

Selecting precision op amps as ADC drivers

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Selecting an operational amplifier (op amp) to drive an analog-to-digital converter (ADC) is not a trivial task. Usually dictated by the end equipment, the choice of ADC is based on trade-offs of several parameters. Even within the same sector or market segment, ADC requirements can differ. For example, in test and measurement you will find a mix between successive approximation register (SAR) and delta-sigma ADCs. SAR ADCs tend to be popular in parametric measurement units, memory testers and battery cell formation testers.

Delta-sigma ADCs are typically used for vibration analysis, data acquisition and scientific instrumentation. Some applications can be common to both, depending on the overall system requirements. Highly accurate weigh scales benefit more from delta-sigma ADCs given their higher resolution, whereas consumer and low-end models rely on the SAR topology to minimize power consumption.

Likewise, datacom optical modules tend to use SAR ADCs whereas telecom optical modules often rely on delta-sigma ADCs even though both applications are part of the same sector, namely data centers.

Paying careful attention to the DC and AC specifications of the op amp (or analog front end) can help avoid ADC performance degradation and minimize errors.

Circuit configuration vs. bandwidth and other errors

An inverting circuit configuration provides the advantage of avoiding common-mode modulation errors and therefore does not require a high common-mode

rejection ratio. It lowers the input impedance to the parallel combinations of input and feedback resistors, however, and induces gain error with the feedback resistor in place. A noninverting configuration typically provides much higher input impedance. The closed-loop bandwidth or effective bandwidth of the op amp is a function of the noise gain (or noninverting gain), not the signal gain.

In **Figure 1**, TI's OPA325 has a gain bandwidth product of 10MHz. In a positive unity gain (buffer) configuration, the bandwidth is 18MHz. The excess bandwidth is attributed to the gain peaking, accounted for in the TINA-TI™ macromodel by the input capacitance and open-loop output impedance. In this case, the signal gain is -1 and the noise gain is 1.

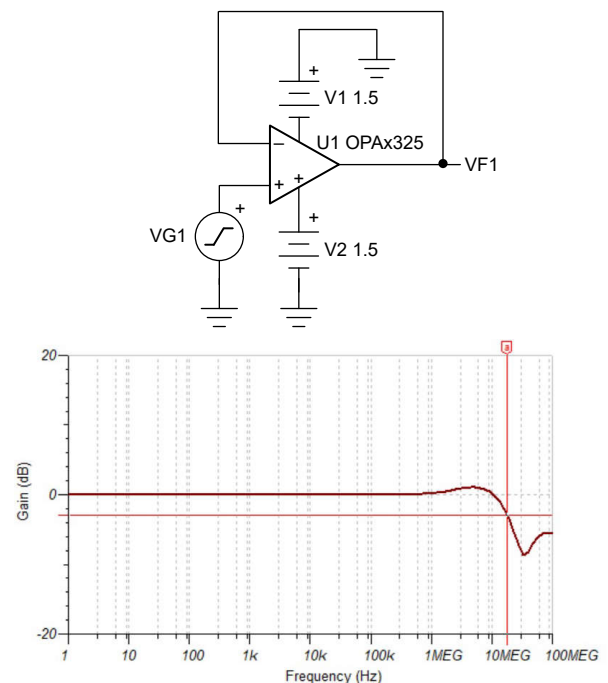


Figure 1. The OPA325 in a buffer configuration

On the other hand, the circuit shown in **Figure 2** exhibits a bandwidth of 6.7MHz, nearly one-third the bandwidth of the buffer in **Figure 1**. In **Figure 2**, the signal gain is -1 but the noise gain is 2. Notice that the gain peaking isn't nearly as noticeable in the inverting configuration, even with a gain of just 2. The higher the gain, the lower the gain peaking.

