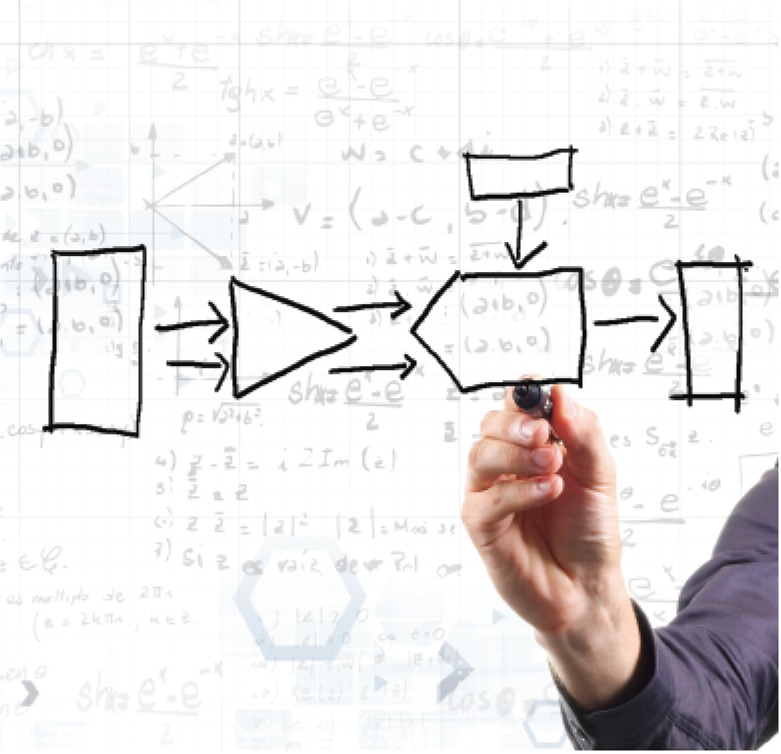
Analog Engineer's

Pocket Reference

Art Kay and Tim Green, Editors



Constants

Constant	Symbol	Value	Units
Speed of light in a vacuum	c	2.997 924 58 x 10^{8}	m/s
Permittivity of vacuum	ε_o	8.854 187 817 620 x 10^{-12}	F/m
Permeability of free space	μ_o	1.256 637 0614 x 10^{-6}	H/m
Planck's constant	h	6.626 069 57 x 10^{-34}	J•s
Boltzmann's constant	k	1.380 648 8 x 10^{-23}	J/K
Faraday's constant	F	9.648 533 99 x 10^{4}	C/mol
Avogadro's constant	N_A	6.022 141 29 x 10^{23}	1/mol
Unified atomic mass unit	m_u	1.660 538 921 x 10^{-27}	kg
Electronic charge	q	1.602 176 565 x 10^{-19}	C
Rest mass of electron	m_e	9.109 382 15 x 10^{-31}	kg
Mass of proton	m_p	1.672 621 777 x 10^{-27}	kg
Gravitational constant	G	6.673 84 x 10^{-11}	Nm^2/kg^2
Standard gravity	g_n	9.806 65	m/s^2
Ice point	T_{ice}	273.15	K
Maximum density of water	ρ	1.00 x 10^{3}	kg/m^3
Density of mercury (0°C)	ρ_{Hg}	1.362 8 x 10^{4}	kg/m^3
Gas constant	R	8.314 462 1	J/(K•mol)
Speed of sound in air (at 0°C)	c_{air}	3.312 x 10^{2}	m/s

Imperial to metric conversions

Unit	Symbol	Equivalent	Unit	
inches	in	25.4 mm/in	millimeter	
mil	mil	0.0254 mm/mil	millimeter	
feet	ft	0.3048 m/ft	meters	
yards	yd	0.9144 m/yd	meters	
miles	mi	1.6093 km/mi	kilometers	
circular mil	cir mil	5.067x10^{-4} mm^2/cir mil	square millimeters	
square yards	yd^2	0.8361 m^2	square meters	
pints	pt oz	0.5682 L/pt	liters	
ounces	lb	28.35 g/oz	grams	
pounds		0.4536 kg/lb	kilograms	
calories	cal	4.184 J/cal	joules	J
horsepower	hp	745.7 W/hp	watts	W

Metric to imperial conversions

Unit	Symbol	Conversion	Unit	Symbol
millimeter	mm	0.0394 in/mm	inch	in
millimeter	mm	39.4 mil/mm	mil	mil
meters	m	3.2808 ft/m	feet	ft
meters	m	1.0936 yd/m	yard	yd
kilometers	km	0.6214 mi/km	miles	mi
square millimeters	mm^2	1974 cir mil/mm^2	circular mil	cir mil
square meters	m^2	1.1960 yd^2/m^2	square yards	yd^2
liters	L	1.7600 pt/L	pints	pt
grams	g	0.0353 oz/g	ounces	oz
kilograms	kg	2.2046 lb/kg	pounds	lb
joules	J	0.239 cal/J	calories	cal
watts	W	1.341×10^{-3} hp/W	horsepower	hp

Conversion between codes, mV, %, and ppm

	Codes	mV	%	ppm
Codes	•	$\text{Codes} \cdot \left(\frac{V_{FSR}}{2^N}\right) \cdot 1000$	$\text{Codes} \cdot \left(\frac{1}{2^N}\right) \cdot 100$	$\text{Codes} \cdot \left(\frac{1}{2^N}\right) \cdot 10^6$
mV	$\text{mV} \cdot \left(\frac{2^N}{V_{FSR} \cdot 1000}\right)$	•	$\text{mV} \cdot \left(\frac{1}{V_{FSR} \cdot 1000}\right) \cdot 100$	$\text{mV} \cdot \left(\frac{1}{V_{FSR} \cdot 1000}\right) \cdot 10^6$
%	$\% \cdot \left(\frac{2^N}{100}\right)$	$\% \cdot \left(\frac{V_{FSR} \cdot 1000}{100}\right)$	•	$\% \cdot \left(\frac{10^6}{100}\right)$
ppm	$\text{ppm} \cdot \left(\frac{2^N}{10^6}\right)$	$\text{ppm} \cdot \left(\frac{V_{FSR} \cdot 1000}{10^6}\right)$	$\text{ppm} \cdot \left(\frac{1}{10^6}\right) \cdot 100$	•

Capacitor type overview

Capacitor type	Description
C0G/NP0 **(Type 1 ceramic)**	Use in signal path, filtering, low distortion, audio, and precision Limited capacitance range: 0.1 pF to 0.47 µF Lowest temperature coefficient: ±30 ppm/°C Low- voltage coefficient Minimal piezoelectric effect Good tolerance: ±1% to ±10% Temperature range: –55°C to 125°C (150°C and higher) Voltage range may be limited for larger capacitance values
X7R **(Type 2 ceramic)**	Use for decoupling and other applications where accuracy and low distortion are not required X7R is an example of a type 2 ceramic capacitor See EIA capacitor tolerance table for details on other types Capacitance range: 10 pF to 47 µF Temperature coefficient: ±833 ppm/°C (±15% across temp range) Substantial voltage coefficient Tolerance: ±5% to –20%/+80% Temperature range: –55°C to 125°C Voltage range may be limited for larger capacitance values

Y5V (Type 2 ceramic)	Use for decoupling and other applications where accuracy and low distortion are not required Y5V is an example of a type 2 ceramic capacitor See EIA capacitor tolerance table for details on other types Temperature coefficient: –20%/+80% across temp range Temperature range: –30°C to 85°C Other characteristics are similar to X7R and other type 2 ceramic
Aluminum oxide electrolytic	Use for bulk decoupling and other applications where large capacitance is required Note that electrolytic capacitors are polarized and will be damaged, if a reverse polarity connection is made Capacitance range: 1 µF to 68,000 µF Temperature coefficient: ±30 ppm/°C Substantial voltage coefficient Tolerance: ±20% Temperature range: –55°C to 125°C (150°C and higher) Higher ESR than other types
Tantalum electrolytic	Capacitance range: 1 µF to 150 µF Similar to aluminum oxide but smaller size
Polypropylene film	Capacitance range: 100 pF to 10 µF Very low voltage coefficient (low distortion) Higher cost than other types Larger size per capacitance than other types Temperature coefficient: 2% across temp range Temperature range: –55°C to 100°C

