Using fully differential op amps as attenuators, Part 3: Single-ended unipolar input signals

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Introduction

Fully differential operational amplifiers (FDAs) can easily be used to attenuate and level-shift high-voltage input signals to match the input requirements of lower-voltage ADCs. This article is Part 3 of a three-part series. In Part 1 (see Reference 2) we considered a balanced, differential bipolar input signal and proposed an architecture utilizing an FDA to accomplish the task. In Part 2 (see Reference 3) we showed how to adapt the circuits presented in Part 1 to a high-voltage, single-ended (SE) bipolar input. In Part 3, we will show how to adapt the circuits presented in Parts 1 and 2 to the more complex case where the input signal is a high-voltage, SE unipolar input with arbitrary common-mode voltage. As mentioned in Part 1, the fundamentals of FDA operation are presented in Reference 1, which provides definitions and derivations.

Single-ended unipolar input

Using an input attenuator

Let's consider a high-amplitude, SE unipolar input signal that needs to be attenuated and level-shifted to the appropriate levels to drive a lower-voltage input ADC. We will use the same basic approach as for the SE bipolar input presented in Part 2; but, to offset the imbalance that would otherwise be caused by the signal's common-mode voltage, we will modify the signal to provide biasing on its alternate input. The proposed input-attenuator circuit for an SE unipolar input signal is shown in Figure 8. R_{S-} and R_{T-} have been added to the circuit in a manner that uses V_{REF} to provide biasing on the alternate input.

The circuit analysis of Figure 8 is very similar to that of Figure 6 in Part 2. For the moment, assume that R_{S-} on the alternate input is grounded instead of tied to V_{REF}. In that case, the only changes in the gain equation are due to changes in reference designators:

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_{T+}}{R_{S+} + R_{T+}} \times \frac{R_F}{R_{G+} + R_{S+} \parallel R_{T+}} \quad (7)$$

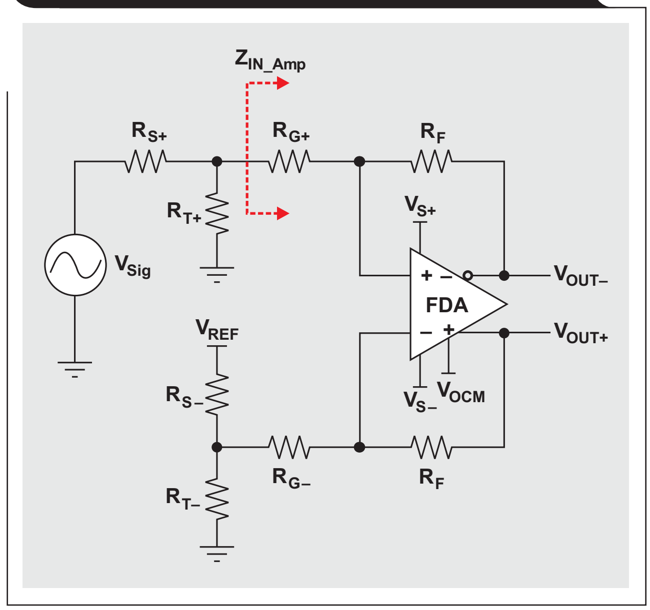
The noise gain of the FDA can be set to 2 by making the second half of Equation 7 equal to 1:

$$R_{G+} + R_{S+} \parallel R_{T+} = R_F \quad (8)$$

With this constraint, the overall gain equation reduces to

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_{T+}}{R_{S+} + R_{T+}}. \quad (9)$$

Figure 8. SE unipolar input-attenuator circuit



If we choose to keep R_F the same on both sides of the FDA, then we need to balance the gain-setting resistances by setting

$$R_{G-} + R_{S-} \parallel R_{T-} = R_{G+} + R_{S+} \parallel R_{T+}. \quad (10)$$

In order to balance the offset due to the common-mode voltage of V_{Sig}, we multiply the common-mode voltage of V_{Sig} by the signal input attenuator (or voltage divider), which equals V_{REF} times the voltage divider on the alternate input:

$$V_{REF} \frac{R_{T-}}{R_{S-} + R_{T-}} = V_{Sig\_Com} \frac{R_{T+}}{R_{S+} + R_{T+}} \quad (11)$$

The input impedance is given by $Z_{IN} = R_{S+} + R_{T+} \parallel Z_{IN\_Amp}$, which is approximated by $Z_{IN} = R_{S+} + R_{T+} \parallel R_{G+}$.

These basic design equations provide the freedom to choose one value in each of the following sets of interactive components:

1. Signal input-attenuator resistors, R_{S+} and R_{T+}
2. Gain-setting resistors, R_F and $R_{G\pm}$
3. V_{REF} voltage-divider resistors, R_{S-} and R_{T-}

We start the design as before by first choosing R_{S+} close to the desired input impedance. We then select R_F in the recommended range for the device and calculate the value of R_{T+} required to provide the desired attenuation. The result can be used to calculate R_{G+}.

For the alternate side of the input signal, we start similarly by first choosing the value of R_{S-}, which will basically set the current in the voltage divider. It is generally best to keep the current small to conserve power; but, since we chose to keep R_F the same on both sides of the FDA, there are limitations because Equation 10 has to be satisfied. The required value of R_{T-} must be calculated to satisfy Equation 11, and then the results can be used along with R_F to calculate R_{G-}.

To see an example Excel® worksheet, go to http://www.ti.com/lit/zip/slyt359 and click Open to view the WinZip® directory online (or click Save to download the WinZip file for offline use). Then open the file FDA_Attenuator_Examples_SE_Unipolar_Input.xls and select the Unipolar SE FDA Input Atten worksheet tab.

Design Example 5

For Example 5, let's say we have a 20-V_{PP} SE unipolar input signal that goes from 0 V to +20 V, we need a 1-kΩ input impedance, and we want to use the ADS8321 SAR ADC with a 5-V_{PP} differential input and a 2.5-V common-mode voltage. We also are using a +5-V single supply to power both the FDA and the ADC, so we want to use that as our reference voltage, V_{REF}, on the alternate input. We choose R_{S+} = 1 kΩ and R_F = 1 kΩ. Rearranging Equation 9 and using substitution, we can calculate

$$R_{T+} = \frac{R_{S+}}{\dfrac{V_{Sig}}{V_{OUT\pm}} - 1} = \frac{1\ k\Omega}{4-1} = 333.3\ \Omega.$$

The nearest standard 1% value, 332 Ω, should be used.

Rearranging Equation 8 and using substitution, we can calculate

$$R_{G+} = R_F - R_{S+} \parallel R_{T+} = 1\ k\Omega - 1\ k\Omega \parallel 332\ \Omega = 750\ \Omega,$$

which is a standard 1% value. We then choose R_{S-} = 1 kΩ and calculate R_{T-} by rearranging Equation 11 and using substitution:

$$R_{T-} = \frac{R_{S-}}{\dfrac{1}{\dfrac{V_{Sig\_Com}}{V_{REF}} \times \dfrac{R_{T+}}{R_{S+}+R_{T+}}} - 1}$$

$$= \frac{1\ k\Omega}{\dfrac{1}{\dfrac{10\ V}{5\ V} \times \dfrac{332\ \Omega}{1\ k\Omega + 332\ \Omega}} - 1} = 1\ k\Omega,$$

which is a standard 1% value. By rearranging Equation 10 and using substitution, we can calculate

$$R_{G-} = R_{G+} + R_{S+} \parallel R_{T+} - R_{S-} \parallel R_{T-}$$
$$= 750\ \Omega + 1\ k\Omega \parallel 332\ \Omega - 1\ k\Omega \parallel 1\ k\Omega = 500\ \Omega.$$

The nearest standard 1% value, 499 Ω, should be used. These values will provide the needed function and keep the FDA stable. Again the V_{OCM} input on the FDA is used to set the output common-mode voltage to 2.5 V.

The input impedance is Z_{IN} = 1254 Ω, which is higher than desired. If the input impedance really needs to be closer to 1 kΩ, we can iterate with a lower value as before. In this case, using R_S = 787 Ω and R_F = 1 kΩ will yield Z_{IN} = 999 Ω, which comes as close as is possible when standard 1% values are used.

