AN4586
Application note

Signal conditioning, differential to single-ended amplification

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Introduction

There is a wide range of applications for which we need to amplify a differential signal and convert it into a single-ended signal. Such applications can be used to condition the signal of Wheatstone bridges, current measurements, or other small signal sources that require an accurate measurement which rejects input common mode voltage (Vicm).

There are different ways to amplify a differential voltage into a single-ended signal. In this document we will see the three more flexible methods that are based on operational amplifiers (op amps):

- Differential amplifier
- 2-op amp instrumentation amplifier
- 3-op amp instrumentation amplifier

For each configuration, the output voltage is calculated to include the inaccuracies due to the external components (the resistors) and the op amp itself. The common mode rejection ratio (CMRR) is also calculated. If we consider a perfect op amp and if the resistors are ideally matched, the CMRR should be infinite.

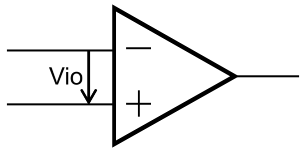
Contents

1 Error contributions

The error contributions which are taken into account in this application note include:

- Resistor inaccuracies
- Main op amp contribution which is the input offset voltage (Vio) (see *Figure 1*).

Figure 1. Input offset voltage



The Vio can be either positive or negative. Also, it can vary with the op amp CMRR, but this parameter is not taken into account in this document.

In the different configurations below, the output voltage formula is written with and without the error inaccuracies.

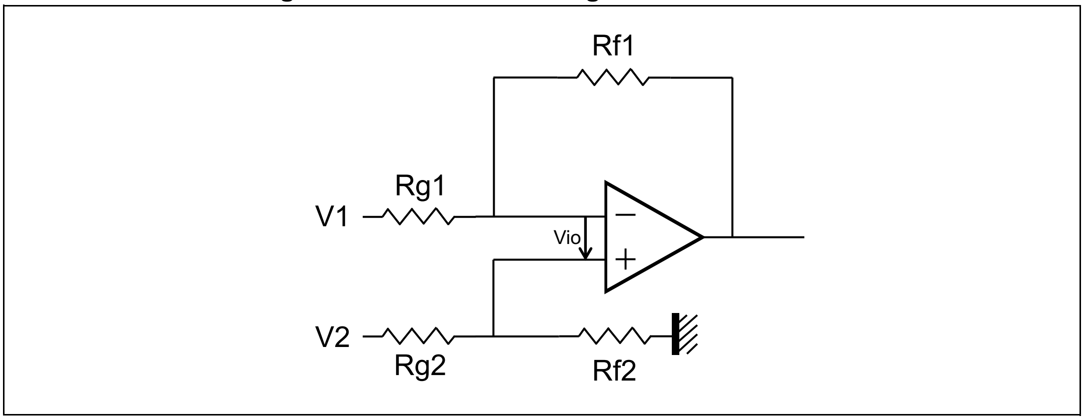
When we consider the error inaccuracies, e_R corresponds to the resistor accuracy. For example, it can be 1 %.

2 Differential configuration

The differential configuration needs only one op amp and is easily set-up. Consequently, it is widely used.

Figure 2 shows the differential configuration schematic.

Figure 2. Differential configuration schematic



If we do not consider the inaccuracies, we have *Equation 1* at the output.

Equation 1

$$\mathrm{Vout} = \mathrm{V2}\frac{\mathrm{Rf2}}{\mathrm{Rg2}}\frac{1+\frac{\mathrm{Rf1}}{\mathrm{Rg1}}}{1+\frac{\mathrm{Rf2}}{\mathrm{Rg2}}} - \mathrm{V1}\frac{\mathrm{Rf1}}{\mathrm{Rg1}}$$

Considering *Rf1* = *Rf2* = *Rf* and *Rg1* = *Rg2* = *Rg*, we get *Equation 2*

Equation 2

$$\mathrm{Vout} = (\mathrm{V2} - \mathrm{V1})\frac{\mathrm{Rf}}{\mathrm{Rg}}$$

Note that the op amp must be used in dual supply if V1 > V2. An alternative option is to use a reference voltage on Rf2 rather than ground and use the op amp in single supply.

Considering the op amp and resistor inaccuracies and with *Rf1* = *Rf2* = *Rf* and *Rg1* = *Rg2* = *Rg*, we get *Equation 3*

Equation 3

$$\boxed{\begin{aligned}\mathrm{Vout} = {} & (\mathrm{V2}-\mathrm{V1})\frac{\mathrm{Rf}}{\mathrm{Rg}}\left(1+\frac{\left(\mathrm{Rf}+\frac{\mathrm{Rg}}{2}\right)(\varepsilon_{\mathrm{Rf1}}-\varepsilon_{\mathrm{Rg1}})+\frac{\mathrm{Rg}}{2}(\varepsilon_{\mathrm{Rf2}}-\varepsilon_{\mathrm{Rg2}})}{\mathrm{Rf}+\mathrm{Rg}}\right) \\ & +\frac{\mathrm{V1}+\mathrm{V2}}{2}\frac{\mathrm{Rf}}{\mathrm{Rg}+\mathrm{Rf}}(\varepsilon_{\mathrm{Rf2}}-\varepsilon_{\mathrm{Rf1}}-\varepsilon_{\mathrm{Rg2}}+\varepsilon_{\mathrm{Rg1}})-\mathrm{Vio}\left(1+\frac{\mathrm{Rf}}{\mathrm{Rg}}(1+\varepsilon_{\mathrm{Rf1}}-\varepsilon_{\mathrm{Rg1}})\right)\end{aligned}}$$

Considering all the resistors have the same tolerance, ε:

- The worst case for the offset on the output voltage is:

$$\pm Vio\left(1 + \frac{Rf}{Rg}(1 + 2\varepsilon)\right)$$

- The worst case for the differential gain is:

$$\frac{Rf}{Rg}(1 \pm 2\varepsilon)$$

- The worst case for the common mode gain is:

$$\frac{Rf}{Rf + Rg}4\varepsilon$$

When we talk about differential configuration, it is important to note that a mismatching between resistors impacts the output voltage. This impact is measured by the CMRR. Vicm can only be partially rejected if the resistors are not perfectly marched. The following CMRR calculations highlight the impact of the resistor inaccuracies. Note that for the CMRR calculation, we do not take into account the Vio variation (caused by the CMRR of the op amp).

Equation 4

$$\boxed{Vout = Gdiff(V2 - V1) + Gcm\frac{V1 + V2}{2}}$$

Equation 5

$$\boxed{CMRR = 20\log\left(\frac{Gdiff}{Gmc}\right) = 20\log\left(\frac{1 + \frac{Rf}{Rg}}{4\varepsilon}\right)}$$

Therefore, the CMRR can be calculated for different gain and resistor inaccuracies (see *Table 1*).

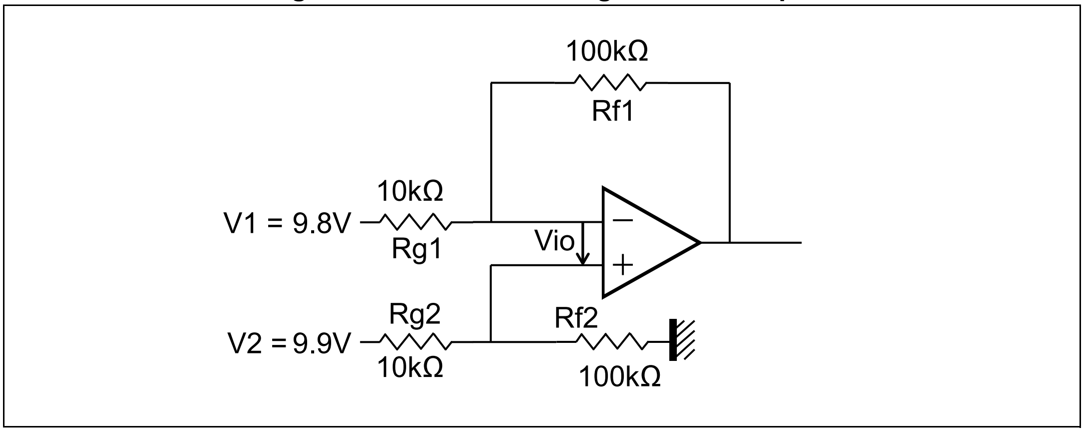
Table 1. CMRR for differential configuration

Resistor inaccuracy (%)	CMRR (dB)		
	Gain = 1	Gain = 10	Gain = 100
10	14	29	48
1	34	49	68
0.1	54	69	88

Thus, for accurate measurements it is recommended to use high accuracy resistors. It helps to reject Vicm.

Regarding Vicm, there is a last criterion that has to be considered for the differential configuration. It is the Vicm range of the op amp. In order to make the application work, the Vicm should not exceed the capabilities of the op amp (see example in *Figure 3*).

Figure 3. Differential configuration example



In *Figure 3*, the Vicm of the op amp is 9 V. Thus, if the op amp is supplied by 5 V, we cannot measure the voltage difference. We may even damage the op amp.

The op amp Vicm range is given as follows:

$$V2 \cdot \frac{Rf2}{Rf2 + Rg2}$$

If Vref is applied on Rf2, the op amp Vicm range becomes:

$$\boxed{\frac{V2}{1 + \frac{Rg2}{Rf2}} + \frac{Vref}{1 + \frac{Rf2}{Rg2}}}$$

A drawback of the differential configuration is its input impedance. This is defined by the resistors and consequently it may not be high enough. Below are given the differential and common mode impedances respectively:

$$Zdiff = 2Rg$$

$$Zcm = \frac{Rg + Rf}{2}$$

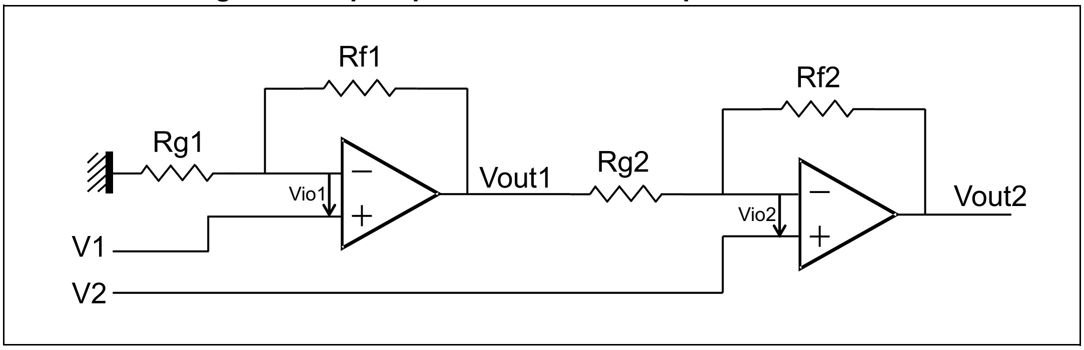
A high input impedance may be mandatory in certain cases so as not to impact the signal being measured. For this reason the instrumentation amplifier configuration has been designed (see *Section 3*).

3 2-op amp instrumentation amplifier

The 2-op amp instrumentation amplifier configuration is composed of one additional op-amp compared to the differential configuration. Because of this, the signal “sees” a high impedance and consequently is not impacted.

Figure 4 shows the 2-op amp instrumentation amplifier schematic.

Figure 4. 2-op amp instrumentation amplifier schematic



If we do not consider the inaccuracies, we have *Equation 6* at the output.

Equation 6

$$Vout2 = V2\left(1+\frac{Rf2}{Rg2}\right)-V1\frac{Rf2}{Rg2}\left(1+\frac{Rf1}{Rg1}\right)$$

Considering $\boxed{Rf1 = Rg2 = R\beta, Rg1 = Rf2 = R\alpha}$ and the input offset voltage of the op amp, we get *Equation 7*:

Equation 7

$$Vout2 = (V2-V1)\left(1+\frac{R\alpha}{R\beta}\right)-(Vio2-Vio1)\left(1+\frac{R\alpha}{R\beta}\right)$$

So, we get *Equation 8*:

Equation 8

$$\boxed{\begin{aligned} Vout2 = {} & Vdiff\left(1+\frac{R\alpha}{R\beta}+\frac{\varepsilon_{Rf1}-\varepsilon_{Rg1}+\left(1+2\,\frac{R\alpha}{R\beta}\right)(\varepsilon_{Rf2}-\varepsilon_{Rg2})}{2}\right) \\ & + Vcm(-\varepsilon_{Rf1}+\varepsilon_{Rg1}-\varepsilon_{Rf2}+\varepsilon_{Rg2}) \\ & + Vio1\left(\left(1+\frac{R\alpha}{R\beta}\right)(1+\varepsilon_{Rf2}-\varepsilon_{Rg2})+\varepsilon_{Rf1}-\varepsilon_{Rg1}\right) \\ & - Vio2\left(1+\frac{R\alpha}{R\beta}(1+\varepsilon_{Rf2}-\varepsilon_{Rg2})\right) \end{aligned}}$$

Considering all the resistors have the same tolerance, ε:

- The worst case for the offset on the output voltage is:

  $$\pm 2Vio\left(1+\frac{R\alpha}{R\beta}(1+2\varepsilon)\right)$$

- The worst case for the differential gain is:

  $$\left(1+\frac{R\alpha}{R\beta}\right)(1\pm 2\varepsilon)$$

- The worst case for the common mode gain is:

  $$4\varepsilon$$

Similar to differential configuration, when there is mismatching between resistors, the CMRR is impacted. Thus, the output voltage is also impacted and the measurement accuracy deteriorates. In order to quantify this impact, we calculate the CMRR using *Equation 9*.

Equation 9

$$CMRR = 20\log\left(\frac{Gdiff}{Gmc}\right) \approx 20\log\left(\frac{1+\frac{R\alpha}{R\beta}}{4\varepsilon}\right)$$

For high gain, the CMRR of the 2-op amp instrumentation amplifier is similar to the CMRR of the differential amplifier. However, the main advantage of the current configuration is that it offers high input impedance. Note also that it cannot be used in unity gain.

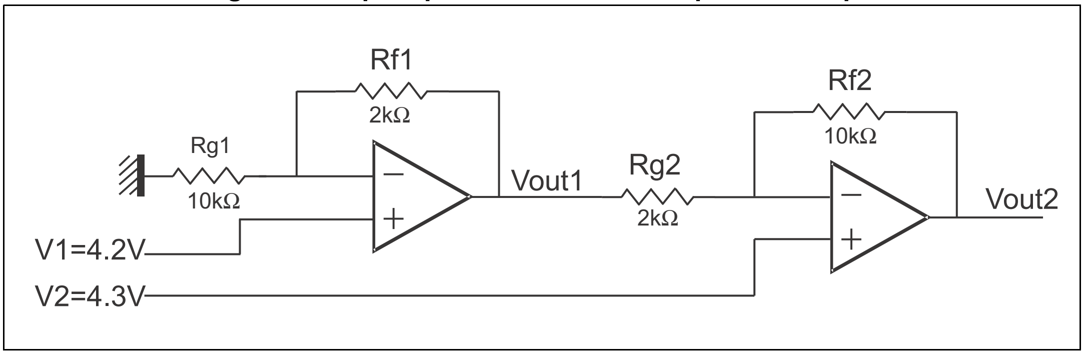
Regarding the Vicm range, the following conditions must be met to make the 2-op amp instrumentation amplifier work:

- V1 and V2 must be included within the op amp's Vicm range
- To avoid that the output of the first op amp is saturated:

  $$\boxed{V1 < \frac{Vcc}{1+\frac{Rf1}{Rg1}}}$$

Figure 5 shows where the second condition has not been met and the first op amp has become saturated.

Figure 5. 2-op amp instrumentation amplifier example



In *Figure 5*, with Vcc = 5 V

$$\frac{Vcc}{1+\frac{Rf1}{Rg1}} = 4.17\ V$$

Thus, we do not have

$$V1 < \frac{Vcc}{1+\frac{Rf1}{Rg1}}$$

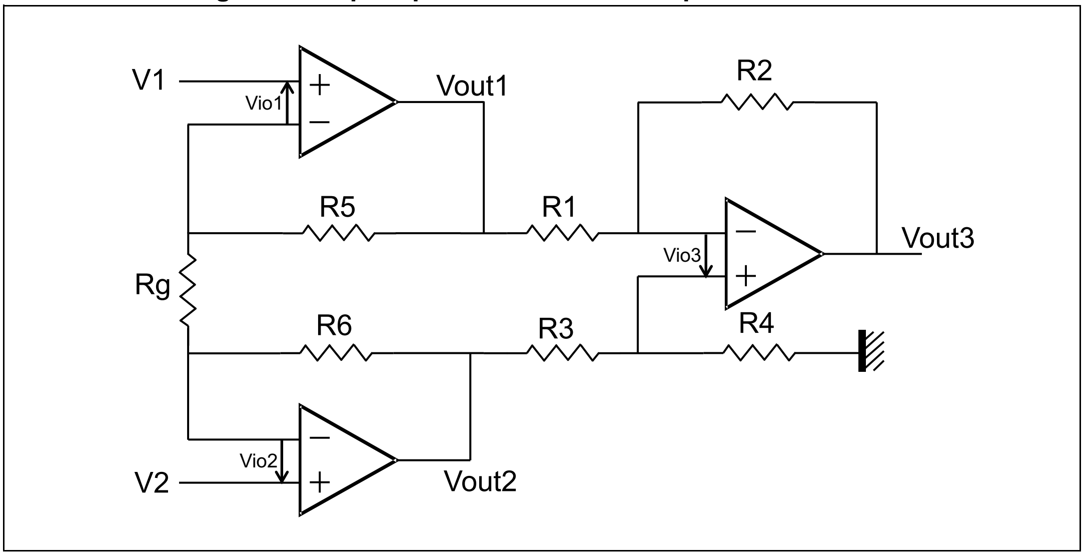
This means that the first op amp is saturated and Vout2 is not equal to the expected value: (4.3 V - 4.2 V) * (1 + 10 k / 2 k) = 0.6 V.

4 3-op amp instrumentation amplifier

The 3-op amp instrumentation amplifier configuration has been designed to improve the CMRR impacted by the resistors, and thus to improve measurement accuracy when Vicm varies.

Figure 6 shows the schematic of a 3-op amp instrumentation amplifier.

Figure 6. 3-op amp instrumentation amplifier schematic



The output voltage of the 3-op amp instrumentation amplifier is defined by *Equation 10*.

Equation 10

$$\mathrm{Vout3} = \mathrm{Gdiff} \cdot \mathrm{Vdiff} + \mathrm{Gcm} \cdot \mathrm{Vicm} + \mathrm{Voffset}$$

By considering $R1 = Rx(1+\varepsilon_{R1})$, $R3 = Rx(1+\varepsilon_{R3})$, $R2 = Ry(1+\varepsilon_{R2})$, $R4 = Ry(1+\varepsilon_{R4})$, $R5 = Rf(1+\varepsilon_{R5})$, and $R6 = Ry(1+\varepsilon_{R6})$, the Gdiff, Gcm and Voffset parameters become as shown in *Equation 11*, *Equation 12*, and *Equation 13* respectively.

Equation 11

$$Gdiff = \frac{Ry}{Rx}\left(1 + \frac{Rf}{Rg}(2 + \varepsilon_{R5} + \varepsilon_{R6} - 2\varepsilon_{Rg}) + \frac{1 + 2\frac{Rf}{Rg}}{Rx + Ry}\left(\left(Ry + \frac{Rx}{2}\right)(\varepsilon_{R2} - \varepsilon_{R1}) + \frac{Rx}{2}\left((\varepsilon_{R4} - \varepsilon_{R3})\right)\right)\right)$$

Equation 12

$$\mathrm{Gcm} = \frac{\mathrm{Ry}}{\mathrm{Rx} + \mathrm{Ry}}(\varepsilon_{R1} + \varepsilon_{R4} - \varepsilon_{R2} - \varepsilon_{R3})$$

Equation 13

$$Voffset = (Vio1 - Vio2)\frac{Ry}{Rx}\left(1 + \frac{Rf}{Rg}(2 + \varepsilon_{R5} + \varepsilon_{R6} - 2\varepsilon_{Rg}) + \frac{1 + 2\frac{Rf}{Rg}}{Rx + Ry}\left(\left(Ry + \frac{Rx}{2}\right)(\varepsilon_{R2} - \varepsilon_{R1}) + \frac{Rx}{2}\left((\varepsilon_{R4} - \varepsilon_{R3}\right)\right)\right)$$
$$- Vio3\left(1 + \frac{Ry}{Rx}(1 + \varepsilon_{R2} - \varepsilon_{R1})\right)$$

Based on the above equations, the worst case for each parameter can be calculated by considering:

$\varepsilon_{diff} = \varepsilon_{R1} = \varepsilon_{R2} = \varepsilon_{R3} = \varepsilon_{R4}$

and

$\varepsilon_{instru} = \varepsilon_{R5} = \varepsilon_{R6} = \varepsilon_{Rg}$

- the worst case for the differential gain is:
  $\frac{Ry}{Rx}\left(1 + 2\frac{Rf}{Rg}\right)(1 + 2\varepsilon_{instru}) + \left(1 + 2\frac{Rf}{Rg}\right)2\varepsilon_{diff}$
- the worst case for the common mode gain is:
  $\frac{Ry}{Rx + Ry}4\varepsilon_{diff}$
- the worst case for offset on the output voltage is:
  $2Vio\frac{Ry}{Rx}\left(1 + 2\frac{Rf}{Rg}\right)(1 + 2\varepsilon_{instru}) + \left(1 + 2\frac{Rf}{Rg}\right)2\varepsilon_{diff} + Vio\left(1 + \frac{Ry}{Rx}(1 + 2\varepsilon_{diff})\right)$

To know how well this configuration rejects the Vicm, we calculate the CMRR using *Equation 14* and *Equation 15*.

Equation 14

$$Vout = (V2 - V1)Gdiff + \frac{V1 + V2}{2}Gcm$$

Equation 15

$$CMRR = 20\log\left(\frac{Gdiff}{Gmc}\right) = 20\log\left(\frac{\frac{Ry}{Rx}\left(1 + 2\frac{Rf}{Rg}\right)}{\frac{Ry}{Rx + Ry}4\varepsilon_{diff}}\right)$$

We can see from *Equation 15* that to have the best CMRR, the maximum gain should be set at the first stage of the 3-op amp instrumentation amplifier structure without saturating op amps 1 and 2. To achieve the global required gain, the remaining gain should be set at the second stage.

Table 2. CMRR for 3-op amp instrumentation amplifier configuration

Resistor inaccuracy (%)	CMRR (dB)		
	Rf/Rg = 2 Ry/Rx = 0.5 Gain = 2.5	Rf/Rg = 15 Ry/Rx = 0.5 Gain = 15.5	Rf/Rg = 100 Ry/Rx = 0.5 Gain = 100.5
10	25.5	41.3	57.5
1	45.5	61.3	77.5
0.1	65.5	81.3	97.5

In *Table 2* we can see that the 3-op amp instrumentation amplifier offers a better CMRR. Moreover, it has a high input impedance thanks to the op amps in the first stage.

However, to amplify the signal properly, it is mandatory that the first stage is not saturated. To achieve this, the following two conditions must be met:

$$Vccn < (V2 - V1)\frac{G \cdot Rx}{2Ry} + \frac{V1 + V2}{2} < Vccp$$

$$Vccn < (V1 - V2)\frac{G \cdot Rx}{2Ry} + \frac{V1 + V2}{2} < Vccp$$

with

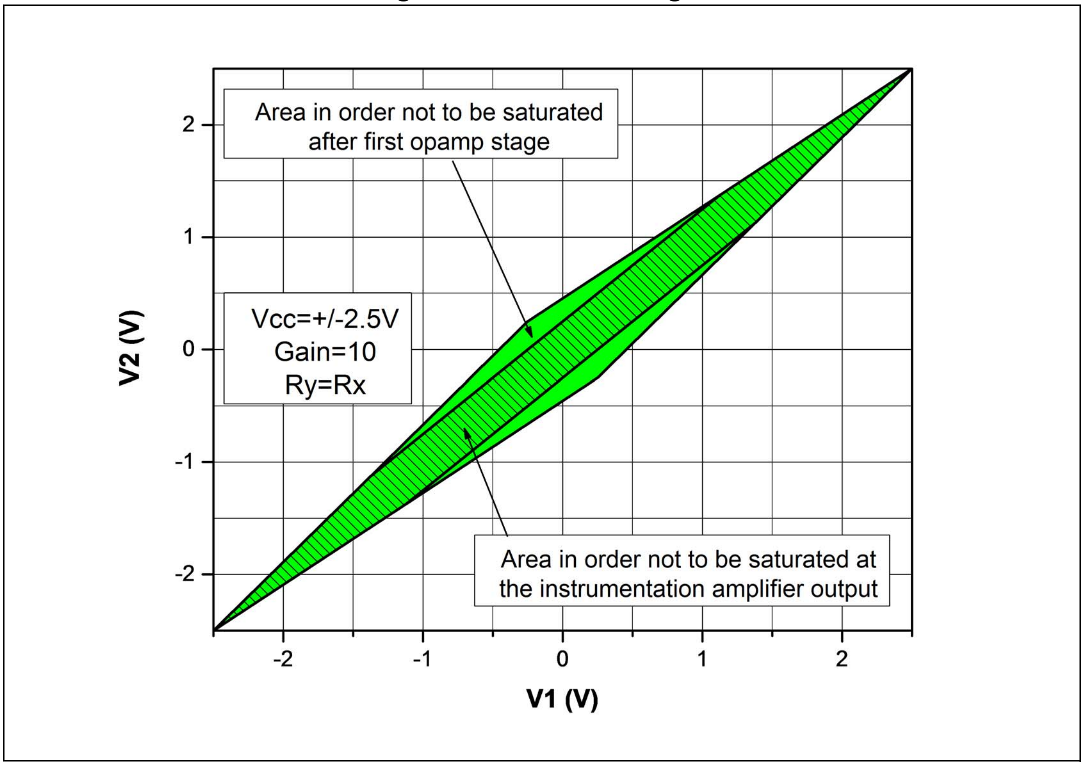
$$G = \frac{Ry}{Rx}\left(1 + 2\frac{Rf}{Rg}\right)$$

