Using fully differential op amps as attenuators, Part 1: Differential bipolar input signals

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Introduction

Conditioning high-voltage input signals to drive ADCs from high-voltage sources can be challenging. How can a higher-voltage signal like ±10 V be attenuated and level-shifted to match the significantly lower differential and common-mode-voltage input required by the ADC? In this article, Part 1 of a three-part series, we consider a balanced, differential bipolar input signal and propose an architecture utilizing a fully differential operational amplifier (FDA) to accomplish the task.

We consider this type of circuit first because it most clearly shows how to approach the design, keep a balanced circuit, and not introduce unwanted offsets. Parts 2 and 3 will appear in future issues of the *Analog Applications Journal*. Part 2 will show how to adapt the circuit to a single-ended bipolar input. Part 3 will show the more generic case of a single-ended unipolar input with arbitrary common-mode voltage. The level of complexity will increase with each step, but ordering the presentation in this manner should help the reader better understand why values are chosen for the final circuit the way they are.

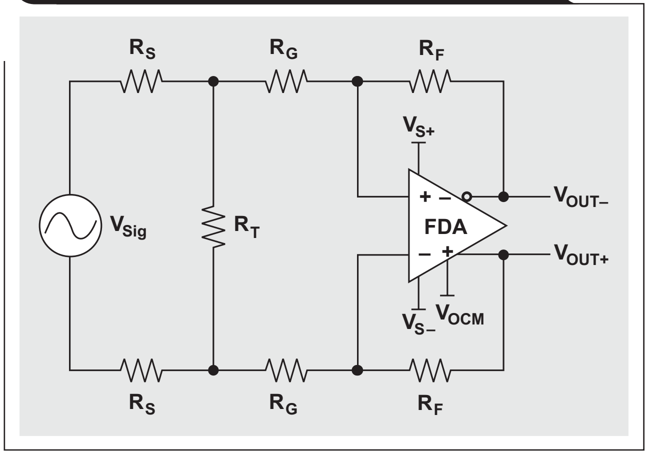
Differential bipolar input

The fundamentals of FDA operation are presented in Reference 1. Since the principles and terminology presented there will be used throughout this article, please see Reference 1 for definitions and derivations.

FDAs can easily be used to attenuate large signals, convert single-ended signals to differential signals, and level-shift voltages to match the input requirements of lower-voltage ADCs. The trick is to implement them in a way that will perform these tasks while keeping the amplifier stable.

FDAs have been compared to two standard, inverting, single-ended output op amps configured in a differential architecture. While this has some validity, one important difference is that a unity-gain, stable op amp is compensated for a noise gain* of 1, while a unity-gain, stable FDA is typically compensated for a noise gain of 2. The implication of this in the context of implementing an attenuator circuit is that the gain resistors can no longer be chosen simply to provide the attenuation. Two approaches are identified in this article; one implements an input attenuator with resistor values chosen to provide a noise gain of 2, and the other implements the attenuator using the gain-setting resistors with added components to get a noise gain of 2.

Figure 1. Attenuator circuit for differential bipolar input



Using an input attenuator

The proposed input-attenuator circuit for a balanced, differential bipolar input signal is shown in Figure 1, whose parameters are defined as follows:

- V_{S+} and V_{S-} are the power supplies to the amplifier.
- V_{Sig} is the input-signal source.
- R_S and R_T are the resistors that provide attenuation of the signal from the source. Their parallel combination also affects the noise gain of the amplifier.
- R_G and R_F are the main gain-setting resistors for the amplifier.

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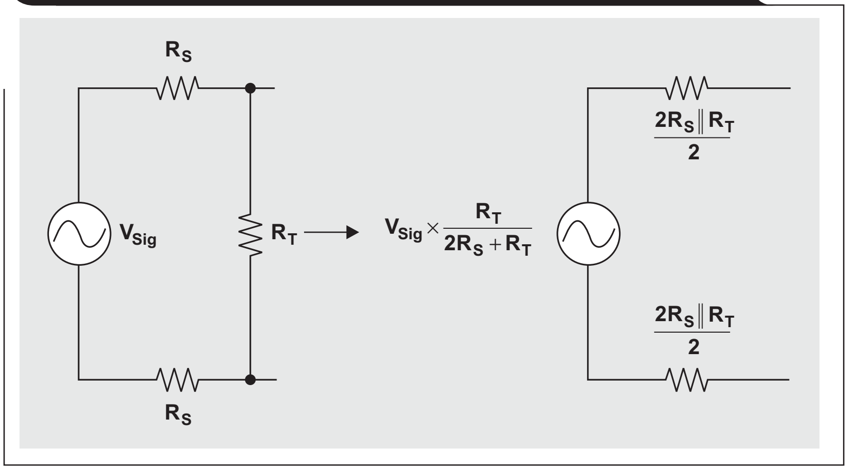
*Noise gain is used to define the stability criteria of an op amp and is calculated as the gain from the input terminal of the op amp to the output. Generally, one speaks of op amp stability in terms of the minimum noise gain required, where larger values are fine, but lower values may lead to instability or oscillation.

Figure 2. Thevenin-equivalent input source and attenuator



For analysis, it is convenient to assume that the FDA is an ideal amplifier with no offset and has infinite gain. The first step in analyzing the circuit in Figure 1 is to simplify it by using only its attenuator portion and the Thevenin equivalent of the input source. This is shown in Figure 2. With the circuit in this form, it is easier to see that its overall gain can be calculated by the formula

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_T}{2R_S + R_T} \times \frac{R_F}{R_G + \frac{2R_S \parallel R_T}{2}}. \tag{1}$$

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

$$R_G + \frac{2R_S \parallel R_T}{2} = R_F \tag{2}$$

With this constraint, the overall gain equation reduces to

$$\frac{V_{OUT\pm}}{V_{Sig}} = \frac{R_T}{2R_S + R_T}. \tag{3}$$

There are two degrees of freedom for choosing components in the gain equation—an infinite number of combinations of R_S and R_T that will give the desired input attenuation, and an infinite number of R_F and R_G values to set the gain.

The differential input impedance of this amplifier circuit is given by $Z_{IN} = 2R_S + R_T \parallel 2R_G$. Depending on the attenuation needed, the input impedance is approximately $2R_S$.

It is recommended that R_F be kept to a range of values for the best performance. Too large a resistance will add excessive noise and will possibly interact with parasitic board capacitance to reduce the bandwidth of the amplifier; and too low a resistance will load the output, causing increased distortion. Design is best accomplished by first choosing R_S close to the desired input impedance, then choosing R_F within the recommended range for the device. For example, the THS4521 performs best with R_F at about 1 kΩ. Next, the value of R_T required to give the desired attenuation is calculated. Then R_G is calculated for the desired gain. These equations are easily solved when set up in a spreadsheet. To see an example Excel® worksheet, go to http://www.ti.com/lit/zip/slyt336 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_Diff_Bipolar_Input.xls and select the Diff Bipolar FDA Input Atten worksheet tab.

Design Example 1

As a design example, let's say we have a 20-V_{PP} differential bipolar (±10-V) signal, and we need a 2-kΩ differential input impedance. We want to use the ADS8321 SAR ADC with a 5-V_{PP} differential input and a 2.5-V common-mode voltage. We choose R_S = 1 kΩ and R_F = 1 kΩ. Rearranging Equation 3 and using substitution, we can calculate

$$R_T = \frac{2R_S}{\frac{V_{Sig}}{V_{OUT\pm}} - 1} = \frac{2\ \text{k}\Omega}{4 - 1} = 666.7\ \Omega.$$

The nearest standard 1% value, 665 Ω, should be used. Then, rearranging Equation 2 and using substitution, we can calculate

$$R_G = R_F - \frac{2R_S \parallel R_T}{2} = 1\ \text{k}\Omega - \frac{2\ \text{k}\Omega \parallel 665\ \Omega}{2} = 750\ \Omega,$$

which is a standard 1% value. These values will provide the needed attenuation function and will keep the FDA stable. The V_{OCM} input on the FDA is then used to set the output common-mode voltage to 2.5 V.

