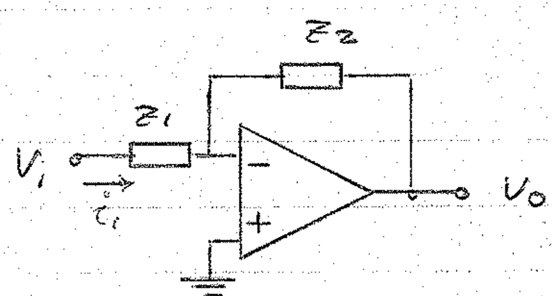


assum op-amp ideal

Determine the voltage transfer function $T = \frac{V_o}{V_i}$ for a sinusoidal input

Solution

Generalize



$V_i = i_i \cdot Z_1$

$V_o = -i_i \; Z_2$

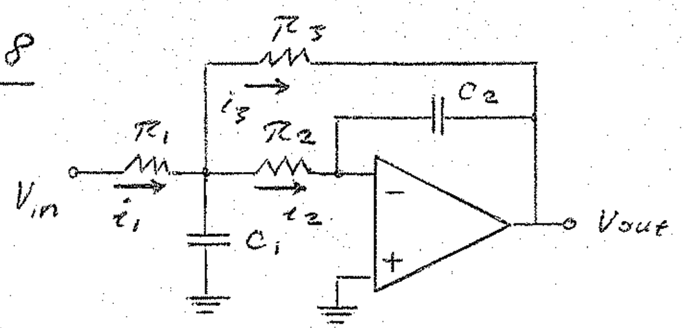
$\therefore \quad T = \frac{V_o}{V_i} = -\frac{Z_2}{Z_1}$

$Z_1 = R_1 \qquad Z_2 = \frac{1}{1/R_2 + sC_2} = \frac{R_2}{1 + sC_2R_2}$

$$\therefore \quad \left\| T(s) = -\frac{R_2}{R_1(1+sC_2R_2)} \right\|$$

In contrast to the ideal integrator, which exhibits an infinite gain at dc, the lossy integrator realizes a finite gain of R_2/R_1. This circuit is therefore less susceptible to saturate due to a (small) dc component (such as the op-amp offset voltage).

Example 8



assume op-amp to be ideal

Establish an equation system that determines the 4 unknowns i_1, i_2, i_3 and V_{out} and find an expression for the voltage transfer function

$$T(s) = \frac{V_{out}(s)}{V_{in}(s)}$$

Solution

KVL 1: $V_{in} = i_1 R_1 + (i_1 - i_2 - i_3)\frac{1}{sC_1}$ (1)

KVL 2: $(i_1 - i_2 - i_3)\frac{1}{sC_1} = i_2 R_2$ (2)

KVL 3: $V_{out} = - i_2 \frac{1}{sC_2}$ (3)

KVL 4: $V_{out} = V_{in} - i_1 R_1 - i_3 R_3$ (4)

$$i_1 = \frac{V_{in}}{R_1} + V_{out}\, sC_2 \frac{R_2}{R_1}$$

$$i_2 = - V_{out}\, sC_2$$

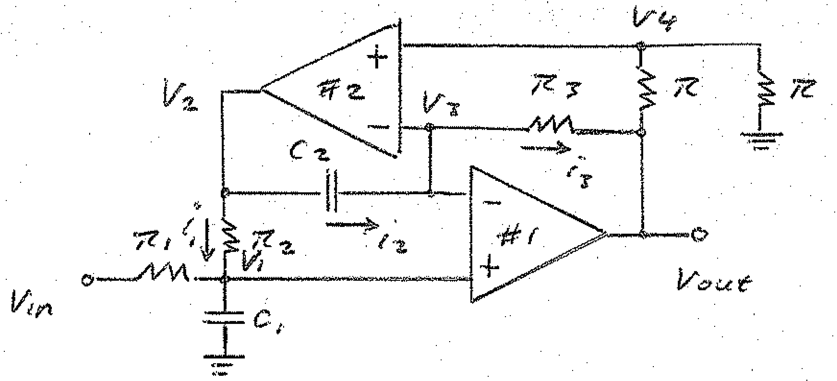
$$i_3 = \frac{V_{in}}{R_1} + V_{out}\left[1 + \frac{R_2}{R_1} + sC_1R_2\right] sC_2$$