Figure 7 highlights the consequences if these two conditions are not met. If the voltage intersection of V1 and V2 is within the green area, the output voltage of the first op amp stage is not saturated.

Figure 7 also specifies the area which is in linear configuration at the output of the instrumentation amplifier. As well as the two conditions listed above, the input voltages have to be compliant with the following condition:

$$Vccn < (V2 - V1)G < Vccp$$

Figure 7. V2 and V1 ranges



5 Summary

Table 3 summarizes the main features of the three most flexible methods (based on op amps) which amplify a differential voltage into a single-ended signal.

Table 3. Main features of the three most flexible methods for amplifying a differential voltage into a single-ended signal

	Differential configuration	2-op amp instrumentation amplifier	3-op amp instrumentation amplifier
Differential gain (Gdiff)	$\frac{Rf}{Rg}$	$1+\frac{R\alpha}{R\beta}$	$\left(1+\frac{Ry}{Rx}\right)\left(1+2\frac{Rf}{Rg}\right)$
Gdiff including errors	$\frac{Rf}{Rg}(1\pm2\varepsilon)$	$\left(1+\frac{R\alpha}{R\beta}\right)(1\pm2\varepsilon)$	$\frac{Ry}{Rx}\left(1+2\frac{Rf}{Rg}\right)(1+2\varepsilon_{instru})+\left(1+2\frac{Rf}{Rg}\right)2\varepsilon_{diff}$
Gcm including resistor tolerance	$\frac{Rf}{Rg+Rf}4\varepsilon$	4ε	$\frac{Ry}{Rx+Ry}4\varepsilon_{diff}$
CMRR due to resistor inaccuracy	$\frac{1+\frac{Rf}{Rg}}{4\varepsilon}$	$\frac{1+\frac{Rf}{Rg}}{4\varepsilon}$	$\frac{\left(1+\frac{Ry}{Rx}\right)\left(1+2\frac{Rf}{Rg}\right)}{4\varepsilon}$
Example of CMRR with gain = 100 and resistor tolerance = 1 %	68 dB	68 dB	74 dB if Rx = Ry 77.5 dB if Rx = 2Ry
Vicm limitation	$V2\cdot\frac{Rf2}{Rf2+Rg2}$ must be included in the op amp Vicm range	V1 and V2 must ve included within the op amps Vicm range $V1<\frac{Vcc}{1+\frac{R\beta}{R\alpha}}$	$Vccn<(V2-V1)\frac{G\cdot Rx}{2Ry}+\frac{V1+V2}{2}<Vccp$ $Vccn<(V1-V2)\frac{G\cdot Rx}{2Ry}+\frac{V1+V2}{2}<Vccp$ $Vccn<(V2-V1)G<Vccp$
Error on Vout due to Vio	$Vio\left(1+\frac{Rf}{Rg}\right)$	$2Vio\left(1+\frac{R\alpha}{R\beta}\right)$	$(Vio1-Vio2)\frac{Ry}{Rx}\left(1+2\frac{Rf}{Rg}\right)-Vio3\left(1+\frac{Ry}{Rx}\right)$
Zdiff	2Rg	∞(1)	∞(1)
Zcm	$\frac{Rg+Rf}{2}$	∞(1)	∞(1)

1. Only limited by op amp input impedance

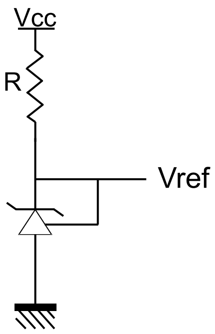
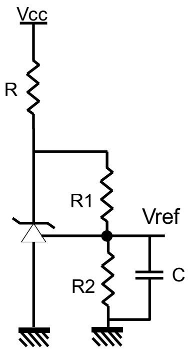
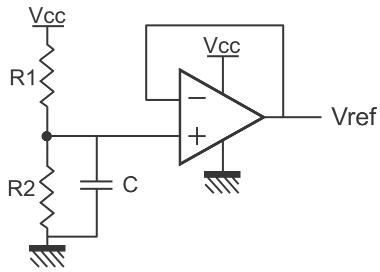
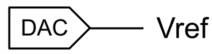
For the 3-op amp instrumentation amplifier, the offset due to the op amp Vio on the output voltage is bigger compared to the other configurations. Consequently, it is recommended to use a high precision op amp such as the TSZ121 (or the TSZ124 for a quad version). The TSZ121 has a maximum Vio of 5 µV and thus it makes accurate measurements.

6 Circuits with a single supply voltage

If the op amp configurations are used with a single supply voltage (i.e. non-symmetrical supply voltage), it is necessary to add a reference voltage. On the three different architectures, the reference voltage (Vref) has to replace the ground so as to shift the output voltage.

Voltage references can be designed with several different configurations: with voltage reference IC, programmable voltage reference IC, divider bridge with buffer, or even with a DAC output. The different circuits are shown in *Table 4*.

Table 4. Reference voltage circuit examples

Voltage reference IC	Programmable voltage reference IC	Divider bridge + buffer	DAC Output
			

The voltage generated by the circuits in *Table 4* has to be added to the output voltage formula. So, we need to take into account the resistor tolerances given earlier in this document and the additional terms below.

- Differential configuration:

$$Vref\left(1+\frac{Rf}{Rf+Rg}4\varepsilon\right)$$

- 2-op amp instrumentation amplifier configuration:

$$Vref(1+4\varepsilon)$$

- 3-op amp instrumentation amplifier configuration:

$$Vref\left(1+\frac{Ry}{Ry+Rx}4\varepsilon_{diff}\right)$$

One last term has to be taken into consideration, which is the accuracy of the voltage reference itself. This accuracy depends on the voltage reference circuits chosen. The accuracy for each circuit is given below.

- Voltage reference IC (e.g. TS4041): 0.5 %
- Programmable voltage reference IC (e.g. TL1431): 0.3 % plus the accuracy of the resistors used for the Vka setting.
- Divider bridge: ± 2ε considering the tolerance, ε, of the resistor used
- DAC output: depends on the DAC specifications

Example

To understand the complete contribution of each parameter, we can consider an example with a 3-op amp instrumentation configuration and a voltage reference IC.

The worst case output voltage is as follows:

$$Vout3 = Gdiff \cdot Vdiff + Gcm \cdot Vicm + Voffset + Vreference$$

When we use Gdiff, Gcm, and Voffset as calculated in the *3-op amp instrumentation amplifier* section we get the following:

$$Vreference = Vref\left(1 + \frac{Ry}{Ry + Rx}4\varepsilon_{diff}\right)(1 + 0.5\%)$$

Where 0.5 % is the accuracy of the voltage reference IC.

7 Precision op amps

Table 5 lists some precision op amps that might be used for differential to single-ended measurements.

Table 5. Some precision op amps

Part number	Vio max (µV)	Vcc range (V)	GBP (Hz)
TSZ121	5	1.8 to 5.5	400 k
TSV731	200	1.5 to 5.5	900 k
TSX711	200	2.7 to 16	2.7 M
TS512A	500	6 to 30	3 M

8 Conclusion

In this application note, we looked at the three main architectures that allow us to perform differential measurements by rejecting the Vicm. Each has its own pros and cons such as a better CMRR, simpler architecture, high input impedance, or a smaller offset on the output voltage.

This document highlights the importance of having very accurate resistors. For precise differential measurements, a 1 % resistor may be not enough. We also saw that a high precision op amp is useful for limiting the offset on the output voltage.

9 Revision history

Table 6. Document revision history

Date	Revision	Changes
27-Oct-2014	1	Initial release

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