To see a TINA-TI™ simulation of the circuit in Example 5, go to http://www.ti.com/lit/zip/slyt359 and click Open to view the WinZip directory online (or click Save to download the WinZip file for offline use). If you have the TINA-TI software installed, you can open the file FDA_Attenuator_ Examples_SE_Unipolar_Input.TSC to view the example (the top circuit labeled "Example 5"). The simulation waveforms are the same as those shown in Figure 3 of Part 1. To download and install the free TINA-TI software, visit www.ti.com/tina-ti and click the Download button.

Using an FDA's R_F and R_G as an attenuator

The proposed circuit using gain-setting resistors to obtain an SE unipolar input signal is shown in Figure 9. In this circuit, the FDA is used as an attenuator in a manner similar to that described in Part 2 for the SE bipolar signal, and the design equations are the same:

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_F}{R_G},$$

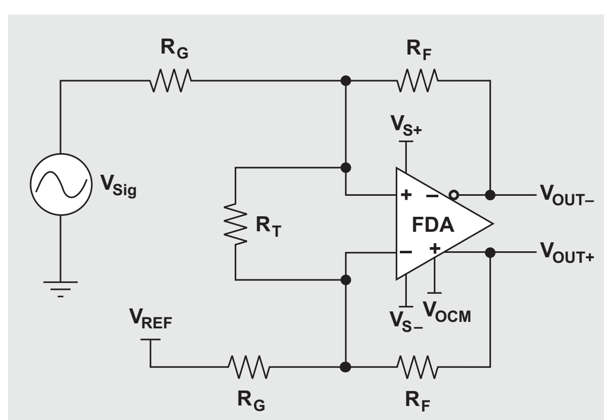
and for stability we set

$$R_F = R_G \parallel \frac{R_T}{2},$$

and $Z_{IN} \approx R_G$.

To avoid a DC offset in the output, V_{REF} is set to equal the common-mode voltage of V_{Sig}. Note that if a reference voltage higher than the input common-mode voltage is available in the system, a resistor divider can be used. This

Figure 9. Using FDA's R_F and R_G as attenuator for SE unipolar input



is accomplished by keeping the parallel combination equal to R_G while simultaneously setting the voltage divider to provide the input common-mode voltage at no load.

Design Examples 6a and 6b

For Example 6a, we will use the same approach as for Example 5, with $R_F = 1\ k\Omega$, and calculate $R_G = 4\ k\Omega$ (the nearest standard 1% value is 4.02 kΩ) and $R_T = 2.6666\ k\Omega$ (the nearest standard 1% value is 2.67 kΩ). This makes $Z_{IN} \approx 4.02\ k\Omega$, and SPICE shows it to be more on the order of 4.46 kΩ. V_{REF} should be set to the common-mode voltage of the input signal and is calculated by

$$V_{REF} = \frac{V_{Sig\_min} + V_{Sig\_max}}{2} = \frac{0\ V + 20\ V}{2} = 10\ V.$$

The function is the same as before, but with this approach the only freedom of choice given the design requirements is the value of R_F.

To see an example Excel worksheet, go to http://www.ti.com/lit/zip/slyt359 and click Open to view the WinZip directory online (or click Save to download the WinZip file for offline use). Then open the file FDA_Attenuator_Examples_SE_Unipolar_Input.xls and select the Unipolar SE FDA RF_RG Atten worksheet tab. To see a TINA-TI simulation of the circuit in Example 6a, go to http://www.ti.com/lit/zip/slyt359 and click Open to view the WinZip directory online (or click Save to download the WinZip file for offline use). If you have the TINA-TI software installed, you can open the file FDA_Attenuator_Examples_SE_Unipolar_Input.TSC to view the example (the middle circuit labeled “Example 6a”). To download and install the free TINA-TI software, visit www.ti.com/tina-ti and click the Download button.

The simulation waveforms for Example 6a show that the signal is distorted. Further investigation will show that the input common-mode voltage range of the THS4509 used in the simulation has been violated at the most positive peaks of the input signal, causing nonlinear operation. In this case the SPICE model shows a problem; but care must be taken to double-check operation against the data sheet, as not all SPICE models will show this error. For instance, replacing the THS4509 model with the THS4520 will simulate fine, but the actual device has a similar input common-mode voltage range.

One way to correct the problem is to use pull-down resistors from the FDA input pins to ground as described in the THS4509 data sheet. In this case, instead of placing the full-value R_T across the inputs, we place half the value (1.33 kΩ) from each input to ground. These resistors will act to pull down the inputs and bring the common-mode voltage back into linear operation. To see a TINA-TI simulation of this corrected circuit (Example 6b), go to http://www.ti.com/lit/zip/slyt359 and click Open to view the WinZip directory online (or click Save to download the WinZip file for offline use). If you have the TINA-TI software installed, you can open the file FDA_Attenuator_Examples_SE_Unipolar_Input.TSC to view the example (the bottom circuit labeled “Example 6b”). Note that the circuit provides the same results as those shown in Figure 3 of Part 1. To download and install the free TINA-TI software, visit www.ti.com/tina-ti and click the Download button.

Another way to eliminate the problem with input common-mode voltage is to use the input attenuator to the FDA as the circuit’s attenuator as described earlier.

Conclusion

We have analyzed two approaches that attenuate and level-shift high-amplitude, SE unipolar signals to the input range of lower-voltage input ADCs. The primary difference between the unipolar input design and the bipolar designs described in Parts 1 and 2 is that a reference voltage to the alternate input must be provided in the unipolar design to make sure the output swing is symmetrical about the common-mode voltage. For the first approach (Example 5), we chose input resistor values to provide the required attenuation and to keep the noise gain of the FDA equal to 2 for stability. This approach allows the use of a lower value for V_{REF}. The second approach (Example 6a) uses the gain-setting resistors of the FDA in much the same way as using an inverting op amp, then a resistor is bootstrapped across the inputs to provide a noise gain of 2. We saw in the simulation that this last approach caused a problem with the input common-mode voltage going too high on the positive peaks of the input signal, but this was easily compensated for by splitting the R_T resistor and tying the center to ground (Example 6b). The two approaches yield the same voltage translation that is needed to accomplish the interface task. Other performance metrics were not analyzed here, but the two approaches have substantially the same noise, bandwidth, and other AC and DC performance characteristics as long as the value of R_F is the same.

The input-attenuator approach in Example 5 is more complex but allows the input impedance to be adjusted independently from the gain-setting resistors used around the FDA. At least to a certain degree, lower values can easily be achieved if desired, but there is a maximum allowable R_{S+} where larger values require the R_{G+} resistor to be a negative value. For example, setting $R_S = 4\ k\Omega$ results in $R_{G+} = 0\ \Omega$. The spreadsheet tool provided will generate “#NUM!” errors for this input as it tries to calculate the nearest standard value, which then replicates throughout the rest of the cells that require a value for R_{G+}; but this value will work.

The approach in Examples 6a and 6b is easier, but the input impedance is set as a multiplication of the feedback resistor and attenuation: $Z_{IN} \approx 2 \times R_F \times$ Attenuation. This does allow some design flexibility by varying the value of R_F, but the impact on noise, bandwidth, distortion, and other performance characteristics should be considered. Also, as mentioned before, voltages at the amplifier nodes should be checked against data-sheet specifications, because SPICE models will not always show problems.

One final note: The source impedance will affect the input gain or attenuation of either circuit and should be included in the value of R_{S+}, especially if it is significant.

References

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Document Title **TI Lit. #**

1. Jim Karki, "Fully-Differential Amplifiers," Application Report. sloa054
2. Jim Karki, "Using Fully Differential Op Amps as Attenuators, Part 1: Differential Bipolar Input Signals," *Analog Applications Journal* (2Q 2009) slyt336
3. Jim Karki, "Using Fully Differential Op Amps as Attenuators, Part 2: Single-Ended Bipolar Input Signals," *Analog Applications Journal* (3Q 2009) slyt341

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