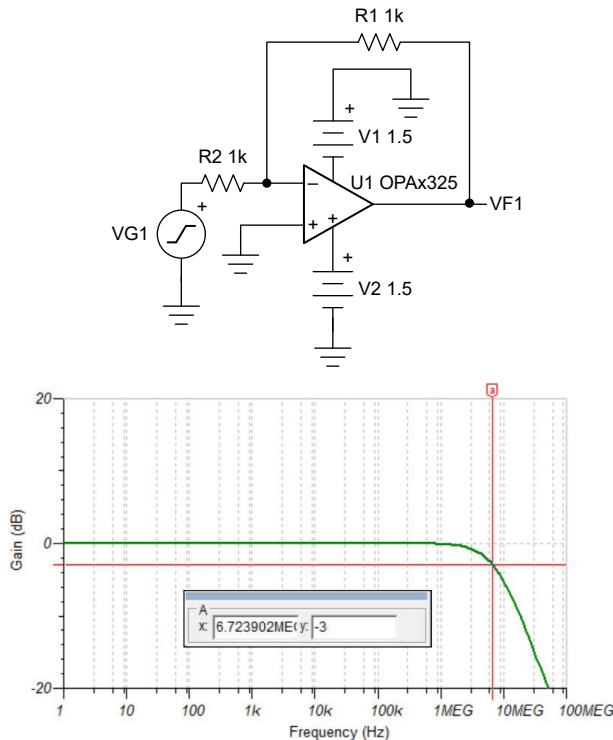


Figure 2. The OPA325 with a noise gain of 2

DC gain error

Open-loop gain (Aol) plays a major role in DC gain accuracy. If you consider the inverting circuit in Figure 2 in a 12-bit system, the Aol must be at least 78dB or 8,192; that is, $2^{12} \times 2$. Almost all modern general-purpose op amps can achieve 78dB of Aol. If you require 16 bits of accuracy (at a noise gain of 2), the minimum Aol must be 102dB, which requires a precision device in most cases. Remember that Aol is also a function of the output load, since the gain of the last stage is a function of $g_m \times R_L$. In the case of the inverting circuit, the feedback resistor (R1 in Figure 2) is the load.

Output limitations and linearity

Op-amp specification tables list the output swing, typically in the range of 10mV to 20mV for complementary metal-oxide semiconductors (CMOS) from the power supply, commonly known as the slam test. To ensure that the op amp stays within the linear region, look at the conditions of the Aol specification to determine the allowable maximum voltage swing. Since ADCs have a high input impedance, look at the highest-value load condition.

For example, the OPA328 has a voltage output swing of $\pm 100\text{mV}$ with a $10\text{k}\Omega$ load. When paired with the ADS8860 using a single-supply 3.3V, the linear range of the OPA328 is from 0.1V to 3.2V, whereas the ADS8860 has an input range of 0V to 3.3V. Clearly, you're not using the full dynamic range, thus resulting in a waste of codes. Using the LM7705 negative bias generator (-0.23V) and increasing the positive power supply to 3.5V will overcome this issue. With the OPA328 output limitation of $\pm 100\text{mV}$ and the LM7705 in place, the valid output range is now -0.1V to 3.4V, which covers the ADS8860 input range without violating its absolute maximum ratings (-0.3V to 3.6V).

Noise and ENOB

When it comes to driving high-resolution ADCs, op-amp noise plays a crucial role. A low-noise amplifier will help achieve a higher effective number of bits (ENOB) for the total system. In other words, the lower the op-amp noise, the smaller the degradation of the ENOB, and the higher the accuracy. Remember that low-noise amplifiers typically require a higher quiescent current, which in turn is proportional to bandwidth expressed as:

$$BW = \frac{g_m}{2\pi C_c} \tag{1}$$

For the same amount of current, a bipolar op amp achieves wider bandwidths (or in other words, is more efficient).

Equation 2 expresses the total noise calculation, including the voltage reference, as:

$$V_{ntotal} = \sqrt{V_{nADC}^2 + V_{nopa}^2 + V_{nref}^2} \quad (2)$$

Starting with the ADS8860, converting the full-scale range (5V) to root mean square (RMS) values using $5 / (2 \times \sqrt{2})$ yields 1.76V. **Equation 3** computes the rms noise of the ADS8860 as:

$$V_{nADC} = \frac{V_{FSR_rms}}{10^{\left(\frac{SNR_{ADC}}{20}\right)}} = \frac{1.76}{10^{\left(\frac{93dB}{20}\right)}} = 39.6\mu V_{rms} \quad (3)$$

Simulating the OPA328 in a positive unity gain yields a total noise of $47\mu V_{rms}$ and about $83\mu V_{rms}$ in an inverting gain of 2 (noise gain). **Figure 3** and **Figure 4** show the respective simulation results.

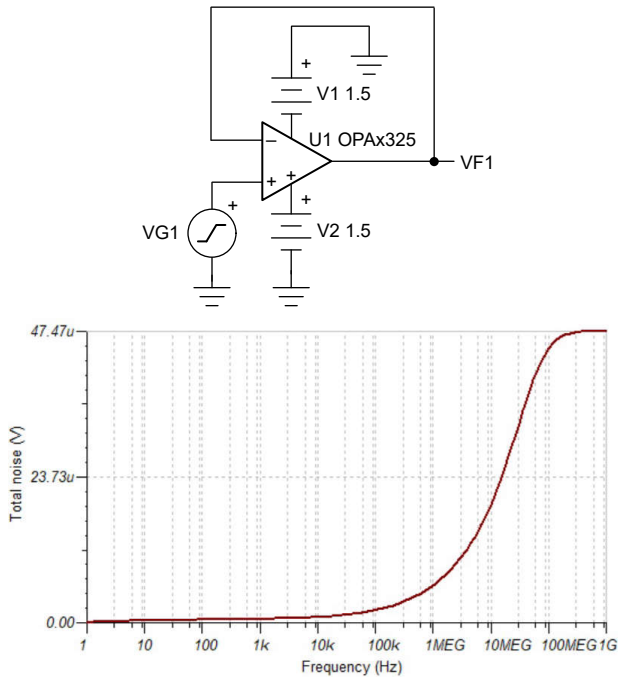


Figure 3. The OPA328's RMS noise in a positive unity gain

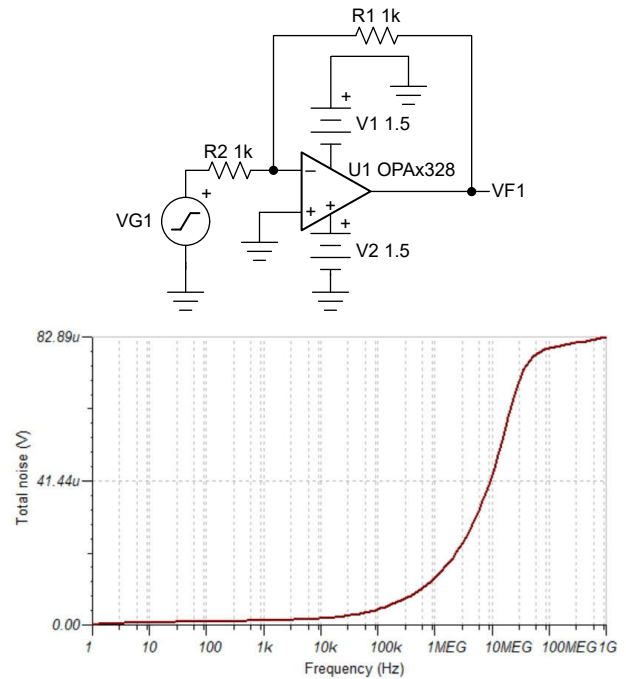


Figure 4. The OPA328's RMS noise in an inverting configuration

Using the OPA325 in the same circuits yields $39\mu V_{rms}$ and $55\mu V_{rms}$, respectively.

While it may seem a natural choice to select the lowest noise op amp, you must remember that a low-noise amplifier is only as good as its bandwidth in terms of noise. In other words, the OPA328 with $6nV/\sqrt{Hz}$ exhibits about 20% higher noise than the OPA325, which has $9nV/\sqrt{Hz}$ of broadband voltage noise density. OPA328 has four times the bandwidth of the OPA325.