$$\therefore \quad T(s) = \frac{V_{out}(s)}{V_{in}(s)} = - \frac{R_3/R_1}{1 + sC_2\left[R_2\left(1 + \frac{R_3}{R_1}\right) + R_3\right] + s^2 C_1 C_2 R_2 R_3}$$

$$T(s) = - \frac{\frac{1}{C_1C_2R_3R_1}}{\frac{1}{C_1C_2R_2R_3} + s\frac{1}{C_1}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) + s^2} = - \frac{\omega_n^2}{\omega_p^2 + s\frac{\omega_p}{Q_p} + s^2}$$

$$\omega_n = \frac{1}{\sqrt{C_1C_2R_1R_2}} \qquad \omega_p = \frac{1}{\sqrt{C_1C_2R_2R_3}} \qquad Q_p = \sqrt{\frac{C_1}{C_2}}\,\frac{\sqrt{R_2R_3}}{R_2 + R_3\left[1 + R_2/R_1\right]}$$

Example 9 2^{nd} order Bandpass Filter



assume op-amps to be ideal

Determine the voltage transfer function $T(s) = \frac{V_{out}(s)}{V_{in}(s)}$

Solution

op-amp #1	$V_1 = V_3$	$i_2 = i_3$
op-amp #2	$V_3 = V_4$	$i_1 R_2 = i_2 \frac{1}{sC_2}$
KVL1:	$V_4 = \frac{1}{2} V_{out}$	
ohm's law:	$i_3 = \frac{V_3 - V_{out}}{R_3} = -\frac{V_{out}}{2R_3}$	
KVL2:	$V_2 = V_3 + i_3 \frac{1}{sC_2} = \frac{1}{2} V_{out}\left[1 - \frac{1}{sC_2 R_3}\right]$	
KVL3:	$V_{in} = V_1 - i_1 R_1 + V_1 s C_1 R_1 = \frac{1}{2} V_{out}\left[1 + sC_1 R_1\right] + \frac{1}{2} V_{out} \frac{R_1}{R_3} \frac{1}{sC_2 R_2}$	

$$\therefore \quad 2V_{in} = V_{out}\left[1 + sC_1R_1 + \frac{R_1}{R_3}\frac{1}{sC_2R_2}\right]$$

$$\frac{V_{out}}{V_{in}} = \frac{sC_2R_2 \cdot 2 \cdot R_3/R_1}{1 + sC_2R_2\,R_3/R_1 + s^2 C_1C_2R_2R_3}$$

$$T(s) = \frac{s \cdot 2 \cdot \frac{1}{C_1R_1}}{\frac{1}{C_1C_2R_2R_3} + s\frac{1}{C_1R_1} + s^2} \triangleq \frac{s\,\omega_k}{\omega_p^2 + s\frac{\omega_p}{Q_p} + s^2}$$

$$\omega_p = \frac{1}{\sqrt{C_1C_2R_2R_3}} \qquad \omega_k = \frac{2}{C_1R_1} \qquad Q_p = \sqrt{\frac{C_1}{C_2}}\,\frac{R_1}{\sqrt{R_2R_3}}$$

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Example of commercial Opamp Data Sheet

December 2001

National Semiconductor

LF155/LF156/LF256/LF257/LF355/LF356/LF357 JFET Input Operational Amplifiers

General Description

These are the first monolithic JFET input operational amplifiers to incorporate well matched, high voltage JFETs on the same chip with standard bipolar transistors (BI-FET™ Technology). These amplifiers feature low input bias and offset currents/low offset voltage and offset voltage drift, coupled with offset adjust which does not degrade drift or common-mode rejection. The devices are also designed for high slew rate, wide bandwidth, extremely fast settling time, low voltage and current noise and a low 1/f noise corner.

