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Selecting the Right Buffer Operational Amplifier for an A/D Converter

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ABSTRACT

Most DSP systems require the presence of data converters to interface the digital portions of the circuit. The selection of a data converter is dictated by system requirements, but the selection of the buffer operational amplifier (op amp) driving the converter is sometimes left to the user. This application note gives the user some guidelines in selecting an op amp that ensures the system uses the converter to its maximum capability.

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1 Introduction

This application note describes general techniques for interfacing op amps to A/D converters. The selection of data converter is usually made first, especially in newer and more critical applications. Some applications may have been waiting for the data converter to become available, and in other cases, the introduction of a data converter spawns new applications.

This note applies specifically to the buffer op amp that drives the A/D, and not any op-amp interface circuitry that performs signal conditioning such as gain, attenuation, offset, or filtering. Combining these functions with the buffer op amp is unwise. For example, the op amp used for A/D interfacing may be optimized for a completely different set of parameters than those used for signal conditioning. There may be both high-speed and load-compensation capacitors utilized with the buffer amplifier that would preclude its use either as a gain stage or as a filter stage.

2 Know Your Application Well

The designer needs to understand exactly what is to be accomplished by the system. The whole purpose of a converter, of course, is to act as the interface between the real world of analog voltages, and the discrete world of digital electronics. That process must provide an accurate representation of the analog voltage to the digital processor; otherwise, the processor will provide erroneous results. It is important to know:

- The level of accuracy required; the number of bits needed
- How fast the converter must operate
- The op amp’s output specifications
- The A/D input specifications
- The available voltage(s) and current(s)
- How the sensor in the system is connected (cabling)
- The nature of the analog signal being monitored
- The type of noise present in the system

2.1 To Use, or Not to Use, an Op Amp

This is an important question. Some applications may already have the correct span and offset to interface directly with the A/D, in which case no op amp is required. Attempting to use one may actually degrade system performance. However, careful attention must be paid to the output specifications of the application circuit and the input characteristics of the A/D converter.

2.2 Has the Selection Already Been Made?

Many A/D data sheets include application notes that specify a buffer op amp. Unless there are overriding reasons to change, follow the recommendation. In most cases, that particular op amp has already been used to prototype an evaluation circuit, and it is known to work.

In some cases, however, newer op amps have been introduced since the data sheet was published. A newer op amp may be able to improve performance of the overall conversion system. A rule-of-thumb is to look for improved op amps similar to the one already used as a buffer. If a dc application uses an op amp with low offsets, a newer op amp with even lower offsets may be used to reduce or eliminate offset-nulling-adjustment potentiometers in the circuit. If a high-speed application uses a high-speed op amp, an op amp with similar characteristics that is even higher speed may yield a better design.

2.3 Accuracy vs Resolution

It is important for the designer to understand the difference between converter accuracy and converter resolution. The number of bits determines resolution of a converter. Insufficient resolution is not error; it is a design characteristic of the A/D. If a given converter's resolution is insufficient, use a converter with better resolution (more bits). Table 1 shows the number of bits and the corresponding voltage step size for three popular voltages:

Table 1. DC Bit Step Size for A/D Converters

BITS	STATES	3 V	5 V	10 V
1	2	1.5	2.5	5
2	4	0.75	1.25	2.5
3	8	0.375	0.625	1.25
4	16	0.1875	0.3125	0.625
5	32	0.09375	0.15625	0.3125
6	64	0.046875	0.078125	0.15625
7	128	0.023438	0.039063	0.078125
8	256	0.011719	0.019531	0.039063
9	512	0.005859	0.009766	0.019531
10	1 024	0.002930	0.004883	0.009766
11	2 048	0.001465	0.002441	0.004883
12	4 096	0.000732	0.001221	0.002441
13	8 192	0.000366	0.000610	0.001221
14	16 384	0.000183	0.000305	0.000610
15	32 768	9.16E-05	0.000153	0.000305
16	65 536	4.58E-05	7.63E-05	0.000153
17	131 072	2.29E-05	3.81E-05	7.63E-05
18	262 144	1.14E-05	1.91E-05	3.81E-05
19	524 288	5.72E-06	9.56E-06	1.91E-05
20	1 048 576	2.86E-06	4.77E-06	9.56E-06
21	2 097 152	1.43E-06	2.38E-06	4.77E-06
22	4 194 304	7.15E-07	1.19E-06	2.38E-06
23	8 388 608	3.58E-07	5.96E-07	1.19E-06
24	6 777 216	1.79E-07	2.98E-07	5.96E-07

The bit step size can become critical, especially for portable equipment where there is a requirement to operate from a low voltage supply to minimize the number of batteries. The buffer amplifier, if it includes gain, will use large resistor values, lowering its noise immunity. These designs will involve a lot of trade-offs.

