Using noise-gain shaping to stabilize fully-differential amplifiers

By Jacob Freet
Applications Engineer, High-Speed Amplifiers

Introduction

Amplifier stability is always a potential area of concern when developing application circuits for high-speed amplifiers, such as SAR-ADC drivers. This is particularly true when using amplifiers to drive capacitive loads, such as the input to a successive-approximation-register (SAR) analog-to-digital converters (ADCs), or when using decompensated amplifiers that are not unity-gain stable. With many high-speed, high-resolution SAR ADCs with fully-differential inputs, fully-differential amplifiers (FDAs) are commonly used to drive the ADCs.

This article describes a technique to stabilize potentially unstable FDA application circuits by using capacitors to shape the noise-gain frequency response. The examples given reference an FDA driving a high-capacitive load, but the technique is applicable for any FDA application or inverting voltage-feedback amplifier configuration. Figure 1 shows a typical application circuit of an FDA driving a SAR-ADC input without any added circuitry to stabilize the amplifier.

Stability theory

It's possible to analyze an FDA's stability much like a standard amplifier in an inverting configuration. The key parameter used to determine the amplifier's circuit stability is the loop-gain response variation over frequency, which can be used to extract the phase margin of the circuit. The loop gain is defined as the amplifier's open-loop gain response (A_{OL}) multiplied by the feedback factor (β), which is created by the combination of the feedback elements. The derivation of the loop-gain, open-loop-gain and feedback-factor responses are beyond the scope of this article, but do exist in TI Precision Labs,[1] as well as many standard amplifier textbooks.

For analytical simplicity, this article assumes that the amplifier used is unity-gain stable and has a single-pole open-loop frequency response, as shown in Figure 2. However, the theory and methods discussed are applicable to amplifiers with multipole responses like decompensated amplifiers.

To calculate the feedback factor, determine the transfer equation from the point of the amplifier's output referenced to its non-inverting input. The inverse of the feedback factor is known as the noise gain of the amplifier circuit, and is often used to illustrate how the feedback network will amplify any voltage noise present at the

Figure 1. Generic SAR-ADC driver circuit using the THS4551 FDA

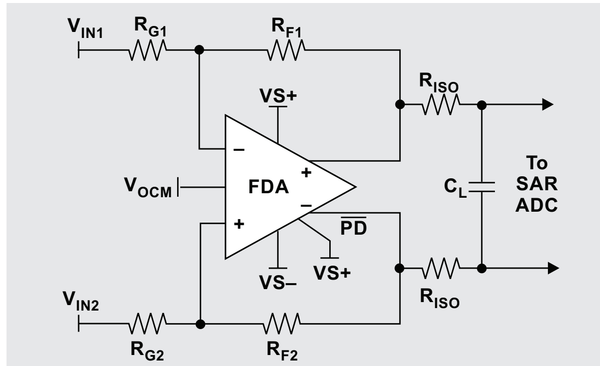
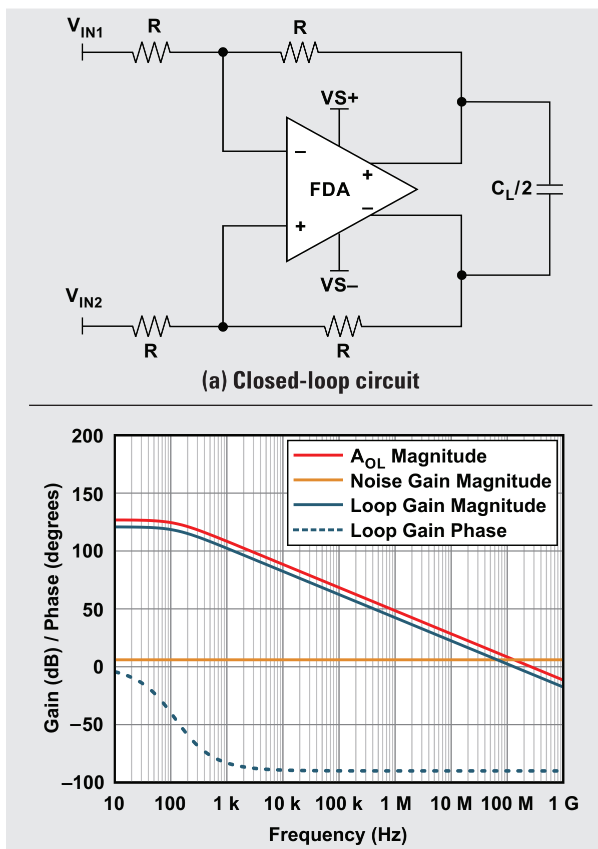