Features

Advantages

- Replace expensive hybrid and module FET op amps
- Rugged JFETs allow blow-out free handling compared with MOSFET input devices
- Excellent for low noise applications using either high or low source impedance—very low 1/f corner
- Offset adjust does not degrade drift or common-mode rejection as in most monolithic amplifiers
- New output stage allows use of large capacitive loads (5,000 pF) without stability problems
- Internal compensation and large differential input voltage capability

Applications

- Precision high speed integrators
- Fast D/A and A/D converters
- High impedance buffers
- Wideband, low noise, low drift amplifiers
- Logarithmic amplifiers
- Photocell amplifiers
- Sample and Hold circuits

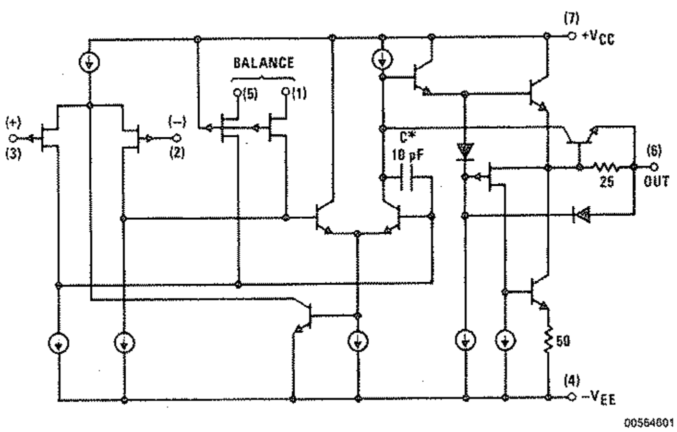
Common Features

- Low input bias current: 30pA
- Low Input Offset Current: 3pA
- High input impedance: $10^{12}\Omega$
- Low input noise current: $0.01\ pA/\sqrt{Hz}$
- High common-mode rejection ratio: 100 dB
- Large dc voltage gain: 106 dB

Uncommon Features

	LF155/ LF355	LF156/ LF256/ LF356	LF257/ LF357 (A_V=5)	Units
Extremely fast settling time to 0.01%	4	1.5	1.5	μs
Fast slew rate	5	12	50	V/μs
Wide gain bandwidth	2.5	5	20	MHz
Low input noise voltage	20	12	12	$nV/\sqrt{Hz}$

Simplified Schematic



*3pF in LF357 series.

BI-FET™, BI-FET II™ are trademarks of National Semiconductor Corporation.

Opamp Data Sheet continued

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, contact the National Semiconductor Sales Office/Distributors for availability and specifications.

	LF155/6	LF256/7/LF356B	LF355/6/7
Supply Voltage	±22V	±22V	±18V
Differential Input Voltage	±40V	±40V	±30V
Input Voltage Range (Note 2)	±20V	±20V	±16V
Output Short Circuit Duration	Continuous	Continuous	Continuous
T_{JMAX}			
H-Package	150°C	115°C	115°C
N-Package		100°C	100°C
M-Package		100°C	100°C
Power Dissipation at T_A = 25°C (Notes 1, 8)			
H-Package (Still Air)	560 mW	400 mW	400 mW
H-Package (400 LF/Min Air Flow)	1200 mW	1000 mW	1000 mW
N-Package		670 mW	670 mW
M-Package		380 mW	380 mW
Thermal Resistance (Typical) θ_{JA}			
H-Package (Still Air)	160°C/W	160°C/W	160°C/W
H-Package (400 LF/Min Air Flow)	65°C/W	65°C/W	65°C/W
N-Package		130°C/W	130°C/W
M-Package		195°C/W	195°C/W
(Typical) θ_{JC}			
H-Package	23°C/W	23°C/W	23°C/W
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C
Soldering Information (Lead Temp.)			
Metal Can Package			
Soldering (10 sec.)	300°C	300°C	300°C
Dual-In-Line Package			
Soldering (10 sec.)	260°C	260°C	260°C
Small Outline Package			
Vapor Phase (60 sec.)		215°C	215°C
Infrared (15 sec.)		220°C	220°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

	LF155/6	LF256/7/LF356B	LF355/6/7
ESD tolerance (100 pF discharged through 1.5kΩ)	1000V	1000V	1000V