Standard capacitance table

Standard capacitance table											
1	1.1	1.2	1.3	1.5	1.6	1.8	2	2.2	2.4	2.7	3
3.3	3.6	3.9	4.3	4.7	5.1	5.6	6.2	6.8	7.5	8.2	9.1

Ceramic capacitor tolerance markings

Code	Tolerance	Code	Tolerance
B	± 0.1 pF	J	± 5%
C	± 0.25 pF	K	± 10%
D	± 0.5 pF	M	± 20%
F	± 1%	Z	+ 80%, –20%
G	± 2%		

EIA capacitor tolerance markings (Type 2 capacitors)

First letter symbol	Low temp limit	Second number symbol	High temp limit	Second letter symbol	Max. capacitance change over temperature rating
Z	+10°C	2	+45°C	A	±1.0%
Y	–30°C	4	+65°C	B	±1.5%
X	–55°C	5	+85°C	C	±2.2%
		6	+105°C	D	±3.3%
					.7%
					.5%
					).0%
					5.0%
					2.0%
					~ 33%
					~ 56%
					~ 82%

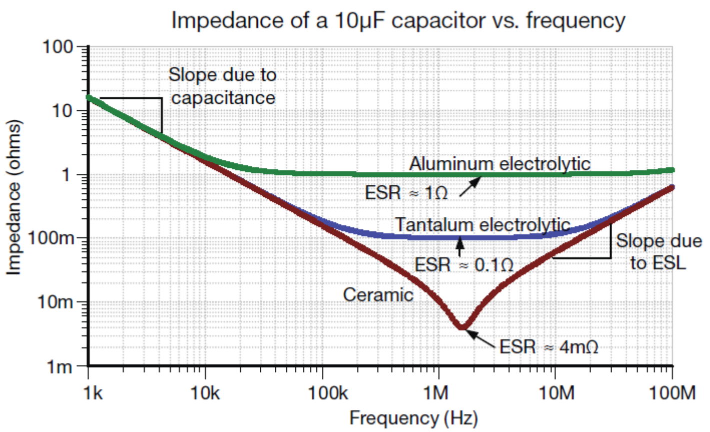


Figure 3: Effect of ESR and ESL on capacitor frequency response

Bipolar junction transistors (BJT)

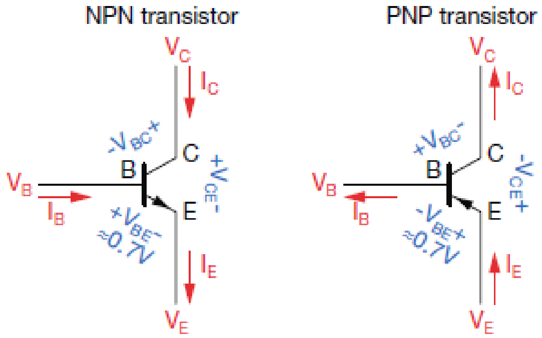


Figure 6: Bipoloar transistors

$$I_C = I_B \cdot \beta$$
(1) Current gain

$$I_C = I_B + I_E$$
(2) Current law for bipolar transistors

$$V_{BE} \approx 0.7V$$
(3) Voltage base to emitter is forward bias for normal operation. Approximately 0.7V.

V_{BC} is reversed biased
(4) Voltage base to collector is reverse bias for normal operation

$$V_{CE} \approx V_{BC} + V_{BE}$$
(5) Collector to emitter voltage

Where

B, E, C = base, emitter, and collector

I_B, I_E, I_C = base, emitter, and collector current

$\beta = h_{fe}$ = current gain

V_{CE}= collector to emitter voltage

V_{BC} = base to collector voltage

V_{BE} = base to emitter voltage

Junction field effect transistors (JFET)

N-channel JFET   P-channel JFET

Junction field effect transistors (JFET)

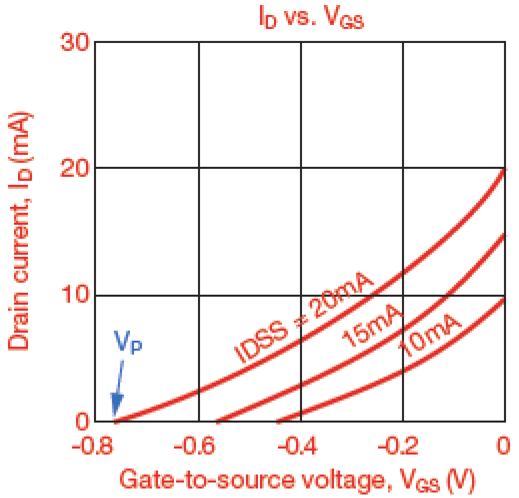


Figure 8: N-channel JFET characteristic curve I_D vs V_{GS}

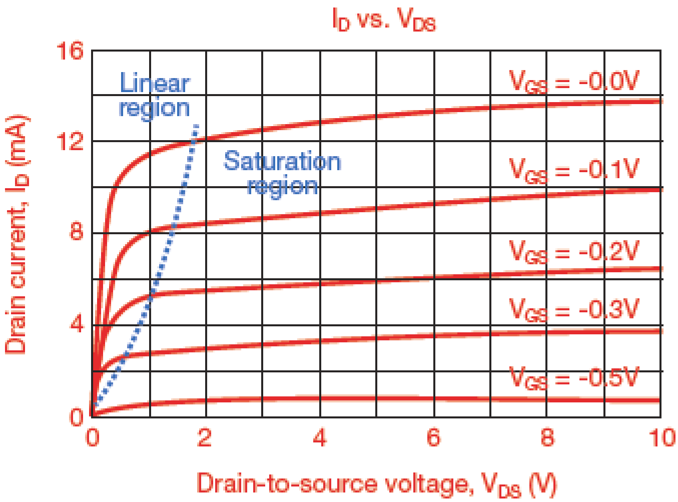


Figure 9: N-channel JFET characteristic curve I_D vs V_{GS}

- The maximum gate-to-source voltage is 0V for an N-channel JFET. Greater than 0V will forward bias the gate-to-source junction and cause abnormal operation.
- The P-channel FET has similar characteristic curves but the polarity is opposite.

Metal oxide semiconductor field effect transistor (MOSFET)

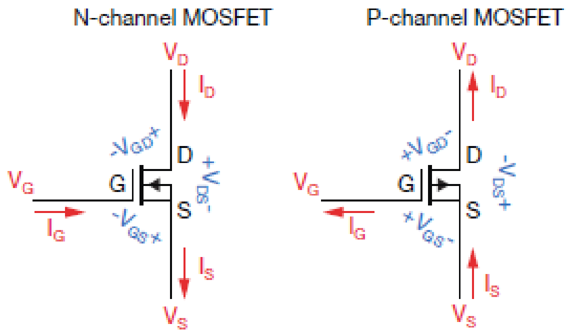


Figure 10: MOSFET transistors

$$I_G \approx 0A$$

(10) Gate is insulated so that input current is negligible

$$I_D = I_S$$

(11) Drain current equal to source current

$$I_D = \mu_n C_{OX} \frac{W}{L}\left((V_{GS} - V_{TH}) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

(12) Drain current in linear region (triode)

$$I_D = \frac{\mu_n C_{OX}}{2} \frac{W}{L} (V_{GS} - V_{TH})^2 \left(1 + \lambda (V_{DS} - V_{DSsat})\right)$$

(13) Drain current in saturation region

Where

G, D, S = gate, drain, and source

μ_n = charge-carrier effective mobility

C_{OX} = capacitance of oxide

W, L = width and length of gate

V_{GS} = gate to source voltage

V_{DS} = drain to source voltage

V_{TH} = threshold voltage

λ = channel length modulation

Metal oxide semiconductor field effect transistor (MOSFET)

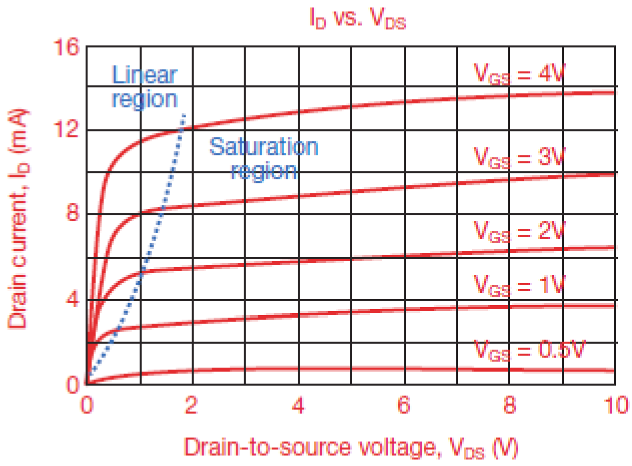


Figure 11: N-channel MOSFET characteristic curve, I_D vs. V_{DS}

- The parameters, such as μ_n, C_{OX}, W, and L, may not be given in discrete MOSFET data sheets.
- The P-channel FET has similar characteristic curves but the polarity is opposite.

Resistor equations

$$R_T = R_1 + R_2 + \cdots + R_N \qquad (14)\ \text{Series resistors}$$

$$R_T = \frac{R_1 \cdot R_2}{R_1 + R_2} \qquad (15)\ \text{Two parallel resistors}$$

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}} \qquad (16)\ \text{Parallel resistors}$$

Where

R_T = equivalent total resistance

R_1, R_2, R_3, …R_N = component resistors

Ohm's law and voltage divider equation

$$V = I \cdot R \qquad (17)\ \text{Ohm's law}$$

$$V_{OUT} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{sup} \qquad (18)\ \text{Voltage divider equation}$$

AC power equation

$$P = \frac{1}{2} \cdot V_p \cdot I_p \cdot \cos\theta$$

Where

P = average power in watts (W) for sinusoidal signals

V_p = peak voltage in volts (V)

I_p = peak current in amps (A)

θ = phase angle between the voltage and current sine waves

Analog

- Resistor equations
- Power equations
- Capacitor equations (series, parallel, charge, energy)
- Inductor equations (series, parallel, energy)
- Capacitor charge and discharge
- RMS and mean voltage definition
- RMS for common signals
- Logarithm laws
- dB definitions
- Pole and zero definition with examples

Capacitor equations

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_N}}$$ (23) Series capacitors

$$C_t = \frac{C_1 C_2}{C_1 + C_2}$$ (24) Two series capacitors

$$C_t = C_1 + C_2 + \ldots + C_N$$ (25) Parallel capacitors

Where

C_t = equivalent total capacitance

$C_1, C_2, C_3 \ldots C_N$ = component capacitors

$$Q = CV$$ (26) Charge storage

$$Q = It$$ (27) Charge defined

Where

Q = charge in coulombs (C)

C = capacitance in farads (F)

V = voltage in volts (V)

I = current in amps (A)

t = time in seconds (s)

$$i = C\frac{dv}{dt}$$ (28) Instantaneous current through a capacitor

Where

i = instantaneous current through the capacitor

C = capacitance in farads (F)

$\frac{dv}{dt}$ = the instantaneous rate of voltage change

$$E = \frac{1}{2}CV^2$$ (29) Energy stored in a capacitor

Where

E = energy stored in a capacitor in joules (J)

V = voltage in volts

C = capacitance in farads (F)

Inductor equations

$$L_t = L_1 + L_2 + \ldots + L_N$$ (30) Series inductors

$$L_t = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_N}}$$ (31) Parallel inductors

$$L_t = \frac{L_1 L_2}{L_1 + L_2}$$ (32) Two parallel inductors

Where

L_t = equivalent total inductance

$L_1, L_2, L_3 \ldots L_N$ = component inductance

$$v = L\frac{di}{dt}$$ (33) Instantaneous voltage across an inductor

Where

v = instantaneous voltage across the inductor

L = inductance in henries (H)

$\frac{di}{dt}$ = instantaneous rate of current change

$$E = \frac{1}{2} L I^2$$ (34) Energy stored in an inductor

Where

E = energy stored in an inductor in joules (J)

I = current in amps

L = inductance in henries (H)

Equation for charging an RC circuit

$$V_C = V_S\left[1 - e^{\left(\frac{-t}{\tau}\right)}\right]$$

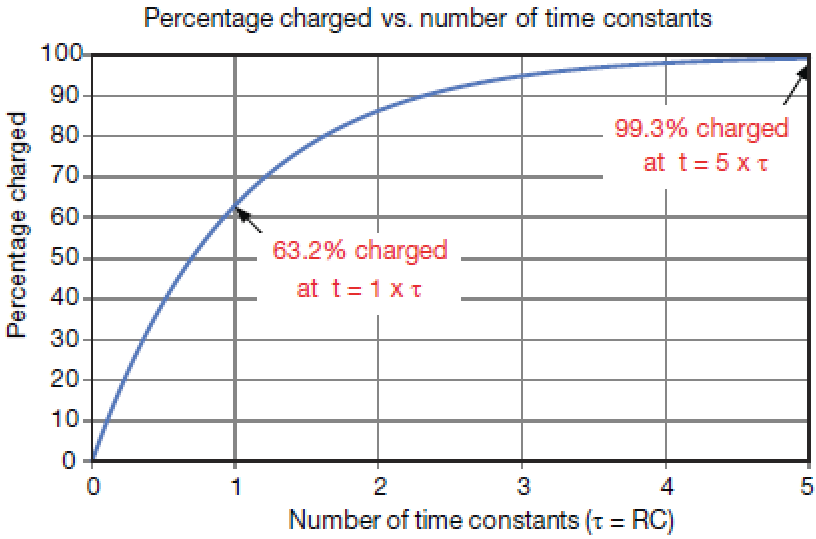
Where

V_C = voltage across the capacitor at any instant in time (t)

V_S = the source voltage charging the RC circuit

t = time in Seconds

τ = RC, the time constant for charging and discharging capacitors



Equation for discharging an RC circuit

$$V_C = V_i\left[e^{\left(\frac{-t}{\tau}\right)}\right]$$

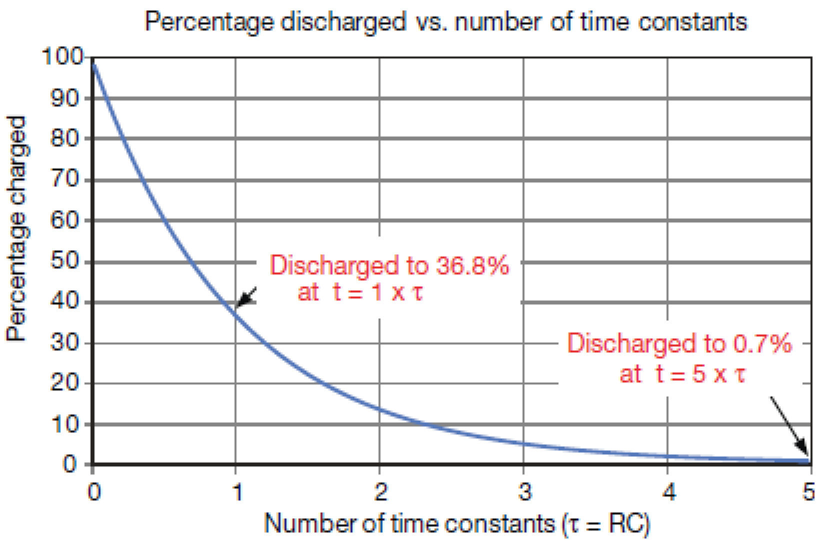
Where

V_C = voltage across the capacitor at any instant in time (t)

V_i = the initial voltage of the capacitor at t = 0s

t = time in seconds

τ = RC, the time constant for charging and discharging capacitors



Capacitor with constant current source

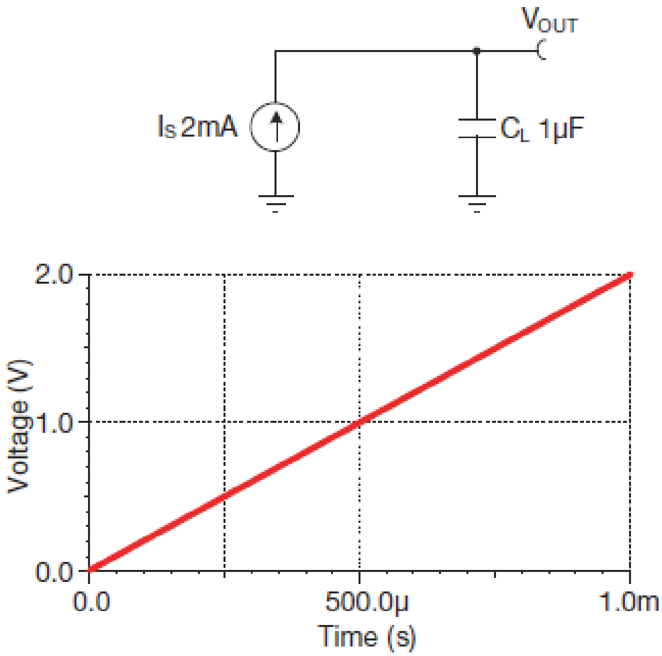


Figure 15: Capacitor with constant current source

$$dv = \frac{i}{C}dt$$ (37) General equation for capacitor voltage current

$$V_{OUT} = \frac{I_S}{C_L}t$$ (38) For constant current

Where

I_S = constant current source in amps (A)

V_{OUT} = voltage developed across the capacitor in volts (V)

C_L = load capacitance in farads (F)

t = time in seconds (s)

AC power equation

$$P = \frac{1}{2} \cdot V_P \cdot I_P \cdot \cos\theta$$

Where

P = average power in watts (W) for sinusoidal signals

V_P = peak voltage in volts (V)

I_P = peak current in amps (A)

θ = phase angle between the voltage and current sine waves

RMS and mean voltage

RMS voltage

$$V_{RMS} = \sqrt{\frac{1}{(T_2 - T_1)} \int_{T1}^{T2} [V(t)]^2 dt}$$

(39) General relationship

Where

$V(t)$ = continuous function of time

t = time in seconds

$T_1 \leq t \leq T_2$ = the time interval that the function is defined over

Mean voltage

$$V_{MEAN} = \frac{1}{(T_2 - T_1)} \int_{T1}^{T2} V(t) dt$$

(40) General relationship

Where

$V(t)$ = continuous function of time

t = time in seconds

$T_1 \leq t \leq T_2$ = the time interval that the function is defined over

$$V_{RMS} = \frac{V_{PEAK}}{\sqrt{2}}$$

(41) RMS for full wave rectified sine wave

$$V_{MEAN} = \frac{2 \times V_{PEAK}}{\pi}$$

(42) Mean for full wave rectified sine wave

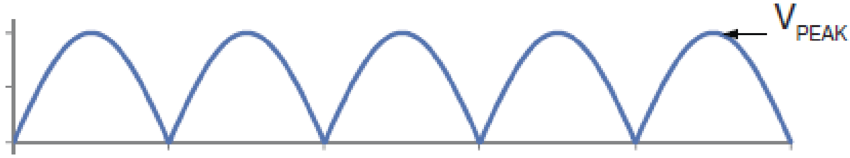


Figure 16: Full wave rectified sine wave

$$V_{RMS} = V_{PEAK}\sqrt{\frac{\tau}{2T}}$$ (43) RMS for a half-wave rectified sine wave

$$V_{MEAN} = \frac{2 \cdot V_{PEAK}}{\pi}\left(\frac{\tau}{T}\right)$$ (44) Mean for a half-wave rectified sine wave

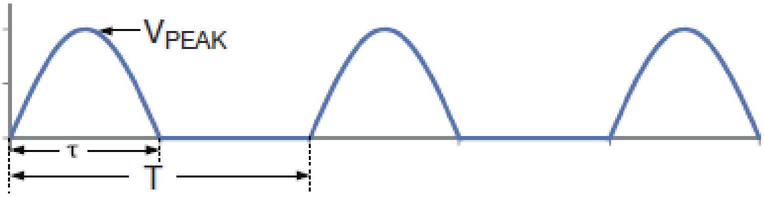


Figure 17: Half-wave rectified sine wave

$$V_{RMS} = V_{PEAK}\sqrt{\frac{\tau}{T}}$$ (45) RMS for a square wave

$$V_{MEAN} = V_{PEAK}\left(\frac{\tau}{T}\right)$$ (46) Mean for a square wave

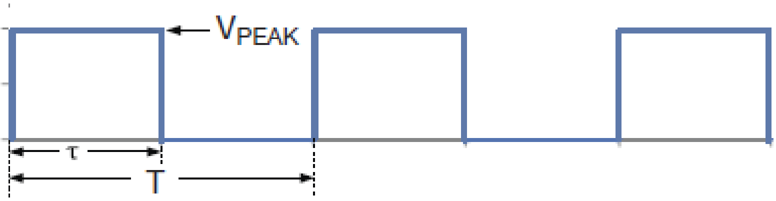


Figure 18: Square wave

$$V_{RMS} = \sqrt{\left(\frac{V_a^2 + V_a \cdot V_b + V_b^2}{3}\right)\left(\frac{\tau}{T}\right)}$$ (47) RMS for a trapezoid

$$V_{MEAN} = \frac{\tau}{2T}(V_a + V_b)$$ (48) Mean for a trapezoid

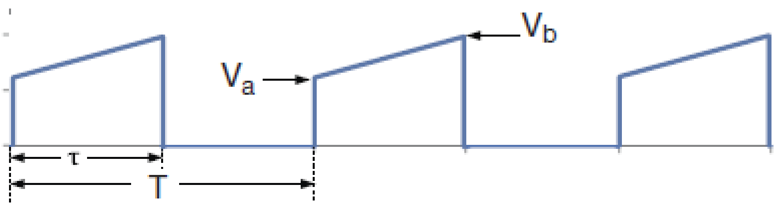


Figure 19: Trapezoidal wave

Logarithmic mathematical definitions

$$\log\left(\frac{A}{B}\right) = \log(A) - \log(B)$$ (51) Log of dividend

$$\log(AB) = \log(A) + \log(B)$$ (52) Log of product

$$\log\left(A^{x}\right) = x\log(A)$$ (53) Log of exponent

$$\log_b(X) = \frac{\log_a(X)}{\log_a(b)}$$ (54) Changing the base of log function

$$\log_2(X) = \frac{\log_{10}(X)}{\log_{10}(2)}$$ (55) Example changing to log base 2

$$\ln(X) = \log_e(X)$$ (56) Natural log is log base e

$$e = 2.718282$$ (57) Exponential function to 6 digits

dB definitions

Definitions

$$\text{Voltage gain (dB)} = 20\log\left(\frac{V_{OUT}}{V_{IN}}\right)$$ (60) Voltage gain in decibels

$$\text{Power gain (dB)} = 10\log\left(\frac{P_{OUT}}{P_{IN}}\right)$$ (61) Power gain in decibels

$$\text{Power measured (dBm)} = 10\log\left(\frac{\text{Power measured (W)}}{1\,\text{mW}}\right)$$ (62) Used for input or output power

Examples of common gain values and dB equivalent

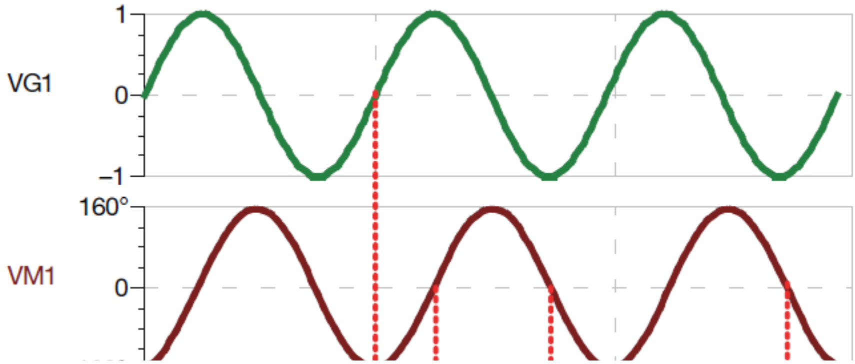
A (V/V)	A (dB)
0.001	–60
0.01	–40
0.1	–20
1	0
10	20
100	40
1,000	60
10,000	80
100,000	100
1,000,000	120
10,000,000	140

Roll-off rate is the decrease in gain with frequency

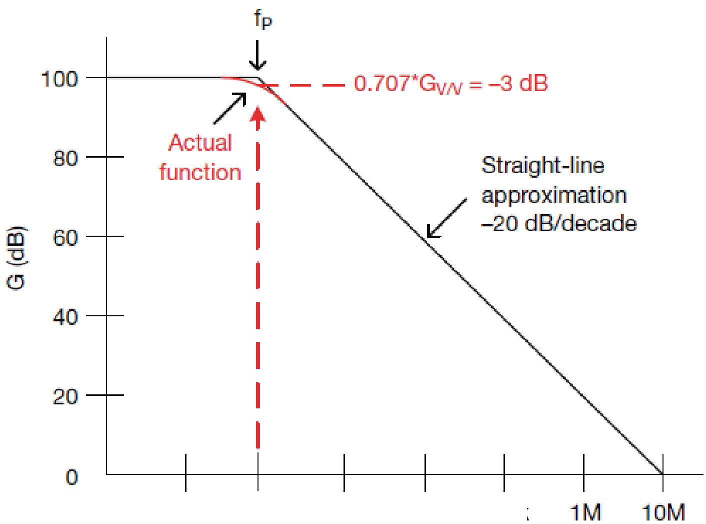
Decade is a tenfold increase or decrease in frequency (from 10 Hz to 100 Hz is one decade)

Octave is the doubling or halving of frequency (from 10 Hz to 20 Hz is one octave)

Time to phase shift



Bode plots: Poles



Where

Pole location = f_P (cutoff freq)

Magnitude ($f < f_P$) = G_{DC} (for example, 100 dB)

Magnitude ($f = f_P$) = –3 dB

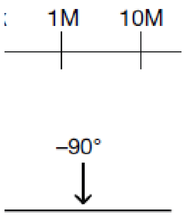
Magnitude ($f > f_P$) = –20 dB/decade

Phase ($f = f_P$) = –45°

Phase ($0.1\ f_P < f < 10\ f_P$) = –45°/decade

Phase ($f > 10\ f_P$) = –90°

Phase ($f < 0.1\ f_P$) = 0°



Bode plots (zeros)

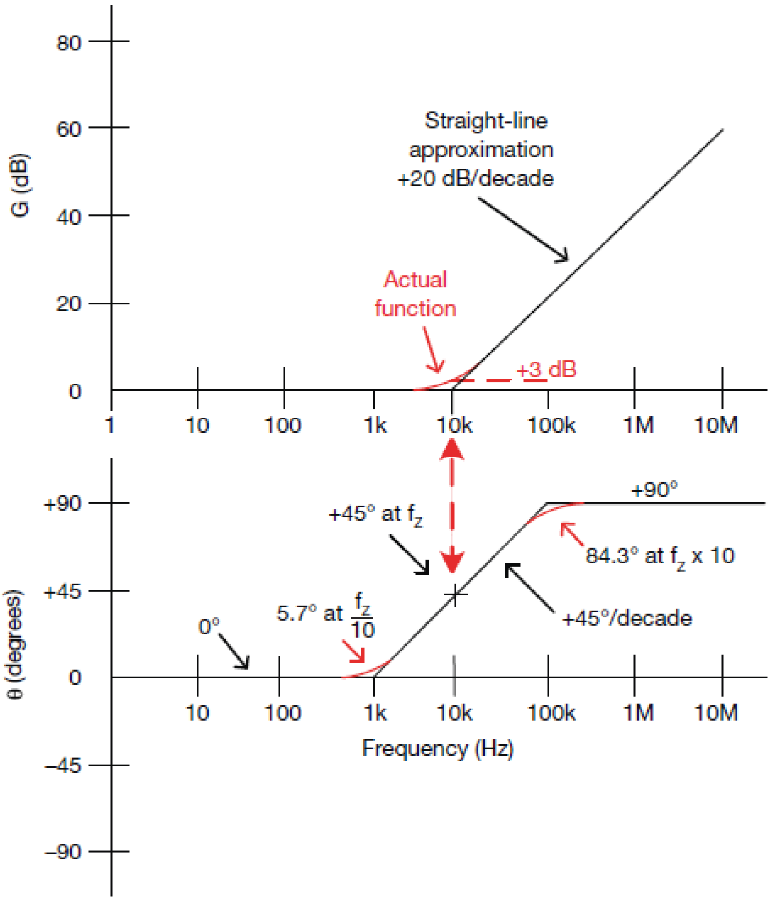


Figure 24: Zero gain and phase

Where

Zero location = f_Z

Magnitude ($f < f_Z$) = 0 dB

Magnitude ($f = f_Z$) = +3 dB

Magnitude ($f > f_Z$) = +20 dB/decade

Phase ($f = f_Z$) = +45°

Phase ($0.1\ f_Z < f < 10\ f_Z$) = +45°/decade

Phase ($f > 10\ f_Z$) = +90°

Phase ($f < 0.1\ f_Z$) = 0°

$$G_V = \frac{V_{OUT}}{V_{IN}} = G_{DC}\left[j\left(\frac{f}{f_Z}\right) + 1\right]$$ (68) As a complex number

$$G_V = \frac{V_{OUT}}{V_{IN}} = G_{DC}\sqrt{\left(\frac{f}{f_Z}\right)^2 + 1}$$ (69) Magnitude

$$\theta = \tan^{-1}\left(\frac{f}{f_Z}\right)$$ (70) Phase shift

$$G_{dB} = 20\ \mathrm{Log}(G_V)$$ (71) Magnitude in dB

Where

G_V = voltage gain in V/V

G_{dB} = voltage gain in decibels

G_{DC} = the dc or low frequency voltage gain

f = frequency in Hz

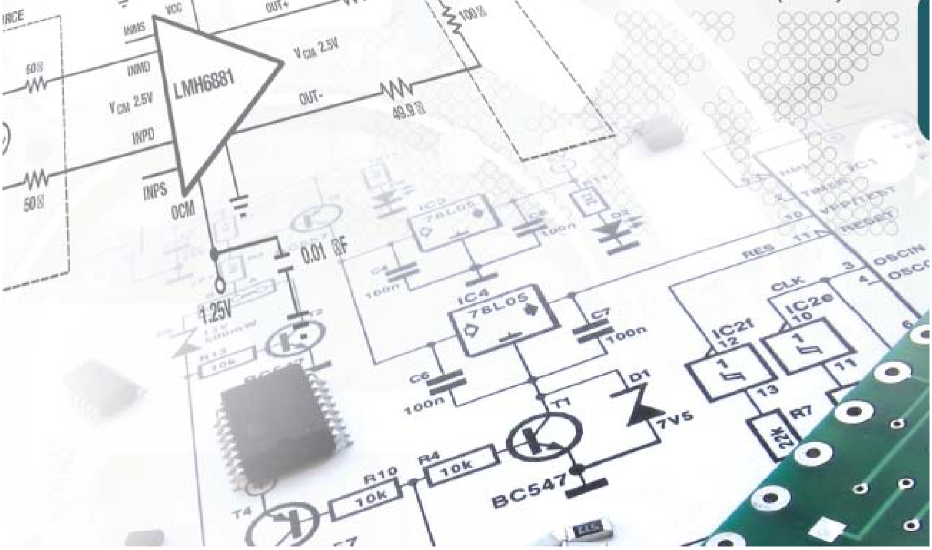
f_Z = frequency at which the zero occurs

θ = phase shift of the signal from input to output

j = indicates imaginary number or $\sqrt{-1}$

Amplifier

- Calculating amplifier offset
- Op amp bandwidth
- Full power bandwidth
- Large signal step response
- Settling time
- Noise equations
- Stability equations
- Instrumentation amplifiers
- Power calculations
- Electrical overstress (EOS)



Basic op amp configurations

$G_{CL} = 1$ (72) Gain for buffer configuration

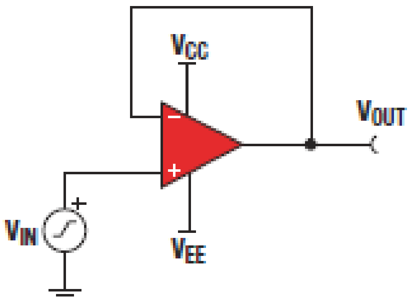


Figure 25: Buffer configuration

$G_{CL} = \frac{R_f}{R_1} + 1$ (73) Gain for non-inverting configuration

Z_{in} = Op amp input impdeance (74) Input impedance. See data sheet for value, but typically greater than 100MΩ to 100TΩ.

$V_{cm} = V_{IN}$ (75) The common mode voltage is equal to the input signal. Check for common mode limitations.

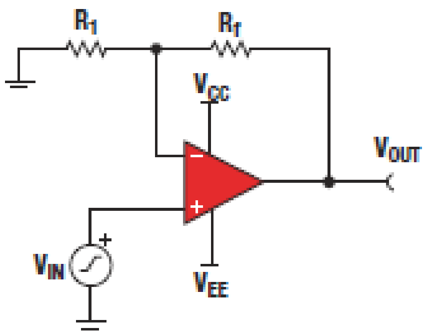


Figure 26: Non-inverting configuration

$$G_{CL} = -\frac{R_f}{R_1}$$ (76) Gain for inverting configuration

$$Z_{in} = R_1$$ (77) Input impedance. Low compared to the non-inverting configuration.

$$V_{cm} = 0V$$ (78) The common mode voltage held constant at 0V so the common mode range and CMRR is not a concern

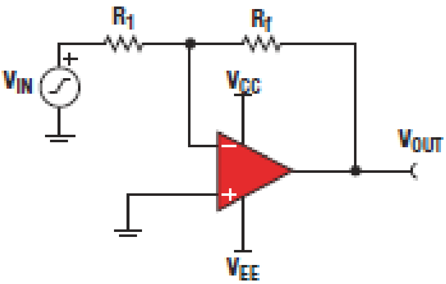


Figure 27: Inverting configuration

$$V_{OUT} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_N}{R_N}\right)$$ (79) Transfer function for inverting summing amplifier

$$V_{OUT} = -\frac{R_f}{R_1}(V_1 + V_2 + \ldots + V_N)$$ (80) Transfer function for inverting summing amplifier, assuming $R_1 = R_2 = \ldots = R_N$

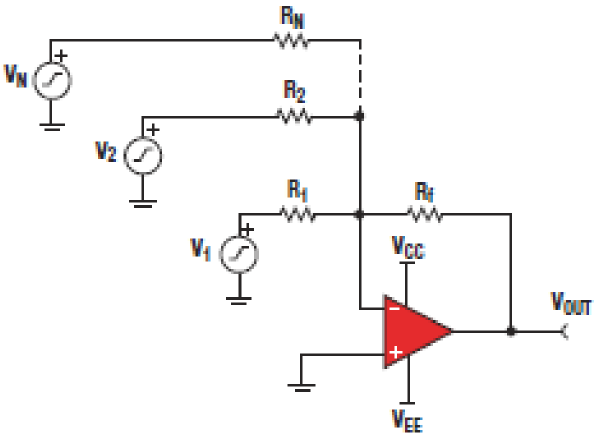


Figure 28: Inverting summing configuration

$$V_{OUT} = \left(\frac{R_f}{R_{in}} + 1\right)\left[\frac{V_1}{N} + \frac{V_2}{N} + \ldots + \frac{V_N}{N}\right]$$

(81) Transfer function for noninverting summing amplifier for equal input resistors

Where

$R_1 = R_2 = \ldots = R_N$

N = number of input resistors

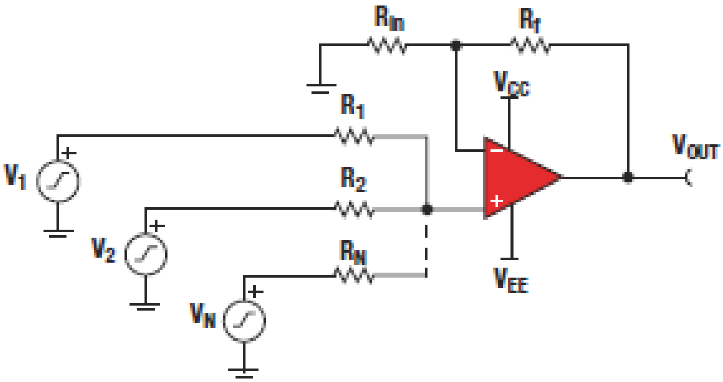


Figure 29: Non-inverting summing configuration

Simple non-inverting amp with C_f filter

$$G_{LF} = \frac{R_f}{R_1} + 1 \quad (82)$$ Gain for non-inverting configuration for $f < f_C$

$$G_{HF} = 1 \quad (83)$$ Gain for non-inverting configuration for $f >> f_C$

$$f_C = \frac{1}{2\pi R_f C_f} \quad (84)$$ Cut off frequency for non-inverting configuration

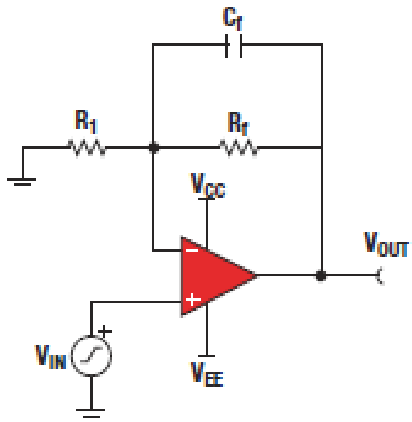


Figure 30: Non-inverting amplifier with C_f filter

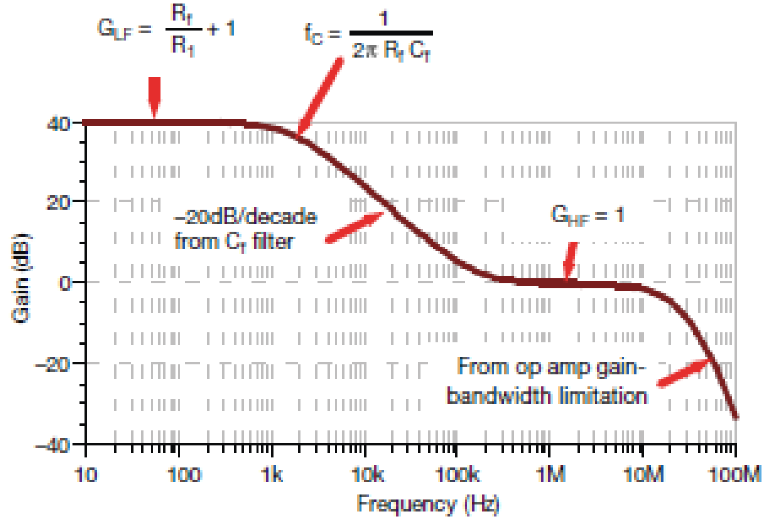


Figure 31: Frequency response for non-inverting op amp with C_f filter

Simple inverting amp with C_f filter

$$G_{LF} = -\frac{R_f}{R_1}$$ (85) Gain for inverting configuration for $f < f_C$

G_{HF} = –20dB/decade after f_C until op amp bandwidth limitation (86) Gain for inverting configuration for $f > f_C$

$$f_C = \frac{1}{2\pi R_f C_f}$$ (87) Cutoff frequency for inverting configuration

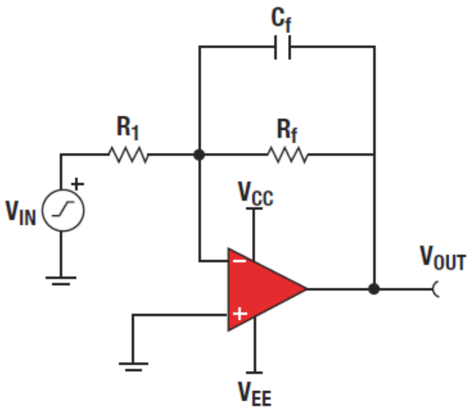


Figure 32: Inverting amplifier with C_f filter

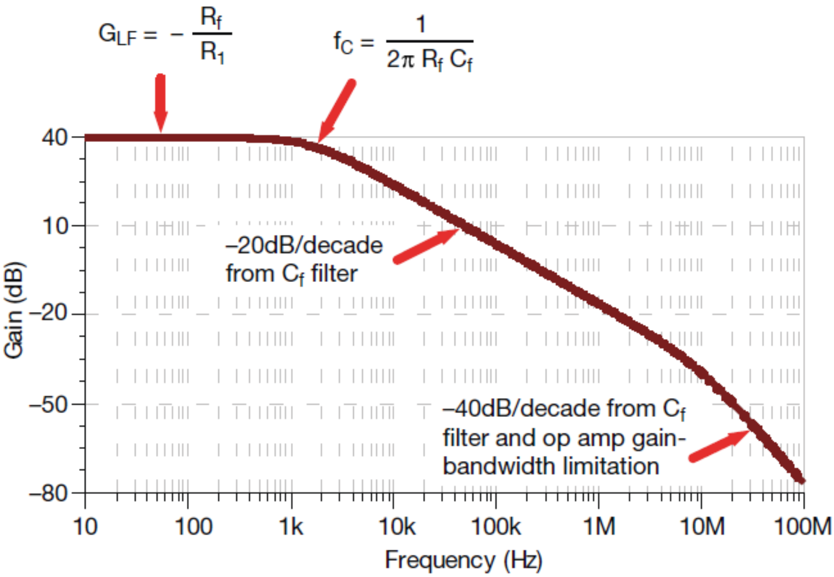


Figure 33: Frequency response for inverting op amp with C_f filter

Differential filter cutoff

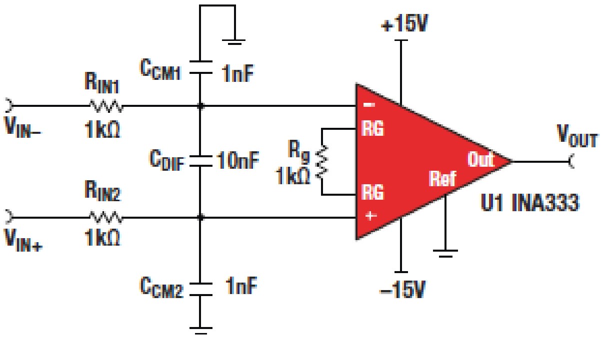


Figure 34: Input filter for instrumentation amplifier

Select $C_{DIF} \geq 10C_{CM1}$	(88) Differential capacitor is sized 10 times the common-mode capacitor
$R_{IN1} = R_{IN2}$	(89) Input resistors must be equal
$C_{CM1} = C_{CM2}$	(90) Common-mode capacitors must be equal
$f_{CM} = \dfrac{1}{2\pi R_{IN1} C_{CM1}}$	(91) Common-mode filter cutoff
$f_{DIF} = \dfrac{1}{2\pi(2R_{IN1})\left(C_{DIF} + \frac{1}{2}C_{CM1}\right)}$	(92) Differential filter cutoff

Where

f_{DIF} = differential cutoff frequency

f_{CM} = common-mode cutoff frequency

R_{IN} = input resistance

C_{CM} = common-mode filter capacitance

C_{DIF} = differential filter capacitance

Note: Selecting $C_{DIF} \geq 10\ C_{CM}$ sets the differential mode cutoff frequency about 20 times lower than the common-mode cutoff frequency. This prevents common-mode noise from being converted into differential noise due to component tolerances.

Calculating amplifier offset voltage

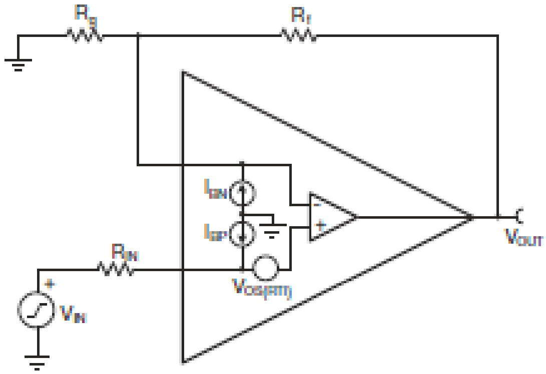


Figure 35: Op amp bias current and offset calculations

$$R_{eq} = \frac{R_f \cdot R_g}{R_f + R_g}$$ (93) Equivalent feedback resistance

$$V_{OS(IBN)} = I_{BN} \cdot R_{eq}$$ (94) Offset RTI from I_{BN} flowing into feedback

$$V_{OS(IBP)} = I_{BP} \cdot R_{IN}$$ (95) Offset RTI from I_{BP} flowing into source impedance

$$V_{OS(total\ worst)} = \pm V_{OS(Amp)} \pm V_{OS(IBN)} \pm V_{OS(IBP)}$$ (96) Directly adding the offset components. Conservative estimate.

$$V_{OS(total\ stat)} = \sqrt{V_{OS(Amp)}^{\ 2} + V_{OS(IBN)}^{\ 2} + V_{OS(IBP)}^{\ 2}}$$ (97) Statistically adding the offset components. More realistic estimate.

$$G_n = \frac{R_f}{R_g} + 1$$ (98) Noise gain of op amp (always non-inverting gain)

$$V_{OS(RTO)} = V_{OS(RTI)} \cdot G_n$$ (99) Offset referred to the output

Where

R_f, R_g = the feedback and gain setting resistors

R_{IN} = resistance seen by noninverting input

I_{BN}, I_{BP} = the current flowing from the inverting (I_{BN}) and noninverting (I_{BP}) op amp input as specified in the data sheet

$V_{os(amp)}$ = the input offset voltage specification from the op amp data sheet

$V_{OS(RTI)}$ = this is the offset referred to the input. This can be either $V_{os(total\ worst)}$ or $V_{os(total\ stat)}$.

Op amp bandwidth

$GBW = G_n \bullet BW$ (100) Gain bandwidth product defined

Where

GBW = gain bandwidth product, listed in op amp data sheet specification table

G_n = closed loop noise gain, always non-inverting gain

BW = the bandwidth limitation of the amplifier

Example

Determine bandwidth using equation 95, where

$G_n = 100$ (from amplifier configuration)

GBW = 22MHz (from data sheet)

Answer

$$BW = \frac{GBW}{G_n} = \frac{22MHz}{100} = 220kHz$$

Note that the same result can be graphically determined using the A_{OL} curve as shown below.

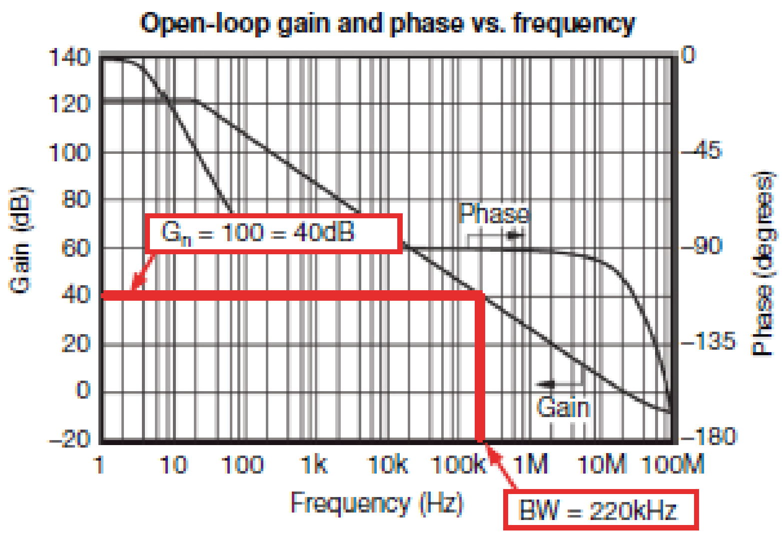


Figure 36: Using A_{OL} to find closed-loop bandwidth

Small signal step response

$$\tau_R = \frac{0.35}{f_C} \qquad (101)\ \text{Rise time for a small signal step}$$

Where

τ_R = the rise time of a small signal step response

f_C = the closed-loop bandwidth of the op amp circuit

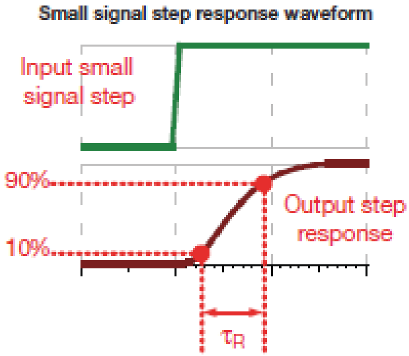


Figure 37: Small signal step response

Full power bandwidth

$$V_P = \frac{SR}{2\pi f} \qquad (102)\ \text{Maximum output without slew-rate induced distortion}$$

Where

V_P = maximum peak output voltage before slew induced distortion occurs

SR = slew rate

f = frequency of applied signal

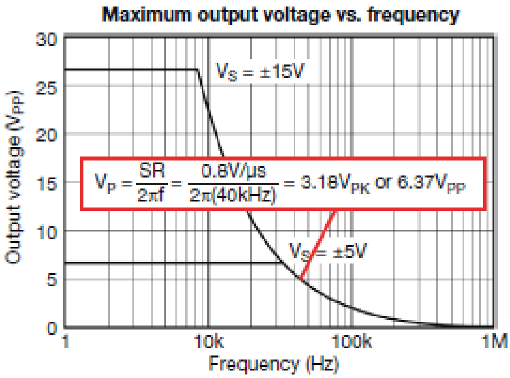


Figure 38: Maximum output without slew-rate induced distortion

Large signal response (slew rate)

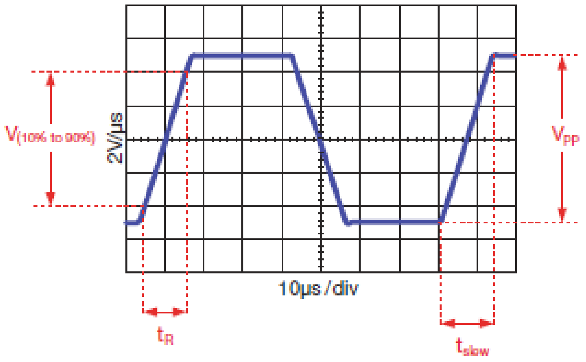


Figure 39: Large signal step response

$$t_R = \frac{V_{(10\%\ to\ 90\%)}}{SR}$$ (103) Rise time for large signal step response

$$t_{slow} \approx \frac{V_{pp}}{SR}$$ (104) Approximate total time for waveform to transition from peak to peak for large signal response

Where

$V_{(10\%\ TO\ 90\%)}$ = the change in output voltage from 10% to 90% for a step input

SR = the slew rate of the amplifier

V_{pp} = peak-to-peak square wave voltage for a step response

Combining noise sources

$$e_{nT} = \sqrt{(e_{n1})^2 + (e_{n2})^2}$$ (105) Combining two uncorrelated noise sources

$$e_{nT} = \sqrt{(e_{n1})^2 + (e_{n2})^2 + 2 \cdot C \cdot e_{n1} \cdot e_{n2}}$$ (106) Combining two correlated noise sources

Where

e_{nT} = total noise

e_{n1}, e_{n2} = noise sources

C = correlation factor, ranges from -1 to +1. C= 0 for uncorrelated sources, C=-1 for inversely correlated, and C=+1 for directly correlated.

Averaging noise sources

$$e_{nAvg} = \frac{e_n}{\sqrt{N}} \qquad \text{(107) Averaging noise}$$

Where

e_{nAvg} = the noise amplitude after averaging

e_n = the noise amplitude before averaging

N = the number of averages

Settling Time

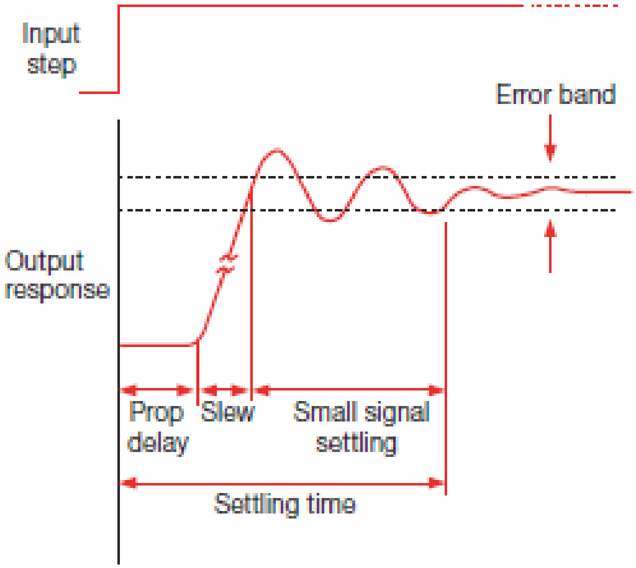


Figure 40: Small signal step response

Where

Settling time = the time from when an input step is applied until the output settles inside an error guard band. Settling time is measured with a large step (near full scale) input.

Prop delay = propagation delay. The time from when the input step is applied until the output begins to respond

Slew = the output is transitioning at the maximum rate given by the slew rate specification in the amplifier data sheet

Over the years and depending on the writer, an OTA has been referred to as a *diamond transistor*, a *voltage-controlled current source*, a *transconductor*, a *macro transistor*, and a *positive second-generation current conveyor* or CCII+. Figure 1 illustrates these terms and the corresponding symbols generally used to represent each.

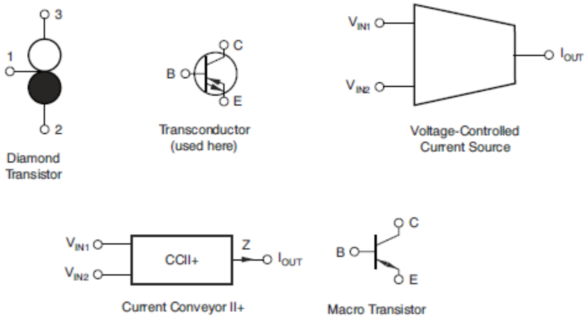


Figure 1. Typical OTA Elements and Accepted References