Figure 2. A 130-MHz FDA that is unity-gain stable with a single-pole open-loop response



(b) Loop-gain response

amplifier's inputs. With both the open-loop response and the feedback factor (or noise gain), either Equation 1 or Equation 2 calculates the loop gain.

$$\text{Loop Gain} = A_{OL} \times \beta \quad (1)$$

$$\text{Loop Gain} = \frac{A_{OL}}{\text{Noise Gain}} \quad (2)$$

The loop-gain response is typically a complex frequency response consisting of both real and imaginary components. Obtaining the phase margin requires extraction of both the magnitude and phase responses from the complex loop-gain response. With both the magnitude and phase response, calculating the change of loop-gain phase response at the frequency where the loop-gain magnitude is equal to unity (0 dB) obtains the phase margin. If the value of the phase is less than 180 degrees, then the circuit is theoretically stable. The phase margin is calculated by subtracting the measured value of the phase from 180. Technically, any phase margin greater than zero is considered stable, although unpredicted secondary effects often come into play that can push the circuit into instability. To account for unpredicted effects, the phase margin should be at least 30 degrees, however 60 degrees is preferable to achieve a flat frequency response. Figure 2 shows the open-loop gain, noise-gain and loop-gain responses for a unity-gain inverting configuration.

Note that the example unity-gain amplifier circuit in Figure 2 is very stable in its configuration, with 90 degrees of phase margin. However, real application circuits are never ideal and include other components that affect amplifier stability. In the case of driving SAR ADCs, the biggest effect on stability is the required charge-bucket capacitor, which is typically 20 times the value of the internal ADC sampling capacitor. Although series resistors are included in front of the capacitor to create a resistor-capacitor (RC) filter—which helps isolate some of the capacitance—these resistors are sometimes not enough to entirely isolate the effect of the charge-bucket capacitor. Adding too much capacitance to the amplifier output has the effect of adding a second pole into the loop-gain response. If the second pole frequency becomes low enough such that it is located below the unity-gain crossover frequency, it will introduce an additional phase shift into the response that can cause the phase margin (PM) to reduce to a point of instability. Figure 3 shows the loop-gain responses from the same theoretical amplifier as Figure 2, with additional capacitance added to the amplifier output.

Although the series output resistors added to the amplifier's output help stabilize the circuit in the presence of a large capacitive load, they can be impractically large when used as the only method of stabilizing the circuit. Resistors that are too large will increase the settling time of the filter and lower the filter frequency created by the combination of output resistors and the charge-bucket capacitor. Circuit performance can be limited if the output-filter's cutoff frequency is lower than the required system bandwidth or the filter settling time is too slow.

Noise-gain shaping technique

Rather than adding additional output resistance, it's possible to shape the noise gain of the amplifier with minimal adverse effect to the circuit, using only additional input and feedback capacitors. This technique does "peak" the noise gain at a certain frequency, which will potentially add additional integrated noise to the circuit. With careful design, however, the frequency of the peaking can occur primarily after the output-filter bandwidth, thus adding little additional noise to the final sampled signal.

An FDA needs three capacitors total for noise-gain shaping, one connected in parallel with each of the two feedback resistors and one connected differentially across the inputs. To successfully use this technique, values must be chosen carefully to minimize added noise while keeping the device stable. Although it is possible to theoretically derive the entire transfer function of the loop gain to predict the value of the capacitors, practically it is much easier to use a heuristic approach—tuning the values until the desired performance is obtained.

Figure 3. Loop gain with various capacitive loads

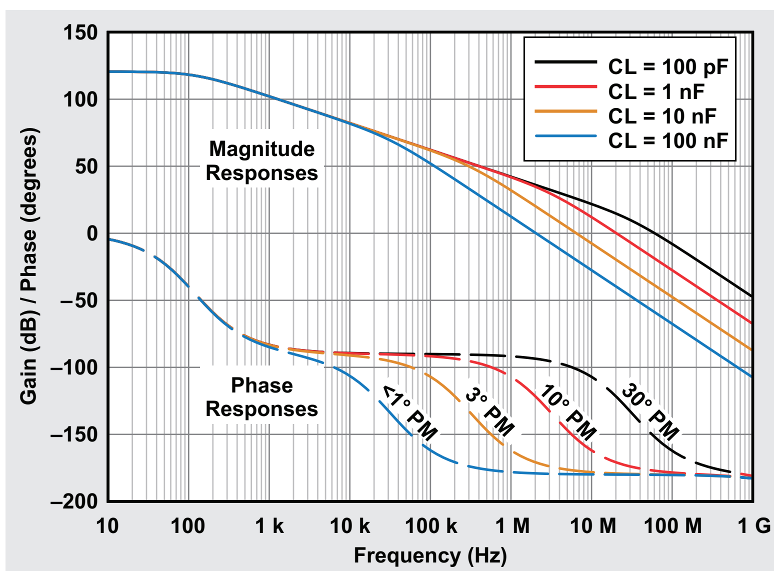
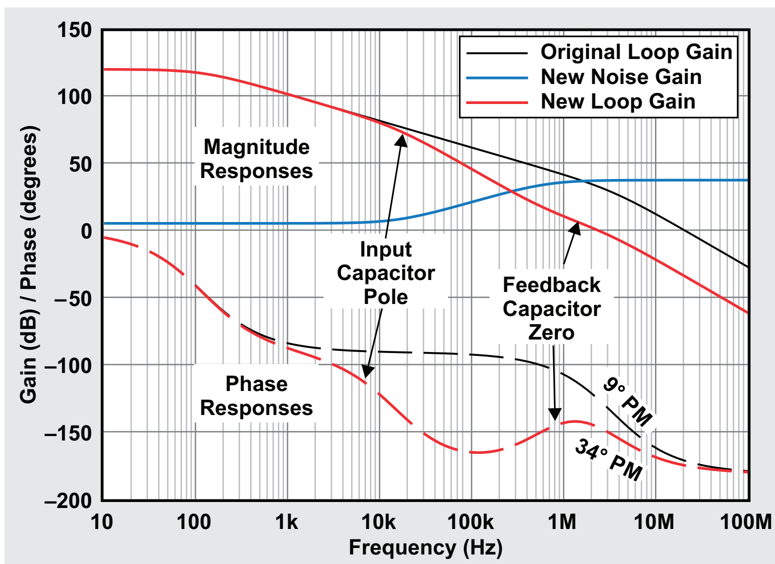


Figure 4 illustrates the effect of shaping the noise gain of the circuit and how it stabilizes the loop-gain response. The input capacitor adds a pole to the response that drops the magnitude value faster to the unity-gain value. The feedback capacitors add a zero that helps extend the phase response past the unity-gain value. The summary of the effect is that the phase is extended past the new unity-gain crossing to keep the circuit stable.

It is best to first pick an input capacitor value that places a zero in the noise-gain response before the second pole in the loop-gain response. Choose the feedback value so that the noise gain flattens out and crosses above the second pole in the loop-gain response. If a value cannot be found for the feedback capacitor that satisfies both criteria, then increase the input capacitor until the response stabilizes. One approach is to choose a very large input capacitor from the start, but that would cause the noise gain to peak far earlier than necessary, thus adding unnecessary noise to the circuit.

Figure 4. Loop gain of circuit with a 1-nF capacitive load and stabilized response with C_{IN} = 10 nF and C_{FB} = 250 pF

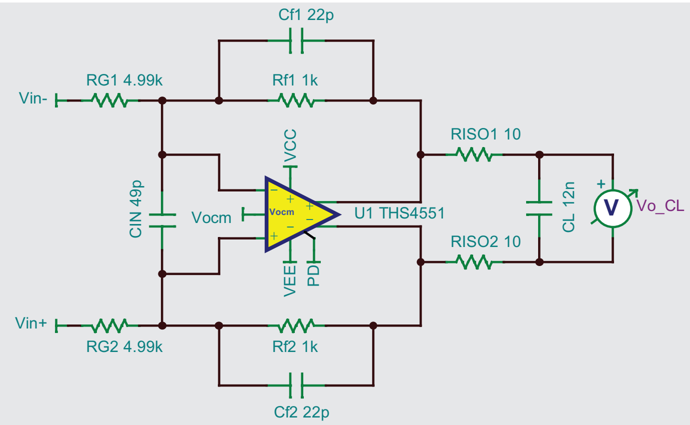


TINA-TI™ software simulation

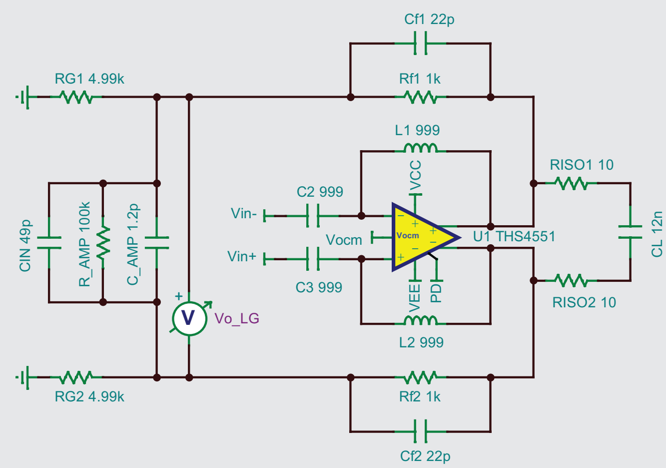
The easiest way to practically use the noise-gain shaping technique is with a SPICE-based simulator such as TINA-TI™ software and an accurate amplifier model. TI's THS4551 FDA is a high-speed differential SAR ADC driver that makes a great choice for stabilizing an ADC driver circuit. Figure 5 shows the circuit configuration for the THS4551 in a gain of 0.2 V/V with the equivalent load circuit to drive the ADS9110 18-bit SAR. It also shows the loop-gain measurement circuit and the ideal noise-gain equivalent circuit. Adding large inductors and capacitors on the inputs of the loop-gain circuit allow the simulator to properly calculate a DC operating point. The loop-gain configuration requires an additional discrete capacitor and resistor at the broken input point to add the amplifier's input capacitance and resistance into the loop.

The closed-loop circuit in Figure 5a is similar to the example circuit shown on page 41 of the THS4551 data sheet, which includes the capacitors to shape the noise gain of the device. Without the added capacitors, the circuit will have an unusably low phase margin that would likely result in oscillation even with the added series output resistors present. This can be verified by running an AC gain and phase simulation with the stabilizing capacitors set to zero. In this case, the phase margin is a mere 1.28 degrees, which would certainly not be stable in a physical implementation. Re-simulating with the added 49-pF input capacitor and 22-pF feedback