For fast ac or RF applications, resolution of an A/D converter is usually expressed either as dynamic range or as total harmonic distortion (Table 2).

Table 2. Converter Bits, THD, and Dynamic Range

BITS	STATES	THD (%)	DYNAMIC RANGE
4	16	0.250000	25.6
8	256	0.390625	49.9
10	1 024	0.097656	62.0
12	4 096	0.024414	74.0
14	16 384	0.006104	86.0
16	65 536	0.001526	98.1
18	262 144	0.000381	110.1
20	1 048 576	0.000095	122.2
22	4 194 304	0.000024	134.2
24	16 777 216	0.000006	146.2

For a given analog input, accuracy is the deviation (error) of the digital output from the theoretical value. There are many sources of A/D error, ranging from offsets, gain, and linearity errors for dc applications to harmonic distortion, noise, and spurs in ac applications. Usually, these errors are less than 1 LSB in magnitude. A very common method of compensating for A/D error is to use a converter that has one or two bits more resolution than the application requires. With the cost of converters coming down, and more advanced models being introduced every day, this may be cost effective. A more detailed discussion of A/D errors can be found in Gaddy[1].

As a rule-of-thumb, every other component in the conversion system should be at least 5 to 10 times better than the converter. This will keep these components from being the dominant error source in the system.

When the signal to noise + distortion (SINAD) of an op amp is specified in the data sheet, there is an easy way to determine if it is suitable for use with a given A/D converter. Looking at the data sheet for a TLV2462, for example, the THD+ Noise is listed as 0.006%. Converting the THD+N to SINAD gives 84.4 dB. The equivalent number of A/D bits, or ENOB, is given by:

$$ENOB = \frac{SINAD - 1.76}{6.02} = 13.7$$

This is the very best that can be expected from the op amp. The data sheet conditions for the 0.006% THD+N are for a supply voltage of 3V, a 10k load, a gain of one on a 1 kHz sine wave at 25°C. Deviate from any of these conditions and the performance will degrade.

The performance of this op amp with an A/D can be as bad as 12 bits in inverting configurations, and less than 10 bits in a noninverting configuration[2]. Therefore, this device puts a serious constraint on system accuracy.

Another way to evaluate whether an op amp is suitable for an A/D is to convert the op-amp noise to voltage, and then compare that voltage to the step size in Table 1.

A/D input voltage range is a very important specification. If a voltage is applied that is out of this range, the A/D input may be damaged. Designers can insure that the A/D is not damaged by using a rail-to-rail op amp that operates off of a voltage range equal to the A/D input range. Beware of this technique. It will prevent A/D damage, but not all rail-to-rail output devices are truly rail-to-rail. They are a few mV within a rail to a few mV within the other rail. This will result in lost codes at each extreme of the A/D, and distortion in sinusoidal waveforms that have amplitudes close to the op-amp rails. For maximum accuracy, design applications to avoid the small voltage rails that remain in the rail-to-rail op-amp output voltage range. Fortunately, if the op-amp output exceeds the input range of the converter, the resistor in the RC network (often specified with the A/D converter inputs) will also limit the current to safe values.

3 Types of Applications

There are some broad categories of AD applications. There is a high probability that your application will fall into one of these. Each has very different requirements for op-amp parameters:

- *Portable:* single supply, rail-to-rail, low power, low voltage
- *General-Purpose:* low cost
- *Instrumentation:* low offset voltages and currents
- *Audio Conversion:* low harmonic distortion and noise
- *High Speed:* Common mode input capacitance, impedance, and voltage, differential gain and phase error, gain bandwidth product, input capacitance, overshoot factor, maximum-output-swing bandwidth.

3.1 Portable

This is a special class of application. Portable equipment manufacturers demand a lot from op amps:

- *Single Supply:* The op amp should be optimized for operation from a single supply.
- *Low Supply Voltage:* Power supply voltage for portable equipment should be specified based on how many batteries are present—in most cases, the fewer the better. The op amp should be optimized for the voltage used in the system. A low supply voltage aggravates several design problems. It reduces the system dynamic range, and it contributes to a higher signal-to-noise ratio. As the batteries discharge, these problems become worse.