Simulating the total noise (RMS) is a crucial piece of your analysis and an easy way to achieve a better ENOB for the system.

For example, in the noise plot of **Figure 5** to reduce the noise to the one-half least significant bit (LSB) of the $39\mu V$ from the ADS8660, you need to limit the bandwidth to about 2MHz.

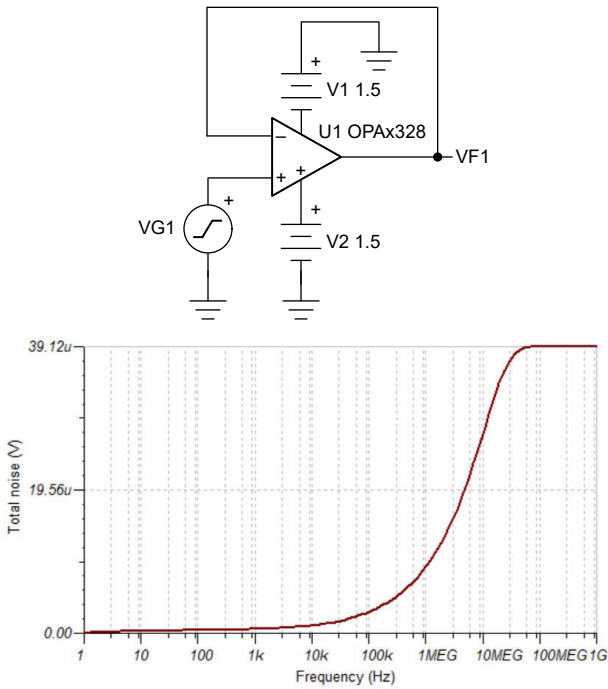


Figure 5. The OPA325 RMS noise in a positive unity gain

Figure 6 shows the rms noise simulation of the OPA325 in an inverting configuration.

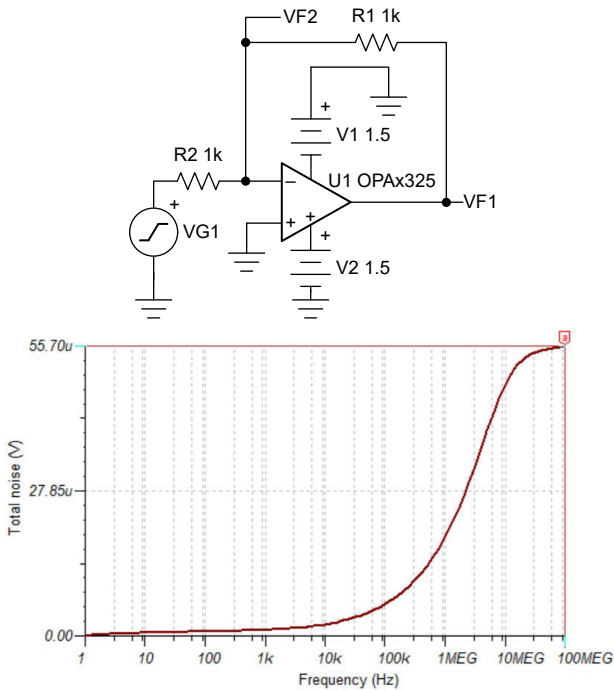


Figure 6. The OPA325 RMS noise in an inverting configuration

Figure 7 shows the REF7050 total noise (RMS) of about 2.2µV and has very little impact on the total

system noise. Including it in Equation 2 yields a total noise of 55.7µV. If you neglect the voltage reference noise, Equation 1 gives you 55.6µV. If you limit the OPA325 bandwidth to 2MHz, the noise is about 18µV and the total system noise is 43µV, clearly dominated by ADS8860 noise.

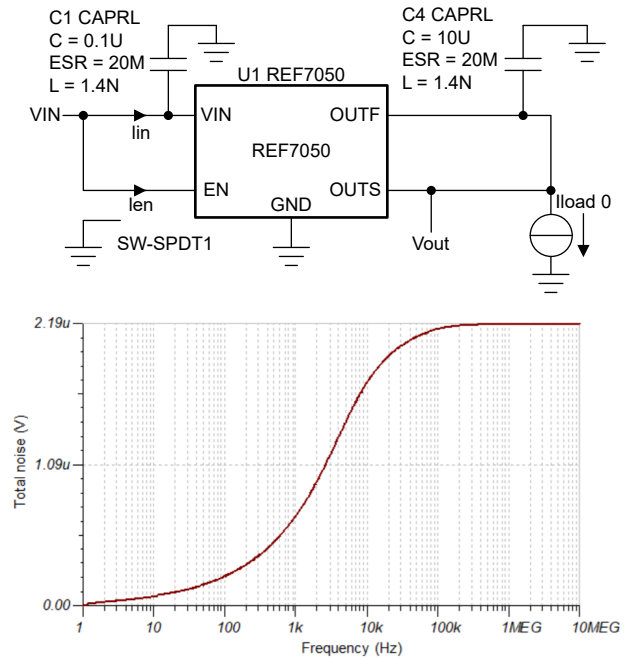


Figure 7. REF7050 RMS noise

Equation 4 expresses the total signal-to-noise ratio (SNR) of the system as:

$$SNR_{total} = 20 \log \left(\frac{V_{FSR_{rms}}}{V_{ntotal}} \right) \quad (4)$$

With a total noise of 55.6µV, the total SNR is 90dB. With the OPA325 bandwidth filtered to 2MHz, the total SNR is 92.2dB, a degradation of less than 1dB from the original SNR of the ADS8860, 93dB.

Input offset voltage and drift

The offset voltage of the op amp is a source of error and affects system accuracy. With a 5V full-scale voltage range, the quantization error for the ADS8860 (16 bits) is $5/(2^{16} + 1)$, which is 76µV. To avoid quantization errors and maintain system accuracy, target one-half LSB, or 38µV. While you can calibrate the input offset voltage out,

offset drift involves more complex calibration methods. Applications such as automotive and downhole drilling require much higher temperatures than lab and field instrumentation, test and measurement, and medical instrumentation. Modern high-precision op amps using techniques such as zero drift or e-trim™ offer the

advantage of very low offset voltage and drift, well below the desirable LSB size, and help achieve higher system accuracy.

Table 1 lists a few precision op amps from TI with various technologies.

Devices	Technology	Vs (V)	Vos max (µV)	TCVos, typical (µV/°C)	Bandwidth (MHz)	Broadband voltage noise (nV/√Hz)
OPA392	e-trim™	1.7-5.5	10	0.18	13	4.4
OPA325	Laser trim, zero crossover	2.2-5.5	150	2	10	9
OPA328	e-trim™, zero crossover	2.2-5.5	50	0.15	40	6.1
OPA383	Zero drift	2.7-5.5	5	0.025	2.5	32
OPA192	e-trim™, multiplexer friendly	4.5-36	25	0.1	10	5.5

Table 1. Low noise precision op amps for driving high resolution ADC'S

Settling time

A wide bandwidth amplifier with a high slew rate, low output impedance and high phase margin settles faster. When driving the ADC, select an op amp with a settling time to the required resolution that matches the ADC acquisition time. Remember that the acquisition time is the sampling time minus the conversion time. Slowing the sampling rate down helps you relax the op-amp settling-time requirement.

Ideally, the op amp should settle within one-half LSB of the ADC to avoid errors. However, very few op-amp datasheets specify settling time up to 16 bits (0.0015%). One often-overlooked specification is the open-loop output impedance. A low open-loop output impedance means a higher phase margin, which in turn means a faster settling time. Furthermore, the shape of the open-loop output impedance affects circuit stability. A flat (resistive) open-loop output impedance op amp is much easier to compensate. A charge bucket resistor-capacitor filter at the output of the op amp creates a pole and degrades the phase margin but minimizes output voltage

droop during the sampling time. Depending on the pole location, you may see excessive ringing (overshoot), which affects the settling time.

Figure 8 shows a circuit using the OPA328 to drive the ADS8860. The sampling rate is set at 500kSPS. The acquisition period of the ADS8860 is $T_{acq} = 2\mu s - 710ns = 1,290ns$.

Lowering the sampling rate to 500kSPS allows the circuit to settle much faster at 425ns, well below one-half LSB.

Figure 9 shows the OPA328 paired to the ADS8860 and uses the circuit to simulate the settling time (**Figure 10**).

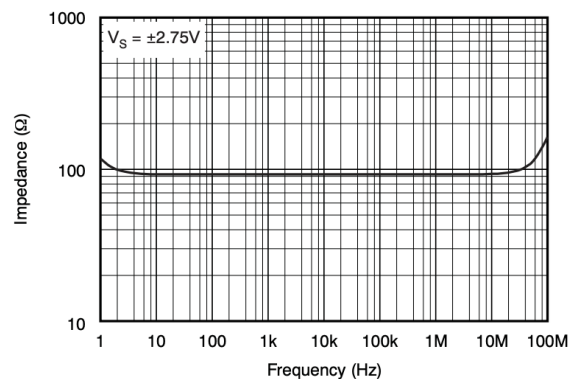


Figure 8. OPA320 open loop output impedance vs. frequency

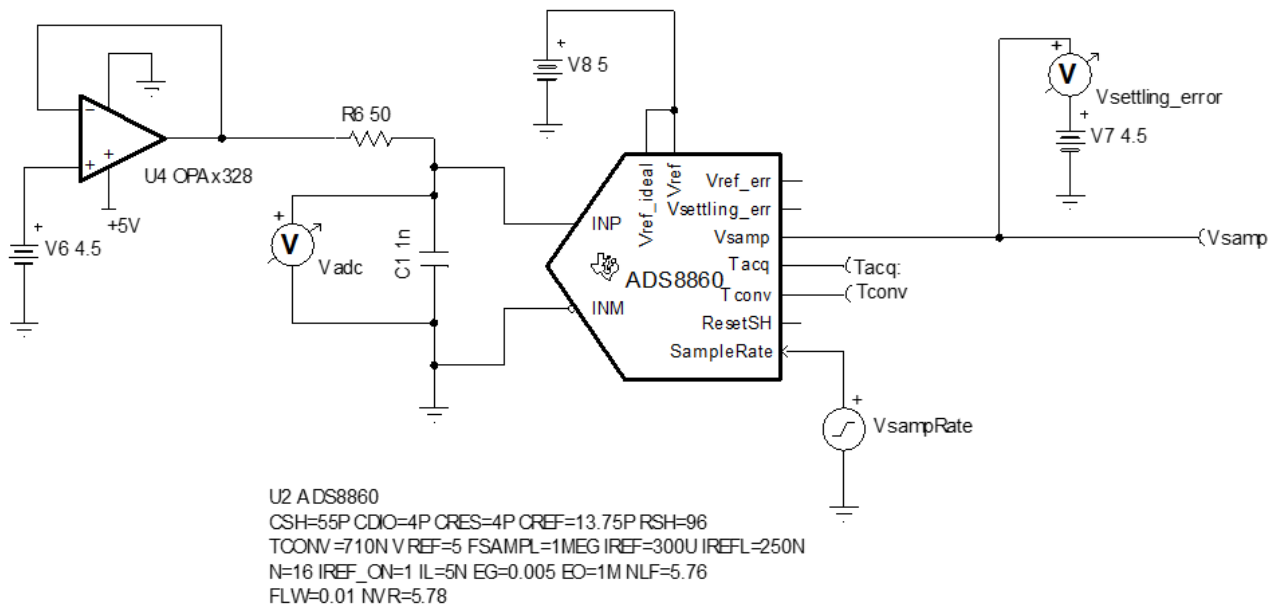


Figure 9. OPA328 driving the ADS8860

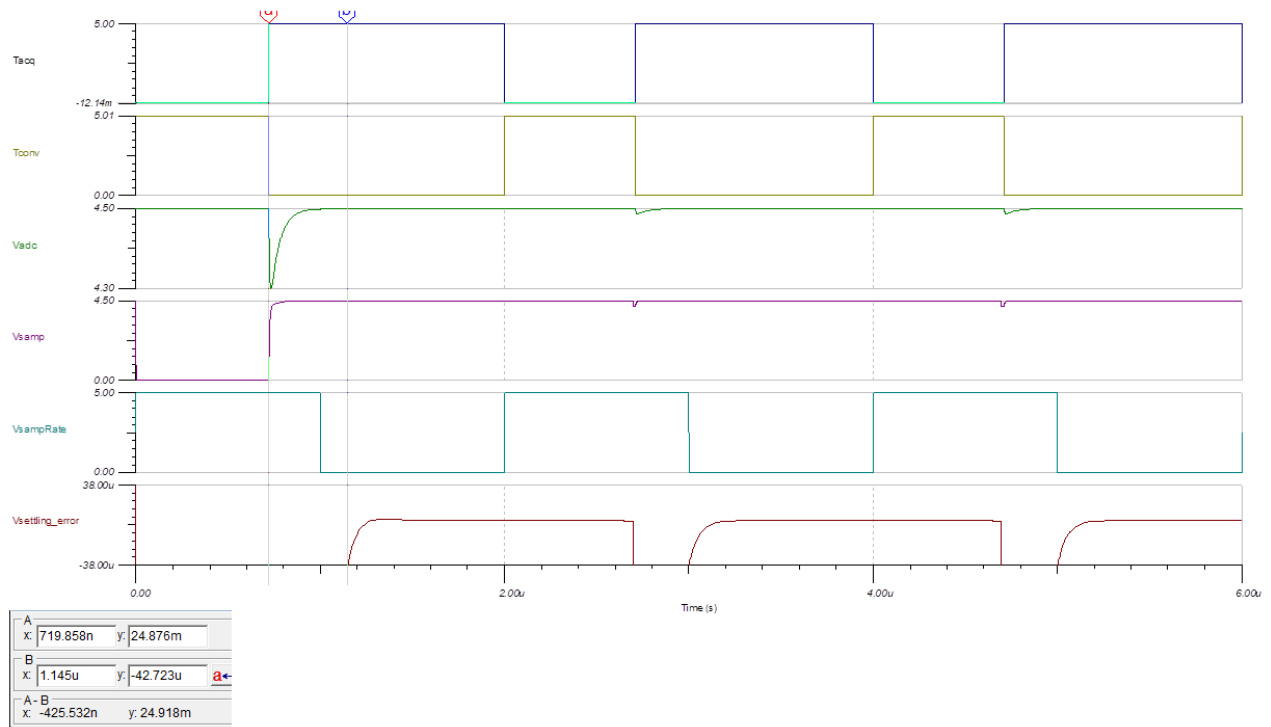


Figure 10. OPA328 settling time driving the ADS8860

Stability

Optimizing the circuit for settling time and noise performance must not come at the expense of stability. The op amps discussed throughout this article have a low, flat open-loop output impedance, which makes compensation much simpler.

Figure 11 shows the OPA328 driving a 1nF capacitor with an isolation resistor outside the feedback loop of 50Ω, the same one used to drive the ADS8860. The phase margin is 61 degrees, guaranteeing stability for a reliable design.

Op-amp stability is paramount. If the op amp is unstable or on the verge of becoming unstable, with severe ringing and overshoot, nothing else matters.

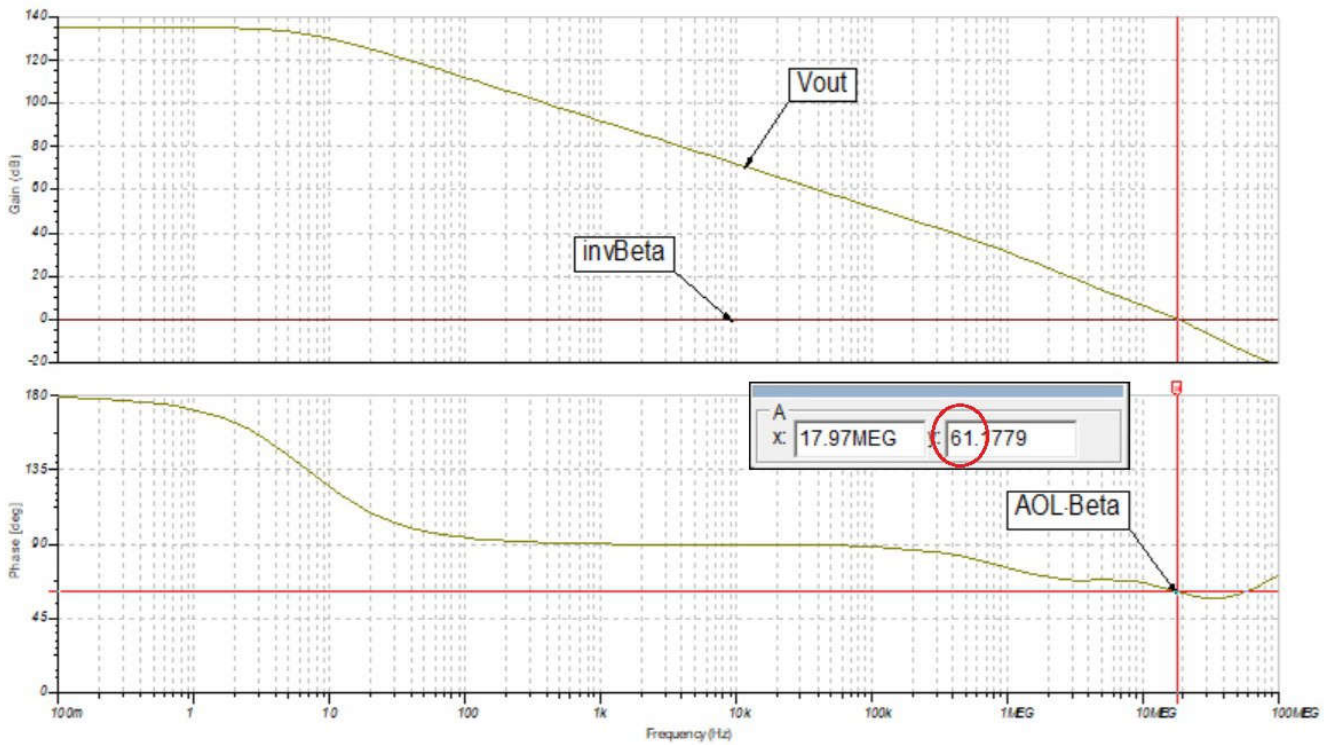
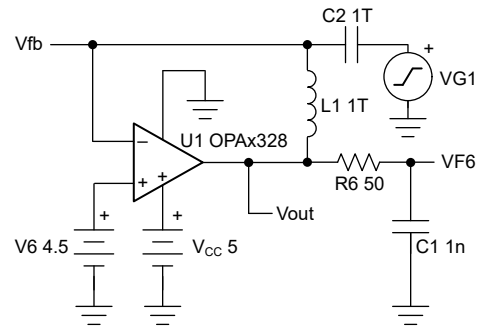


Figure 11. OPA328 open loop gain and phase margin with a heavy capacitive load

Conclusion

The choice of op amp as an ADC driver starts with the application. Portable equipment for test and measurement, medical apparatuses and barcode scanners all rely on low power consumption, whereas gas exploration, displacement measurement and semiconductor test equipment require higher resolution and therefore low-noise precision op amps. There is no panacea when it comes to op-amp selection for a given ADC; rather, there are optimization schemes for one aspect over others.

About the author

Soufiane Bendaoud is business development manager for precision amplifiers at Texas Instruments, with more than 25 years of analog signal chain expertise. He has authored more than 60 technical articles, application notes and papers, and regularly provides technical training to engineers around the world.

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