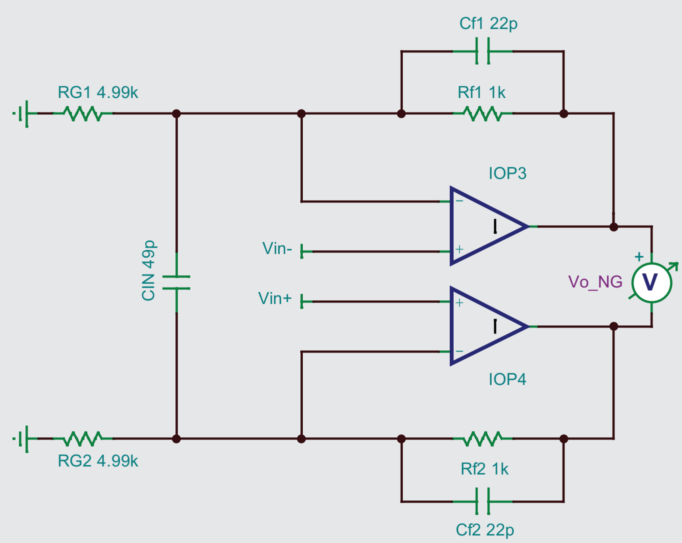
Figure 5. TINA-TI™ software schematics



(a) THS4551 closed-loop circuit

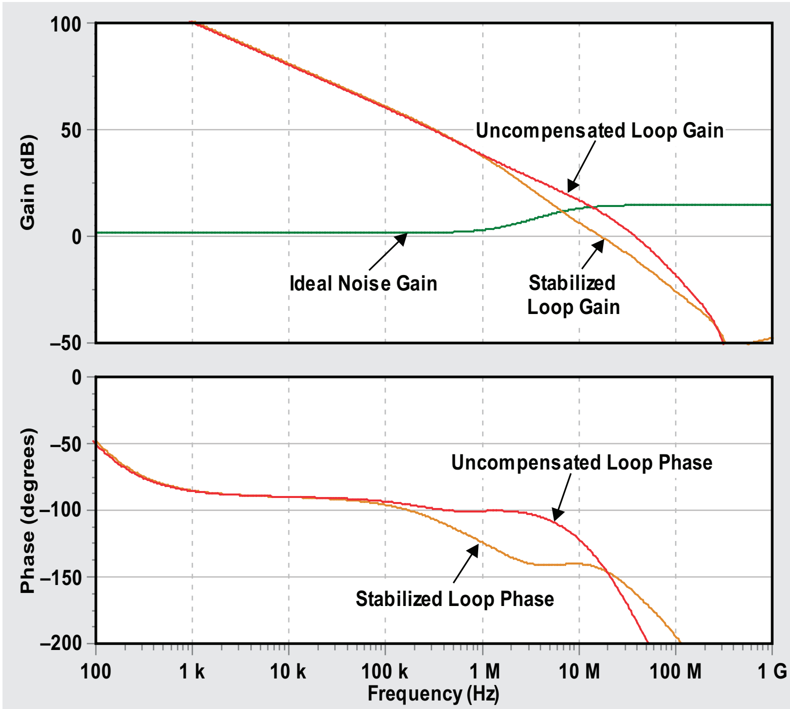


(b) THS4551 loop-gain circuit



(c) Ideal noise-gain circuit

Figure 6. TINA-TI loop-gain simulation results



capacitors used in the data sheet example yields a significantly more stable phase margin of 36.19 degrees. Figure 6 illustrates the difference between the two loop-gain response simulations using the TINA-TI software simulator with the loop-gain and noise-gain configuration circuits from Figure 5.

Although the stabilized circuit will have lower bandwidth than the unstable version, it is still much higher than the low-pass filter created by the output resistors and capacitor, and has no detrimental effect on performance. Since most of the noise-gain peaking occurs after the filter cutoff frequency, the circuit only adds a negligible 33 nV_{RMS} to the total output noise of 5.4 μV_{RMS} as measured from DC to the filter cutoff frequency. This comparison can be replicated in TINA-TI software by running a total noise simulation on the closed-loop circuit.

Conclusion

Unstable circuits are a common but challenging issue in many high-speed amplifier applications. This article detailed the theory and application of a noise-gain shaping technique that can stabilize an amplifier circuit while minimizing undesired noise effects. Although the example given was a fully differential configuration, the technique works for any voltage-feedback inverting-configuration amplifier. The technique may not be best for every single application, but it does offer a reliable way to stabilize circuits in many common configurations. For further reference, the THS4551 datasheet includes several example circuits using noise-gain shaping techniques with available TINA-TI files for download.

Reference

1. TI Precision Labs online video training series for op amps.

Related Web sites

Design tools and information:
TINA-TI™ software simulator
THS4551 SPICE model
TI Precision Labs – Op Amps: Stability videos
Overview of fully-differential op amps

Product information:
THS4551
ADS9110

TI Worldwide Technical Support

TI Support

Thank you for your business. Find the answer to your support need or get in touch with our support center at

www.ti.com/support

China: http://www.ti.com.cn/guidedsupport/cn/docs/supporthome.tsp

Japan: http://www.tij.co.jp/guidedsupport/jp/docs/supporthome.tsp

Technical support forums

Search through millions of technical questions and answers at TI's E2E™ Community (engineer-to-engineer) at

e2e.ti.com

China: http://www.deyisupport.com/

Japan: http://e2e.ti.com/group/jp/

TI Training

From technology fundamentals to advanced implementation, we offer on-demand and live training to help bring your next-generation designs to life. Get started now at

training.ti.com

China: http://www.ti.com.cn/general/cn/docs/gencontent.tsp?contentId=71968

Japan: https://training.ti.com/jp

A011617

SLYT733

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES