

Analog Engineer's

Pocket Reference

Art Kay and Tim Green, Editors

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Analog Engineer's Pocket Reference

Fourth Edition

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Message from the editors:

This pocket reference is intended as a valuable quick guide for often used board- and system-level design formulae. This collection of formulae is based on a combined 50 years of analog board- and system-level expertise. Much of the material herein was referred to over the years via a folder stuffed full of printouts. Those worn pages have been organized and the information is now available via this guide in a bound and hard-to-lose format!

Here is a brief overview of the key areas included:

- Key constants and conversions
- Discrete components
- AC and DC analog equations
- Op amp basic configurations
- OP amp bandwidth and stability
- Overview of sensors
- PCB trace R, L, C
- Wire L, R, C
- Binary, hex and decimal formats
- A/D and D/A conversions

We hope you find this collection of formulae as useful as we have. Please send any comments and/or ideas you have for the next edition of the *Analog Engineer's Pocket Reference* to artkay_timgreen@list.ti.com

Additional resources:

- Browse TI Precision Labs (www.ti.com/precisionlabs), a comprehensive online training curriculum for analog engineers, which applies theory to real-world, hands-on examples.
- Search for complete board-and-system level circuits in the TI Designs – Precision reference design library (www.ti.com/precisiondesigns).
- Read how-to blogs from TI precision analog experts at the Precision Hub (www.ti.com/thehub).
- Find solutions, get help, share knowledge and solve problems with fellow engineers and TI experts in the TI E2E™ Community (www.ti.com/e2e).

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Conversions

- Standard decimal prefixes •
- Metric conversions •
- Temperature scale conversions •
- Error conversions (ppm and percentage) •



Table 1: Physical constants

Constant	Symbol	Value	Units
Speed of light in a vacuum	c	$2.997\,924\,58 \times 10^8$	m/s
Permittivity of vacuum	ϵ_0	$8.854\,187\,817\,620 \times 10^{-12}$	F/m
Permeability of free space	μ_0	$1.256\,637\,0614 \times 10^{-6}$	H/m
Planck's constant	h	$6.626\,069\,57 \times 10^{-34}$	J•s
Boltzmann's constant	k	$1.380\,648\,8 \times 10^{-23}$	J/K
Faraday's constant	F	$9.648\,533\,99 \times 10^4$	C/mol
Avogadro's constant	N_A	$6.022\,141\,29 \times 10^{23}$	1/mol
Unified atomic mass unit	m_u	$1.660\,538\,921 \times 10^{-27}$	kg
Electronic charge	q	$1.602\,176\,565 \times 10^{-19}$	C
Rest mass of electron	m_e	$9.109\,382\,15 \times 10^{-31}$	kg
Mass of proton	m_p	$1.672\,621\,777 \times 10^{-27}$	kg
Gravitational constant	G	$6.673\,84 \times 10^{-11}$	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	1.00×10^3	kg/m ³
Density of mercury (0°C)	ρ_{Hg}	$1.362\,8 \times 10^4$	kg/m ³
Gas constant	R	8.314 462 1	J/(K•mol)
Speed of sound in air (at 273°K)	c_{air}	3.312×10^2	m/s

Table 2: Standard decimal prefixes

Multiplier	Prefix	Abbreviation
10^{12}	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Table 3: Imperial to metric conversions

Unit	Symbol	Equivalent	Unit	Symbol
inches	in	25.4 mm/in	millimeter	mm
mil	mil	0.0254 mm/mil	millimeter	mm
feet	ft	0.3048 m/ft	meters	m
yards	yd	0.9144 m/yd	meters	m
miles	mi	1.6093 km/mi	kilometers	km
circular mil	cir mil	$5.067 \times 10^{-4} \text{ mm}^2/\text{cir mil}$	square millimeters	mm^2
square yards	yd^2	0.8361 m^2	square meters	m^2
pints	pt	0.5682 L/pt	liters	L
ounces	oz	28.35 g/oz	grams	g
pounds	lb	0.4536 kg/lb	kilograms	kg
calories	cal	4.184 J/cal	joules	J
horsepower	hp	745.7 W/hp	watts	W

Table 4: 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	$1974 \text{ cir mil}/\text{mm}^2$	circular mil	cir mil
square meters	m^2	$1.1960 \text{ yd}^2/\text{m}^2$	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	$1.341 \times 10^{-3} \text{ hp}/\text{W}$	horsepower	hp

Example

Convert 10 mm to mil.

Answer

$10 \text{ mm} \times 39.4 \frac{\text{mil}}{\text{mm}} = 394 \text{ mil}$

Table 5: Temperature conversions

$^{\circ}\text{C} = \frac{5}{9} (^{\circ}\text{F} - 32)$	Fahrenheit to Celsius
$^{\circ}\text{F} = \frac{9}{5} (^{\circ}\text{C}) + 32$	Celsius to Fahrenheit
$\text{K} = ^{\circ}\text{C} + 273.15$	Celsius to Kelvin
$^{\circ}\text{C} = \text{K} - 273.15$	Kelvin to Celsius

Table 6: Error conversions

$\text{Error}(\%) = \frac{\text{Measured} - \text{Ideal}}{\text{Ideal}} \times 100$	Error in measured value
$\text{Error}(\% \text{ FSR}) = \frac{\text{Measured} - \text{Ideal}}{\text{Full-scale range}} \times 100$	Error in percent of full-scale range
$\% = \frac{\text{ppm}}{10^6} \times 100$	Part per million to percent
$\text{m}\% = \frac{\text{ppm}}{10^6} \times 100 \times 1000$	Part per million to milli-percent
$\text{ppm} = \% \times 10^4$	Percent to part per million
$\text{ppm} = \text{m}\% \times 10$	Milli-percent to part per million

Example

Compute the error for a measured value of 0.12V when the ideal value is 0.1V and the range is 5V.

Answer

$\text{Error}(\%) = \frac{0.12\text{V} - 0.1\text{V}}{0.1\text{V}} \times 100 = 20\%$	Error in measured value
$\text{Error}(\% \text{ FSR}) = \frac{0.12 - 0.1\text{V}}{5\text{V}} \times 100 = 0.4\%$	Percent FSR

Example

Convert 10 ppm to percent and milli-percent.

Answer

$\frac{10 \text{ ppm}}{10^6} \times 100 = 0.001\%$	Part per million to percent
$\frac{10 \text{ ppm}}{10^6} \times 100 \times 1000 = 1 \text{ m}\%$	Part per million to milli-percent

Discrete Components

- Resistor color code •
- Standard resistor values •
- Capacitance specifications •
- Capacitance type overview •
- Standard capacitance values •
- Capacitance marking and tolerance •

Discrete

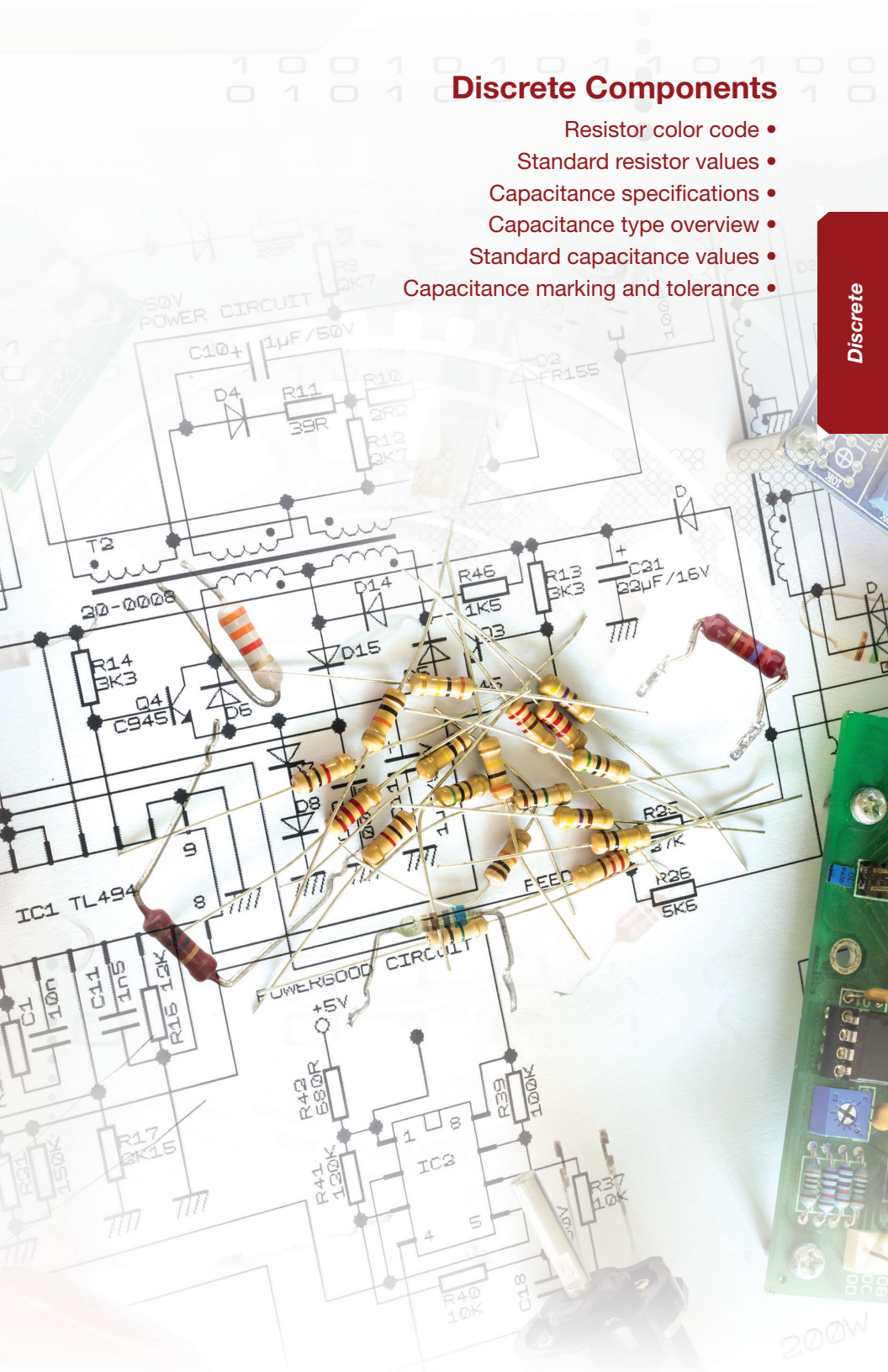


Table 7: Resistor color code

Color	Digit	Additional Zeros	Tolerance	Temperature Coefficient	Failure Rate
Black	0	0		250	
Brown	1	1	1%	100	1
Red	2	2	2%	50	0.1
Orange	3	3		15	0.01
Yellow	4	4		25	0.001
Green	5	5	0.5%	20	
Blue	6	6	0.25%	10	
Violet	7	7	0.1%	5	
Grey	8	8	0.05%	1	
White	9	9			
Gold	-na-	-1	5%		
Silver	-na-	-2	10%		
No Band	-na-	-na-	20%		

4 Band example: yellow violet orange silver indicate 4, 7, and 3 zeros.
i.e. a 47kΩ, 10% resistor.

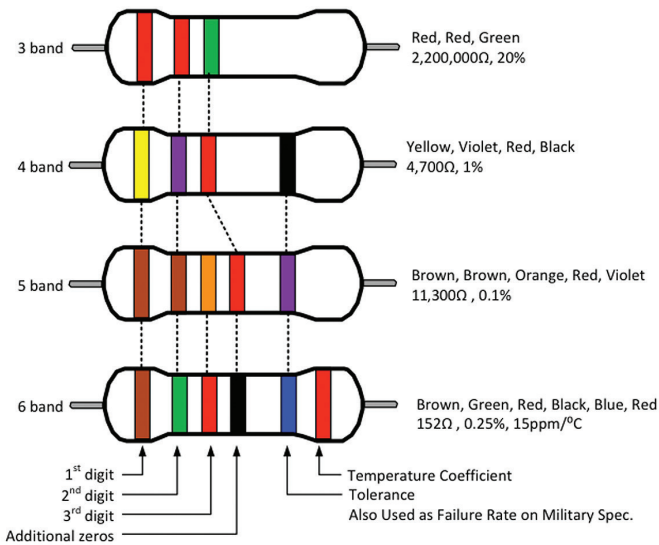


Figure 1: Resistor color code

Table 8: Standard resistor values

Standard resistance values for the 10 to 100 decade																							
0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%	0.1% 0.25% 0.5%	1%	2% 5% 10%
10.0	10.0	10	14.7	14.7	15	21.5	21.5	21.5	31.6	31.6	31.6	46.4	46.4	46.4	68.1	68.1	68						
10.1			14.9			21.8			32.0			47.0			69.0								
10.2	10.2		15.0	15.0	15	22.1	22.1	22	32.4	32.4	22	47.5	47.5	47.5	69.8	69.8							
10.4			15.2			22.3			32.8			48.1			70.6								
10.5	10.5		15.4	15.4		22.6	22.6		33.2	33.2		48.7	48.7	48.7	71.5	71.5							
10.6			15.6			22.9			33.6			49.3			72.3								
10.7	10.7		15.8	15.8		23.2	23.2		34.0	34.0		49.9	49.9	49.9	73.2	73.2							
10.9			16.0		16	23.4			34.4			50.5			74.1								
11.0	11.0	11	16.2	16.2		23.7	23.7		34.8	34.8		51.1	51.1	51.1	75.0	75.0	75						
11.1			16.4			24.0		24	35.2			51.7			75.9								
11.3	11.3		16.5	16.5		24.3	24.3		35.7	35.7		52.3	52.3	52.3	76.8	76.8							
11.4			16.7			24.6			36.1		36	53.0			77.7								
11.5	11.5		16.9	16.9		24.9	24.9		36.5	36.5		53.6	53.6	53.6	78.7	78.7							
11.7			17.2			25.2			37.0			54.2			79.6								
11.8	11.8		17.4	17.4		25.5	25.5		37.4	37.4		54.9	54.9	54.9	80.6	80.6							
12.0		12	17.6			25.8			37.9			55.6			81.6								
12.1	12.1		17.8	17.8		26.1	26.1		38.3	38.3		56.2	56.2	56.2	82.5	82.5	82						
12.3			18.0		18	26.4			38.8			56.9			83.5								
12.4	12.4		18.2	18.2		26.7	26.7		39.2	39.2	27	57.6	57.6	57.6	84.5	84.5							
12.6			18.4			27.1			39.7			58.3			85.6								
12.7	12.7		18.7	18.7		27.4	27.4		40.2	40.2		59.0	59.0	59.0	86.6	86.6							
12.9			18.9			27.7			40.7			59.7			87.6								
13.0	13.0	13	19.1	19.1		28.0	28.0		41.2	41.2		60.4	60.4	60.4	88.7	88.7							
13.2			19.3			28.4			41.7			61.2			89.8								
13.3	13.3		19.6	19.6		28.7	28.7		42.2	42.2		61.9	61.9	61.9	90.9	90.9	91						
13.5			19.8			29.1			42.7			62.6			92.0								
13.7	13.7		20.0	20.0	20	29.4	29.4		43.2	43.2	43	63.4	63.4	63.4	93.1	93.1							
13.8			20.3			29.8			43.7			64.2			94.2								
14.0	14.0		20.5	20.5		30.1	30.1	30	44.2	44.2		64.9	64.9	64.9	95.3	95.3							
14.2			20.8			30.5			44.8			65.7			96.5								
14.3	14.3		21.0	21.0		30.9	30.9		45.3	45.3		66.5	66.5	66.5	97.6	97.6							
14.5			21.3			31.2			45.9			67.3			98.8								

Practical capacitor model and specifications

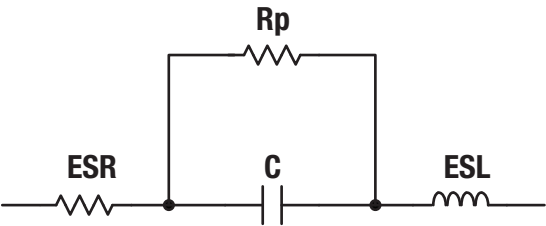


Figure 2: Model of a practical capacitor

Table 9: Capacitor specifications

Parameter	Description
C	The nominal value of the capacitance Table 11 lists standard capacitance values
ESR	Equivalent series resistance Ideally this is zero Ceramic capacitors have the best ESR (typically in milliohms). Tantalum Electrolytic have ESR in the hundreds of milliohms and Aluminum Electrolytic have ESR in the ohms
ESL	Equivalent series inductance Ideally this is zero ESL ranges from 100 pH to 10 nH
Rp	Rp is a parallel leakage resistance (or insulation resistance) Ideally this is infinite This can range from tens of megaohms for some electrolytic capacitors to tens of gigohms for ceramic
Voltage rating	The maximum voltage that can be applied to the capacitor Exceeding this rating damages the capacitor
Voltage coefficient	The change in capacitance with applied voltage in ppm/V A high-voltage coefficient can introduce distortion COG capacitors have the lowest coefficient The voltage coefficient is most important in applications that use capacitors in signal processing such as filtering
Temperature coefficient	The change in capacitance with across temperature in ppm/°C Ideally, the temperature coefficient is zero The maximum specified drift generally ranges from 10 to 100ppm/°C or greater depending on the capacitor type (See Table 10 for details)

Practical capacitors vs. frequency

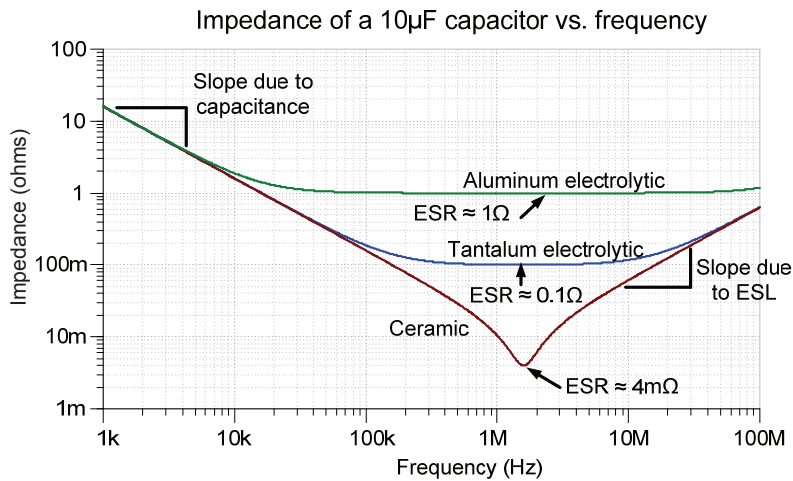


Figure 3: Effect of ESR and ESL on capacitor frequency response

Table 10: Capacitor type overview

Capacitor type	Description
COG/NPO (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

Table 11: 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	

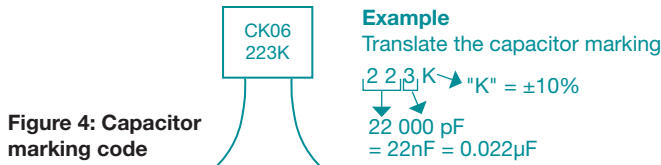


Table 12: Ceramic capacitor tolerance markings

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%		

Table 13: 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	+125°C	E	±4.7%
				F	±7.5%
				P	±10.0%
				R	±15.0%
				S	±22.0%
				T	±22% ~ 33%
				U	±22% ~ 56%
				V	±22% ~ 82%

Example
X7R: -55°C to +125°C, ±15.0%

Diodes and LEDs

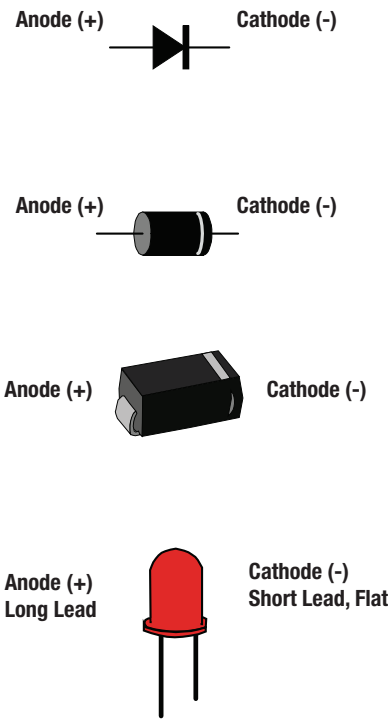


Figure 5: Diode and LED pin names

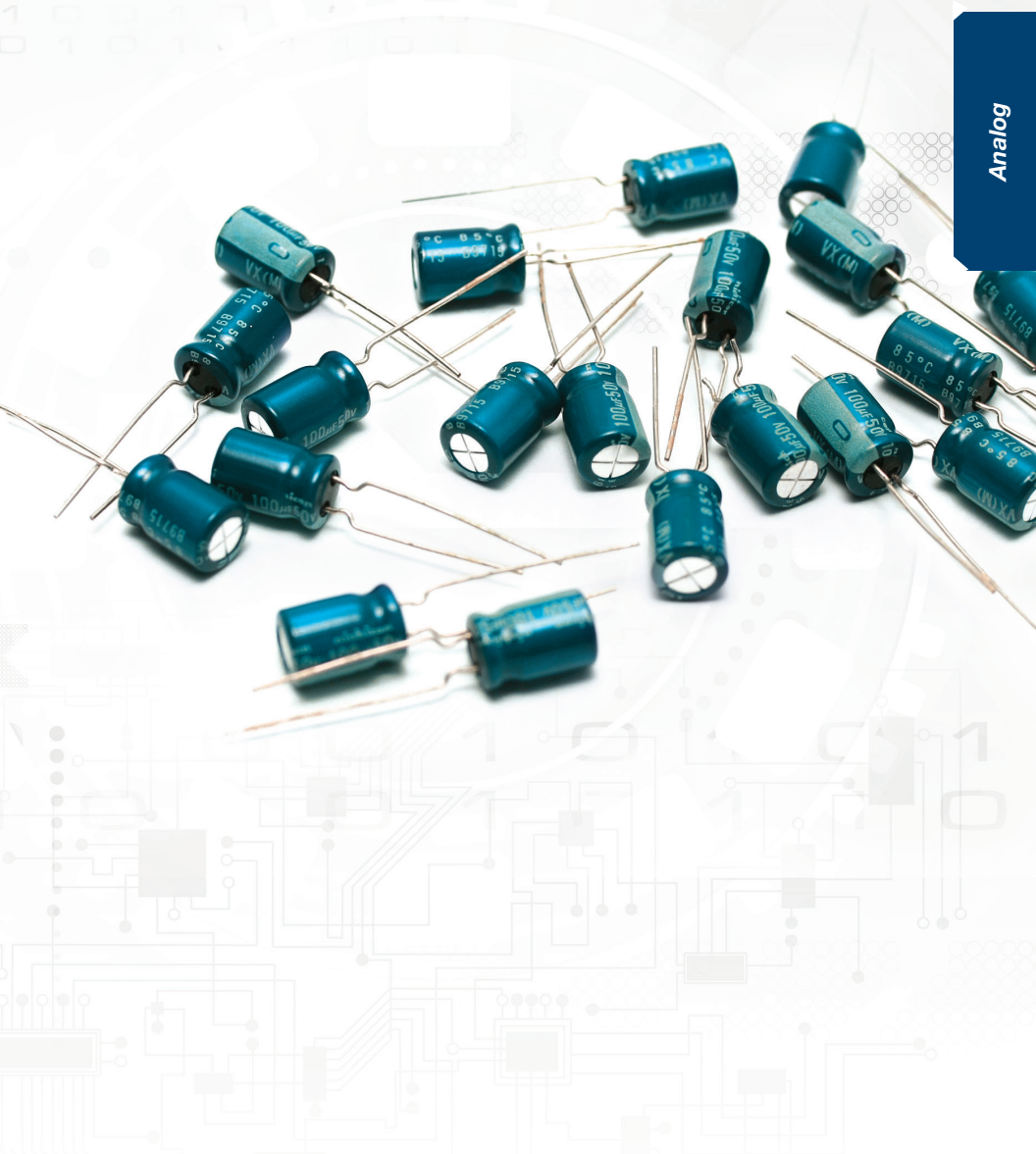
Color	Wavelength (nm)	Voltage (approximate range)
Infrared	940-850	1.4 to 1.7
Red	660-620	1.7 to 1.9
Orange / Yellow	620-605	2 to 2.2
Green	570-525	2.1 to 3.0
Blue/White	470-430	3.4 to 3.8

Table 14: LED forward voltage drop by color

Note: The voltages given are approximate, and are intended to show the general trend for forward voltage drop of LED diodes. Consult the manufacturer's data sheet for more precise values.

Analog

- 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

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_N}} \quad (1) \text{ Series capacitors}$$

$$C_t = \frac{C_1 C_2}{C_1 + C_2} \quad (2) \text{ Two series capacitors}$$

$$C_t = C_1 + C_2 + \dots + C_N \quad (3) \text{ Parallel capacitors}$$

Where

C_t = equivalent total capacitance

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

$$Q = CV \quad (4) \text{ Charge storage}$$

$$Q = It \quad (5) \text{ Charge defined}$$

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)

$$i = C \frac{dv}{dt} \quad (6) \text{ Instantaneous current through a capacitor}$$

Where

i = instantaneous current through the capacitor

C = capacitance in farads (F)

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

$$E = \frac{1}{2} CV^2 \quad (7) \text{ Energy stored in a capacitor}$$

Where

E = energy stored in an capacitor in Joules (J)

V = voltage in volts

C = capacitance in farads (F)

Inductor equations

$$L_t = L_1 + L_2 + \dots + L_N \quad (8) \text{ Series inductors}$$

$$L_t = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \dots + \frac{1}{L_N}} \quad (9) \text{ Parallel inductors}$$

$$L_t = \frac{L_1 L_2}{L_1 + L_2} \quad (10) \text{ Two parallel inductors}$$

Where

L_t = equivalent total inductance

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

$$v = L \frac{di}{dt} \quad (11) \text{ Instantaneous voltage across an inductor}$$

Where

v = instantaneous voltage across the inductor

L = inductance in Henries (H)

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

$$E = \frac{1}{2} LI^2 \quad (12) \text{ Energy stored in an inductor}$$

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

$$V_C = V_S \left[1 - e^{\left(\frac{-t}{\tau}\right)} \right] \quad (13) \text{ General relationship}$$

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

Graphing equation 13 produces the capacitor charging curve below. Note that the capacitor is 99.3% charged at five time constants. It is common practice to consider this *fully charged*.

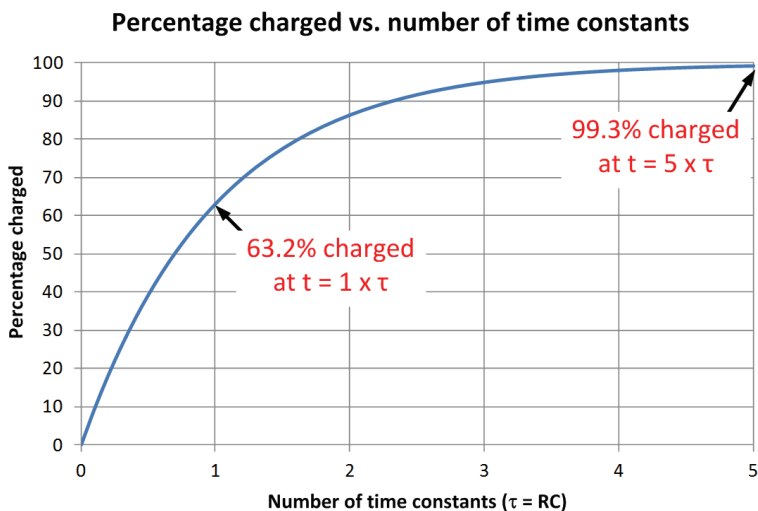


Figure 6: RC charge curve

Equation for discharging an RC circuit

$$V_C = V_i \left[e^{\left(\frac{-t}{\tau}\right)} \right] \quad (14) \text{ General Relationship}$$

Where

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

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

t = time in seconds

$\tau = RC$, the time constant for charging and discharging capacitors

Graphing equation 14 produces the capacitor discharge curve below. Note that the capacitor is discharged to 0.7% at five time constants. It is common practice to consider this *fully discharged*.

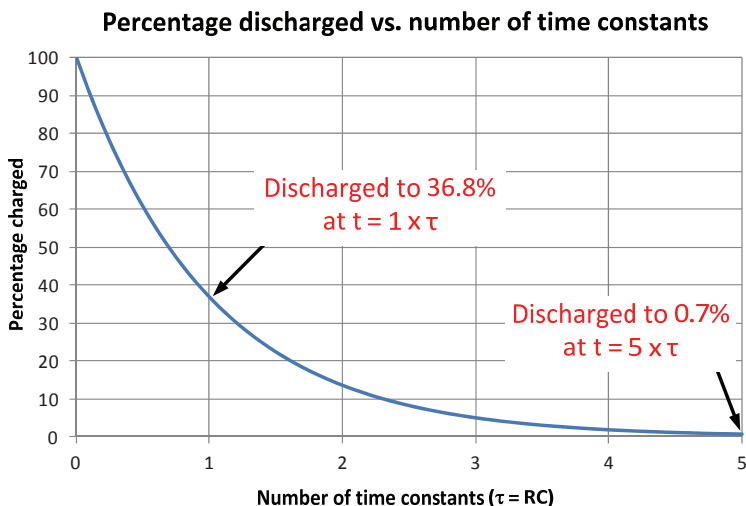


Figure 7: RC discharge curve

RMS voltage

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

(15) 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

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

(16) 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

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

(17) RMS for full wave rectified sine wave

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

(18) Mean for full wave rectified sine wave

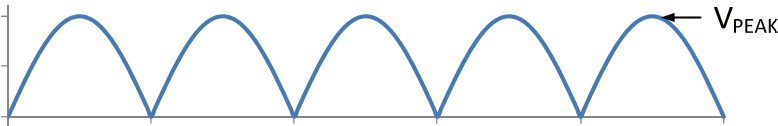


Figure 8: Full wave rectified sine wave

RMS voltage and mean voltage

$$V_{\text{RMS}} = V_{\text{PEAK}} \sqrt{\left(\frac{\tau}{2T}\right)} \quad (19) \text{ RMS for a half-wave rectified sine wave}$$

$$V_{\text{MEAN}} = \frac{2 \times V_{\text{PEAK}}}{\pi} \left(\frac{\tau}{T}\right) \quad (20) \text{ Mean for a half-wave rectified sine wave}$$

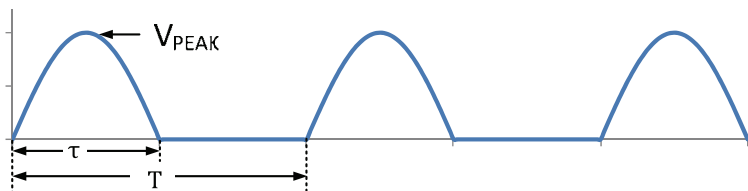


Figure 9: Half-wave rectified sine wave

$$V_{\text{RMS}} = V_{\text{PEAK}} \sqrt{\frac{\tau}{T}} \quad (21) \text{ RMS for a square wave}$$

$$V_{\text{MEAN}} = V_{\text{PEAK}} \frac{\tau}{T} \quad (22) \text{ Mean for a square wave}$$

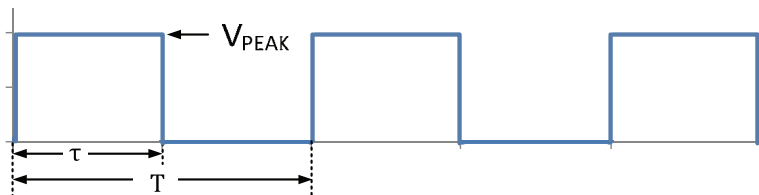


Figure 10: Square wave

RMS voltage and mean voltage

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

(23) RMS for a trapezoid

$$V_{\text{MEAN}} = \frac{\tau}{2T} (V_a + V_b)$$

(24) Mean for a trapezoid

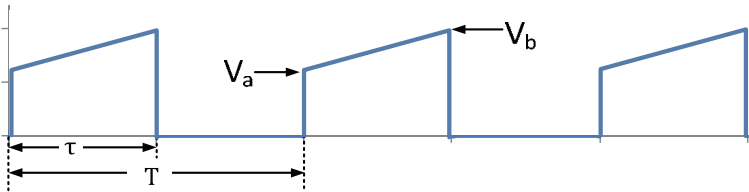


Figure 11: Trapezoidal wave

$$V_{\text{RMS}} = V_{\text{PEAK}} \sqrt{\frac{\tau}{3T}}$$

(25) RMS for a triangle wave

$$V_{\text{MEAN}} = \frac{\tau}{2T} V_{\text{PEAK}}$$

(26) Mean for a triangle wave

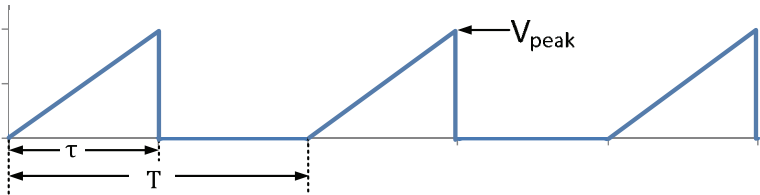


Figure 12: Triangle wave

Logarithmic mathematical definitions

$$\log\left(\frac{A}{B}\right) = \log(A) - \log(B) \quad (27) \text{ Log of dividend}$$

$$\log(AB) = \log(A) + \log(B) \quad (28) \text{ Log of product}$$

$$\log(A^x) = x \log(A) \quad (29) \text{ Log of exponent}$$

$$\log_b(X) = \frac{\log_a(X)}{\log_a(b)} \quad (30) \text{ Changing the base of log function}$$

$$\log_2(X) = \frac{\log_{10}(X)}{\log_{10}(2)} \quad (31) \text{ Example changing to log base 2}$$

$$\ln(X) = \log_e(X) \quad (32) \text{ Natural log is log base } e$$

$$e = 2.718282 \quad (33) \text{ Exponential function to 6 digits}$$

Alternative notations

$$\exp(x) = e^x \quad (34) \text{ Different notation for exponential function}$$

$$3.54\text{E}-2 = 3.54 \times 10^{-2} \quad (35) \text{ Different notation for scientific notation, sometimes confused with exponential function}$$

dB definitions

Bode plot basics

The frequency response for the magnitude or gain plot is the change in voltage gain as frequency changes. This change is specified on a Bode plot, a plot of frequency versus voltage gain in dB (decibels). Bode plots are usually plotted as semi-log plots with frequency on the x-axis, log scale, and gain on the y-axis, linear scale. The other half of the frequency response is the phase shift versus frequency and is plotted as frequency versus degrees phase shift. Phase plots are usually plotted as semi-log plots with frequency on the x-axis, log scale, and phase shift on the y-axis, linear scale.

Definitions

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

(36) Voltage gain in decibels

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

(37) Power gain in decibels

$$\text{Power Measured(dBm)} = 10 \log \left(\frac{\text{Power Measured (W)}}{1 \text{ mW}} \right)$$

(38) Used for input or output power

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

Table 15: Examples of common gain values and dB equivalent

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)

Figure 13 illustrates a method to graphically determine values on a logarithmic axis that are not directly on an axis grid line.

1. Given $L = 1\text{cm}$; $D = 2\text{cm}$, measured with a ruler.
2. $L/D = \log_{10}(f_p)$
3. $f_p = 10^{(L/D)} = 10^{(1\text{cm}/2\text{cm})} = 3.16$
4. Adjust for the decade range (for this example, $f_p = 31.6\text{ Hz}$)

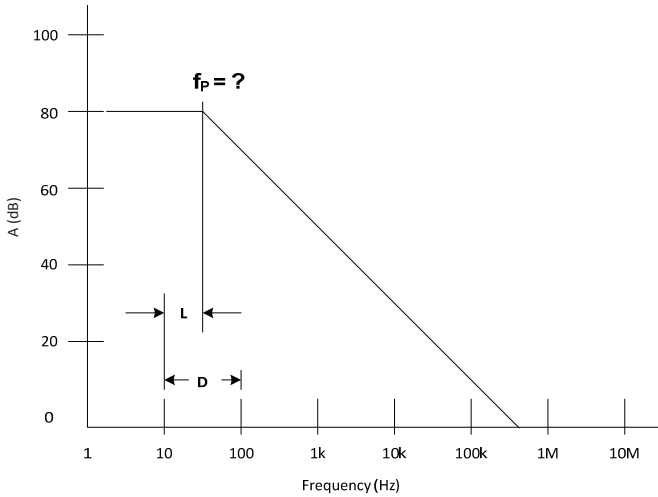


Figure 13: Finding values on logarithmic axis not directly on a grid line

Bode plots: Poles

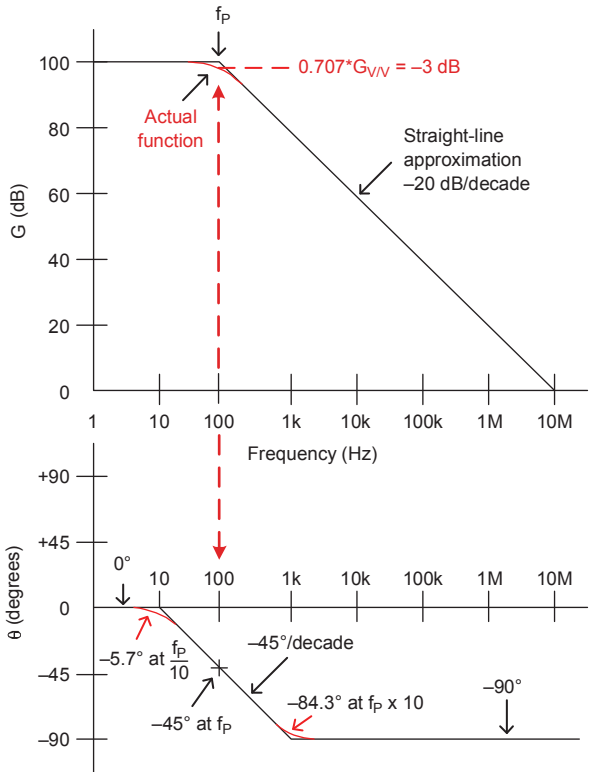


Figure 14: Pole gain and phase

- 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 ($0.1 f_P < f < 10 f_P$) = $-45^\circ/\text{decade}$
- Phase ($f > 10 f_P$) = -90°
- Phase ($f < 0.1 f_P$) = 0°

Pole (equations)

$$G_V = \frac{V_{OUT}}{V_{IN}} = \frac{G_{DC}}{j\left(\frac{f}{f_P}\right) + 1} \quad (39) \text{ As a complex number}$$

$$G_V = \frac{V_{OUT}}{V_{IN}} = \frac{G_{DC}}{\sqrt{\left(\frac{f}{f_P}\right)^2 + 1}} \quad (40) \text{ Magnitude}$$

$$\theta = -\tan^{-1}\left(\frac{f}{f_P}\right) \quad (41) \text{ Phase shift}$$

$$G_{dB} = 20 \text{ Log}(G_V) \quad (42) \text{ Magnitude in dB}$$

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_P = frequency at which the pole occurs

θ = phase shift of the signal from input to output

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

Bode plots (zeros)

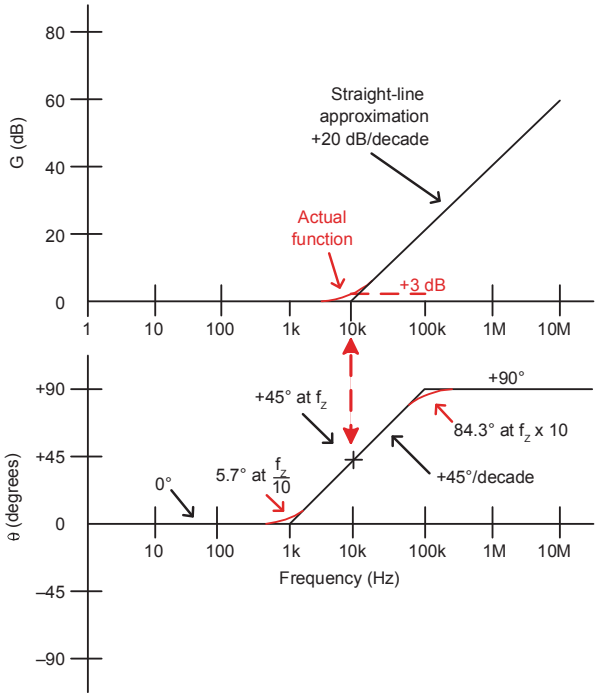


Figure 15: Zero gain and phase

- 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°

Zero (equations)

$$G_V = \frac{V_{OUT}}{V_{IN}} = G_{DC} \left[j \left(\frac{f}{f_Z} \right) + 1 \right] \quad (43) \text{ As a complex number}$$

$$G_V = \frac{V_{OUT}}{V_{IN}} = G_{DC} \sqrt{\left(\frac{f}{f_Z} \right)^2 + 1} \quad (44) \text{ Magnitude}$$

$$\theta = \tan^{-1} \left(\frac{f}{f_Z} \right) \quad (45) \text{ Phase shift}$$

$$G_{dB} = 20 \log(G_V) \quad (46) \text{ Magnitude in dB}$$

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 $\sqrt{-1}$

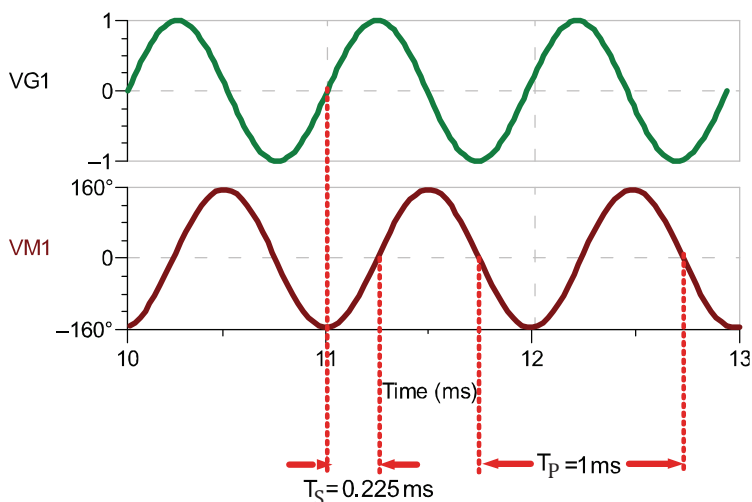


Figure 16: Time to phase shift

$$\theta = \frac{T_S}{T_P} \cdot 360^\circ \quad (47) \text{ Phase shift from time}$$

Where

T_S = time shift from input to output signal

T_P = period of signal

θ = phase shift of the signal from input to output

Example

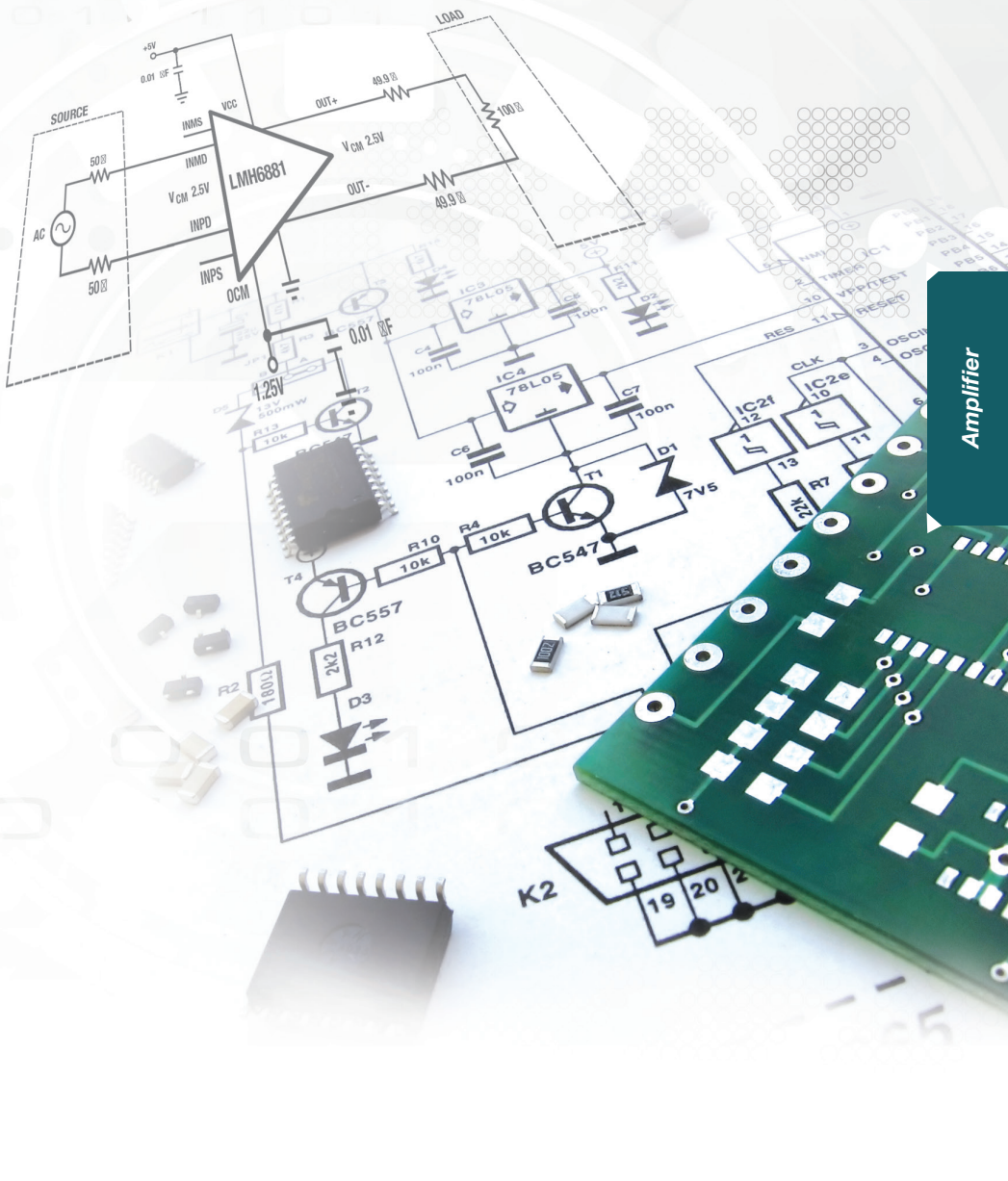
Calculate the phase shift in degrees for Figure 16.

Answer

$$\theta = \frac{T_S}{T_P} \cdot 360^\circ = \left(\frac{0.225\text{ ms}}{1\text{ ms}} \right) \cdot 360^\circ = 81^\circ$$

Amplifier

- Basic op amp configurations
- Op amp bandwidth
- Full power bandwidth
- Small signal step response
- Noise equations
- Stability equations
- Stability open loop SPICE analysis



Basic op amp configurations

$$G_{CL} = 1$$

(48) Gain for buffer configuration

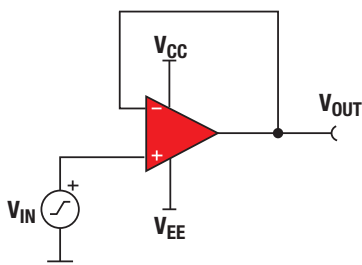


Figure 17: Buffer configuration

$$G_{CL} = \frac{R_f}{R_1} + 1$$

(49) Gain for non-inverting configuration

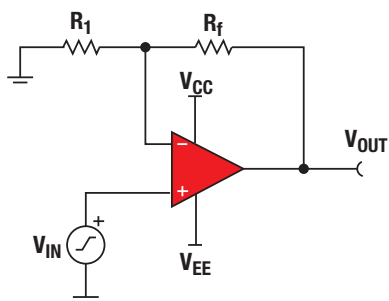


Figure 18: Non-inverting configuration

Basic op amp configurations (cont.)

$$G_{CL} = -\frac{R_f}{R_1} \quad (50) \text{ Gain for inverting configuration}$$

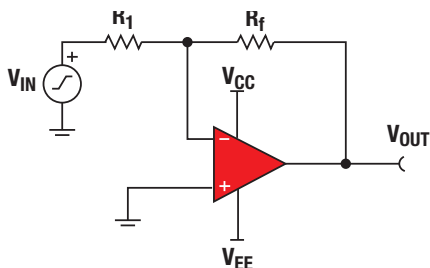


Figure 19: Inverting configuration

$$V_{OUT} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \dots + \frac{V_N}{R_N} \right) \quad (51) \text{ Transfer function for inverting summing amplifier}$$

$$V_{OUT} = -\frac{R_f}{R_1} (V_1 + V_2 + \dots + V_N) \quad (52) \text{ Transfer function for inverting summing amplifier, assuming } R_1 = R_2 = \dots = R_N$$

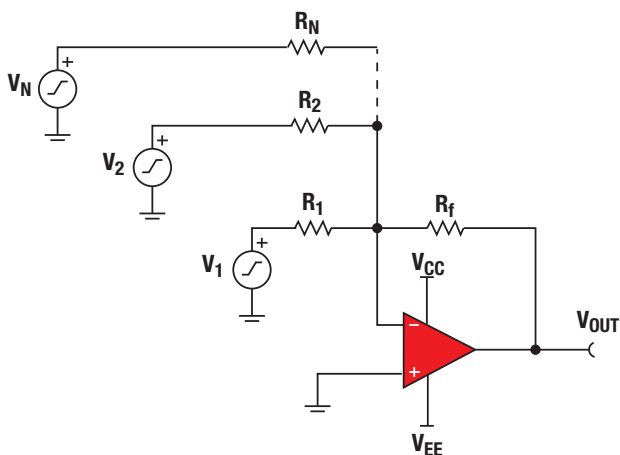


Figure 20: Inverting summing configuration

Basic op amp configurations (cont.)

$$V_{OUT} = \left(\frac{R_f}{R_{in}} + 1 \right) \left[\frac{V_1}{N} + \frac{V_2}{N} + \dots + \frac{V_N}{N} \right] \quad (53) \text{ Transfer function for noninverting summing amplifier for equal input resistors}$$

Where

$R_1 = R_2 = \dots = R_N$

N = number of input resistors

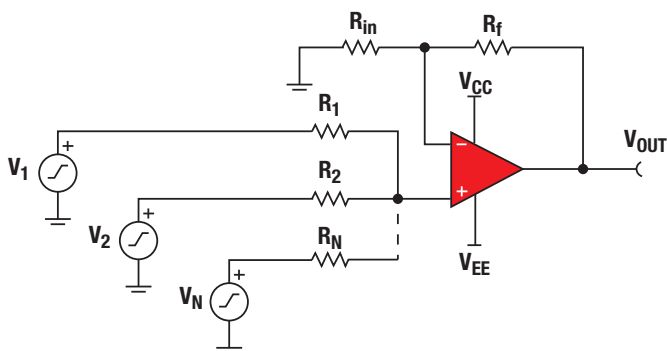


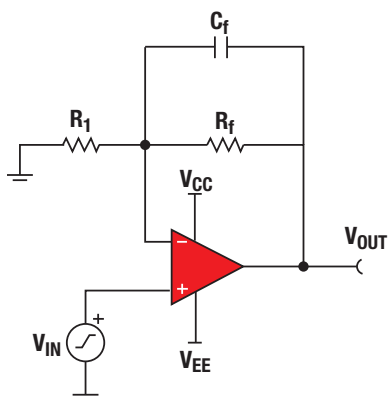
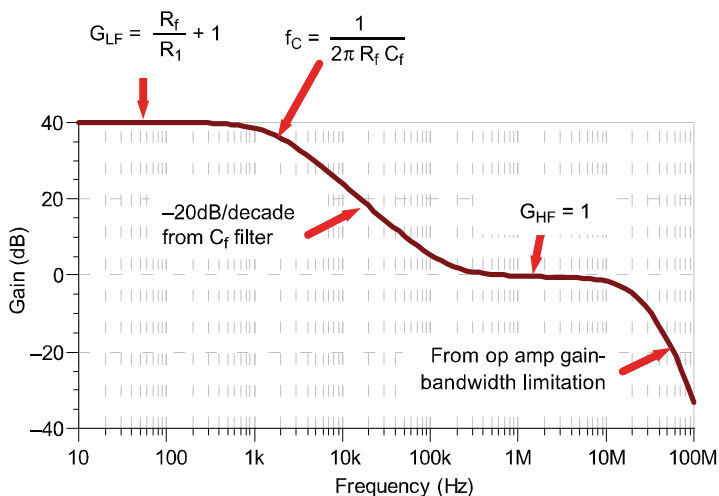
Figure 21: Non-inverting summing configuration

Simple non-inverting amp with C_f filter

$$G_{LF} = \frac{R_f}{R_1} + 1 \quad (54) \text{ Gain for non-inverting configuration for } f < f_c$$

$$G_{HF} = 1 \quad (55) \text{ Gain for non-inverting configuration for } f \gg f_c$$

$$f_c = \frac{1}{2\pi R_f C_f} \quad (56) \text{ Cut off frequency for non-inverting configuration}$$

Figure 22: Non-inverting amplifier with C_f filterFigure 23: Frequency response for non-inverting op amp with C_f filter

Simple inverting amp with C_f filter

$$G_{LF} = -\frac{R_f}{R_1}$$

(57) Gain for inverting configuration for $f < f_c$

$$G_{HF} = -20\text{dB/decade after } f_c \text{ until op amp bandwidth limitation}$$

(58) Gain for inverting configuration for $f > f_c$

$$f_c = \frac{1}{2\pi R_f C_f}$$

(59) Cutoff frequency for inverting configuration

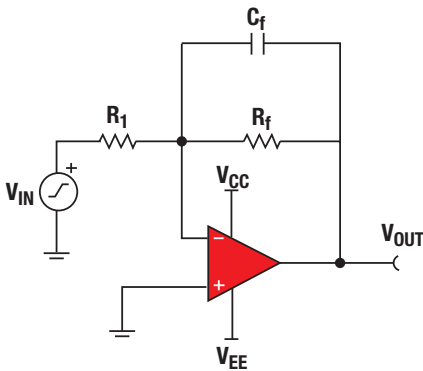


Figure 24: Inverting amplifier with C_f filter

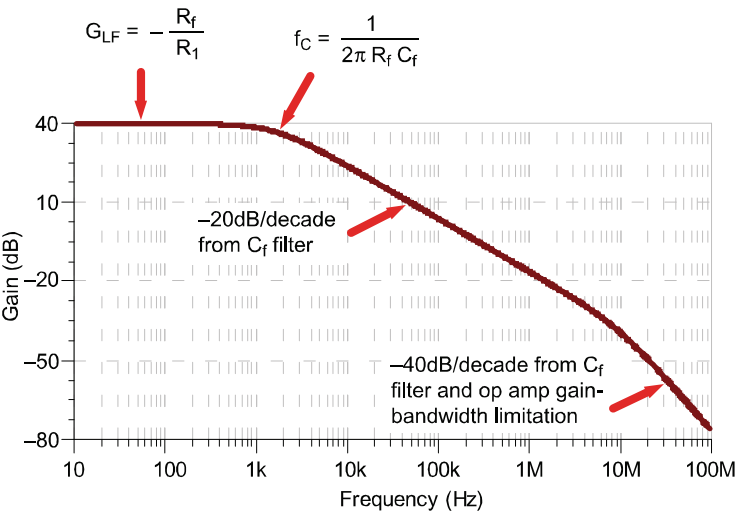


Figure 25: Frequency response for inverting op amp with C_f filter

Op amp bandwidth

$$GBW = \text{Gain} \cdot BW$$

(60) Gain bandwidth product defined

Where

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

Gain = closed loop gain, set by op amp gain configuration

BW = the bandwidth limitation of the amplifier

Example

Determine bandwidth using equation 60

Gain = 100 (from amplifier configuration)

GBW = 22MHz (from data sheet)

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

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

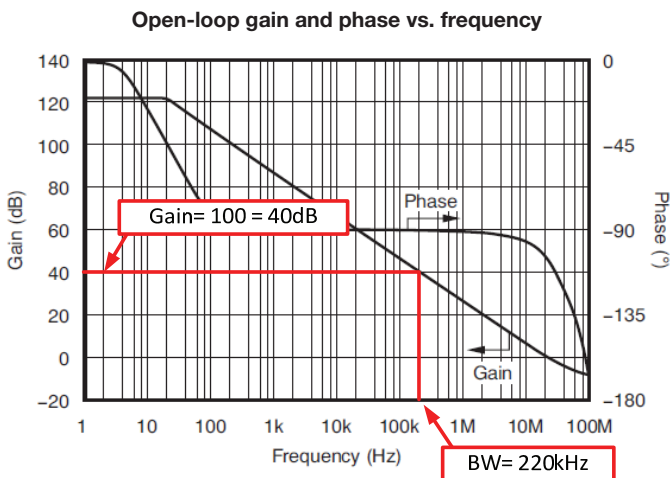


Figure 26: Using A_{OL} to find closed-loop bandwidth

Full power bandwidth

$$V_P = \frac{SR}{2\pi f}$$

(61) 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

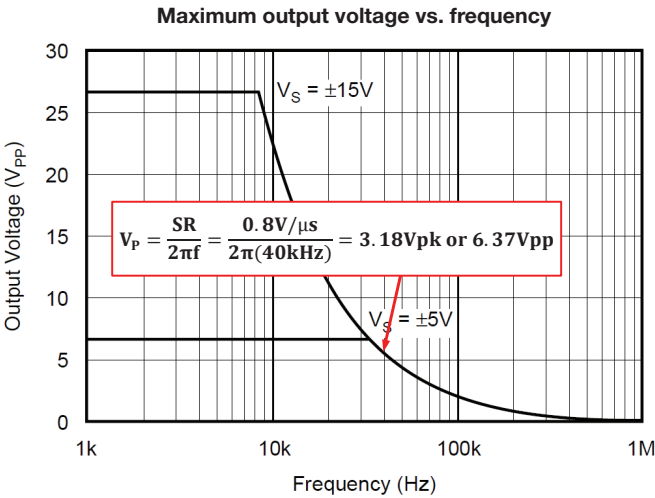


Figure 27: Maximum output without slew-rate induced distortion

Notice that the above figure is graphed using equation 61 for the OPA277. The example calculation shows the peak voltage for the OPA277 at 40kHz. This can be determined graphically or with the equation.

Example

$$V_P = \frac{SR}{2\pi f} = \frac{0.8V/\mu s}{2\pi(40kHz)} = 3.18V_{pk} \text{ or } 6.37V_{pp}$$

Small signal step response

$$\tau_R = \frac{0.35}{f_C} \quad (62) \text{ Rise time for a small signal step}$$

Where

τ_R = the rise time of a small signal step response

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

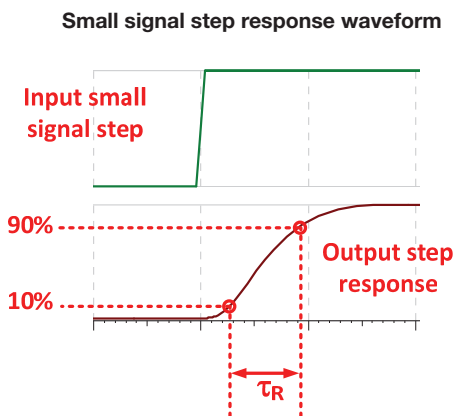


Figure 28: Maximum output without slew-rate induced distortion

Op amp noise model

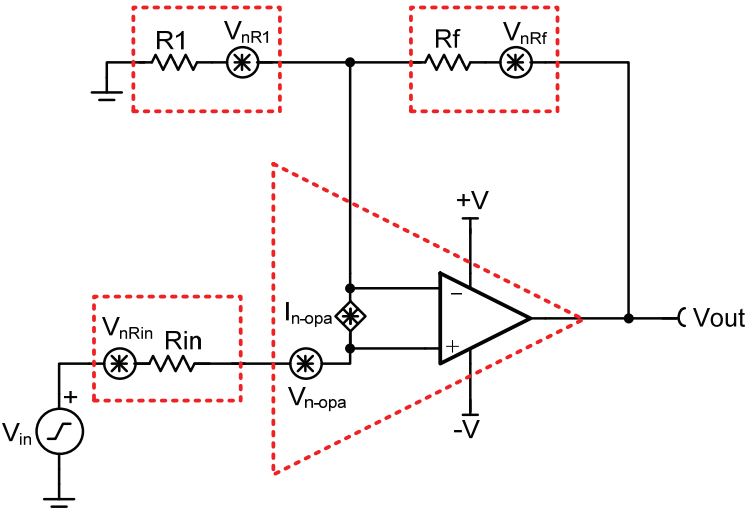


Figure 29: Op amp noise model

Op amp intrinsic noise includes:

- Noise caused by op amp (current noise + voltage noise)
- Resistor noise

Noise bandwidth calculation

$$BW_N = K_N f_C$$

(63) Noise bandwidth

Where

BW_N = noise bandwidth of the system
 K_N = the brick wall correction factor for different filter order
 f_C = -3 dB bandwidth of the system

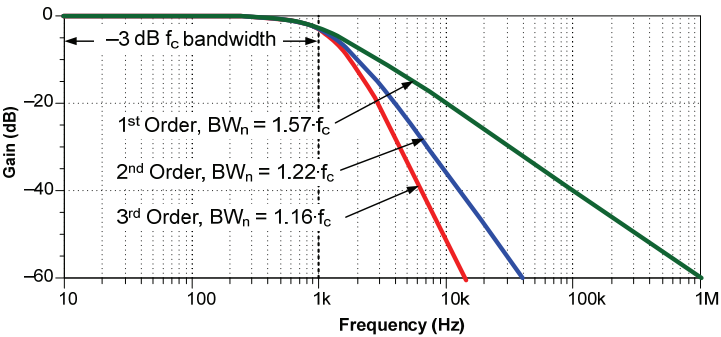


Figure 30: Op amp bandwidth for three different filters orders

Table 16: Brick wall correction factors for noise bandwidth

Number of poles	KN brick wall correction factor
1	1.57
2	1.22
3	1.13
4	1.12

Broadband total noise calculation

$$E_N = e_{BB} \sqrt{BW_N}$$

(64) Total rms noise from broadband

Where

E_N = total rms noise from broadband noise
 e_{BB} = broadband noise spectral density (nV/rtHz)
 BW_N = noise bandwidth (Hz)

1/f total noise calculation

$$E_{N_NORMAL} = e_{BF}\sqrt{f_0}$$

(65) Normalized 1/f noise at 1 Hz

Where

E_{N_NORMAL} = 1/f noise normalized to 1 Hz

e_{BF} = noise spectral density measured in the 1/f region

f_0 = the frequency that the 1/f noise e_{BF} is measured at

$$E_{N_FLICKER} = E_{N_NORMAL} \sqrt{\ln\left(\frac{f_H}{f_L}\right)}$$

(66) 1/f total noise calculation

Where

$E_{N_FLICKER}$ = total rms noise from flicker

E_{N_NORMAL} = 1/f noise normalized to 1Hz

f_H = upper cutoff frequency or noise bandwidth

f_L = lower cutoff frequency, normally set to 0.1Hz

Table 17: Peak-to-peak conversion

Number of standard deviations	Percent chance reading is in range
2σ (same as ±1σ)	68.3%
3σ (same as ±1.5σ)	86.6%
4σ (same as ±2σ)	95.4%
5σ (same as ±2.5σ)	98.8%
6σ (same as ±3σ)	99.7%
6.6σ (same as ±3.3σ)	99.9%

Thermal noise calculation

$$E_{n_R} = \sqrt{4kTR\Delta f} \quad (67) \text{ Total rms Thermal Noise}$$

$$e_{n_R} = \sqrt{4kTR} \quad (68) \text{ Thermal Noise Spectral Density}$$

Where

E_{n_R} = Total rms noise from resistance, also called thermal noise (V rms)

e_{n_R} = Noise spectral density from resistance, also called thermal noise ($V/\sqrt{\text{Hz}}$)

k = Boltzmann's constant $1.38 \times 10^{-23} \text{ J/K}$

T = Temperature in Kelvin

Δf = Noise bandwidth in Hz

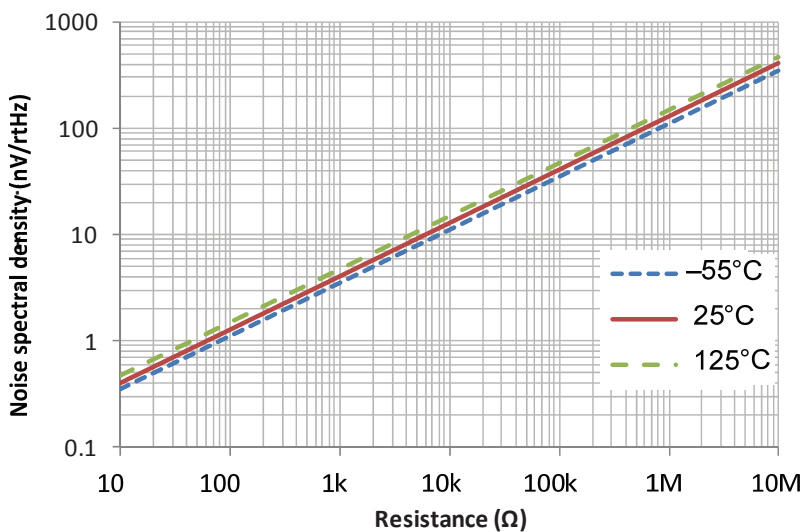


Figure 31: Noise spectral density vs. resistance

Ac response versus frequency (Dominant 2-Pole System)

Figure 32 illustrates a bode plot with four different examples of ac peaking.

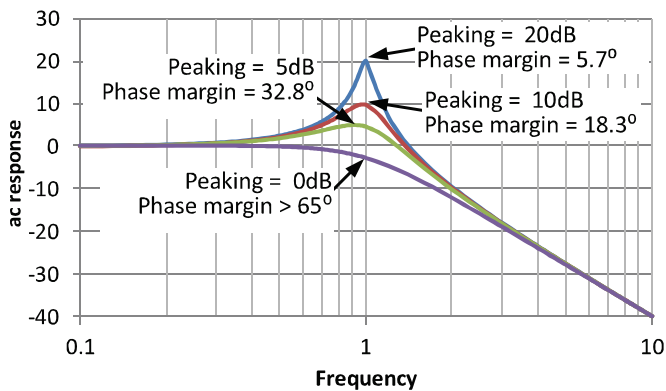


Figure 32: Stability – ac peaking relationship example

Phase margin versus ac peaking

This graph illustrates the phase margin for any given level of ac peaking. Note that 45° of phase margin or greater is required for stable operation.

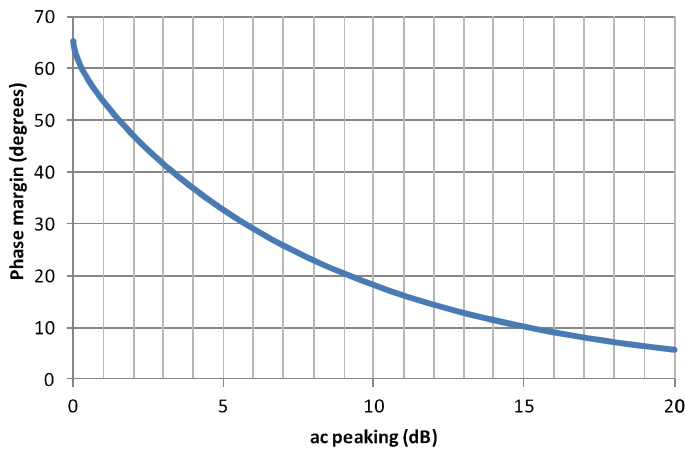


Figure 33: Stability – phase margin vs. peaking for a two-pole system

Transient overshoot (Dominant 2-Pole System)

Figure 34 illustrates a transient response with two different examples of percentage overshoot.

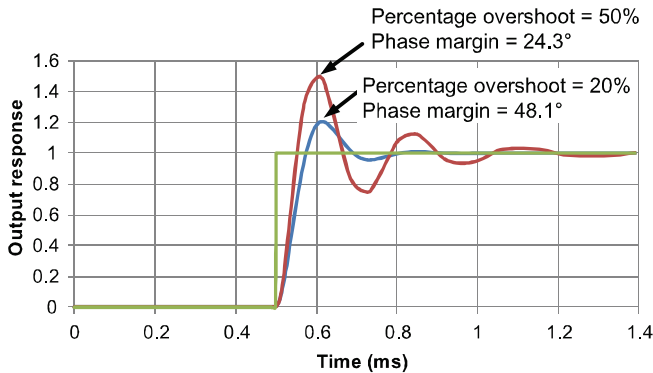


Figure 34: Stability – transient overshoot example

Phase margin versus percentage overshoot

This graph illustrates the phase margin for any given level of transient overshoot. Note that 45° of phase margin or greater is required for stable operation.

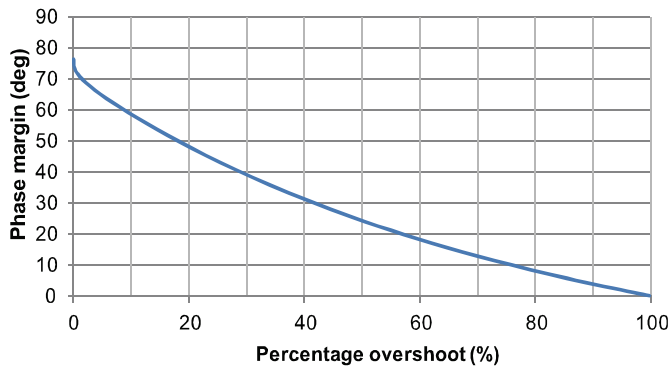


Figure 35: Stability – phase margin vs. percentage overshoot

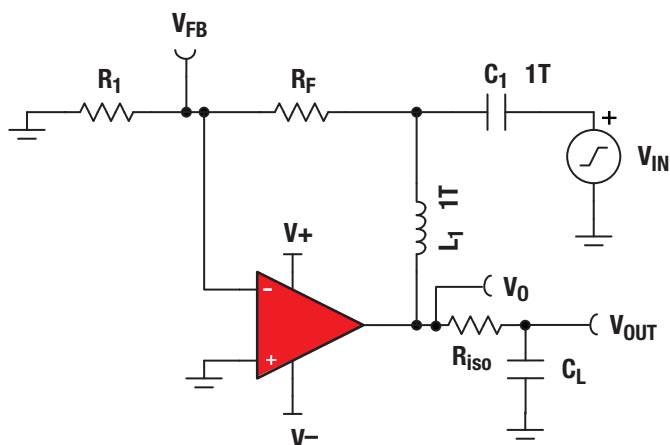


Figure 36: Common spice test circuit used for stability

$$A_{OL_LOADED} = \frac{V_O}{V_{FB}} \quad (69) \text{ Loaded open-loop gain}$$

$$\beta = V_{FB} \quad (70) \text{ Feedback factor}$$

$$\frac{1}{\beta} = \frac{1}{V_{FB}} \quad (71) \text{ Closed-loop noise gain}$$

$$A_{OL_LOADED} \times \beta = V_O \quad (72) \text{ Loop gain}$$

Where

V_O = the voltage at the output of the op amp.

V_{OUT} = the voltage output delivered to the load, which may be important to the application but is not considered in stability analysis.

V_{FB} = feedback voltage

R_F , R_1 , R_{iso} and C_L = the op amp feedback network and load.

Other op amp topologies will have different feedback networks; however, the test circuit will be the same for most cases.

Figure 37 shows the exception to the rule (multiple feedback).

C_1 and L_1 are components that facilitate SPICE analysis. They are large (1TF, 1TH) to make the circuit closed-loop for dc, but open loop for ac frequencies. SPICE requires closed-loop operation at dc for convergence.

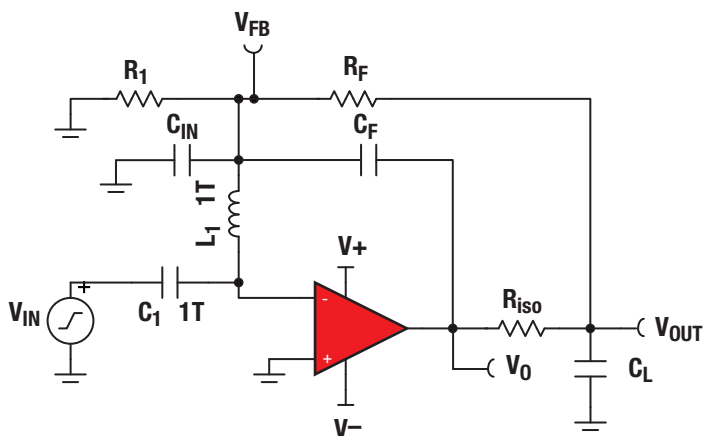


Figure 37: Alternative (multiple feedback) SPICE test circuit used for stability

$$A_{OL_LOADED} = V_O \quad (73) \text{ Loaded open loop gain}$$

$$\beta = \frac{V_{FB}}{V_O} \quad (74) \text{ Feedback factor}$$

$$\frac{1}{\beta} = \frac{V_O}{V_{FB}} \quad (75) \text{ Closed-loop noise gain}$$

$$A_{OL_LOADED} \times \beta = V_{FB} \quad (76) \text{ Loop gain}$$

Where

V_O = the voltage at the output of the op amp.

V_{OUT} = the voltage output delivered to the load. This may be important to the application but is not considered in stability analysis.

V_{FB} = feedback voltage

R_F , R_1 , R_{ISO} and C_F = the op amp feedback network. Because there are two paths for feedback, the loop is broken at the input.

C_1 and L_1 are components that facilitate SPICE analysis. They are large (1TF, 1TH) to make the circuit closed loop for dc, but open loop for ac frequencies. SPICE requires closed-loop operation at dc for convergence.

C_{IN} = the equivalent input capacitance taken from the op amp datasheet. This capacitance normally does not need to be added because the model includes it. However, when using this simulation method the capacitance is isolated by the 1TH inductor.

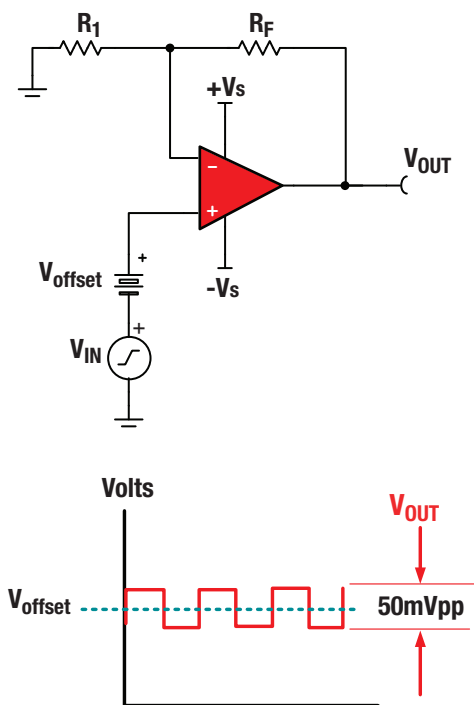


Figure 38: Transient real world stability test

Test tips

- Choose test frequency $\ll f_{cl}$
- Small signal ($V_{pp} \leq 50$ mV) ac output square wave (for example, 1 kHz)
- Adjust V_{IN} amplitude to yield output ≤ 50 mVpp
- Worst cases is usually when $V_{offset} = 0$ (Largest R_O , for $I_{OUT} = 0A$).
- Use V_{offset} as desired to check all output operating points for stability
- Set scope = ac couple and expand vertical scope scale to look for amount of overshoot, undershoot, and ringing on V_{OUT}
- Use 1x attenuation scope probe on V_{OUT} for best resolution

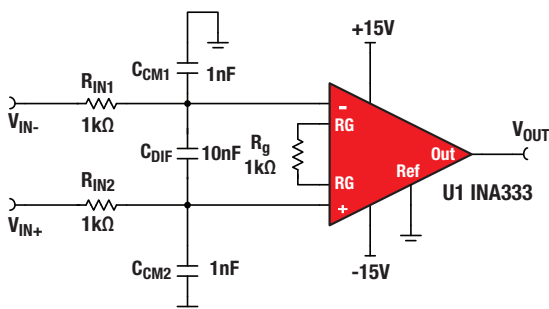


Figure 39: Input filter for instrumentation amplifier

Select $C_{DIF} \geq 10C_{CM1}$

(77) Differential filter is sized 10 times the common-mode filter

$R_{IN1} = R_{IN2}$

(78) Input resistors must be equal

$C_{CM1} = C_{CM2}$

(79) Common-mode capacitors must be equal

$$f_{CM} = \frac{1}{2\pi R_{IN1} C_{CM1}}$$

(80) Differential filter cutoff

$$f_{DIF} = \frac{1}{2\pi(2R_{IN1})(C_{DIF} + \frac{1}{2}C_{CM1})}$$

(81) Common-mode 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 10 times lower than the common-mode cutoff frequency. This prevents common-mode noise from being converted into differential noise due to component tolerances.

Notes

This image shows a single sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

PCB and Wire

- PCB trace resistance for 1oz and 2oz Cu
- Conductor spacing in a PCB for safe operation
- Current carrying capacity of copper conductors
- Package types and dimensions
- PCB trace capacitance and inductance
- PCB via capacitance and inductance
- Common coaxial cable specifications
- Coaxial cable equations
- Resistance per length for wire types
- Maximum current for wire types

Table 18: Printed circuit board conductor spacing

Voltage between conductors (dc or ac peaks)	Minimum spacing						
	Bare board				Assembly		
	B1	B2	B3	B4	A5	A6	A7
0-15	0.05 mm [0.00197 in]	0.1 mm [0.0039 in]	0.1 mm [0.0039 in]	0.05 mm [0.00197 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]
16-30	0.05 mm [0.00197 in]	0.1 mm [0.0039 in]	0.1 mm [0.0039 in]	0.05 mm [0.00197 in]	0.13 mm [0.00512 in]	0.25 mm [0.00984 in]	0.13 mm [0.00512 in]
31-50	0.1 mm [0.0039 in]	0.6 mm [0.024 in]	0.6 mm [0.024 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.4 mm [0.016 in]	0.13 mm [0.00512 in]
51-100	0.1 mm [0.0039 in]	0.6 mm [0.024 in]	1.5 mm [0.0591 in]	0.13 mm [0.00512 in]	0.13 mm [0.00512 in]	0.5 mm [0.020 in]	0.13 mm [0.00512 in]
101-150	0.2 mm [0.0079 in]	0.6 mm [0.024 in]	3.2 mm [0.126 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
151-170	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	3.2 mm [0.126 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
171-250	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	6.4 mm [0.252 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.4 mm [0.016 in]
251-300	0.2 mm [0.0079 in]	1.25 mm [0.0492 in]	12.5 mm [0.492 in]	0.4 mm [0.016 in]	0.4 mm [0.016 in]	0.8 mm [0.031 in]	0.8 mm [0.031 in]
301-500	0.25 mm [0.00984 in]	2.5 mm [0.0984 in]	12.5 mm [0.492 in]	0.8 mm [0.031 in]	0.8 mm [0.031 in]	1.5 mm [0.0591 in]	0.8 mm [0.031 in]

B1 Internal conductors

B2 External conductors uncoated sea level to 3050m

B3 External conductors uncoated above 3050m

B4 External conductors coated with permanent polymer coating (any elevation)

A5 External conductors with conformal coating over assembly (any elevation)

A6 External component lead/termination, uncoated, sea level to 3050m

A7 External component lead termination, with conformal coating (any elevation)

Extracted with permission from IPC-2221B, Table 6-1.

For additional information, the entire specification can be downloaded at www.ipc.org

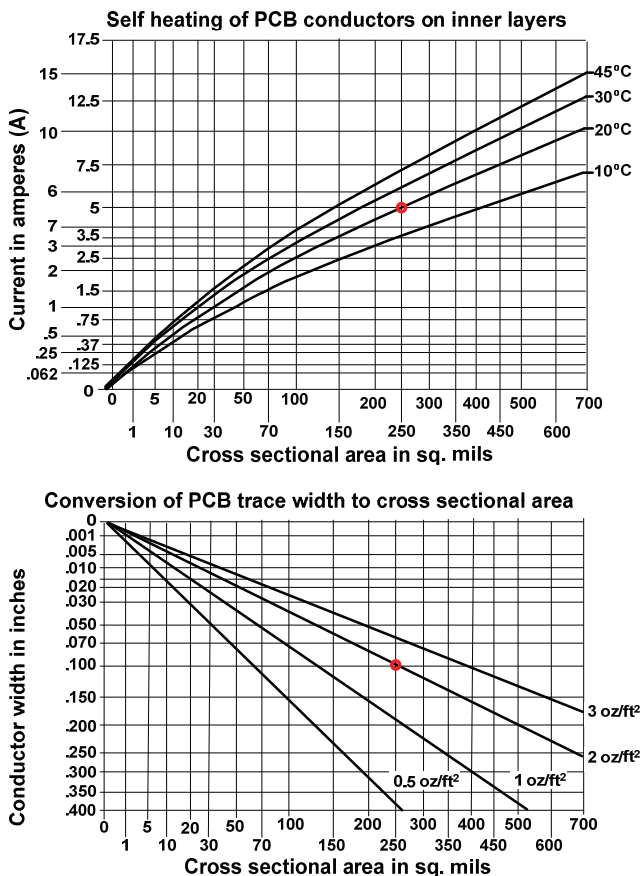


Figure 40: Self heating of PCB traces on inside layer

Example

Find the current that will cause a 20°C temperature rise in a PCB trace that is 0.1 inch wide and uses 2 oz/ft² copper. (Assume traces on outside of PCB.)

Answer

First translate 0.1 inch to 250 sq. mils. using bottom chart. Next find the current associated with 10°C and 250 sq. mils. using top chart (Answer = 5A).

Extracted with permission from IPC-2152, Figure 5-1.

For additional information the entire specification can be downloaded at www.ipc.org

PCB trace resistance for 1 oz-Cu

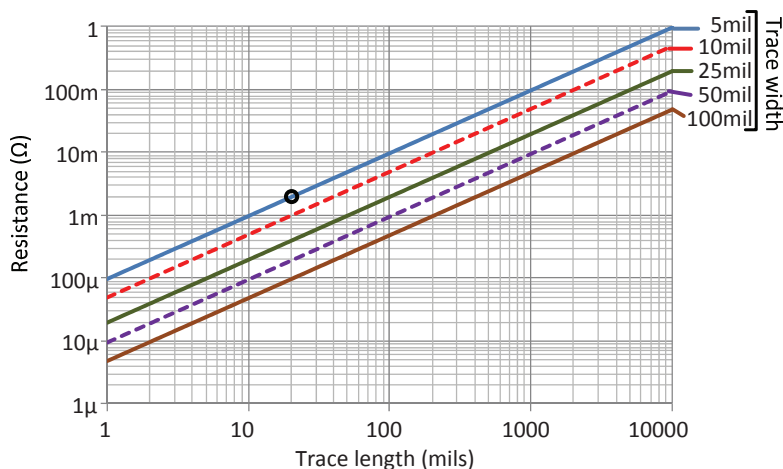


Figure 41: PCB trace resistance vs. length and width for 1 oz-Cu, 25°C

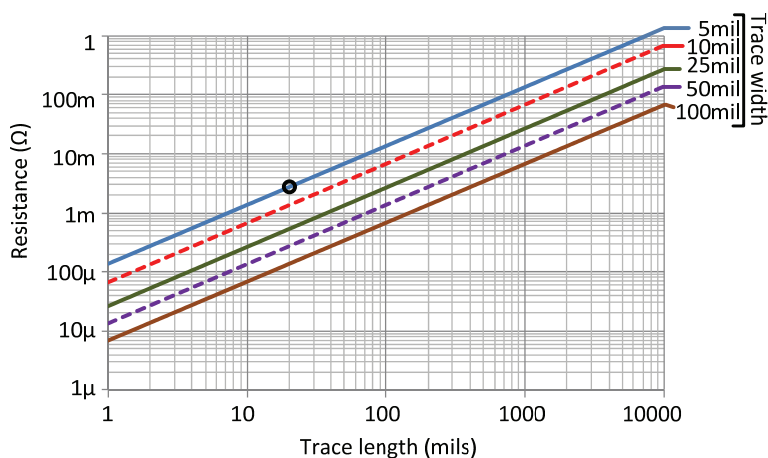


Figure 42: PCB trace resistance vs. length and width for 1 oz-Cu, 125°C

Example

What is the resistance of a 20 mil long, 5 mil wide trace for a 1 oz-Cu thickness at 25°C and 125°C?

Answer

$R_{25C} = 2 \text{ m}\Omega$, $R_{125C} = 3 \text{ m}\Omega$. The points are circled on the curves.

PCB trace resistance for 2 oz-Cu

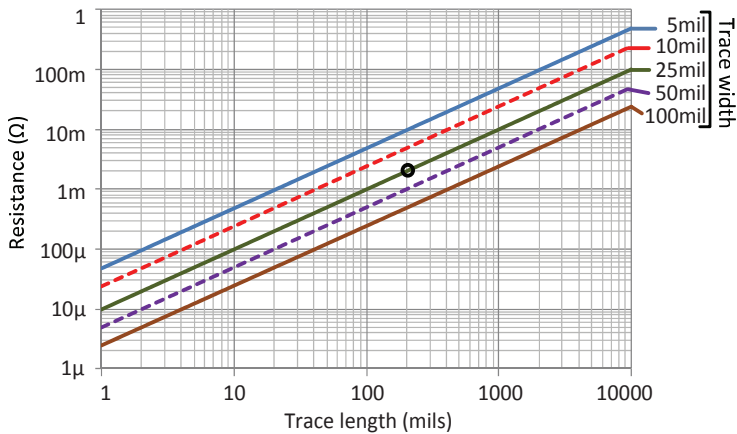


Figure 43: PCB trace resistance vs. length and width for 2 oz-Cu, 25°C

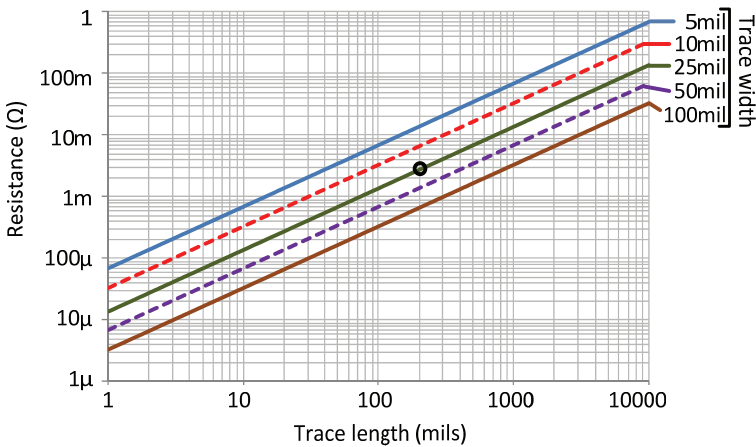


Figure 44: PCB trace resistance vs. length and width for 2 oz-Cu, 125°C

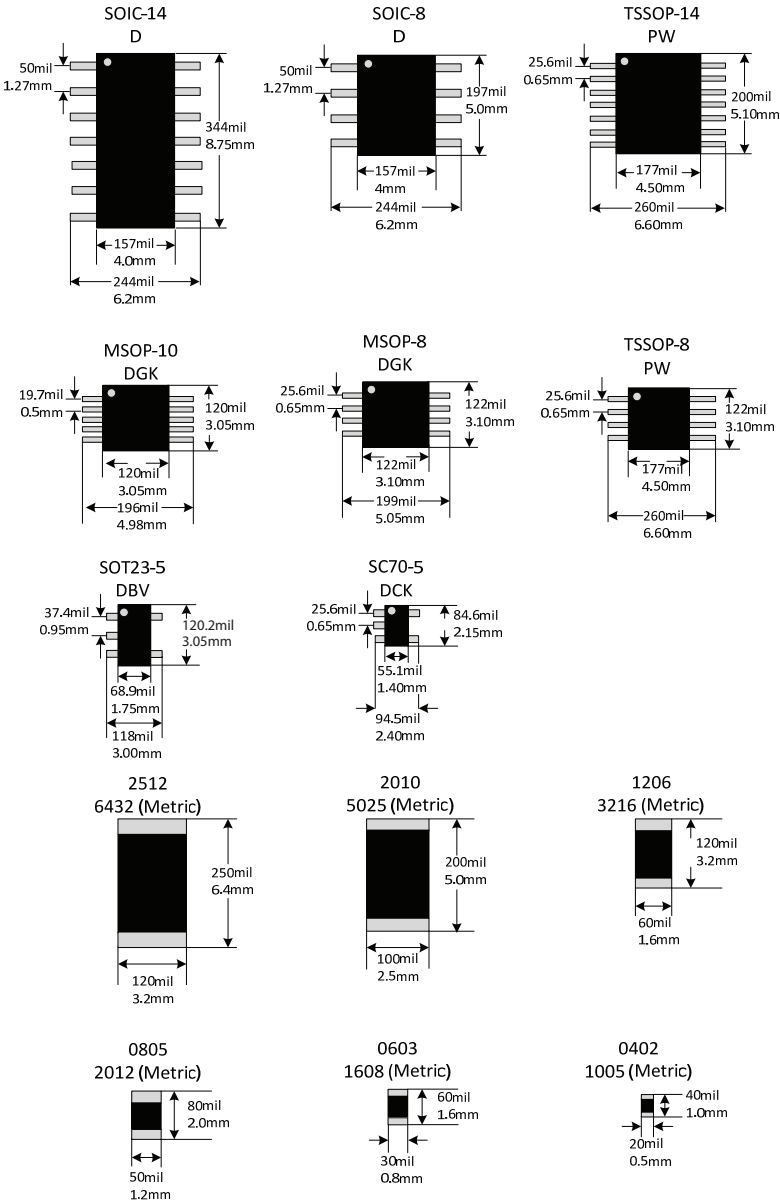
Example

What is the resistance of a 200 mil long, 25 mil wide trace for a 2 oz-Cu thickness at 25°C and 125°C?

Answer

$R_{25C} = 2\text{ m}\Omega$, $R_{125C} = 3\text{ m}\Omega$. The points are circled on the curves.

Common package type and dimensions



PCB parallel plate capacitance

$$C(\text{pF}) = \frac{k \cdot \ell \cdot w \cdot \epsilon_r}{h} \quad (82) \text{ Capacitance for parallel copper planes}$$

Where

k = Permittivity of free space.

Both the metric and imperial version of the constant are given.

$k = 8.854 \cdot 10^{-3} \text{ pF/mm}$, or $2.247 \cdot 10^{-4} \text{ pF/mil}$

ℓ = length (metric in mm, or imperial in mil)

w = width (metric in mm, or imperial in mil)

h = separation between planes (metric in mm, or imperial in mil)

ϵ_r = PCB relative dielectric constant ($\epsilon_r \approx 4.5$ for FR-4)

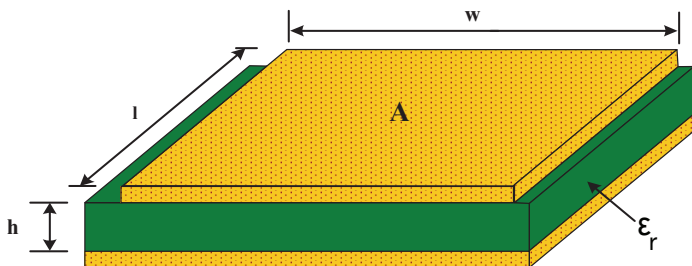


Figure 45: PCB parallel plate capacitance

Example Calculate the total capacitance for $\ell=5.08\text{mm}$,
 $w=12.7\text{mm}$, $h=1.575\text{mm}$, $\epsilon_r = 4.5$

$$C(\text{pF}) = \frac{(8.854 \cdot 10^{-3} \text{ pF/mm}) \cdot (5.08\text{mm}) \cdot (12.7\text{mm}) \cdot (4.5)}{1.575\text{mm}} = 1.63\text{pF}$$

Example Calculate the total capacitance for $\ell=200\text{mil}$,
 $w=500\text{mil}$, $h=62\text{mil}$, $\epsilon_r = 4.5$

$$C(\text{pF}) = \frac{(2.247 \cdot 10^{-4} \text{ pF/mil}) \cdot (200\text{mil}) \cdot (500\text{mil}) \cdot (4.5)}{62\text{mil}} = 1.63\text{pF}$$

Microstrip capacitance and inductance

$$L(\text{nH}) = k_L \cdot \ell \cdot \ln\left(\frac{5.98 \cdot h}{0.8 \cdot w + t}\right) \quad (83) \text{ Inductance for microstrip}$$

$$C(\text{pF}) = \frac{k_C \cdot \ell \cdot (\epsilon_r + 1.41)}{\ln\left(\frac{5.98 \cdot h}{0.8 \cdot w + t}\right)} \quad (84) \text{ Capacitance for microstrip}$$

Where

k_L = PCB inductance per unit length.

Both the metric and imperial version of the constant are given.

k_L = 2nH/cm, or 5.071nH/in

k_C = PCB capacitance per unit length.

Both the metric and imperial version of the constant are given.

k_C = 0.264pF/cm, or 0.67056pF/in

ℓ = length of microstrip (metric in cm, or imperial in inches)

w = width of microstrip (metric in mm, or imperial in mil)

t = thickness of copper (metric in mm, or imperial in mil)

h = separation between planes (metric in mm, or imperial in mil)

ϵ_r = relative permittivity, approximately 4.5 for FR-4 PCB

For imperial:
Copper thickness (mils) =
1.37 * (number of ounces)
i.e. 1oz Cu = 1.37mils
i.e. 1/2oz Cu = 0.684mils

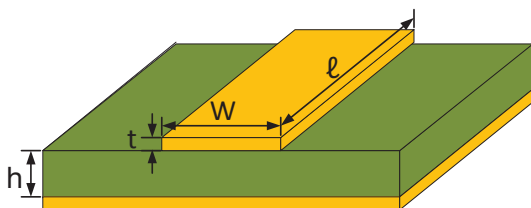


Figure 46: PCB Microstrip capacitance and inductance

Example

Calculate the total inductance and capacitance for $\ell=2.54\text{cm}$, $w=0.254\text{mm}$, $t=0.0356\text{mm}$, $h=0.8\text{mm}$, $\epsilon_r = 4.5$ for FR-4

$$L(\text{pF}) = (2 \text{ nH/cm}) \cdot (2.54\text{cm}) \cdot \ln\left(\frac{5.98 \cdot 0.8\text{mm}}{0.8 \cdot 0.254\text{mm} + 0.0356\text{mm}}\right) = 15.2\text{nH}$$

$$C(\text{pF}) = \frac{(0.264\text{pF/cm}) \cdot (2.54\text{cm})(4.5 + 1.41)}{\ln\left(\frac{5.98 \cdot 0.8\text{mm}}{0.8 \cdot 0.254\text{mm} + 0.0356\text{mm}}\right)} = 1.3\text{pF}$$

Example Calculate the total inductance and capacitance for $\ell=1\text{in}$, $w=10\text{mil}$, $t=1.4\text{mil}$, $h=31.5\text{mil}$, $\epsilon_r = 4.5$ for FR-4

$L = 15.2\text{nH}$, $C=1.3\text{pF}$. Note: this is the same problem as above with imperial units.

Adjacent copper traces

$$C(\text{pF}) \approx \frac{k \cdot t \cdot \ell}{d} \quad (85) \text{ Same layer}$$

$$C(\text{pF}) \approx \frac{k \cdot \epsilon_r \cdot w \cdot \ell}{h} \quad (86) \text{ Different layers}$$

Where

ℓ = length of the copper trace (mil, or mm)

$k = 8.854 \cdot 10^{-3} \text{ pF/mm}$, or $k = 2.247 \cdot 10^{-4} \text{ pF/mil}$

t = thickness of trace (in mil, or mm)

d = distance between traces if on same layer (mil, or mm)

w = width of trace. (mil, or mm)

h = separation between planes. (mil, or mm)

ϵ_r = PCB dielectric constant ($\epsilon_r = 4.5$ for FR-4)

For imperial:
Copper thickness (mils) =
 $1.37 \cdot (\text{number of ounces})$
i.e. 1oz Cu = 1.37mils
i.e. ½oz Cu = 0.684mils

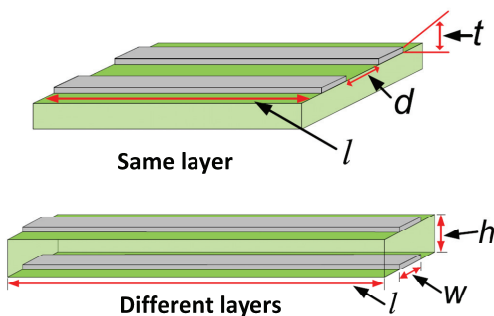


Figure 47: Capacitance for adjacent copper traces

Example: Calculate the total capacitance for both cases: $\ell = 2.54\text{mm}$, $t = 0.0348\text{mm}$, $d = 0.254\text{mm}$, $w = 0.635\text{mm}$, $h = 1.6\text{mm}$, $\epsilon_r = 4.5$ for FR-4

$$C(\text{pF}) \approx \frac{(8.854 \cdot 10^{-3} \text{ pF/mm}) (0.0348\text{mm}) (2.54\text{mm})}{0.254\text{mm}} = 0.0031\text{pF} \text{ Same layer}$$

$$C(\text{pF}) \approx \frac{(8.854 \cdot 10^{-3} \text{ pF/mm}) (4.5\text{mm}) (0.635\text{mm}) (2.54\text{mm})}{1.6\text{mm}} = 0.04\text{pF} \text{ Adjacent layers}$$

Example: Calculate the total capacitance for both cases: $\ell = 100\text{mil}$, $t = 1.37\text{mil}$, $d = 10\text{mil}$, $w = 25\text{mil}$, $h = 63\text{mil}$, $\epsilon_r = 4.5$ for FR-4

$C = 0.0031\text{pF}$ (Same layer), $C = 0.4\text{pF}$ (Adjacent layers). Note: this is the same problem as above with imperial units.

PCB via capacitance and inductance

$$L(\text{nH}) \approx k_L \cdot h \left[1 + \ln \left(\frac{4h}{d} \right) \right] \quad (87) \text{ Inductance for via}$$

$$C(\text{pF}) \approx \frac{k_C \cdot \epsilon_r \cdot h \cdot d_1}{d_2 - d_1} \quad (88) \text{ Capacitance for via}$$

Where

k_L = PCB inductance per unit length.

Both the metric and imperial version of the constant are given.

$k_L = 0.2 \text{ nH/mm}$, or $5.076 \cdot 10^{-3} \text{ nH/mil}$

k_C = PCB capacitance per unit length.

Both the metric and imperial version of the constant are given.

$k_C = 0.0555 \text{ pF/mm}$, or $1.41 \cdot 10^{-3} \text{ pF/mil}$

h = separation between planes

d = diameter of via hole

d_1 = diameter of the pad surrounding the via

d_2 = distance to inner layer ground plane.

ϵ_r = PCB dielectric constant ($\epsilon_r = 4.5$ for FR-4)

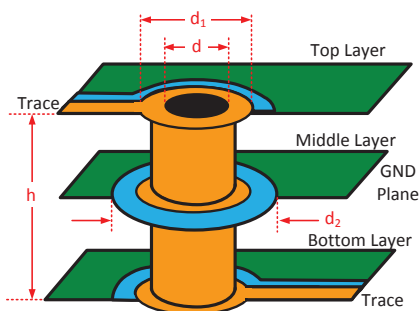


Figure 48: Inductance and capacitance of via

Example: Calculate the total inductance and capacitance for $h=1.6\text{mm}$, $d=0.4\text{mm}$, $d_1=0.8\text{mm}$, $d_2=1.5\text{mm}$

$$L(\text{nH}) \approx (0.2 \text{ nH/mm}) \cdot (1.6\text{mm}) \left[1 + \ln \left(\frac{4 \cdot 1.6\text{mm}}{0.4\text{mm}} \right) \right] = 1.2\text{nH}$$

$$C(\text{pF}) \approx \frac{(0.0555 \text{ pF/mm}) \cdot (4.5) \cdot (1.6\text{mm}) \cdot (0.8\text{mm})}{1.5\text{mm} - 0.8\text{mm}} = 0.46\text{pF}$$

Example: Calculate the total inductance and capacitance for $h=63\text{mil}$, $d=15.8\text{mil}$, $d_1=31.5\text{mil}$, $d_2=59\text{mil}$

$L=1.2\text{nH}$, $C=0.46\text{pF}$. Note: this is the same problem as above with imperial units.

Table 19: Coaxial cable information

Type	Z_0	Capacitance / length (pF/feet)	Outside diameter (inches)	dB attenuation /100 ft at 750 MHz	Dielectric type	Application
RG-58	53.5 Ω	28.8	0.195	13.1	PE	Test equipment and RF power to a few hundred watts, and a couple hundred MHz
RG-8	52 Ω	29.6	0.405	5.96	PE	RF power to a few kW, up to several hundred MHz
RG-214/U	50 Ω	30.8	0.425	6.7	PE	
9914	50 Ω	26.0	0.405	4.0	PE	
RG-6	75 Ω	20	0.270	5.6	PF	Video and CATV applications. RF to a few hundred watts, up to a few hundred MHz, sometimes to higher frequencies if losses can be tolerated
RG-59/U	73 Ω	29	0.242	9.7	PE	
RG-11/U	75 Ω	17	0.412	3.65	PE	RF power to a few kW, up to several hundred MHz
RG-62/U	93 Ω	13.5	0.242	7.1	ASP	Used in some test equipment and 100 Ω video applications
RG-174	50 Ω	31	0.100	23.5	PE	Miniature coax used primarily for test equipment interconnection. Usually short runs due to higher loss.
RG-178/U	50 Ω	29	0.071	42.7	ST	

Coaxial cable equations

$$\frac{C}{\ell} = \frac{2\pi\epsilon}{\ln\left(\frac{D}{d}\right)} \quad (89) \text{ Capacitance per length}$$

$$\frac{L}{\ell} = \frac{\mu}{2\pi} \ln\left(\frac{D}{d}\right) \quad (90) \text{ Inductance per length}$$

$$Z_o = \sqrt{\frac{L}{C}} = \frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \quad (91) \text{ Characteristic impedance}$$

Where

L = inductance in henries (H)

C = capacitance in farads (F)

Z = impedance in ohms (Ω)

d = diameter of inner conductor

D = inside diameter of shield, or diameter of dielectric insulator

ϵ = dielectric constant of insulator ($\epsilon = \epsilon_r \epsilon_o$)

μ = magnetic permeability ($\mu = \mu_r \mu_o$)

ℓ = length of the cable

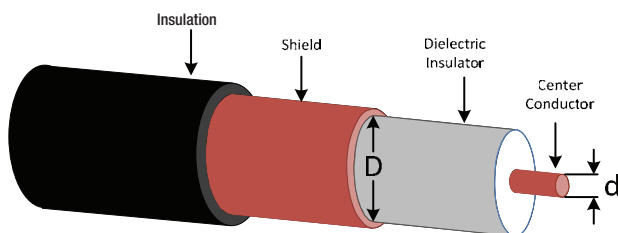


Figure 49: Coaxial cable cutaway

Table 20: Resistance per length for different wire types (AWG)

AWG	Stds	Outside diameter		Area		dc resistance	
		in	mm	circular mils	mm ²	Ω / 1000 ft	Ω / km
36	Solid	0.005	0.127	25	0.013	445	1460
36	7/44	0.006	0.152	28	0.014	371	1271
34	Solid	0.0063	0.160	39.7	0.020	280	918
34	7/42	0.0075	0.192	43.8	0.022	237	777
32	Solid	0.008	0.203	67.3	0.032	174	571
32	7/40	0.008	0.203	67.3	0.034	164	538
30	Solid	0.010	0.254	100	0.051	113	365
30	7/38	0.012	0.305	112	0.057	103	339
28	Solid	0.013	0.330	159	0.080	70.8	232
28	7/36	0.015	0.381	175	0.090	64.9	213
26	Solid	0.016	0.409	256	0.128	43.6	143
26	10/36	0.021	0.533	250	0.128	41.5	137
24	Solid	0.020	0.511	404	0.205	27.3	89.4
24	7/32	0.024	0.610	448	0.229	23.3	76.4
22	Solid	0.025	0.643	640	0.324	16.8	55.3
22	7/30	0.030	0.762	700	0.357	14.7	48.4
20	Solid	0.032	0.813	1020	0.519	10.5	34.6
20	7/28	0.038	0.965	1111	0.562	10.3	33.8
18	Solid	0.040	1.020	1620	0.823	6.6	21.8
18	7/26	0.048	1.219	1770	0.902	5.9	19.2
16	Solid	0.051	1.290	2580	1.310	4.2	13.7
16	7/24	0.060	1.524	2828	1.442	3.7	12.0
14	Solid	0.064	1.630	4110	2.080	2.6	8.6
14	7/22	0.073	1.854	4480	2.285	2.3	7.6

Table 21: Maximum current vs. AWG

Wire gauge	Polyethylene Neoprene Polyvinylchloride (semi-ridged) at 80°C	Polypropylene Polyethylene (high density) at 90°C	Polyvinylchloride Nylon at 105°C	Kynar Polyethylene Thermoplastic at 125°C	Kapton Teflon Silicon at 200°C
AWG	I _{max} (A)	I _{max} (A)	I _{max} (A)	I _{max} (A)	I _{max} (A)
30	2	3	3	3	4
28	3	4	4	5	6
26	4	5	5	6	7
24	6	7	7	8	10
22	8	9	10	11	13
20	10	12	13	14	17
18	15	17	18	20	24
16	19	22	24	26	32
14	27	30	33	40	45
12	36	40	45	50	55
10	47	55	58	70	75

Note: Wire is in free air at 25°C

Example

What is the maximum current that can be applied to a 30 gauge Teflon wire in a room temperature environment?
What will the self-heating be?

Answer

I_{max} = 4A
Wire temperature = 200°C

Sensor

- Thermistor •
- Resistive temperature detector (RTD) •
- Diode temperature characteristics •
- Thermocouple (J and K) •



Table 22: Temperature sensor overview

	Thermistor	RTD	Diode	Thermocouple
	<p>Resistance vs Temperature</p> <p>40kΩ, 18Ω, -55°C, 125°C</p>	<p>RTD vs Temperature</p> <p>18Ω, 390Ω, -200°C, 850°C</p>	<p>Diode vs Temperature</p> <p>0.4V, 0.8V, -55°C, 125°C</p> <p>-2mV/°C</p>	<p>Thermocouple vs Temperature</p> <p>-10mV, 80mV, -200°C, 1,300°C</p>
Temp range	-55°C < T < 150°C	-200°C < T < 850°C	-55°C < T < 150°C	-250°C < T < 1800°C
Cost	Low	High	Low	Low
Accuracy	Good accuracy at one temperature Less accurate over full range	Excellent accuracy	Poor accuracy without calibration	Good accuracy with polynomial correction
Linearity	Very nonlinear. Follows reciprocal of logarithmic function	Fairly linear Nonlinearity < 4.5% of full scale Relatively simple quadratic function	Fairly linear Slope $\approx -2\text{mV}/^\circ\text{C}$ Slope varies according to current excitation, diode type, and diode processing	Fairly linear Nonlinearity < 10% of full scale Complex 10th order polynomial
Construction	Less rugged	Depends on Type (can be rugged)	Rugged	Most rugged
Output range	Typically 10s to 100s of kΩ full scale Very wide variation in resistance	18 to 390 Ω for PT100 180 to 3.9 kΩ for PT1000	0.4 to 0.8V	10s of millivolts
Applications	General purpose	Scientific and industrial	Low cost temperature monitor Low cost linear response	Industrial temperature measurement
General	Requires excitation	Requires excitation	Requires excitation	Self-powered Requires cold junction comp

Thermistor: Resistance to temperature, Steinhart-Hart equation

$$\frac{1}{T} = a + b \ln(R) + c (\ln(R))^3 \quad (92) \text{ Convert resistance to temperature for a thermistor}$$

Where

T = temperature in Kelvin

a, b, c = Steinhart-Hart equation constants

R = resistance in ohms

Thermistor: Temperature to resistance, Steinhart-Hart equation

$$R = \exp \left[\left(y - \frac{x}{2} \right)^{\frac{1}{3}} - \left(y + \frac{x}{2} \right)^{\frac{1}{3}} \right] \quad (93) \text{ Convert temperature to resistance for a thermistor}$$

$$x = \frac{a - \frac{1}{T}}{c} \quad (94) \text{ Factor used in Equation 93}$$

$$y = \sqrt{\left(\frac{b}{3c} \right)^3 + \frac{x^2}{4}} \quad (95) \text{ Factor used in Equation 93}$$

Where

R = resistance in Ω

T = temperature in Kelvin

a, b, c = Steinhart-Hart equation constants

x, y = Steinhart-Hart factors used in temperature to resistance equation

RTD equation temperature to resistance

$R_{\text{rtd}} = R_0 [1 + A_0 T + B_0 T^2 + C_0 (T - 100) T^3]$ (96) RTD resistance for $T < 0^\circ\text{C}$

$R_{\text{rtd}} = R_0 [1 + A_0 T + B_0 T^2]$ (97) RTD resistance for $T > 0^\circ\text{C}$

Where

R_{rtd} = resistance of RTD over temperature range of $(-200^\circ\text{C} < T < 850^\circ\text{C})$

$R_0 = 100\Omega$ for PT-100, 1000Ω for PT-1000

A_0, B_0, C_0 = Callendar-Van Dusen coefficients

T = temperature in degrees Celsius ($^\circ\text{C}$)

RTD equation resistance to temperature ($T > 0^\circ\text{C}$)

$$T = \frac{-A_0 + \sqrt{A_0^2 - 4B_0 \left(1 - \frac{R_{\text{RTD}}}{R_0}\right)}}{2B_0}$$
 (98) RTD resistance for $T > 0^\circ\text{C}$

Where

R_{RTD} = resistance of RTD over temperature range of $(-200^\circ\text{C} < T < 850^\circ\text{C})$

$R_0 = 100\Omega$

A_0, B_0, C_0 = Callendar-Van Dusen coefficients

T = temperature in degrees Celsius ($^\circ\text{C}$)

Table 23: Callendar-Van Dusen coefficients for different RTD standards

	IEC-751 DIN 43760 BS 1904 ASTM-E1137 EN-60751	JISC 1604	US Industrial Standard D-100 American	US Industrial Standard American	ITS-90
A_0	+3.9083E-3	+3.9739E-3	+3.9787E-3	+3.9692E-3	+3.9888E-3
B_0	-5.775E-7	-5.870E-7	-5.8686E-7	-5.8495E-7	-5.915E-7
C_0	-4.183E-12	-4.4E-12	-4.167E-12	-4.233E-12	-3.85E-12

Example

What is the temperature given an ITS-90 PT100 resistance of 120Ω ?

Answer

$$T = \frac{-(3.9888 \cdot 10^{-3}) + \sqrt{(3.9888 \cdot 10^{-3})^2 - 4(-5.915 \cdot 10^{-7}) \left(1 - \frac{120}{100}\right)}}{2(-5.915 \cdot 10^{-7})} = 50.5^\circ\text{C}$$

RTD equation resistance to temperature (T<0°C)

$$T = \sum_{i=0}^n \alpha_i (R_{\text{rtd}})^i$$

(99) RTD resistance for T<0°C

Where

- T = temperature in degrees Celsius (°C)
- R_{RTD} = resistance of RTD over temperature range of (T<0°C)
- α_i = polynomial coefficients for converting RTD resistance to temperature for T<0°C

Table 24: Coefficients for 5th order RTD resistance to temperature

	IEC-751 DIN 43760 BS 1904 ASTM-E1137 EN-60751	JISC 1604	US Industrial Standard D-100 American	US Industrial Standard American	ITS-90
α ₀	−2.4202E+02	−2.3820E+02	−2.3818E+02	−2.3864E+02	−2.3791E+02
α ₁	2.2228E+00	2.1898E+00	2.1956E+00	2.1973E+00	2.2011E+00
α ₂	2.5857E-03	2.5226E-03	2.4413E-03	2.4802E-03	2.3223E-03
α ₃	−4.8266E-06	−4.7825E-06	−4.7517E-06	−4.7791E-06	−4.6280E-06
α ₄	−2.8152E-08	−2.7009E-08	−2.3831E-08	−2.5157E-08	−1.9702E-08
α ₅	1.5224E-10	1.4719E-10	1.3492E-10	1.4020E-10	1.1831E-10

Example

Find the temperature given an ITS-90 PT100 resistance of 60 Ω.

Answer

$$T = (-2.3791\text{E} + 02) \cdot (60)^0 + (2.2011\text{E} + 00) \cdot (60)^1 + (2.3223\text{E} - 03) \cdot (60)^2 + \dots + (2.3223\text{E} - 03) \cdot (60)^5 = -98.6^{\circ}\text{C}$$

Diode equation vs. temperature

$$V_D = \frac{nkT}{q} \ln\left(\frac{I}{I_S} + 1\right) \approx \frac{nkT}{q} \ln\left(\frac{I}{I_S}\right) \quad (100) \text{ Diode voltage}$$

Where

V_D = diode voltage vs. temperature and current

n = diode ideality factor (ranges from 1 to 2)

$k = 1.38 \times 10^{-23}$ J/K, Boltzmann's constant

T = temperature in Kelvin

$q = 1.60 \times 10^{-19}$ C, charge of an electron

I = forward diode current in amps

I_S = saturation current

$$I_S = \alpha T^{(3/n)} \exp\left(-\frac{qV_G}{nkT}\right) \quad (101) \text{ Saturation current}$$

Where

I_S = saturation current

α = constant related to the cross sectional area of the junction

V_G = diode voltage vs. temperature and current

n = diode ideality factor (ranges from 1 to 2)

$k = 1.38 \times 10^{-23}$ J/K, Boltzmann's constant

T = temperature in Kelvin

$q = 1.60 \times 10^{-19}$ C, charge of an electron

Diode voltage versus temperature

Figure 50 shows an example of the temperature drift for a diode. Depending on the characteristics of the diode and the forward current the slope and offset of this curve will change. However, typical diode drift is about $-2\text{mV}/^\circ\text{C}$. A forward drop of about 0.6V is typical for room temperature.

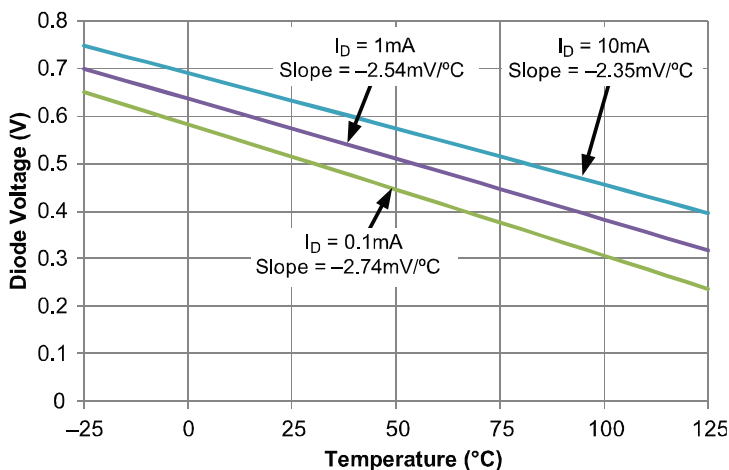


Figure 50: Diode voltage drop vs. temperature

Type J thermocouples translating temperature to voltage
(ITS-90 standard)

$$V_t = \sum_{i=0}^n c_i (T)^i$$

(102) Thermoelectric voltage

Where

V_T = thermoelectric voltage

T = temperature in degrees Celsius

c_i = translation coefficients

Table 25: Type J thermocouple temperature to voltage coefficients

Type J thermocouple temperature to voltage		
	−219°C to 760°C	760°C to 1,200°C
c_0	0.000000000E+00	2.9645625681E+05
c_1	5.0381187815E+01	−1.4976127786E+03
c_2	3.0475836930E-02	3.1787103924E+00
c_3	−8.5681065720E-05	−3.1847686701E-03
c_4	1.3228195295E-07	1.5720819004E-06
c_5	−1.7052958337E-10	−3.0691369056E-10
c_6	2.0948090697E-13	—
c_7	−1.2538395336E-16	—
c_8	1.5631725697E-20	—

Type J thermocouples translating voltage to temperature
(ITS-90 standard)

$$T = \sum_{i=0}^n c_i (V_t)^i$$

(103) Temperature

Table 26: Type J thermocouple voltage to temperature coefficients

Type J thermocouple temperature to voltage			
	-219°C to 0°C	0°C to 760°C	760°C to 1,200°C
C ₀	0.000000000E+00	0.000000000E+00	-3.113581870E+03
C ₁	1.952826800E-02	1.978425000E-02	3.005436840E-01
C ₂	-1.228618500E-06	-2.001204000E-07	-9.947732300E-06
C ₃	-1.075217800E-09	1.036969000E-11	1.702766300E-10
C ₄	-5.908693300E-13	-2.549687000E-16	-1.430334680E-15
C ₅	-1.725671300E-16	3.585153000E-21	4.738860840E-21
C ₆	-2.813151300E-20	-5.344285000E-26	—
C ₇	-2.396337000E-24	5.099890000E-31	—
C ₈	-8.382332100E-29	—	—

Type K thermocouples translating temperature to voltage
(ITS-90 standard)

$$V_T = \sum_{i=0}^n c_i (T)^i$$

(104) Thermoelectric voltage for T<0°C

$$V_t = \left[\sum_{i=0}^n c_i (T)^i \right] + \alpha_0 e^{[\alpha_1 (T-126.9686)]^2}$$

(105) Thermoelectric voltage for T>0°C

Where

V_T = thermoelectric voltage

T = temperature in degrees Celsius

c_i = translation coefficients

α₀, α₁ = translation coefficients

Table 27: Type K thermocouple temperature to voltage coefficients

	−219°C to 760°C	760°C to 1,200°C
C ₀	0.000000000E+00	−1.7600413686E+01
C ₁	3.9450128025E+01	3.8921204975E+01
C ₂	2.3622373598E-02	1.8558770032E-02
C ₃	−3.2858906784E-04	−9.9457592874E-05
C ₄	−4.9904828777E-06	3.1840945719E-07
C ₅	−6.7509059173E-08	−5.6072844889E-10
C ₆	−5.7410327428E-10	5.6075059059E-13
C ₇	−3.1088872894E-12	−3.2020720003E-16
C ₈	−1.0451609365E-14	9.7151147152E-20
C ₉	−1.9889266878E-17	−1.2104721275E-23
C ₁₀	−1.6322697486E-20	—
α ₀	—	1.1859760000E+02
α ₁	—	−1.1834320000E-04

Type K thermocouples translating voltage to temperature (ITS-90 standard)

$$T = \sum_{i=0}^n c_i (V_t)^i$$

(106) Temperature

Table 28: Type K thermocouple voltage to temperature coefficients

	−219°C to 0°C	0°C to 760°C	760°C to 1,200°C
C ₀	0.0000000E+00	0.0000000E+00	−1.3180580E+02
C ₁	2.5173462E-02	2.5083550E-02	4.8302220E-02
C ₂	−1.1662878E-06	7.8601060E-08	−1.6460310E-06
C ₃	−1.0833638E-09	−2.5031310E-10	5.4647310E-11
C ₄	−8.9773540E-13	8.3152700E-14	−9.6507150E-16
C ₅	−3.7342377E-16	−1.2280340E-17	8.8021930E-21
C ₆	−8.6632643E-20	9.8040360E-22	−3.1108100E-26
C ₇	−1.0450598E-23	−4.4130300E-26	—
C ₈	−5.1920577E-28	1.0577340E-30	—
C ₉	—	−1.0527550E-35	—

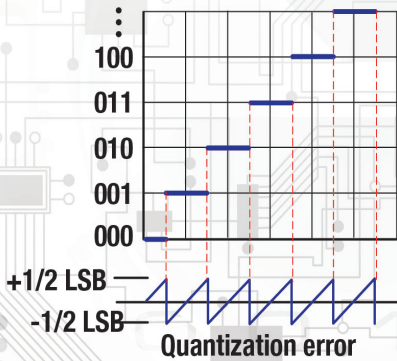
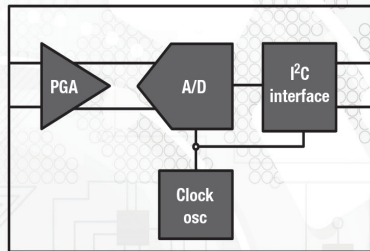
Table 29: Seebeck coefficients for different material

Material	Seebeck coefficient	Material	Seebeck coefficient	Material	Seebeck coefficient
Aluminum	4	Gold	6.5	Rhodium	6
Antimony	47	Iron	19	Selenium	900
Bismuth	−72	Lead	4	Silicon	440
Cadmium	7.5	Mercury	0.6	Silver	6.5
Carbon	3	Nichrome	25	Sodium	−2.0
Constantan	−35	Nickel	−15	Tantalum	4.5
Copper	6.5	Platinum	0	Tellurium	500
Germanium	300	Potassium	−9.0	Tungsten	7.5

Note: Units are $\mu\text{V}/^{\circ}\text{C}$. All data at temperature of 0°C

A/D conversion

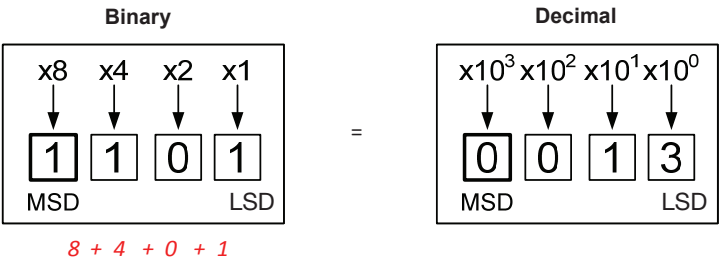
- Binary/hex conversions
- A/D and D/A transfer function
- Quantization error
- Signal-to-noise ratio (SNR)
- Signal-to-noise and distortion (SINAD)
- Total harmonic distortion (THD)
- Effective number of bits (ENOB)
- Noise-free resolution and effective resolution



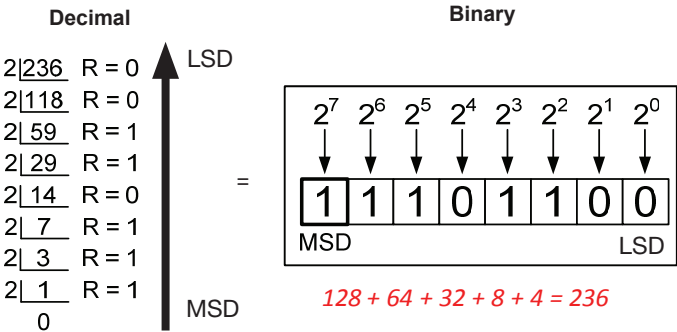
Numbering systems: Binary, decimal, and hexadecimal

Binary (Base-2)	0					1										
Decimal (Base-10)	0	1	2	3	4	5	6	7	8	9						
Hexadecimal (Base-16)	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F

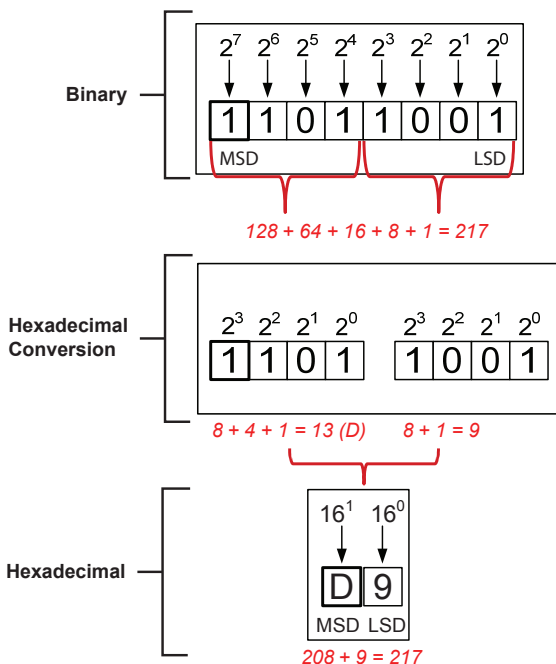
Example conversion: Binary to decimal



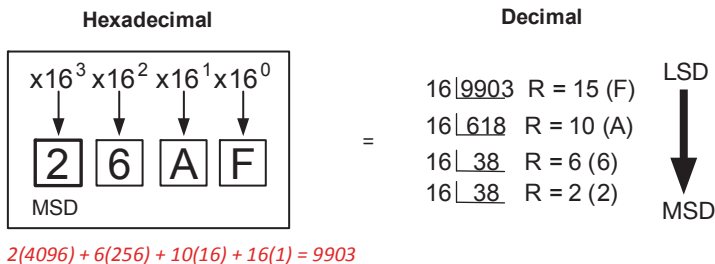
Example conversion: Decimal to binary



LSD = Least Significant Digit
MSD = Most Significant Digit

Example conversion: Binary to hexadecimal**Example Conversion: Hexadecimal to decimal and decimal to hexadecimal**

Decimal (Base-10)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hexadecimal (Base-16)	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F



LSD = Least Significant Digit
MSD = Most Significant Digit

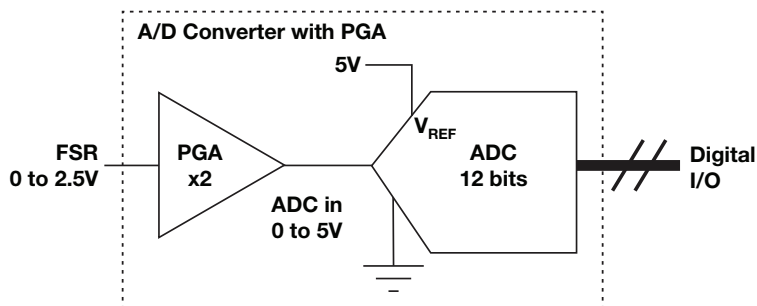


Figure 51: ADC full-scale range (FSR) unipolar

Full Scale Range (FSR) Unipolar

$$\text{FSR} = \frac{V_{\text{REF}}}{\text{PGA}}$$

$$1\text{LSB} = \frac{\text{FSR}}{2^n}$$

Example calculation for the circuit above.

$$\text{FSR} = \frac{V_{\text{REF}}}{\text{PGA}} = \frac{5\text{V}}{2} = 2.5\text{V}$$

$$1\text{LSB} = \frac{\text{FSR}}{2^n} = \frac{2.5\text{V}}{2^{12}} = 610.35\mu\text{V}$$

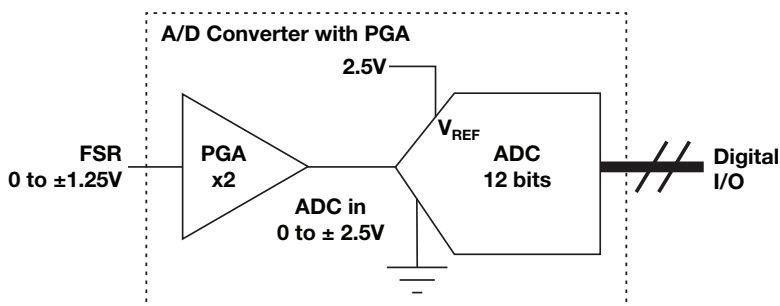


Figure 52: ADC full-scale range (FSR) Bipolar

Full Scale Range (FSR) Bipolar

$$\text{FSR} = \frac{V_{\text{REF}}}{\text{PGA}}$$

$$1\text{LSB} = \frac{\text{FSR}}{2^n}$$

Example calculation for the circuit above.

$$\text{FSR} = \frac{\pm V_{\text{REF}}}{\text{PGA}} = \frac{\pm 2.5\text{V}}{2} = \pm 1.25\text{V} \Rightarrow 2.5\text{V}$$

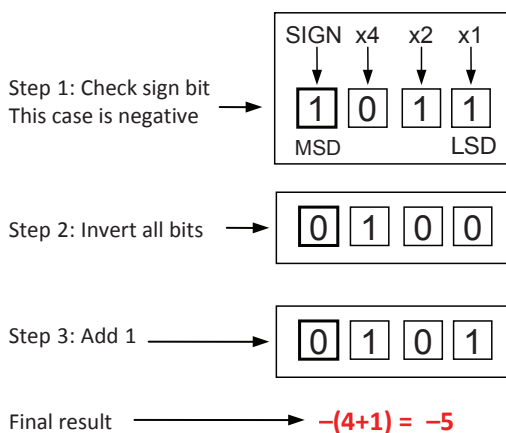
$$1\text{LSB} = \frac{\text{FSR}}{2^n} = \frac{2.5\text{V}}{2^{12}} = 610.35\mu\text{V}$$

Table 30: Different data formats

Code	Straight binary	Offset binary	2's complement
Binary	Decimal value	Decimal value	Decimal value
11111111	255	127	-1
11000000	192	64	-64
10000000	128	0	-128
01111111	127	-1	127
01000000	64	-64	64
00000000	0	-128	0

Converting two's complement to decimal:

Negative number example



Converting two's complement to decimal:

Positive number example

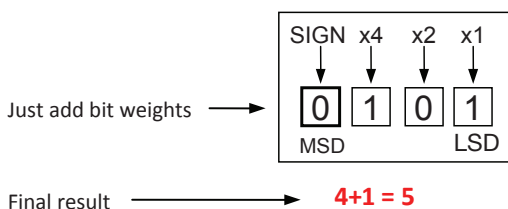


Table 31: LSB voltage vs. resolution and reference voltage

		FSR (Full-Scale Range)			
		1.024V	1.25V	2.048V	2.5V
Resolution	8	4 mV	4.88 mV	8 mV	9.76 mV
	10	1 mV	1.22 mV	2 mV	2.44 mV
	12	250 µV	305 µV	500 µV	610 µV
	14	52.5 µV	76.3 µV	125 µV	152.5 µV
	16	15.6 µV	19.1 µV	31.2 µV	38.14 µV
	18	3.91 µV	4.77 µV	7.81 µV	9.53 µV
	20	0.98 µV	1.19 µV	1.95 µV	2.384 µV
	22	244 nV	299 nV	488 nV	596 nV
	24	61 nV	74.5 nV	122 nV	149 nV

Table 32: LSB voltage vs. resolution and reference voltage

		FSR (Full-Scale Range)			
		3V	3.3V	4.096V	5V
Resolution	8	11.7 mV	12.9 mV	16 mV	19.5 mV
	10	2.93 mV	3.222 mV	4 mV	4.882 mV
	12	732 µV	806 µV	1 mV	1.221 mV
	14	183 µV	201 µV	250 µV	305 µV
	16	45.77 µV	50.35 µV	62.5 µV	76.29 µV
	18	11.44 µV	12.58 µV	15.6 µV	19.07 µV
	20	2.861 µV	3.147 µV	3.91 µV	4.768 µV
	22	715 nV	787 nV	976 nV	1.192 µV
	24	179 nV	196 nV	244 nV	298 nV

DAC definitions

Resolution = n	The number of bits used to quantify the output
Number of Codes = 2^n	The number of input code combinations
Full-scale Range = FSR	Sets the LSB voltage or current size and converter range
LSB = $FSR / 2^n$	The voltage step size of each code
Full-scale code = $2^n - 1$	The largest code that can be written
Full-scale voltage = $FSR - 1\text{LSB}$	Full-scale output voltage of the DAC
Transfer function = $FSR \times (\text{code} / 2^n)$	Relationship between input code and output voltage or current

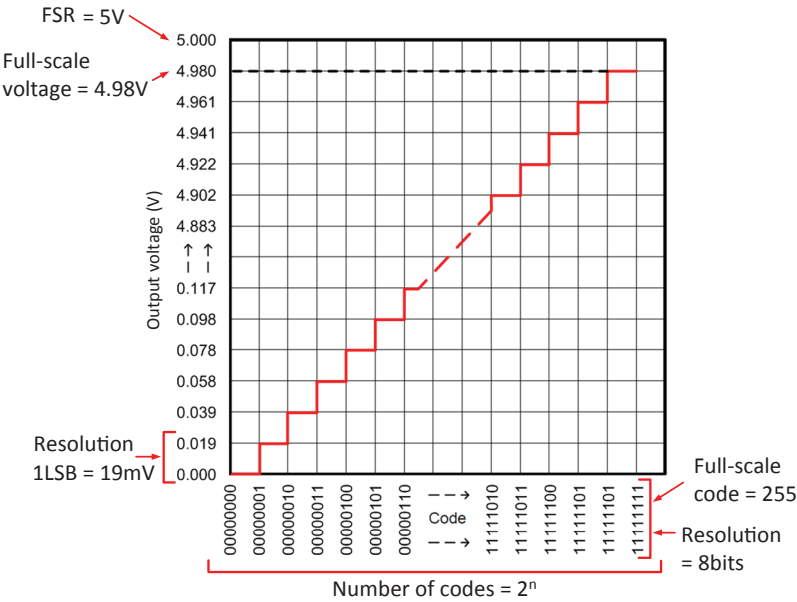


Figure 53: DAC transfer function

ADC definitions

Resolution = n	The number of bits used to quantify the output
Number of codes = 2 ⁿ	The number of input code combinations
Full-scale Range = FSR	Sets the LSB voltage or current size and converter range
LSB = FSR / 2 ⁿ	The voltage step size of each code
Full-scale code = 2 ⁿ - 1	The largest code that can be written
Full-scale voltage = FSR - 1LSB	Full-scale output voltage of the ADC
Transfer function = FSR x (code/ 2 ⁿ)	Relationship between input code and output voltage or current

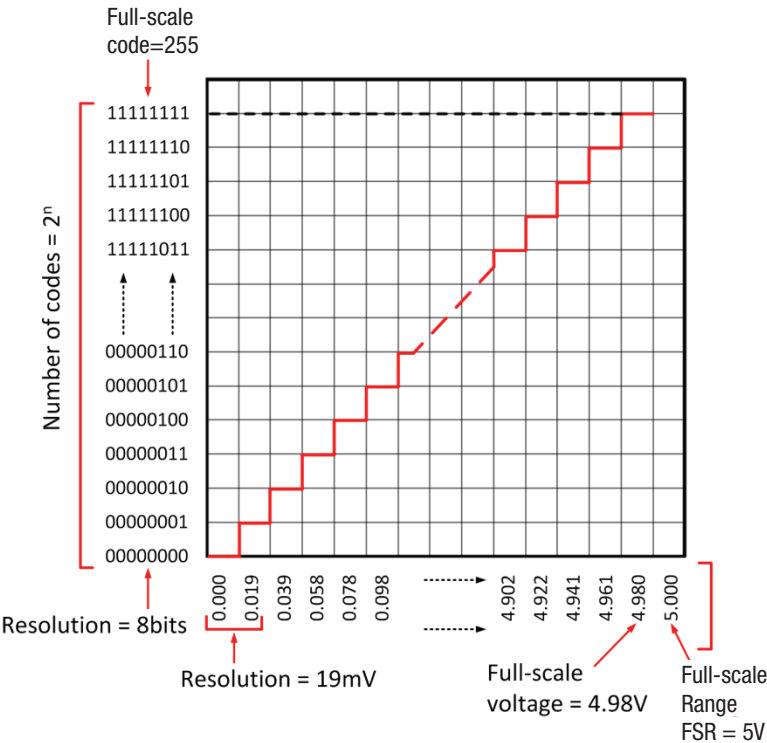


Figure 54: ADC transfer function

Quantization error of ADC

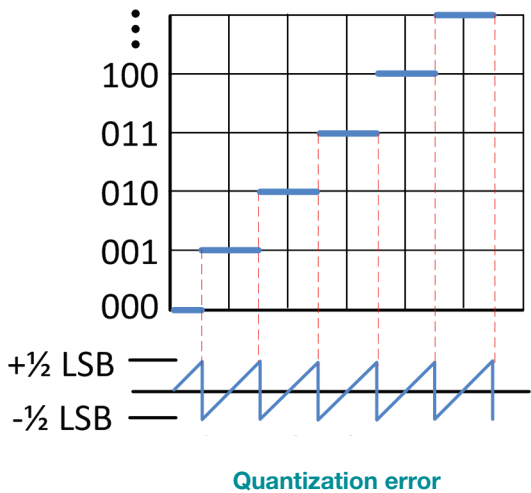


Figure 55: Quantization error of an A/D converter

Quantization error

The error introduced as a result of the quantization process. The amount of this error is a function of the resolution of the converter. The quantization error of an A/D converter is $\frac{1}{2}$ LSB. The quantization error signal is the difference between the actual voltage applied and the ADC output (Figure 55). The rms of the quantization signal is $1\text{LSB}/\sqrt{12}$

Signal-to-noise ratio (SNR) from quantization noise only

$$\text{MaxRMSSignal} = \frac{\text{FSR}/2}{\sqrt{2}} = \frac{1\text{LSB} \times 2^{N-1}}{\sqrt{2}} \quad (107)$$

$$\text{RMSNoise} = \frac{1\text{LSB}}{\sqrt{12}} \text{ from quantization only} \quad (108)$$

$$\text{SNR} = \frac{\text{MaxRMSSignal}}{\text{RMSNoise}} = \frac{1\text{LSB} \times 2^{N-1}/\sqrt{2}}{1\text{LSB}/\sqrt{12}} = 2^{N-1}\sqrt{6} \quad (109)$$

$$\text{SNR(dB)} = 20\log(\text{SNR}) = [20\log(2)]N + 20\log\left(\frac{\sqrt{6}}{2}\right) \quad (110)$$

$$\text{SNR(dB)} \approx 6.02N + 1.76 \quad (111)$$

Where

FSR = full-scale range of the A/D converter

1LSB = the voltage of 1LSB, $V_{\text{REF}}/2^N$

N = the resolution of the A/D converter

MaxRMSSignal = the rms equivalent of the ADC's full-scale input

RMSNoise = the rms noise from quantization

SNR = the ratio of rms signal to rms noise

Example

What is the SNR for an 8-bit A/D converter with 5V reference, assuming only quantization noise?

Answer

$$\text{SNR} = 2^{N-1}\sqrt{6} = 2^{8-1}\sqrt{6} = 314$$

$$\text{SNR(dB)} = 20\log(314) = 49.9 \text{ dB}$$

$$\text{SNR(dB)} = 6.02(8) + 1.76 = 49.9 \text{ dB}$$

Total harmonic distortion (Vrms)

$$THD(\%) = \left(\frac{RMSDistortion}{MaxRMSSignal} \right) \cdot 100 = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1} \cdot 100 \tag{112}$$

$$THD(dB) = 20\log\left(\frac{RMSDistortion}{MaxRMSSignal}\right) \tag{113}$$

Where

THD = total harmonic distortion, the ratio of the rms distortion to the rms signal

RMSDistortion = the rms sum of all harmonic components

MaxRMSSignal = the rms value of the input signal

V₁ = the fundamental, generally the input signal

V₂, V₃, V₄, ...V_n = harmonics of the fundamental

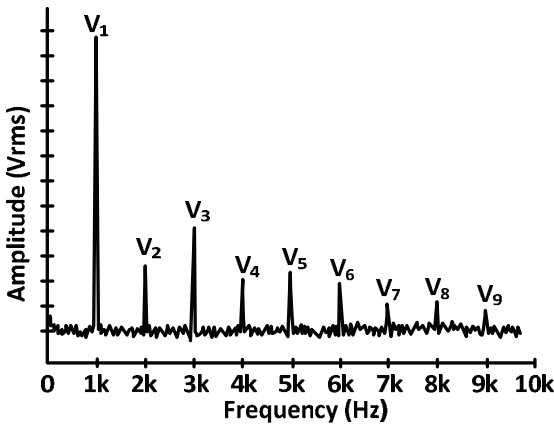


Figure 56: Fundamental and harmonics in Vrms

Total harmonic distortion (dBc)

$$\text{THD(dBc)} = 10 \log \left[10^{\left(\frac{D_2}{10}\right)} + 10^{\left(\frac{D_3}{10}\right)} + 10^{\left(\frac{D_4}{10}\right)} + \dots + 10^{\left(\frac{D_n}{10}\right)} \right] \quad (114)$$

Where

THD = total harmonic distortion. The ratio of the rms distortion to the rms signal

D_1 = the fundamental, generally the input signal. This is normalized to 0 dBc

$D_2, D_3, D_4, \dots D_n$ = harmonics of the fundamental measured relative to the fundamental

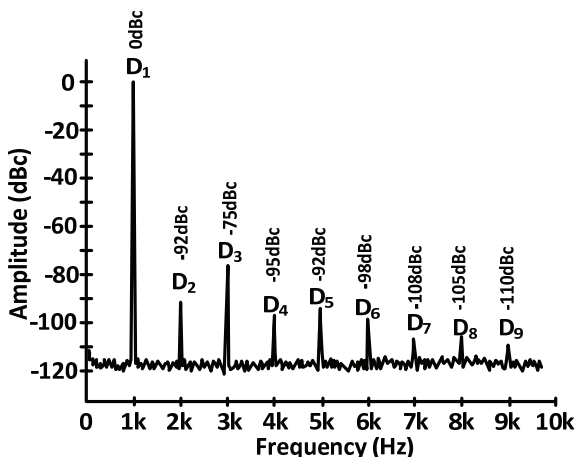


Figure 57: Fundamental and harmonics in dBc

Example

Determine THD for the example above.

Answer

$$\text{THD(dBc)} = 10 \log \left[10^{\left(\frac{-92}{10}\right)} + 10^{\left(\frac{-75}{10}\right)} + 10^{\left(\frac{-95}{10}\right)} + \dots + 10^{\left(\frac{-110}{10}\right)} \right]$$

$$\text{THD(dBc)} = -74.76 \text{ dB}$$

Ac signals

Signal-to-noise and distortion (SINAD) and effective number of bits (ENOB)

$$\text{SINAD(dB)} = 20 \log \left(\frac{\text{MaxRMSSignal}}{\sqrt{\text{RMSNoise}^2 + \text{RMSDistortion}^2}} \right) \quad (115)$$

$$\text{SINAD(dB)} = -20 \log \left(\sqrt{10^{\left(\frac{-\text{SNR(dB)}}{10}\right)} + 10^{\left(\frac{\text{THD(dB)}}{10}\right)}} \right) \quad (116)$$

$$\text{ENOB} = \frac{\text{SINAD(dB)} - 1.76\text{dB}}{6.02} \quad (117)$$

Where

MaxRMSSignal = the rms equivalent of the ADC's full-scale input

RMSNoise = the rms noise integrated across the A/D converters

RMSDistortion = the rms sum of all harmonic components

SINAD = the ratio of the full-scale signal-to-noise ratio and distortion

THD = total harmonic distortion. The ratio of the rms distortion to the rms signal.

SNR = the ratio of rms signal to rms noise

Example

Calculate the SNR, THD, SINAD and ENOB given the following information:

MaxRMSSignal = 1.76 Vrms

RMSDistortion = 50 μ Vrms

RMSNoise = 100 μ Vrms

Answer

$$\text{SNR(dB)} = 20 \log \left(\frac{1.76 \text{ Vrms}}{100 \mu\text{Vrms}} \right) = 84.9 \text{ dB}$$

$$\text{THD(dB)} = 20 \log \left(\frac{50 \mu\text{Vrms}}{1.76 \text{ Vrms}} \right) = -90.9 \text{ dB}$$

$$\text{SINAD(dB)} = 20 \log \left(\frac{1.76 \text{ V rms}}{\sqrt{(100 \mu\text{Vrms})^2 + (50 \mu\text{Vrms})^2}} \right) = 83.9 \text{ dB}$$

$$\text{SINAD(dB)} = -20 \log \left(\sqrt{10^{\left(\frac{-83.9 \text{ dB}}{10}\right)} + 10^{\left(\frac{-90.9 \text{ dB}}{10}\right)}} \right) = 83.9 \text{ dB}$$

$$\text{ENOB} = \frac{83.9\text{dB} - 1.76\text{dB}}{6.02} = 13.65$$

Dc signals

Noise free resolution and effective resolution

$$\text{NoiseFreeResolution} = \log_2 \left(\frac{2^N}{\text{PeaktoPeakNoiseinLSB}} \right) \quad (118)$$

$$\text{EffectiveResolution} = \log_2 \left(\frac{2^N}{\text{rmsNoiseinLSB}} \right) \quad (119)$$

$$\text{PeaktoPeakNoiseinLSB} \approx 6.6 \times \text{rmsNoiseinLSB} \quad (120)$$

$$\text{EffectiveResolution} \approx \text{NoiseFreeResolution} + 2.7 \quad (121)$$

Note: The maximum effective resolution is never greater than the ADC resolution. For example, a 24-bit converter cannot have an effective resolution greater than 24 bits.

Example

What is the noise-free resolution and effective resolution for a 24-bit converter assuming the peak-to-peak noise is 7 LSBs?

Answer

$$\text{NoiseFreeResolution} = \log_2 \left(\frac{2^{24}}{7} \right) = 21.2$$

$$\text{EffectiveResolution} = \log_2 \left(\frac{2^{24}}{6.6} \right) = 23.9$$

$$\text{EffectiveResolution} = 21.2 + 2.7 = 23.9$$

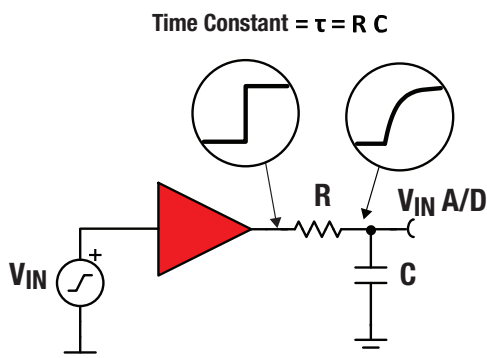


Figure 58: Settling time for RC circuit-related to A/D converters

Table 33: Conversion accuracy achieved after a specified time

Settling time in time constants (N_{TC})	Accuracy in bits (N)	Settling time in time constants (N_{TC})	Accuracy in bits
1	1.44	10	14.43
2	2.89	11	15.87
3	4.33	12	17.31
4	5.77	13	18.76
5	7.21	14	20.20
6	8.66	15	21.64
7	10.10	16	23.08
8	11.54	17	24.53
9	12.98	18	25.97

$$N = \log_2(e^{-N_{TC}}) \tag{122}$$

Where

N = the number of bits of accuracy the RC circuit has settled to after N_{TC} number of time constants.

N_{TC} = the number of RC time constants

Note: For a FSR step. For single-ended input ADC with no PGA front end
 $FSR \text{ (Full Scale Range)} = V_{REF}$

Table 34: Time required to settle to a specified conversion accuracy

Accuracy in bits (N)	Settling time in time constants (N _{TC})	Accuracy in bits (N)	Settling time in time constants (N _{TC})
8	5.5	17	11.78
9	6.24	18	12.48
10	6.93	19	13.17
11	7.62	20	13.86
12	8.32	21	14.56
13	9.01	22	15.25
14	9.70	23	15.94
15	10.40	24	16.64
16	11.04	25	17.33

$$N_{TC} = \ln(2^N)$$

(123)

Where

N_{TC} = the number of time constants required to achieve N bits of settling

N = the number of bits of accuracy

Note: For a FSR step. For single-ended input ADC with no PGA front end
FSR (Full Scale Range) = V_{REF}

[illegible]

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