DC Electrical Characteristics

(Note 3)

Symbol	Parameter	Conditions	LF155/6			LF256/7 LF356B			LF355/6/7			Units
			Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
V_{OS}	Input Offset Voltage	R_S=50Ω, T_A=25°C		3	5		3	5		3	10	mV
		Over Temperature			7			6.5			13	mV
$\Delta V_{OS}/\Delta T$	Average TC of Input Offset Voltage	R_S=50Ω		5			5			5		μV/°C
$\Delta TC/\Delta V_{OS}$	Change in Average TC with V_{OS} Adjust	R_S=50Ω, (Note 4)		0.5			0.5			0.5		μV/°C per mV
I_{OS}	Input Offset Current	T_J=25°C, (Notes 3, 5)		3	20		3	20		3	50	pA
		$T_J \le T_{HIGH}$			20			1			2	nA

Opamp Data Sheet continued

DC Electrical Characteristics (Continued)

(Note 3)

Symbol	Parameter	Conditions	LF155/6			LF256/7 LF356B			LF355/6/7			Units
			Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
I_B	Input Bias Current	T_J=25°C, (Notes 3, 5)		30	100		30	100		30	200	pA
		$T_J \le T_{HIGH}$			50			5			8	nA
R_{IN}	Input Resistance	T_J=25°C		10^{12}			10^{12}			10^{12}		Ω
A_{VOL}	Large Signal Voltage Gain	V_S=±15V, T_A=25°C V_O=±10V, R_L=2k	50	200		50	200		25	200		V/mV
		Over Temperature	25			25			15			V/mV
V_O	Output Voltage Swing	V_S=±15V, R_L=10k	±12	±13		±12	±13		±12	±13		V
		V_S=±15V, R_L=2k	±10	±12		±10	±12		±10	±12		V
V_{CM}	Input Common-Mode Voltage Range	V_S=±15V	±11	+15.1		±11	±15.1		+10	+15.1		V
				−12			−12			−12		V
CMRR	Common-Mode Rejection Ratio		85	100		85	100		80	100		dB
PSRR	Supply Voltage Rejection Ratio	(Note 6)	85	100		85	100		80	100		dB

DC Electrical Characteristics

$T_A = T_J = 25°C$, $V_S = ±15V$

Parameter	LF155		LF355		LF156/256/257/356B		LF356		LF357		Units
	Typ	Max	Typ	Max	Typ	Max	Typ	Max	Typ	Max	
Supply Current	2	4	2	4	5	7	5	10	5	10	mA

AC Electrical Characteristics

$T_A = T_J = 25°C$, $V_S = ±15V$

Symbol	Parameter	Conditions	LF155/355	LF156/256/356B	LF156/256/356/LF356B	LF257/357	Units
			Typ	Min	Typ	Typ	
SR	Slew Rate	LF155/6: A_V=1,	5	7.5	12		V/μs
		LF357: A_V=5				50	V/μs
GBW	Gain Bandwidth Product		2.5		5	20	MHz
t_s	Settling Time to 0.01%	(Note 7)	4		1.5	1.5	μs
e_n	Equivalent Input Noise Voltage	R_S=100Ω					
		f=100 Hz	25		15	15	$nV/\sqrt{Hz}$
		f=1000 Hz	20		12	12	$nV/\sqrt{Hz}$
i_n	Equivalent Input Current Noise	f=100 Hz	0.01		0.01	0.01	$pA/\sqrt{Hz}$
		f=1000 Hz	0.01		0.01	0.01	$pA/\sqrt{Hz}$
C_{IN}	Input Capacitance		3		3	3	pF

Notes for Electrical Characteristics

Note 1: The maximum power dissipation for these devices must be derated at elevated temperatures and is dictated by T_{JMAX}, θ_{JA}, and the ambient temperature, T_A. The maximum available power dissipation at any temperature is $P_D=(T_{JMAX}-T_A)/\theta_{JA}$ or the 25°C P_{dMAX}, whichever is less.

Note 2: Unless otherwise specified the absolute maximum negative input voltage is equal to the negative power supply voltage.

Note 3: Unless otherwise stated, these test conditions apply: