Measurement circuits and systems

instrumentation and differential amplifiers

Choose yourself and new technologies

References

C. Kitchin, L. Counts,
A Designer's Guide To Instrumentation Amplifiers,
Analog Devices,3rd edition, 2006

https://www.analog.com/en/education/education-library/dh-designers-guide-to-instrumentation-amps.html

outline:

1. Introduction: understanding IN-AMP
2. IN-AMP inside
3. monolithic in-amps review
   - auto-zeroing amps
4. monolithic dif-amps review
5. application tips
6. application circuits
7. summary

instrumentation amplifier (in-amp)

1. Not all amplifiers used in instrumentation applications are instrumentation amplifiers,
2. and by no means are all in-amps used only in instrumentation applications.

In-amps are used in many applications, from motor control to data acquisition to automotive. The intent of this guide is to explain the fundamentals of what an instrumentation amplifier is, how it operates, and how and where to use it. In addition, several different categories of instrumentation amplifiers are addressed in this guide.

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in-amps vs. op-amps: what are the differences?

IN-AMP	OP-AMP
Internal closed-loop gain	closed-loop gain is determined by external resistors
Gain adjustet resistor(s) is not connected with any input	Loop resistors affect input impedance (can change the input resistance)

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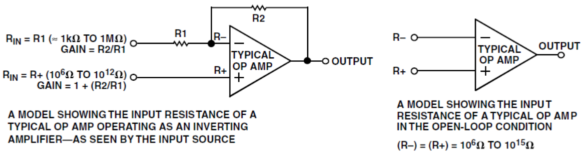
Op-amps features



OP AMP INPUT CHARACTERISTICS

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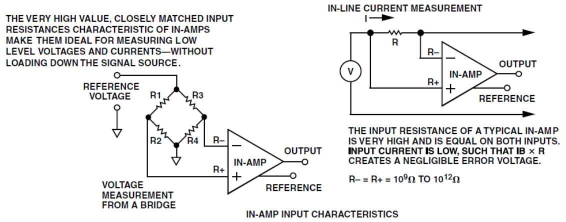
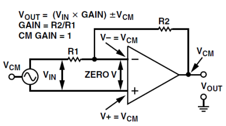
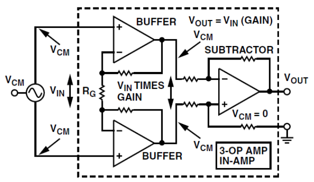
In-amp properties

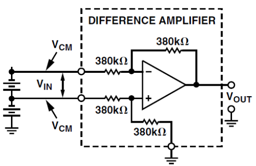


CMRR in-amp vs. op_amp

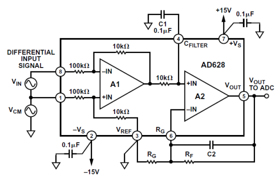




Differential Amplifiers (not an in-amp)



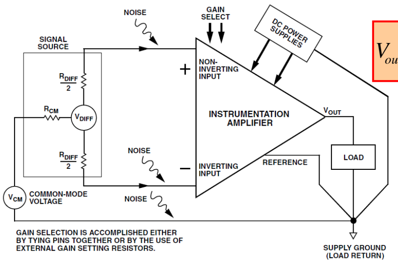
- limited input resistance
- VCM can be higher than supply voltage of tha amp



In-amp applications

- **Data Acquisition**
- **Medical Instrumentation (EEG, EEC)**
- **Monitor and Control Electronics (current, voltage monitoring)**
- **Power Control Applications**
- **Audio Applications (very high CMRR vs.frequency)**
- ***High Speed Signal Conditioning (including video signals) ??***

common mode and differential signals

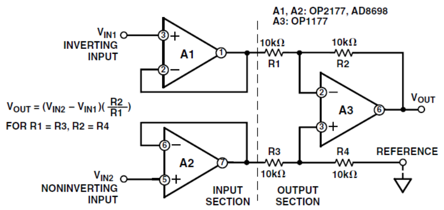


$$V_{out} = GV_{DIFF} + \frac{G}{CMRR}(V_{CM})$$

in-amp properties

- **High AC (and DC) Common-Mode Rejection**
- **Low Offset Voltage and Offset Voltage Drift** (1 uV/deg to 10uV/deg)
- **A Matched, High Input Impedance**
- **Low Input Bias and Offset Current Errors (pA)**
- **Low Noise** -10 nV/√*Hz* @ 1 kHz (gain > 100)
- **Low Nonlinearity** (0.01% or better)
- **Simple Gain Selection**
- **Adequate Bandwidth (up to 5MHz)**
- **Differential to Single-Ended Conversion**
- **Rail-to-Rail Input and Output Swing (offten)**
- **Power vs. Bandwidth, Slew Rate, and Noise (disadventage – power desipation)**

INSIDE AN INSTRUMENTATION AMPLIFIER



A subtractor circuit with input buffering.

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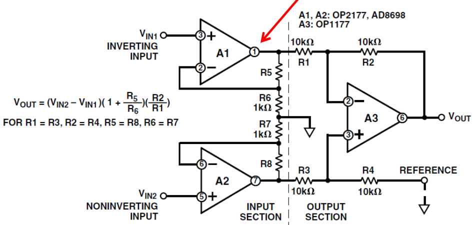
in-amp inside cont.

$$V_{o1} = \frac{V_{in1} + V_{in2}}{2}\frac{R_5}{R_6} = V_{CM}\frac{R_5}{R_6}$$



\ buffered subtractor circuit with buffer amplifiers operating with gain.

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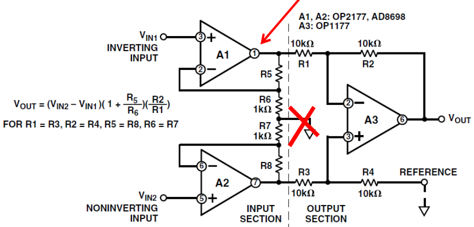
in-amp inside cont.

$$V_{o1} = \frac{V_{in1} + V_{in2}}{2}\frac{R_5}{R_6} = V_{CM}\frac{R_5}{R_6}$$



\ buffered subtractor circuit with buffer amplifiers operating with gain.

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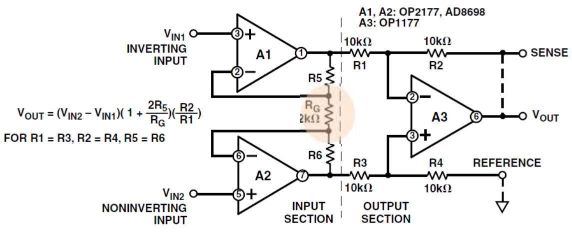
in-amp inside cont.

change of one resistor change the gain



The classic 3-op amp in-amp circuit.

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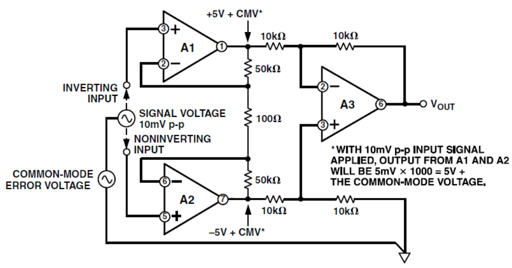
Common Mode Voltage



A 3-op amp in-amp showing reduced CMV range.

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simpler in-amp

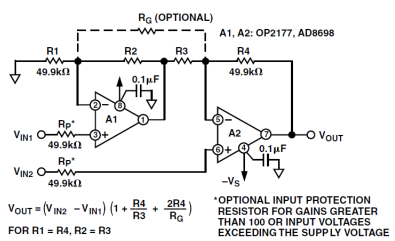

Figure 2-6. A 2-op amp in-amp circuit.

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single supply consideration

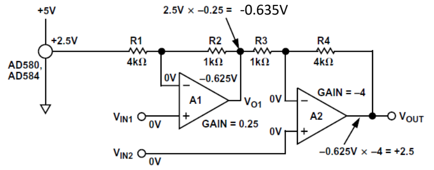

Figure 2-8. Output swing limitations of 2-op amp in-amp using a 2.5 V reference.

$$V_{o1} = V_{CM} + (V_{CM} - V_{REF})\frac{R_2}{R_1} \geq 0$$

????????

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3op-amp vs. 2 op-amp

3op-amp	2 op-amp
Single supply can be easy applied.	Limited input voltages for single supply (1st stage can be working with negative output)
Signals from both inputs have the same path to output.	Lower CMRR (it comes from the inherent imbalance in the common-mode signal paths of the both inputs especially for high frequencies)

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MONOLITHIC IN-AMPs

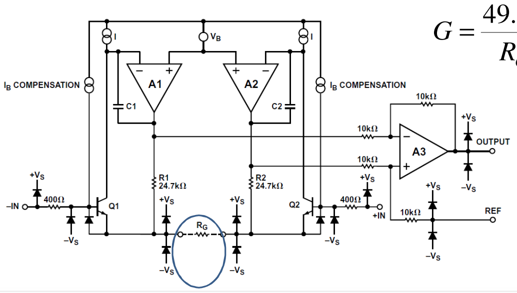
Table 3-1. Latest Generation Analog Devices In-Amps Summarized[1]

Product	Features	Power Supply Current Typ	–3 dB BW Typ (G = 10)	CMR G = 10 (dB) Min	Input Offset Voltage Max	V_{OS} Drift (μV/°C) Max	RTI Noise[2] (nV/√Hz) (G = 10)	Input Bias Current (nA) Max
AD8221	Precision, high BW	0.9 mA	560 kHz	100[3]	60 μV	0.4	11 max	1.5
AD620	General-purpose	0. 9 mA	800 kHz	95[3]	125 μV	1	16 max	2
AD8225	Precision gain = 5	1.1 mA	900 kHz[4]	83[4, 5]	150 μV	0.3	45 typ[4]	1.2
AD8220	R-R, JFET input	750 μA	1500 kHz	100	250 μV	5	17 typ	10 pA
AD8222	Dual, precision, high BW	1.8 mA	750 kHz	100[3]	120 μV	0.4	11 max	2
AD8230	R-R, zero drift	2.7 mA	2 kHz	110	10 μV	10	240 typ	1
AD8250	High BW, programmable gain	3.5 mA	3.5 MHz	100	100 μV	1	13 typ	15
AD8251	High BW, programmable gain	3.5 mA	3.5 MHz	100	100 μV	1	13 typ	15
AD8553	Auto-zero with shutdown	1.1 mA	1 kHz	100	20 μV	0.1	150 typ	1
AD8555	Zero drift dig prog	2.0 mA	700 kHz[6]	80[6]	10 μV	0.07	32 typ	22
AD8556	Dig prog IA with filters	2.0 mA	700 kHz[6]	80[6]	10 μV	0.07	32 typ	54
AD622	Low cost	0.9 mA	800 kHz	86[3]	125 μV	1	14 typ	5
AD621	Precise gain	0.9 mA	800 kHz	93[3]	250 μV[7]	2.5[7]	17 max[7]	2
AD623	Low cost, S.S.	375 μA	800 kHz	90[3]	200 μV	2	35 typ	25
AD627	Micropower, S.S.	60 μA	80 kHz	100	250 μV	3	42 typ	10

NOTES
S.S. = single supply.
[1]Refer to ADI website at www.analog.com for latest products and specifications.
[2]At 1 kHz. RTI noise = $\sqrt{((e_{ni})^2 + (e_{no/G})^2)}$.
[3]For dc to 60 Hz, 1 kΩ source imbalance.
[4]Operating at a gain of 5.
[5]For 10 kHz, 1 kΩ source imbalance.
[6]Operating at a gain of 70.
[7]Referred to input (RTI).

In-amp example

$$G = \frac{49.4\cdot 10^3}{R_G + 1}$$



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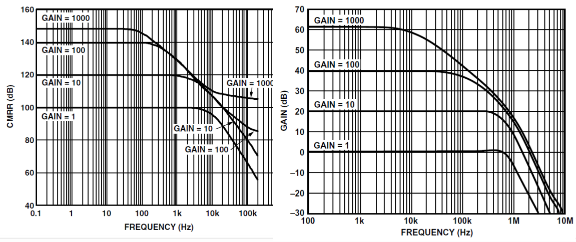

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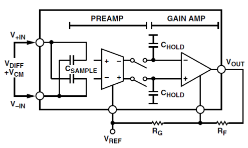
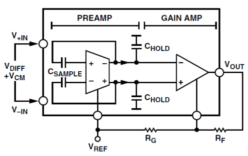
Auto-Zeroing Instrumentation Amplifiers (AD8230)



The differential component of the input signal is stored on sampling capacitors, C_{SAMPLE}. The gain amp conditions the signal stored on the hold capacitors, C_{HOLD}. Gain is set with the RG and RF resistors.



The differential signal is transferred to the hold capacitors, refreshing the value stored on C_{HOLD}. The gain amp continues to condition the signal stored on the hold capacitors, C_{HOLD}.

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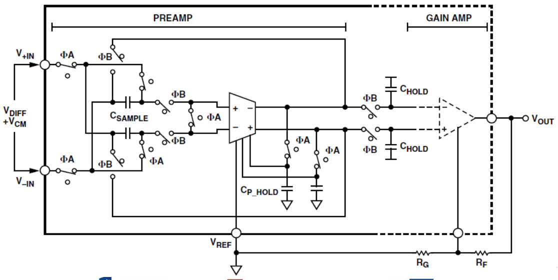
Auto-Zeroing In-Amps preamplifier phase A



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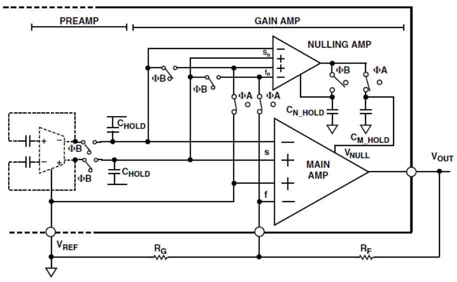
Auto-Zeroing In-Amps gain amplifier phase A



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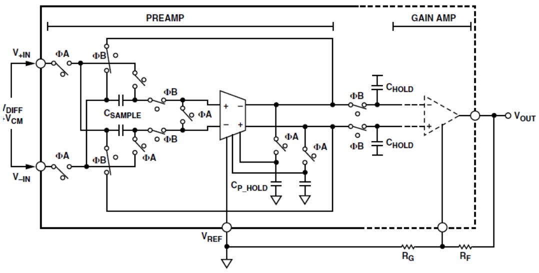
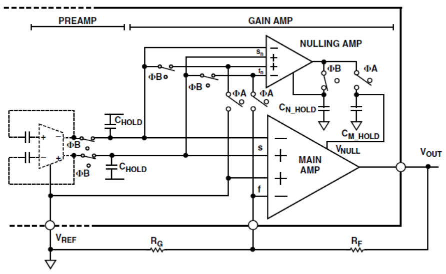
Auto-Zeroing In-Amps preamplifier phase B



Auto-Zeroing In-Amps gain amplifier phase B



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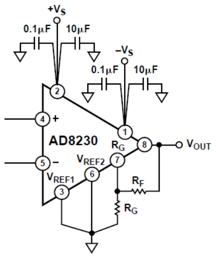
Gain setting



$$G = 2\left(1 + \frac{R_F}{R_G}\right)$$

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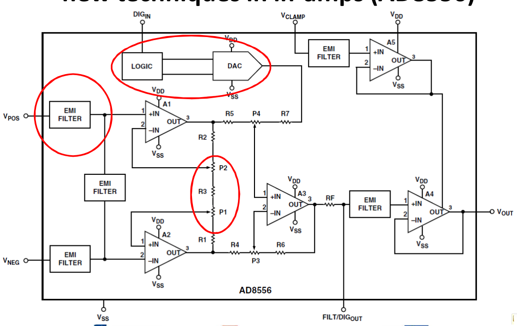
new techniques in in-amps (AD8556)



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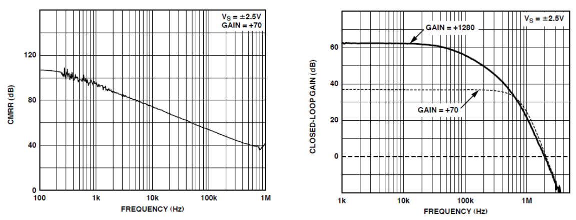
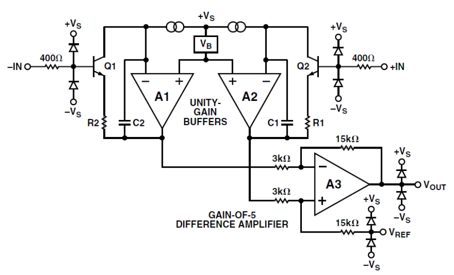
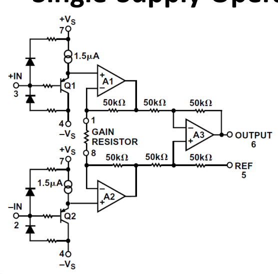
AD8555

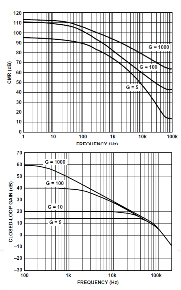


Fixed Gain (Low Drift) In-Amps: AD8225



Monolithic In-Amps Optimized for Single-Supply Operation: AD627





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MONOLITHIC DIFFERENCE AMPLIFIERS

Table 4-1. Latest Generation of Analog Devices Difference Amps Summarized[1]

Product	Features	Power Supply Current Typ	–3 dB BW Typ (G = 10)	CMR G = 10 (dB) Min	Input Offset Voltage Max	V_{OS} Drift (µV/°C) Max	RTI Noise[2] (nV/√Hz) (G = 10)
AD8202	S.S., 28 V CMV, G = 20	250 µA	50 kHz	80[3, 4, 5]	1 mV[6]	10	300 typ[3]
AD8203	S.S., 28 V CMV, G = 14	250 µA	60 kHz[7]	80[5, 7]	1 mV[6]	10	300 typ[7]
AD8205	S.S., 65 V CMV, G = 50	1 mA	50 kHz[8]	80[4, 5, 6]	2 mV[6]	15 typ	500 typ[8]
AD8206	S.S., 65 V CMV, G = 20	1 mA	100 kHz[3]	76[3, 9]	2 mV[6]	15 typ	500 typ[3]
AD8210	S.S., current shunt monitor	500 µA	500 kHz[3]	100[3, 5]	1 mV[6]	5 typ	80 typ[3]
AD8212	Adjustable gain; CMV up to 500 V[10]	200 µA	500 kHz	90	1 mV	10	100 typ
AD8213	Dual channel	1.3 mA[11]	500 kHz	100	1 mV	10	70 typ
AD8130	270 MHz receiver	12 mA	270 MHz	83[12, 13]	1.8 mV	3.5 mV	12.5 typ[12, 14]
AD628	High CMV	1.6 mA	600 kHz[15]	75[15]	1.5 mV	4	300 typ[15]
AD629	High CMV, G = 1	0.9 mA	500 kHz	77[12]	1 mV	6	550 typ[12]
AD626	High CMV	1.5 mA	100 kHz	55[16]	500 µV	1	250 typ
AMP03	High BW, G = 1	3.5 mA	3 MHz	85[12]	400 µV	NS	750 typ[12]

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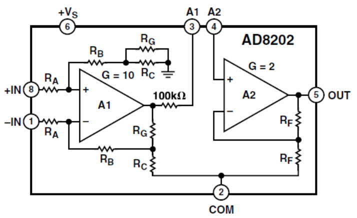
monolithic dif-amp, an example



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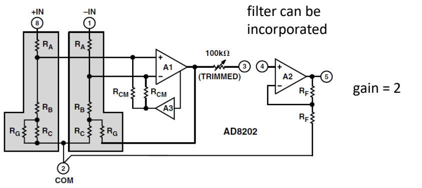
monolithic dif-amp, an example

bridge (subtractor) circuit

filter can be incorporated



gain = 2

preamp gain = 10

Amplifier A3 detects the common-mode signal applied to A1 and adjusts the voltage on the matched RCM resistors to reduce the common-mode voltage range at the A1 inputs.

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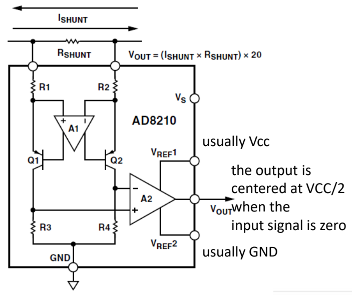
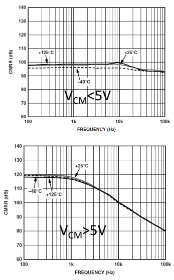
current shunt monitor





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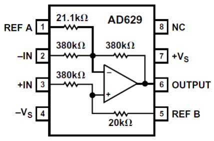

- •unity-gain difference amplifier common-mode input voltages of up to 270 V.
- •excellent CMR in the presence of high common-mode input voltages
- •operate from a wide power supply range of □2.5 V to □18 V.

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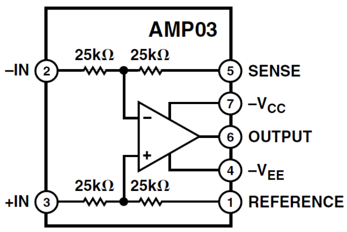
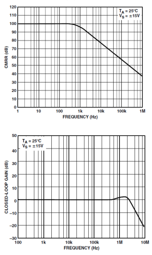
monolithic, unity-gain, 3 MHz dif-amp

basic analog building block for differential amplifier and instrumentation applications





Analog Device advertisement materials

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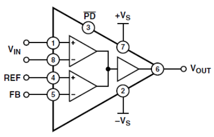
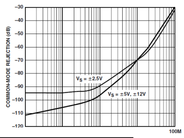
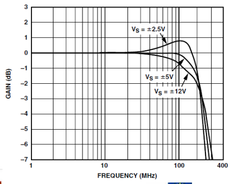
High Frequency Diff- Receiver/Amplifiers







•3 dB bandwidth of 270MHz,
•80dB CMR at 2MHz, and a 70 dB CMR at 10 MHz
•active feedback !!! – feedback do not affect the inputs

Making use of an in-amps

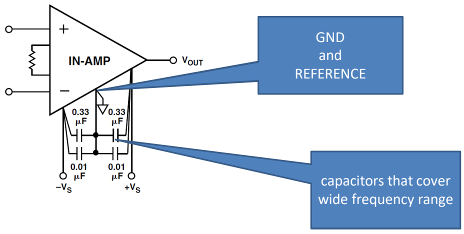
Application assumption:
•Dual-Supply Operation or Single-Supply Operation
•Need for True R-R Devices
•CMRR
•offset
•offset drift
•noise
•gain

Application tips

•power supply bypassing, decoupling, and stability issues
•input ground return
•center polarization of input and output (especially case of single supply)
•properly driving an in-amp's reference input
•input protection from esd and dc overload

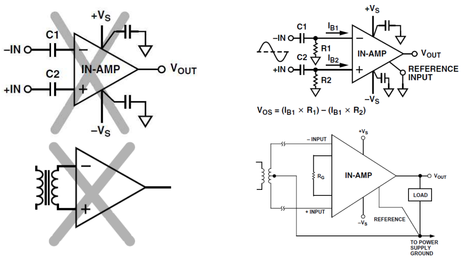
Application tips

power supply bypassing, decoupling, and stability issues



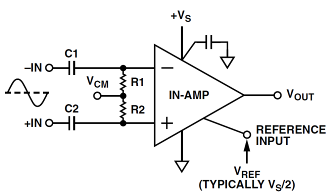
Application tips

input ground return



Application tips

center polarization of input and output

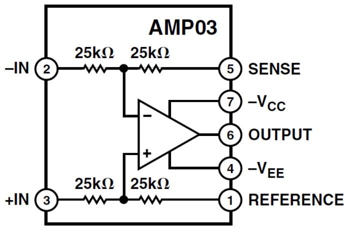


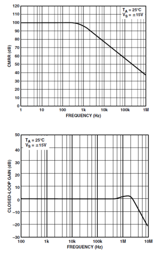
$C_1R_1=C_2R_2$
for CMR (h.f.)

$$I_{B1}R_1 - I_{B2}R_2 = \Delta U_{off}$$

monolithic, unity-gain, 3 MHz dif-amp

basic analog building block for differential amplifier and instrumentation applications





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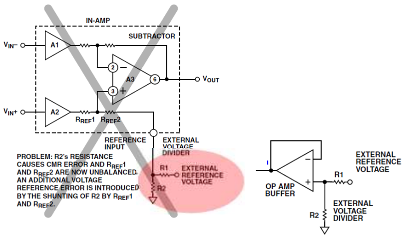
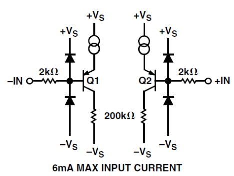
Application tips

properly driving an in-amp's reference input



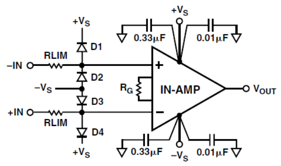
Application tips

input protection from ESD and dc overload



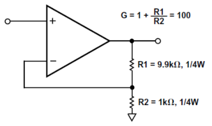
internal protection

additional external protection with Schotky diodes



Application tips

gain drift



Different power dissipation in R1 and R2 can cause gain drift even then temperature coefficients of both resistors are equal

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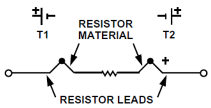
Application tips

gain and ofset drift



TYPICAL RESISTOR THERMOCOUPLE EMFs	
• CARBON COMPOSITION	400μV/°C
• METAL FILM	20μV/°C
• EVENOHM OR MANGANIN WIRE-WOUND	2μV/°C
• RCD COMPONENTS HP-SERIES	0.05μV/°C

Error (voltage offset) is due to temperature difference of resistor (or any other component) terminals.

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Application tips

RTI vs. RTO errors

Total Error, RTI = Input Error + (Output Error/Gain)

Total Error, RTO = (Gain * Input Error) + Output Error

VOLTAGE OFFSET	(Total RTI Error = $V_{OSI} + V_{OSO}/G$)		
Input Offset, V_{OSI}	$V_S = \pm 5$ V to ± 15 V	30	125
Over Temperature	$V_S = \pm 5$ V to ± 15 V		185
Average TC	$V_S = \pm 5$ V to ± 15 V	0.3	1.0
Output Offset, V_{OSO}	$V_S = \pm 15$ V	400	1000
	$V_S = \pm 5$ V		1500
Over Temperature	$V_S = \pm 5$ V to ± 15 V		2000
Average TC	$V_S = \pm 5$ V to ± 15 V	5.0	15
Offset Referred to the			

Total Offset Error RTI = VOSI + (VOSO/G) = 30μV + (400 μV/10) = 30 V + 40V = 70 μ V

Total Offset Error RTO = (G (VOSI)) + VOSO = (10 (30 μV)) + 400 μV = 700 μ V

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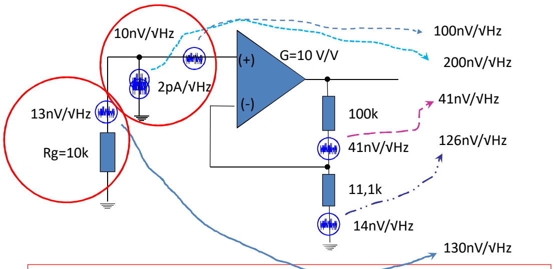
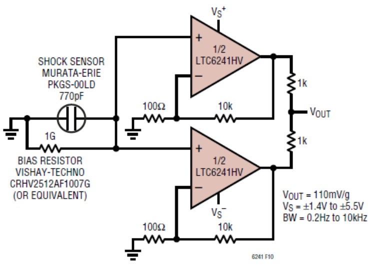
Application tips - Noise Errors



$$F=\frac{(130)^2+(200)^2+(100)^2+(41)^2+(126)^2}{(130)^2}=\frac{(130)^2+(260)^2}{(130)^2}=1+4=5=7dB$$

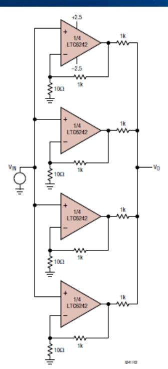
LTC6241 low noise amplifier



Linear Technology advertisement materials

LTC6241 twice better SNR

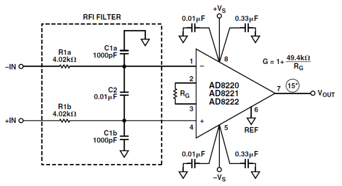
(neglecting source noise)



Linear Technology advertisement materials

Application tips

Practical RFI Filters



$$B_{DF} = \frac{1}{2\pi R(2C_2 + C_1)}$$

$$B_{CM} = \frac{1}{2\pi R_1 C_1}$$

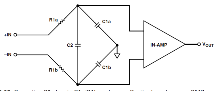


Figure 5-25. Capacitor C2 shunts C1a/C1b and very effectively reduces ac CMR errors due to component mismatching.

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Application tips

Practical RFI Filters

Selecting RFI Input Filter Component Values Using a Cookbook Approach

The general rules of designing of RC input filter.

1. the two series resistors
   - typical values between 2 kΩ and 10 k Ω; check if input circuit can drive these impedance,
   - these resistors should not contribute more noise than that of the in-amp itself.
2. value for capacitor C2
   - C2 sets the filter's differential (signal) bandwidth; best to set this as low as possible without attenuating the input signal;a differential bandwidth of 10 times the highest signal frequency is usually adequate.
3. select values for capacitors C1a and C1b; which set the common-mode bandwidth;
   - for decent ac CMR, these should be 10% the value of C2 or less,
   - The common-mode bandwidth should always be less than 10% of the in-amp's bandwidth at unity gain.

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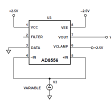
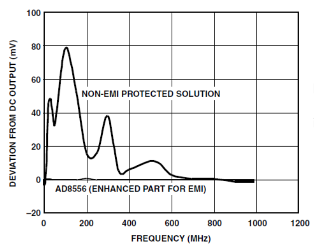
EMI protection result





DC offset without EMI protection is due to RECTIFIKATION !!! of inpur RF signals.

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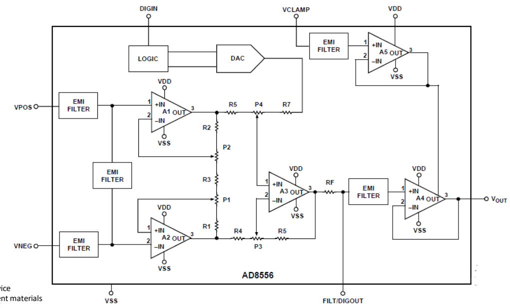
on chip emi filter



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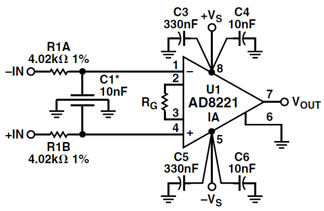
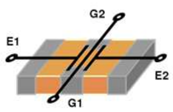
EMI filter with X2Y capacitor.





X2Y capacitor

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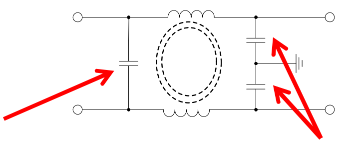
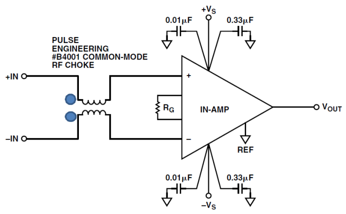
By the way….
X and Y capacitors in EMI filter



X capacitor failure could not lead to electric shock (hot to neutral)

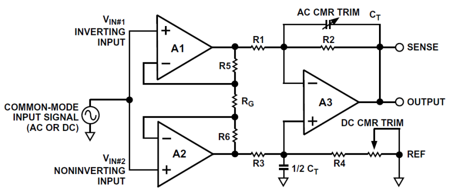
2 Y capacitors failure could lead to electric shock if the ground connection were lost

Common mode chock as emi filter



USING LOW-PASS FILTERING TO IMPROVE SIGNAL-TO-NOISE RATIO
To extract data from a noisy measurement, low-pass filtering can be used to greatly improve the signal-to-noise ratio of the measurement by removing all signals that are not within the signal bandwidth. In some cases, band-pass filtering (reducing response both below and above the signal frequency) can be employed for an even greater improvement in measurement resolution

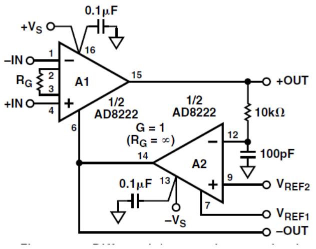
External CMRR trimming



TIP: discrete design of an In-amp has usually better performance (bandwidth and CMRR)

IN-AMP AND DIFF AMP APPLICATIONS CIRCUITS

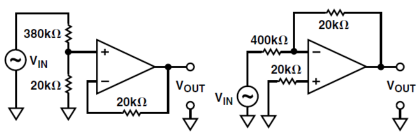
A True Differential Output In-Amp Circuit



$$V_{OCM} = \frac{V_{ref1} + V_{ref2}}{2}$$

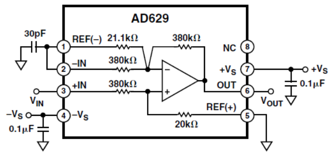
TIP: this is very useful with AD converter – V_{ref2} can be connected with U_{ref} of ADC and V_{ref1} with ADC ground so 0V of input is ½ value of ADC

High voltage measurements



TIP:
1. (on the left) single supply can be used and Vout is positive
2. (on the right) dual supply have to be applied, Vout is negative
3. If Vin are negative tips 1 and 2 have to be exchanged
4. power is dissipated in one resistor – self heating occurs
5. high temp gradient can cause nonlinearities , offset, drift, lower CMRR

High voltage measurements improopvemet



TIP: one chip – one temperature !

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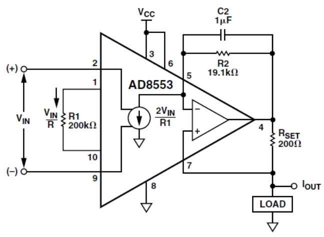
Precision Current Source



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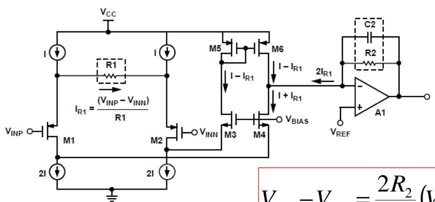

$$V_{out} - V_{ref} = \frac{2R_2}{R_1}(V_+ - V_-)$$

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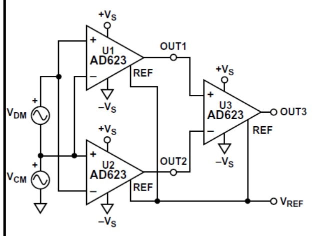
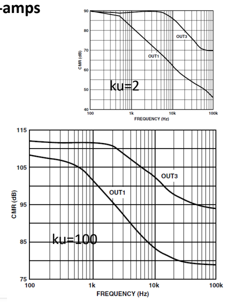
Extremely high CMRR

In-amp build of 3 In-amps





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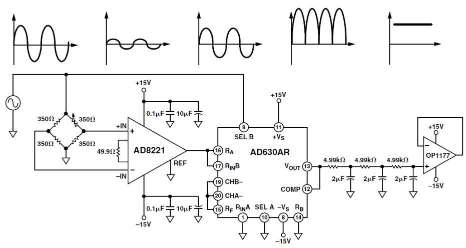
Strain gage excitation using sin signal



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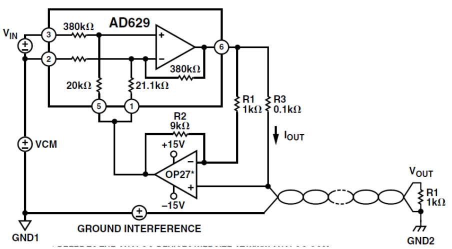
Current transmitter



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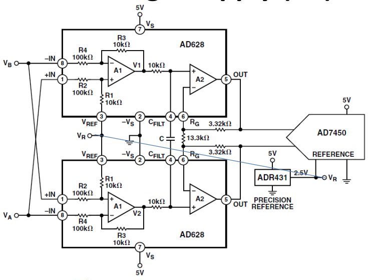
High level (+-10V) to single supply (5V) ADC



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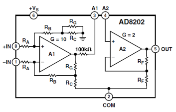
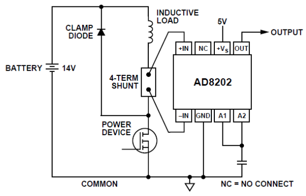
Current probe





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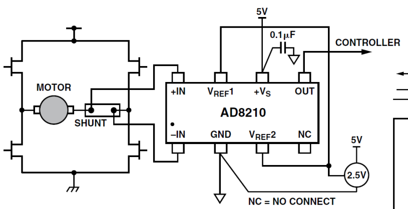
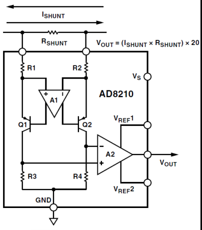
two directional current sensor





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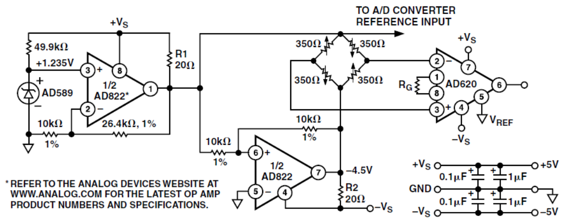
low impedance bridge excitation



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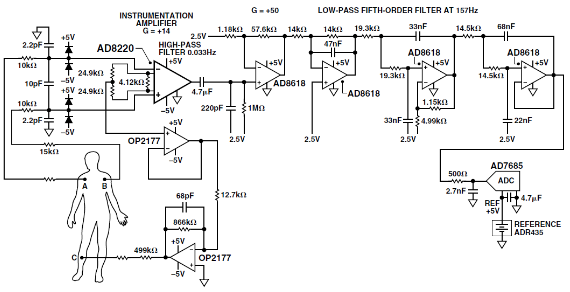
ECG signals acquisition



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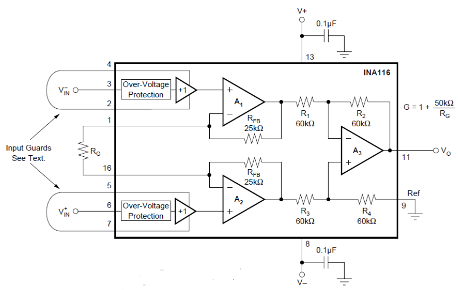
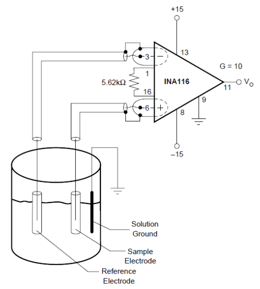
Driven Shield Inputs - example



pH transducer



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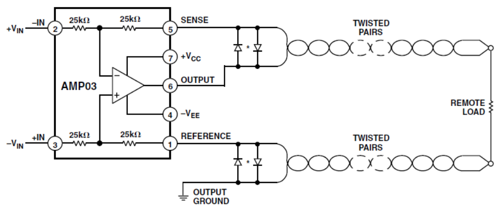
remote load driver



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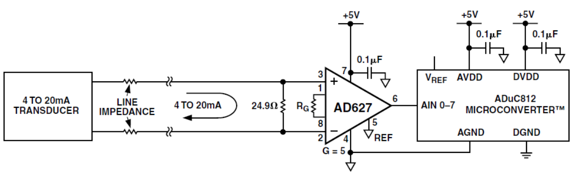
4-20mA loop receiver



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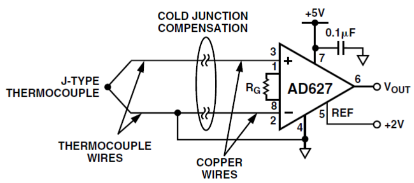
termocouple transducer



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summary

1. Properties of an in-amp
2. in-amp vs. op-amp
3. in-amp vs. dif-amp
4. in-amp of 3 vs. 2 op-amp
5. Application tips:
   - •EMI filtering
   - •input protection
   - •DC biasing
   - •thermal noise
   - •single supply problems
   - •CMR trimming

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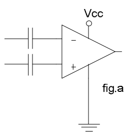
Test questions (an example):

- Draw two basic diagrams of a instrumentation amplifiers ?
- Compare in-amp vs. op-amp
- What wrong with the circuit (in-amp with two capacitor at the input) ? (fig.a)



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