

Ways to Optimize the Performance of a Difference Amplifier

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There are times when a small signal needs to be measured in the presence of a large common-mode signal. Traditional instrumentation amplifiers (in amps) that have two op amp or three op amp internal configurations are commonly used in these applications. Although in amps have good common-mode rejection ratios (CMRR), price and sometimes specifications prevent their usage in these applications. In amps may not have the right bandwidth, dc accuracy, or power consumption requirements that the user requires. Therefore, in these situations, users build their own difference amplifiers by using a single amplifier and external resistors as an alternative to instrumentation amplifiers. Unless a set of tightly matched resistors is used, CMRR of these circuits will be very low. This Application Note presents several ways to build and optimize the performance of a discrete difference amplifier. It also recommends amplifiers that will make the overall solution cost/performance competitive with monolithic instrument amplifiers.

A typical difference amplifier using a single amplifier connected to a sensor bridge is shown in Figure 1.

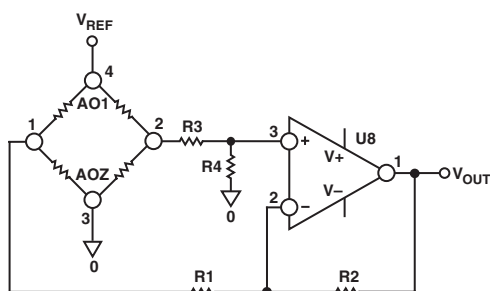


Figure 1.

By applying the superposition principle, it can be shown that the output is a function of the difference of the two inputs. The transfer function of the circuit in Figure 1 is:

$$V_{OUT} = \frac{R2}{R1} \left[\left(\frac{1 + \frac{R2}{R1}}{1 + \frac{R3}{R4}} \right) V2 - V1 \right] \quad (1)$$

A special situation arises when

$$\frac{R2}{R1} = \frac{R4}{R3}$$

and the above equation is reduced to:

$$\frac{R2}{R1} = \frac{R4}{R3} \quad (2)$$

$$V_{OUT} = \frac{R2}{R1} (V2 - V1)$$

The output is the difference of the two inputs times a gain factor that can be set to unity. Equation 2 holds true if the ratio of the resistors is tightly matched. Assuming perfectly matched resistors with values of $R2 = R4 = 10 \text{ k}\Omega$, $R1 = R3 = 1 \text{ k}\Omega$, $V1 = 2.5 \text{ V}$, $V2 = 2.6 \text{ V}$, then $V_{OUT} = 1 \text{ V}$.

As stated above, one of the shortcomings of the circuit in Figure 1 is the poor CMRR, which is caused by mismatch of the resistors. In order to investigate this, the circuit is redrawn for clarity in Figure 2.

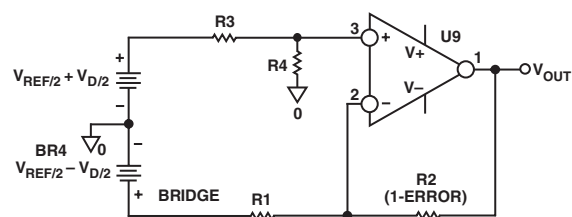


Figure 2.

Resistor tolerance of R2 is introduced as an error, R2 (1 – error). Using superposition and letting R1 = R3 and R2 = R4, the output voltage (V_{OUT}), after writing the equations and some arrangement, is:

$$V_{OUT} = \left\{ \left[\frac{R2}{R1} \left(1 - \frac{R1+2R2}{R1+R2} \times \frac{error}{2} \right) \right] \right. \\ \left. v_d + \left(\frac{R2}{R1+R2} \times error \right) V_{REF} \right\} \quad (3)$$

From Equation 3, the common-mode gain (A_{cm}) and differential gain (A_{dm}) can be defined as:

$$A_{cm} = \frac{R2}{R1+R2} \times error \\ A_{dm} = \frac{R2}{R1} \left(1 - \frac{R1+2R2}{R1+R2} \times \frac{error}{2} \right) \quad (4)$$

It can be seen in Equation 4 that when there is no error in the resistor value (i.e., error = 0), then A_{cm} = 0 and the amplifier responds only to the differential voltage as it is supposed to

$$\left(V_{OUT} = \frac{R2}{R1} \times V_D \right)$$

Therefore, when the resistor ratio error is zero (error = 0), then the CMRR of the circuit becomes very much dependent on the CMRR of the amplifier selected for the job.

When the resistor error is not zero, as in Figure 2, then the CMRR of the circuit can be written as:

$$CMRR = 20 \log \left(\frac{A_{dm}}{A_{cm}} \right) \\ CMRR = 20 \log \frac{\frac{R2}{R1} \left(1 - \frac{R1+2R2}{R1+R2} \times \frac{error}{2} \right)}{\frac{R2}{R1+R2} \times error} \quad (5)$$

For a fraction of error in R2, the second term in the above equation can be ignored and:

$$CMRR = 20 \log \frac{\frac{R2}{R1}}{\frac{R2}{R1+R2} \times error} \quad (6)$$

For a unity gain discrete difference amplifier with R2 = R4 = 10 kΩ, R1 = R3 = 10 kΩ and error = 1%, the approximate value of CMRR is 46 dB. This is much worse than the CMRR of a monolithic difference amplifier (AMP03) whose CMRR graph is shown in Figure 3.

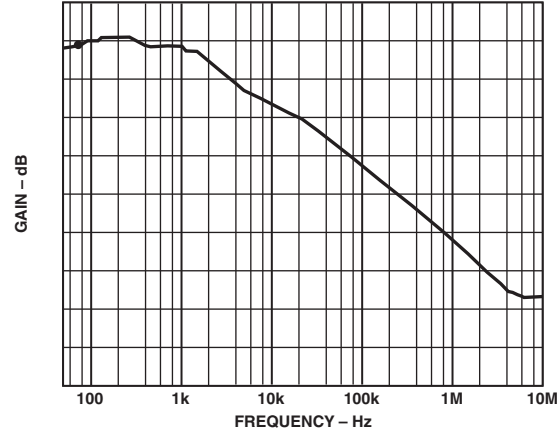


Figure 3. CMRR of AMP03 (Monolithic Difference Amplifier) vs. Frequency

As shown above, errors caused by resistor mismatches can be a big drawback of discrete difference amplifiers. But there are some ways to optimize the circuit. Here are some solutions to the above problems:

- In Equation 3 the differential gain is directly related to the Ratio of (R2/R1). Therefore, one way to optimize the performance of the above circuit is to put the amplifier in a high gain configuration when possible (using larger resistors for higher gain settings introduces noise issues that need to be dealt with). The higher the gain by selecting larger values for R2 = R4 and smaller values for R1 = R3, the better the CMRR. As an example, when R2 = R4 = 10 kΩ and R1 = R3 = 1 kΩ and error = 0.1%, then CMRR improves to better than 80 dB. As a reminder for high gain configurations, select amplifiers with very low I_B and very high gains (such as the AD8551 family of amplifiers from Analog Devices) to reduce gain error. Gain error and linearity of the circuit become functions of the amplifier's performance.

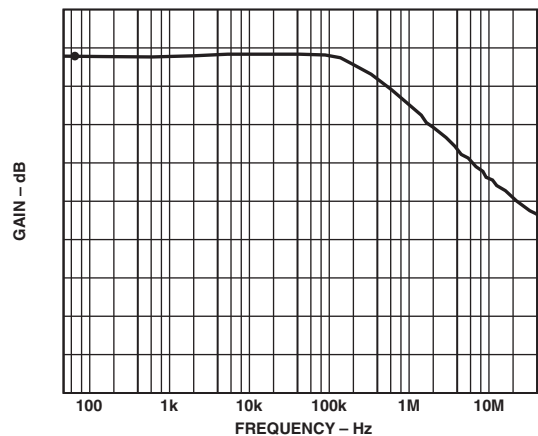


Figure 4a. CMRR of AD8605 with G = 1

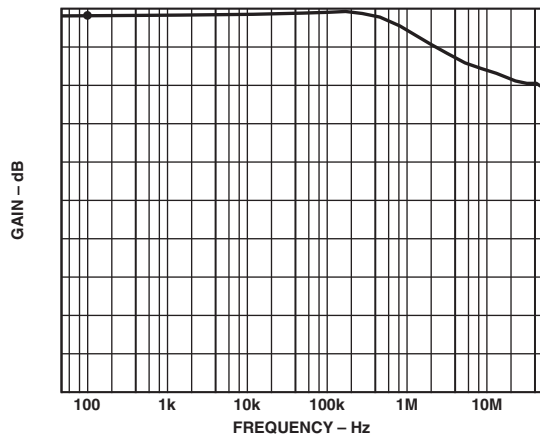


Figure 4b. CMRR of AD8605 with $G = 10$

b. Select resistors that have much tighter tolerance and accuracy. The more closely they are matched, the better the CMRR. As an example, if a CMRR of 90 dB from the above circuit is needed, then match resistors approximately to 0.02%. Then the circuit's CMRR is as good as some high precision in-amp with better ac and dc specifications.

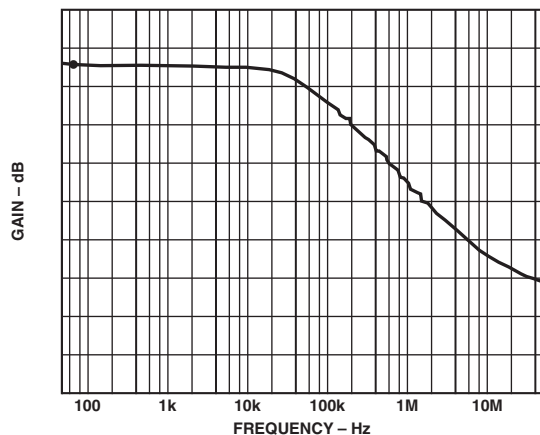


Figure 5a. CMRR of OP1177 ($G = 1$)

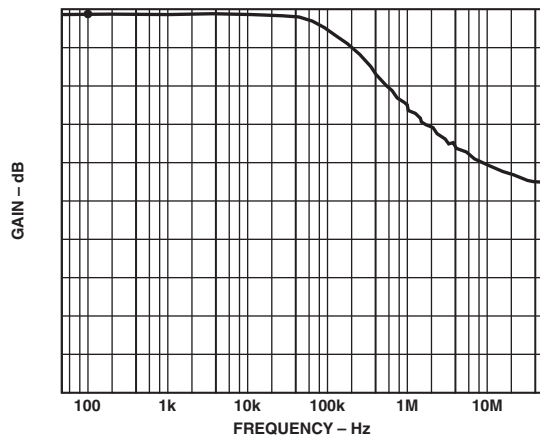


Figure 5b. CMRR of OP1177 ($G = 10$)

c. Another way that the CMRR of the circuit in Figure 1 can be enhanced is by using a mechanical trim potentiometer as shown in Figure 6.

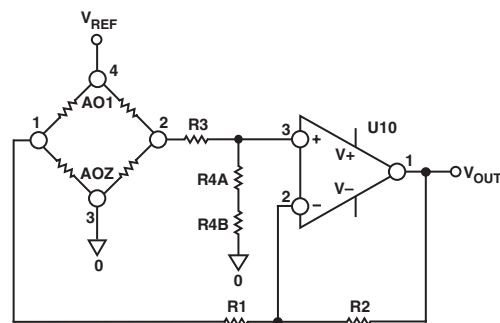


Figure 6.

This method allows the user to use lower tolerance resistors but requires periodic adjustment with time.

d. As an alternative to circuits in which a high degree of precision is not required, digital potentiometers can be used as shown in Figure 7. AD5235, a nonvolatile memory, dual 1024 position digital potentiometer, is used along with AD8628 to form a difference amplifier with a gain of 15 ($G = 15$). By using a potentiometer, programming capability is achieved, allowing gain setting and trimming in one step. Another benefit of this circuit is that the dual resistors (AD5235) have a tempco of 50 ppm, which makes the matching on the resistor ratios easier. Other digital potentiometers can be selected based on the accuracy and tolerance expected out of the circuit.

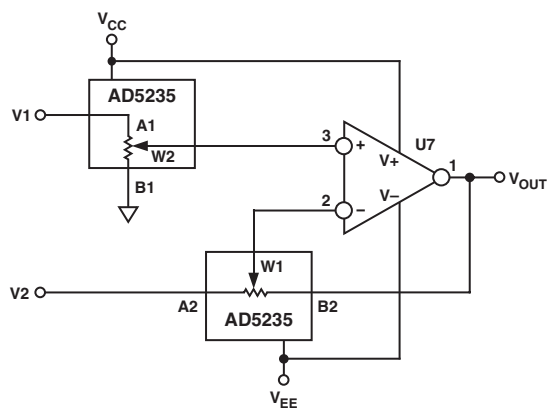


Figure 7.

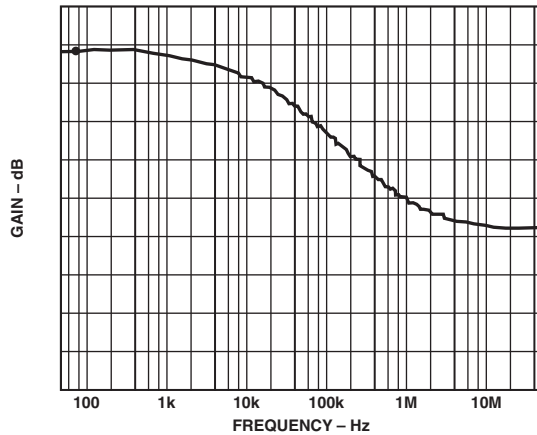


Figure 8. CMRR vs. Frequency for the Circuit in Figure 7

- e. Use dual or quad amplifiers to build instrument amplifiers that give better CMRR and high input impedances. This is a costlier solution and it is exactly what monolithic instrumentations have done. The appropriate amplifier should be chosen based on real needs—such as better BW, I_{SY} , and V_{OS} —which an instrumentation amplifier may not offer.

Auto-zero amplifiers, such as the AD8628 and AD855x family, are the best choice in these types of applications. These amplifiers have very high dc accuracy and will not add any error to the output. The long-term stability of auto-zero amplifiers prevents repeated calibration needed in some systems. With the CMRR of auto-zero amplifiers at 140 dB minimum, the resistor match will be the limiting factor in most circuits. Therefore, it is best for users to build their own difference amplifiers and optimize their performance using the above guidelines.

Part Number	V_{OS} (μ V)	I_B (nA)	BW (MHz)	Rail-to-Rail	Package
AD8628	5	0.1	2	Yes	SOT-23
AD8551/AD8552/AD8554	5	0.05	1	Yes	SOIC
AD8510/AD8512/AD8514	500	0.03	8	No	MSOP
OP1177/OP2177/OP4177	60	2	1.3	No	MSOP
AD8605/AD8606/AD8608	300	0.06	8	Yes	SOT-23
OP184/OP284/OP484	65	350	3.25	Yes	SOIC