- *Low Power:* All other op amp and converter parameters may be important, but performance is carefully weighed against battery life. Nobody is going to buy the product if it drains batteries in 5 minutes (no matter how good the performance is). The op amp should have as low a power consumption as possible. Feedback and other resistors should be as high as possible, without compromising the noise performance of the circuit. CMOS op amps are generally the lowest power devices, but BiFETs and Bipolar can also be low power. Low power also mean low speed, especially if it is also a low-voltage device.

- Rail-to-Rail: This is critical because a significant portion of the dynamic range will be lost at low supply voltages. The input common-mode range must exceed the power rail, the A/D-input range, and any connected-sensor range, even when the batteries are at their end-of-life voltage.

Buffer op amps should be selected with these primary characteristics. Once potential op amps with these characteristics are identified, the designer should look at secondary characteristics that, in any other type of application, would be primary.

Portable devices often make use of selective shutdown of unused functions to conserve power. The op amps used in such devices must have a dedicated shutdown function. Shutdown may not mean total shutdown because internal bias components on the IC may still draw current. The designer must take into account shut down and wake-up times and transients during shutdown and wake-up.

Suggested op amps for portable systems include:

- Rail-to-Rail Output:
  - TLC2211
  - TLC225X

- Rail-to-Rail Input and Output:
  - TLV245X
  - TLV246X
  - TLV247X
  - TLV276X
  - TLV277X
  - TLV240X

3.2 General-Purpose

This type of application is driven by one overriding op-amp parameter: *cost.* All too often, the designer picks a very-old-technology part, such as a 741 or LM324. The only real advantage that these devices provide is a legacy of successful applications. So many designs have used these parts in the past that their characteristics, both good and bad, are well known.

Often times, these legacy parts are designed into new products because there is a bin of them sitting in the prototype lab, and it is easier to use them than it is to obtain sample parts. If the system design goals can be met or exceeded using these parts, all is well. However, designers must beware of using these parts in demanding applications because marginal performance will eventually damage the reputation of both the product and its manufacturer.

The difference between modern low cost op amps, legacy parts, and high cost op amps is in which parameters are optimized. A legacy part is optimized for *nothing*. A modern low cost op amp may be optimized for one or two parameters. A high cost part may be optimized for several parameters, targeting a specific class of applications.

Before using a legacy part, consider the following:

- Does the system need low dc drift errors (for medium to high-resolution systems)?
- Does the system need high common-mode rejection?
- The input impedance must not load the sensor.
- The output must be able to drive the A/D input.

Look at the following low-cost op amps whenever a 741 or LM324 will not meet system specifications:

- General-Purpose:
  - TLC07X
  - TLC08X
- Rail-to-Rail Output:
  - TLC2201/2
  - TLC2272/4
  - TLV2221
  - TLV2231
  - TLV2432
  - TLV2442/4
- Rail-to-Rail Input and Output:
  - TLV246X
  - TLV247X
  - TLV277X

3.3 Instrumentation

This type of application is concerned with the physical monitoring of a real-world value using a mechanical to electrical converter of some type. It may be a strain-gauge type of pressure transducer, an RTD temperature monitor, or any of dozens of more exotic sensors.

Speed is not an issue in transducer-based systems because the mechanical changes that cause transducer responses usually occur relatively slowly. Most transducer-interfaced systems either present their results on a visual display, or send them to a data acquisition system at regular intervals. Depending on the application, these intervals can range from a few milliseconds to once every few years. Therefore, the converter and op amp do not have to be fast. They can be optimized for good dc characteristics at the expense of speed. This also means that successive approximation (SAR) type A/Ds can be used for the converter.

If the unit is a voltmeter or multimeter, however, the input can change rapidly. A flash A/D converter may be required, or a sample-and-hold may have to be used on the input of the A/D. The sample and hold is probably fabricated directly on the A/D, but carefully read the device data sheet to make sure.

3.3.1 Selecting an Op Amp for an Instrumentation Application

Important op-amp parameters include:

- *Supply Voltage:* The op amp must be optimized for operation at the available supply voltage(s).

- *Input Voltage Range:* The op amp must be able to handle the expected extremes of input voltage. What may not be so obvious is what happens should the transducer fail open or shorted. This is a real world consideration. When the transducer is remotely located at the end of a cable—as in medical equipment—cable breaks and shorts are almost inevitable. If the transducer cable has a connector, the designer can count on the fact that somebody is going to power up the equipment without the cable attached, then plug the cable in, or unplug the cable while the instrument is being operated. Does the resulting condition potentially damage the op amp or A/D? What about voltmeters? Has the input been designed so that no reasonable operator error would damage the op amp or A/D?

- *Output Voltage Swing:* The op amp must never violate the absolute ratings of the A/D input, even if the transducer fails open or shorted.

- *Input Offset Voltage or Current:* This contributes a dc offset to the system, scaling the output bits of the converter up or down. It can be discounted in autocalibrating systems.

- *Input Offset Voltage Long Term Drift:* This contributes a dc offset to the system that occurs (and gets continually worse) after a calibration has been performed. It can be discounted in autocalibrating systems.

- *Temperature Coefficient of Input Offset Voltage or Current:* These contribute to dc offset errors in the system as the temperature changes. These cannot be discounted on autocalibrating systems unless the system performs autocalibration periodically. Beware of thermal drifts in instrumentation systems. These can be compensated by frequent autocalibration cycles (discussed later), but thermal drift is indistinguishable from signal.

- *Other Considerations:* Some transducer interfaces (such as strain gauges) require differential- or instrumentation-amplifier types of interface. In these applications, common mode rejection ratio is important.

The instrumentation-amplifier topology should be used instead of the differential-amplifier topology. Although this increases the number of op amps and therefore the cost of the circuit, it is the best option because it matches the input impedance of the inverting and noninverting inputs. An instrumentation-amplifier topology also matches the input impedance of both inputs for a sensor, which can be important for sensors that have a low output voltage range.

Using inverting op-amp circuit topologies can minimize common mode voltage; otherwise, common mode voltage will introduce nonlinear errors because it is sensitive to input-voltage.

The output impedance of the op amp is also important. In many cases, the op amp must charge the internal A/D capacitance, which will limit the sample rate of the A/D conversion system (discussed later). If the A/D is a high-resolution type (14 or 16 bits), the output impedance of the op amp forms a voltage divider with the PCB trace that connects the op amp to the A/D input. The output impedance is also temperature and frequency dependent.

Recommended amplifiers for instrumentation applications:

- TLC220X
- TLE202X
- TLE214X
- TLE22X7

3.3.2 Remember: Other Components Produce Errors in Instrumentation Applications

If the designer discounts errors from the op amp and converter, only a network of gain-setting resistors, (probably with 1% tolerance) is left. A whole literature exists on statistical analysis of these multiple-resistor networks, but such is beyond the scope of this note. Taking a common sense approach, it is obvious that in a high gain circuit, the effect of 1% tolerance in a feedback resistor is going to be a lot worse than the effect of 1% tolerance in an input resistor. Even ignoring the effects of additive tolerances and so on, it is obvious from Table 1 and applying the 5-to-10-times rule, that the very best A/D that should be used in such a system is 3 to 4 bits—a dismal prospect. If 0.1% resistors were used, the best A/D converter would be 6 to 7 bits.

The standard technique for dealing with this is to add trimming potentiometers to the conditioning circuitry. Cermet is the best adjustment element, because it is continuous. Wire wound potentiometers have discreet steps and can be inductive. Carbon potentiometers can have thermal noise.

Theoretically, any dc accuracy can be achieved by using a trim potentiometer (trimpot) to cancel dc errors. Unfortunately, that is not the case in practice, because the trimpot has thermal characteristics. Good quality models are rated at ±100 ppm/°C. Assume that the pot forms a substantial portion of the adjustment range. From Table 1 and the 5-to-10-times-better rule, the best converter that can be used is 10 to 11 bits, and that is over a temperature range of only ±1°C—not very useful. Assuming an ambient temperature environment (±10°C), an 8-bit converter operating with 7-bit accuracy is reasonable when it has been calibrated with a trimpot.

Some applications do not allow trimpots, and others require more accuracy. The next level of accuracy can be achieved with select-in-test resistors. The variable element is taken out of the circuit; the calibration is done once and for all. The very best temperature coefficient of fixed resistors, however, is ±25 ppm/°C. This means that 12 to 13 bits of conversion are possible at a single temperature, or 9 to 10 bits over a small range of room temperatures.

The best way to combat dc errors is to use the processing power of a DSP chip in the circuit to autocalibrate the system at power up. During autocalibration, a known reference is applied to the input, and the A/D converter output is sampled by the DSP. The DSP applies a correction factor to all readings received from the system, canceling the effects of resistor tolerances, resistor temperature drifts, and any transducer effects. Whenever more accuracy is needed, the system can interrupt normal operation at prescribed intervals to rerun its autocalibration routine. The accuracy of these systems is limited by the accuracy of internal references and temperature changes subsequent to running the autocalibration routine.

Provided that the ambient temperature does not change between autocalibration cycles, autocalibration is a powerful technique that works well. If a portable voltmeter, for instance, is taken from indoors to outdoors, it should be turned off and re-powered so that the autocalibration cycle can run again. If a portable instrument has been moved from one environment to another, the ambient temperature changes will slowly creep into the unit and its autocalibration will be affected. The solution is to power down and up as the unit warms or cools.

Reasonable accuracy can be expected from such dc acquisition systems. In a portable unit,12 to 14 bits are possible, and perhaps as many as 16 or more in a lab unit. Be very cautious about more accuracy because the moment an air conditioner kicks in and puts air into the unit, it will start to drift.

3.4 Audio Conversion

This type of application occurs in the recording or broadcasting of studio audio, when an op amp is interfacing with an A/D converter for the purpose of converting analog audio into digital, allowing digital manipulation of the sound path.

Instead of dc voltages, as in the previous section, the op amp and converter need to process audio information composed of sine waves with varying amplitudes. There can be a wide dynamic range, creating some segments that are quiet and others that are quite loud.

The converter itself must be able to take samples at a rate above the threshold of human hearing (about 20 kHz). The A/D converter must sample at a frequency that will not cause 20 kHz to alias and be mixed back to the ear at the wrong frequency. The Nyquist sampling limit forces the converter to operate at greater than twice the maximum audio frequency. Very often that conversion frequency is 44.1 kHz, the standard frequency for compact disk encoding, or 48 kHz for DAT. Oversampling by a factor of two requires doubling the conversion frequency. Almost without exception, a sigma delta converter will be used for this type of application.

The minimum number of bits required for audio conversion is 16. If the only source of noise in the system were the converter itself, the noise would be 1 part in 65536, or a signal to noise ratio of 96.3 dB. Cost is usually of secondary concern in recording / broadcast equipment. Many pieces of equipment employ 18, 20, 22 even 24 bit A/D converters to raise the signal to noise ratio.

The following op-amp parameters are important for audio applications:

- Bandwidth for 0.1 dB flatness: The op-amp response should be flat over the entire frequency range from 20 Hz to 20 kHz.
- Crosstalk: If a dual op-amp package is used, crosstalk will reduce the stereo separation of the system.
- Input noise voltage and current: For example, the op-amp circuitry should produce a noise level of –116.3 dBV or less for a 16 bit audio system. This is a very demanding requirement.
- Gain bandwidth product: The op amp must have sufficient gain at 20 kHz.
- Noise figure
- Total harmonic distortion

Suggested op amps for audio applications:

- ±15V Supply:
    - NE553X
    - OP27
    - TLE20X7
    - TLE2227
- ±5V Supply:
    - TLC220X
- 5V Supply:
    - TLC227X

3.5 High Speed, RF, and Video

This is a new class of application that has become possible only with the release of new parts that can handle the frequencies involved. Poor design can cause RF spurs in transceivers, noisy video, and even oscillation. An op amp should be much faster than the conversion frequency of the converter so that it does not degrade the converter's performance.

Input signals for this type of application can be very weak and subject to all kinds of noise and distortion. In particular, the power-supply rejection ratio must be high, because these applications frequently include high-speed digital circuitry in close proximity to the analog circuitry. A well-regulated supply and proper decoupling techniques are important.

Important op-amp parameters include:

- *High Slew Rate:* Current feedback amplifiers are better than voltage feedback amplifiers. The worst case slew rate will be on power up when the system may have to slew across the entire input range. The slew rate required by an application is defined by:

  $$Slew\,Rate(V/\mu s) \geq 2\pi \times Peak Voltage\,Swing \times Application\,Bandwidth\,in\,MHz$$

  Therefore, a 50-MHz application with a 1-Vp A/D input requires an op-amp slew rate of 628 V/µs to slew across the entire input range. This is obtainable with some members of the THS series of op amps from Texas Instruments. There is a slight break for system designers: for ac applications; the op amp is seldom if ever required to slew across the entire input range. Remember that to avoid the op amp being a limiting factor on overall system performance, the slew rate should be as high as possible. Once the input capacitor of the A/D converter is charged, the effective slew rate required goes down dramatically.

- *Settling Time:* This adds to the A/D input capacitor charging time, and limits the A/D sample speed. Settling time is sensitive to input amplitude, input overdrive, and load. The worst-case op-amp setting time can be calculated from:

  $$t_S = 0.11\,(1+N)\,/\,f_{-3dB}$$

  where N is the number of A/D bits and f_{-3db} is the amplifier’s –3dB corner frequency

  The setting time required for a 12-bit A/D converter and a 100-MHz op amp is 14.3 ns. No such parts exist! Fortunately, the primary limitation for smaller changes in voltage is the slew rate of the amplifier. The settling time for voltage steps smaller than full scale is difficult to predict. It is dependent on signal amplitude and stray capacitance. Choose an op amp with fast settling time, and be aware that initial conversions may contain errors due to slew rate and settling time limitations.

- *Common-Mode Input Capacitance, Impedance, and Voltage:* These parameters are important in differential applications, such as balanced line drivers. At high speeds, even small amounts of capacitance can limit the maximum usable frequency and make it susceptible to oscillation.

- *Differential Gain and Phase Error:* This is important in video circuits. The NTSC waveform has large dc steps (called the front porch and back porch) that frame the video modulation.

The color-burst signal is inserted into the back porch of the horizontal-blanking signal. A large differential gain error can degrade the color information. These errors are actually tested at the colorburst frequency (3.58 MHz).

- *Gain Bandwidth Product:* This becomes critical at high speeds. Not only should the op amp be able to maintain its gain over the frequency range of interest, but it should not do so at the expense of other parameters.
- *Input Capacitance:* This parameter is absolutely critical. It limits both the speed of the circuit and its tendency to oscillate.

The load is a concern in high-speed applications. Flash converters, for instance, have a large, nonlinear capacitive input. This can be compensated by using an RC de-coupling filter on the op-amp output. The A/D manufacturer usually recommends the values. If not, experiment with resistors in the 10-Ω to 200-Ω range, and capacitors in the 1-nF to 10-nF range.

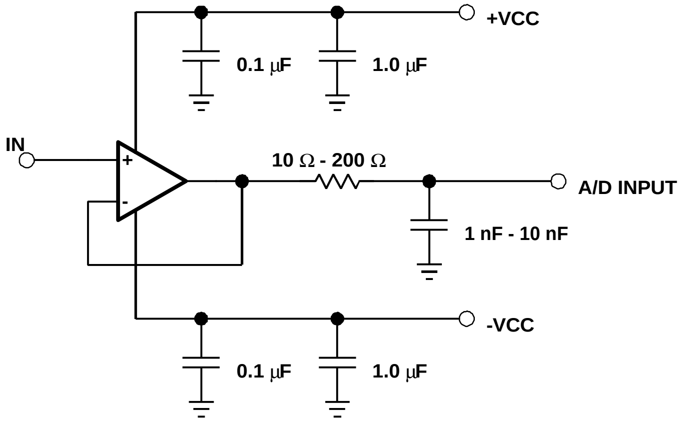

Figure 1. Isolating the Input Capacitance of an A/D Converter

Note that proper bypassing is imperative for the buffer op amp.

The output filter:

- Reduces the level of broadband noise,
- De-couples the input capacitance of the A/D from the amplifier,
- Eliminates high-frequency pulsed-charge effects from the sampling front end of the converter, and
- Presents well-behaved low source impedance to the A/D.

The following op amps are recommended for high-speed applications:

- THS3001

- THS4011
- THS7001

4 Differential Output Op Amps—a Way to Eliminate That Transformer

Differential-output op amps have been increasing in popularity in recent years. Differential output op amps actually revive a design concept almost 50 years old. The original tube-based op amp, the K2-W, was a differential-output device. A differential-output op amp is a way of interfacing directly to differential-input A/D converters, without using a transformer.

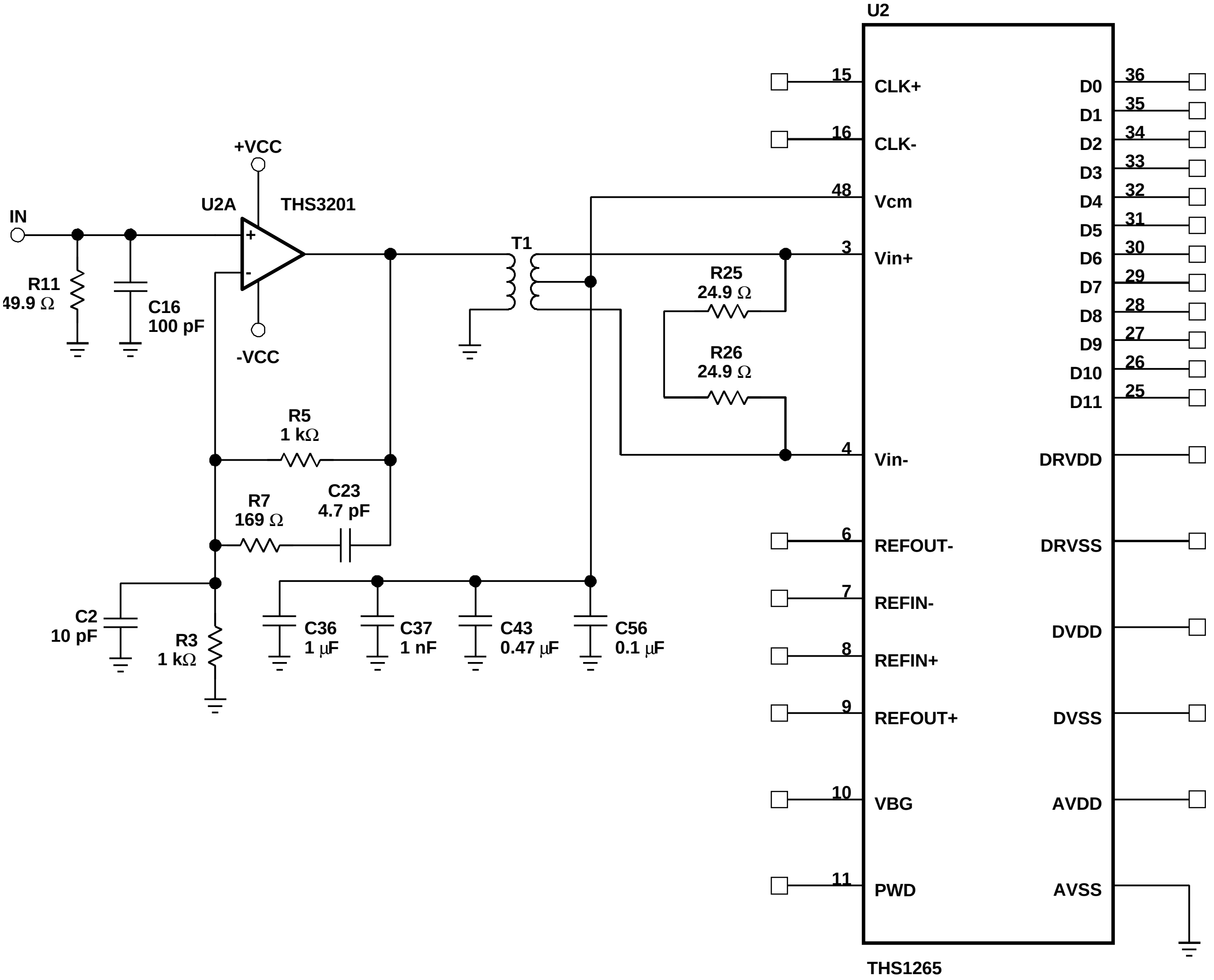

Figure 2. Traditional Method of Interfacing to Differential-Input A/D Converters

Figure 2 shows how differential A/D converters have been interfaced in the past. The differential inputs of the A/D converter are connected through a transformer to a single-ended op amp / signal source. This schematic is a portion of the schematic[3] for the THS1050 EVM. A high-speed current-feedback amplifier (the THS 3201) is matched to the input impedance by R11, a 49.9-Ω resistor. R5 and R3 set the gain at two. Capacitors C16, C2, and C23, and resistor R7 are compensation components. C36, C37, C43, and C56 bypass V_{CM}, the common mode voltage of the A/D, which is coupled to the center tap of T1.

There are some disadvantages to this approach, however:

- It does not take advantage of the noise rejection possible with differential circuitry, although it does provide a stable input to the A/D.
- The circuit does not include dc in the frequency response. By definition, transformer T1 isolates dc and limits low-frequency ac response of the circuit. Because there are always offsets inherent in any system, the ac range of the circuit must be limited to the range that will not allow dc offsets to produce clipping or nonlinearity. Therefore, a number of counts at the low and high end of the A/D range are lost. For a 12-bit converter that is capable of 4096 (1000H) states, perhaps only 3840 (F00H) can actually be used. Therefore the converter is effectively less than 12 bits. This is just as constraining to system accuracy as the ENOB.

Figure 3 shows an improved A/D Interface. A differential op amp, the THS 4141, has been substituted for the single-ended op amp. This allows the transformer to be eliminated. R1, R2, R4, and R9 set the gain of the op amp; C1 and C13 are compensation capacitors. C15 and C29 compensate for converter input capacitance, and R10 and R13 isolate C15 and C29 from the op-amp output. Note that the common-mode pin of the converter is connected to the common-mode pin of the differential op amp, and is heavily bypassed.

The main advantage of this circuit is that it includes dc in the frequency range—it is dc accurate. Offsets can be cancelled and the full range of the converter can be used. The circuit is still not totally differential, because the input voltage remains ended. The evaluation board on which this schematic was based was not set up for differential input voltages.

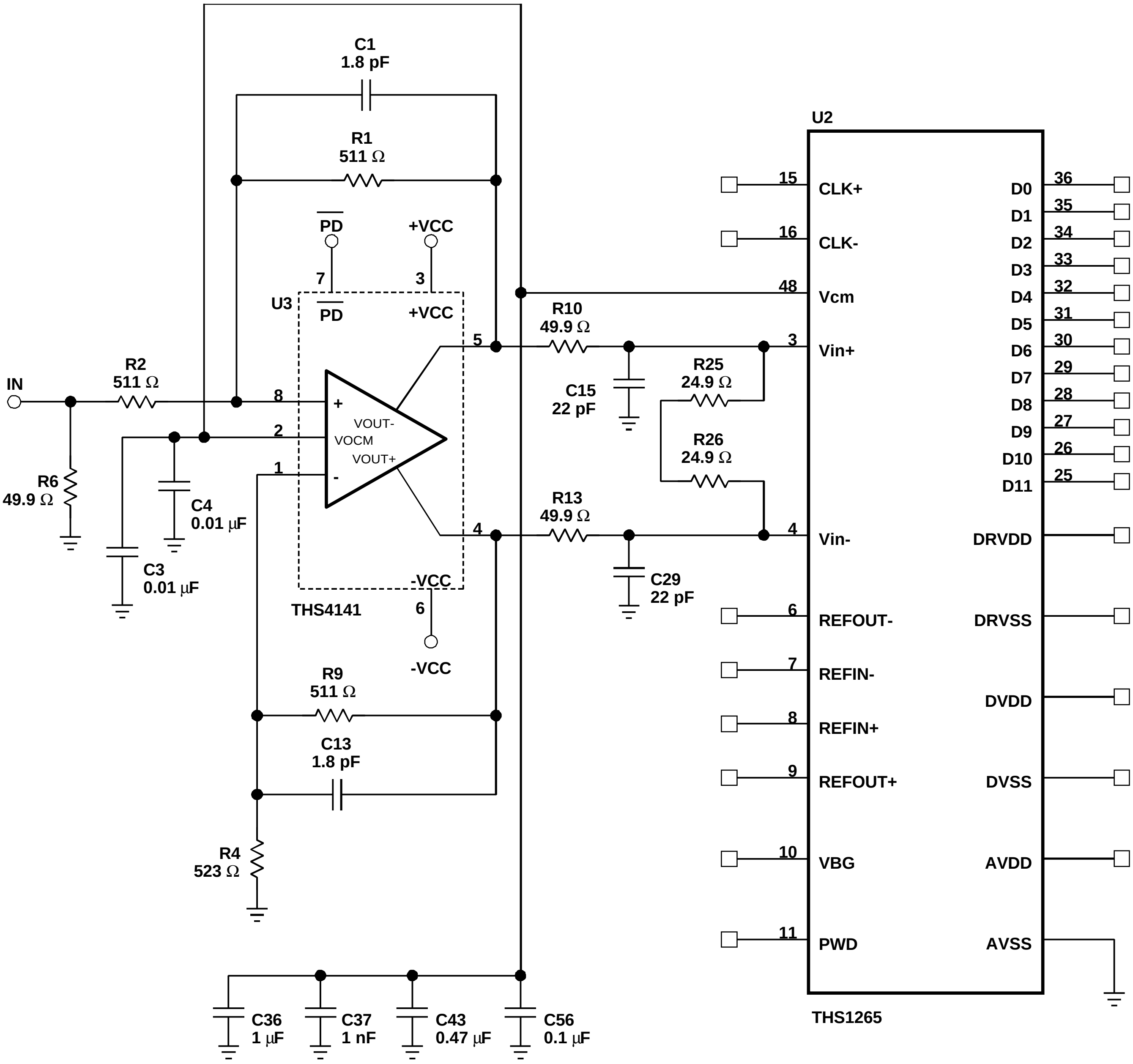

Figure 3. Improved Differential A/D Interface

5 Bibliography

In addition to the material directly referenced, the following articles and reports provide useful information:

Op-Amp Considerations for Driving ADCs, Ronald Mancini, TI Marketing Presentation, June 5, 2000.

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6 References

1. *Selecting an A/D Converter*, Larry Gaddy, Burr Brown Application Bulletin AB-098.
2. *Evaluating Operational Amplifiers as Input Amplifiers for A-to-D Converters*, James Karki, Texas Instruments Analog Applications Journal, August 1999.
3. *THS 1050/1060 EVM User's Guide*, Texas Instruments, Literature Number SLAU044.

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