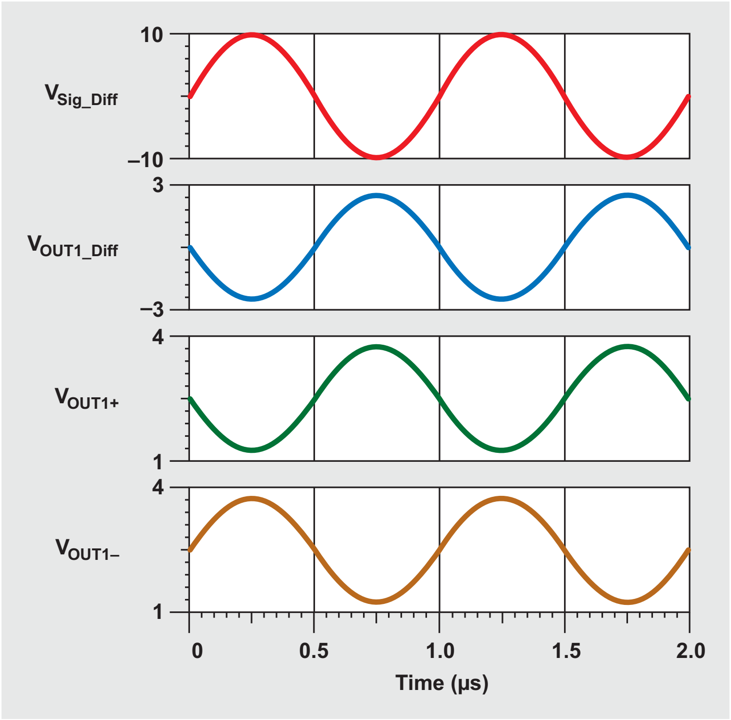
The input impedance is

$$Z_{IN} = 2R_S + R_T \parallel 2R_G = 2\ \text{k}\Omega + 665\ \Omega \parallel 1.5\ \text{k}\Omega = 2461\ \Omega,$$

which is higher than desired. If the input impedance really needs to be closer to 2 kΩ, we can iterate with a lower value. In this case, using R_S = 806 Ω and R_F = 1 kΩ will yield Z_{IN} = 2014 Ω, which comes as close as is possible when standard 1% values are used.

SPICE simulation is a great way to validate the design. To see a TINA-TI™ simulation of the circuit in Example 1,

Figure 3. TINA-TI simulation waveforms of differential bipolar input in Example 1



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The simulation waveforms in Figure 3 show that the circuit simulates as expected. V_{Sig1_Diff} is the 20-V_{PP} input; V_{OUT1_Diff} is the differential output of the amplifier circuit; and V_{OUT1+} and $V_{OUT1–}$ are the individual outputs of the amplifier.

Using an FDA’s R_F and R_G as an attenuator

The proposed circuit using gain-setting resistors to obtain a balanced, differential bipolar input signal is shown in Figure 4. In this circuit, the FDA is used as an attenuator in a manner similar to using an inverting op amp. The gain (or attenuation) is set by R_F and R_G:

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

R_T is used to set the noise gain to 2 for stability:

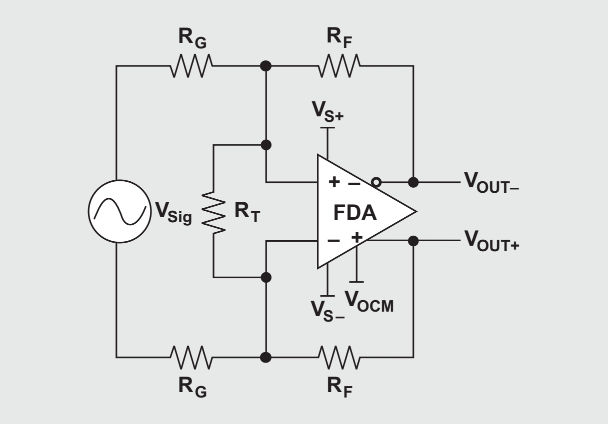
$$R_F = R_G \left\| \frac{R_T}{2} \right.$$

The equation for input impedance is $Z_{IN} = 2R_G$.

Design Example 2

Using the same approach as for Example 1, with $R_F = 1$ kΩ, we calculate $R_G = 4$ kΩ (the nearest standard 1% value is 4.02 kΩ) and $R_T = 2.67$ kΩ (a standard 1% value). This makes $Z_{IN} = 8.04$ kΩ. The simulation results are the same as before, but with this approach the only freedom of choice given the design requirements is the value of R_F.

Figure 4. Using FDA’s R_F and R_G as attenuator for differential bipolar input



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Conclusion

We have analyzed two approaches that attenuate and level-shift high-amplitude, differential bipolar signals to the input range of lower-voltage input ADCs. The first approach uses an input attenuator with values chosen to provide the required attenuation and to keep the noise gain of the FDA equal to 2 for stability. The second approach 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. 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 shown in Example 1 is more complex but allows the input impedance to be adjusted independently of 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.

It should be noted that a circuit similar to the one in Example 1, with a maximum R_S value and $R_G = 0\ \Omega$, results in the same circuit as the one in Example 2 that uses the gain-setting resistors as the attenuator. It should also be noted that 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.

The approach in Example 2 is easier, but the input impedance is set as a multiplication of the feedback resistor and attenuation: $Z_{IN} = 2 \times R_F \times$ 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.

Reference

For more information related to this article, you can download an Acrobat® Reader® file at www-s.ti.com/sc/techlit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

Document Title	**TI Lit. #**
1. Jim Karki, "Fully-Differential Amplifiers," Application Report	sloa054

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