Chapter VII

MATCHING IN-AMP CIRCUITS TO MODERN ADCs

Calculating ADC Requirements

The resolution of commercial ADCs is specified in bits. In an ADC, the available resolution equals $(2^n) - 1$, where n is the number of bits. For example, an 8-bit converter provides a resolution of $(2^8) - 1$, which equals 255. In this case, the full-scale input range of the converter divided by 255 will equal the smallest signal it can resolve. For example, an 8-bit ADC with a 5 V full-scale input range will have a limiting resolution of 19.6 mV.

In selecting an appropriate ADC to use, we need to find a device that has a resolution better than the measurement resolution but, for economy's sake, not a great deal better.

Table 7-1 provides input resolution and full-scale input range using an ADC with or without an in-amp preamplifier. Note that the system resolution specified in the figure refers to that provided by the converter together with the in-amp preamp (if used). Also, note that for any low level measurement, not only are low noise semiconductor devices needed, but also careful attention to component layout, grounding, power supply bypassing, and often, the use of balanced, shielded inputs.

For many applications, an 8-bit or 10-bit converter is appropriate. The decision to use a high resolution converter alone, or to use a gain stage ahead of a lower resolution converter, depends on which is more important: component cost, or parts count and ease of assembly.

One very effective way to raise system resolution is to amplify the signal first, to allow full use of the dynamic range of the ADC. However, this added gain ahead of the converter will also increase noise. Therefore, it is often useful to add low-pass filtering between the output of an in-amp (or other gain stage) and the input of the converter. Also, in most cases, the system bandwidth should not be set higher than that required to accurately measure the signal of interest. A good rule of thumb is to set the –3 dB corner frequency of the low-pass filter at 10 to 20 times the highest frequency that will be measured.

Adding amplification before the ADC will also reduce the circuit's full-scale input range, but it will lower the resolution requirements (and, therefore, the cost) of the ADC (see Figure 7-1).

For example, using an in-amp with a gain of 10 ahead of an 8-bit, 5 V ADC will increase circuit resolution from 19.5 mV (5 V/256) to 1.95 mV. At the same time, the full-scale input range of the circuit will be reduced to 500 mV (5 V/10).

Table 7-1. Typical System Resolutions vs. Converter Resolution and Preamp (IA) Gain

Converter Type	$(2^n) - 1$	Converter Resolution mV/Bit $(5\,V/((2^n) - 1))$	In-Amp Gain	FS Range (V p-p)	System Resolution (mV p-p)
10-Bit	1023	4.9 mV	1	5	4.9
10-Bit	1023	4.9 mV	2	2.5	2.45
10-Bit	1023	4.9 mV	5	1	0.98
10-Bit	1023	4.9 mV	10	0.5	0.49
12-Bit	4095	1.2 mV	1	5	1.2
12-Bit	4095	1.2 mV	2	2.5	0.6
12-Bit	4095	1.2 mV	5	1	0.24
12-Bit	4095	1.2 mV	10	0.5	0.12
14-Bit	16,383	0.305 mV	1	5	0.305
14-Bit	16,383	0.305 mV	2	2.5	0.153
14-Bit	16,383	0.305 mV	5	1	0.061
14-Bit	16,383	0.305 mV	10	0.5	0.031
16-Bit	65,535	0.076 mV	1	5	0.076
16-Bit	65,535	0.076 mV	2	2.5	0.038
16-Bit	65,535	0.076 mV	5	1	0.015
16-Bit	65,535	0.076 mV	10	0.5	0.008

Matching ADI In-Amps with Some Popular ADCs

Table 7-2 shows recommended ADCs for use with the latest generation of ADI in-amps.

Table 7-2. Recommended ADCs for Use with ADI In-Amps

ADI In-Amp	**AD8221AR**
Small Signal BW:	562 kHz
Noise (e_{NI}):	8 nV/√Hz
V_{OS}:	60 μV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	±3.9 V
CMR:	90 dB (dc to 60 Hz)
Nonlinearity:	10 ppm max
Supply Voltage:	±5 V
Supply Current:	1 mA max
0.01% Settling Time for 5 V Step:	5 μs
0.001% Settling Time for 5 V Step:	6 μs
Recommended ADI ADC#1	
AD7685, AD7687	
Resolution:	16 bits
Input Range:	0 V to 5 V
Sampling Rate:	Up to 250 kSPS
S/D Supply:	3 V or 5 V
Power:	1.7 mW @ 2.5 V and 6 mW typ @ 5 V
Comments:	Same package, the AD7685 can be driven through a simple RC from the AD8221 directly. The REF pin can be driven to fit the ADC range.
Recommended ADI ADC#2	
AD7453/AD7457	
Resolution:	12 bits
Input Range:	0 V to V_{DD}
Sampling Rate:	555 kSPS/100 kSPS
S/D Supply:	3 V or 5 V
Power:	0.3 mA @ 100 kSPS
Comments:	Single channel, pseudo differential inputs in a SOT-23 package

ADI In-Amp	**AD620AR**
Small Signal BW:	800 kHz
Noise (e_{NI}):	9 nV/√Hz
V_{OS}:	125 μV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	±3.9 V
CMR:	73 dB (dc to 60 Hz)
Nonlinearity:	40 ppm max
Supply Voltage:	±5 V
Supply Current:	1.3 mA max
0.01% Settling Time for 5 V Step:	7 μs
Recommended ADI ADC#1	
AD7610, AD7663	
Resolution:	16 bits
Input Range:	Multiple, such as ±10 V, ±5 V, ...
Sampling Rate:	Up to 250 kSPS
S/D Supply:	5 V
Power:	2.7 mA @ 100 kSPS
Comments:	Allow more and larger input ranges
Recommended ADI ADC#2	
AD7895	
Resolution:	12 bits
Input Range:	Multiple, such as ±10 V, ±2.5 V, 0 V to 2.5 V
Sampling Rate:	200 kSPS
S/D Supply:	5 V
Power:	2.2 mA @ 100 kSPS
Comments:	Allows a bipolar or unipolar input with a single supply

Table 7-2. Recommended ADCs for Use with ADI In-Amps (continued)

ADI In-Amp	**AD8225 Fixed Gain of 5**
Small Signal BW:	900 kHz
Noise (e_{NI}):	8 nV/$\sqrt{\text{Hz}}$
V_{OS}:	125 µV max
In-Amp Gain:	5
Maximum Output Voltage Swing:	±4 V
CMR:	90 dB (dc to 60 Hz)
Nonlinearity:	10 ppm max
Supply Voltage:	±5 V
Supply Current:	1.2 mA max
0.01% Settling Time for 5 V Step:	3.2 µs
0.001% Settling Time for 5 V Step:	4 µs
Recommended ADI ADC#1	
AD7661	
Resolution:	16 bits
Input Range:	0 V to 2.5 V
Sampling Rate:	Up to 100 kSPS
S/D Supply:	5 V
Power:	8 mA @ 100 kSPS with reference
Comments:	Provide a reference voltage
Recommended ADI ADC#2	
AD7940	
Resolution:	14 bits
Input Range:	0 V to V_{DD}
Sampling Rate:	100 kSPS
S/D Supply:	3 V or 5 V
Power:	0.83 mA @ 100 kSPS
Comments:	Single channel in an SOT-23

ADI In-Amp	**AD623AR**
Small Signal BW:	100 kHz
Noise (e_{NI}):	35 nV/$\sqrt{\text{Hz}}$
V_{OS}:	200 µV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	±4.5 V
CMR:	90 dB (dc to 60 Hz)
Nonlinearity:	50 ppm typ
Supply Voltage:	±5 V
Supply Current:	0.55 mA max
0.01% Settling Time for 5 V Step:	20 µs

Recommended ADI ADC#1	
AD7866	
Resolution:	12 bits
Input Range:	0 V to V_{REF} V or 0 V to 2 × V_{REF} V
Sampling Rate:	1 MSPS for both ADCs
S/D Supply:	Single, 2.7 V to 5.25 V
Power:	24 mW max at 1 MSPS with 5 V supply 11.4 mW max at 1 MSPS with 3 V supply
Comments:	Dual, 2-channel, simultaneous sampling ADC with a serial interface
Recommended ADI ADC#2	
AD7862/AD7864	
Resolution:	12 bits
Input Range:	0 V to +2.5 V, 0 V to +5 V, ±2.5 V, ±5 V, ±10 V
Sampling Rate:	600 kSPS for one channel
S/D Supply:	Single, 5 V
Power:	90 mW typ
Comments:	4-channel, simultaneous sampling ADC with a parallel interface
Recommended ADI ADC#3	
AD7863/AD7865	
Resolution:	14 bits
Input Range:	0 V to +2.5 V, 0 V to +5 V, ±2.5 V, ±5 V, ±10 V
Sampling Rate:	175 kSPS for both channels/ 360 kSPS for one channel, respectively
S/D Supply:	Single, 5 V
Power:	70 mW typ/115 mV typ, respectively
Comments:	2-/4-channel, respectively, simultaneous sampling ADC with a parallel interface
Recommended ADI ADC#4	
AD7890/AD7891/AD7892	
Resolution:	12 bits
Input Range:	0 V to +2.5 V, 0 V to +4.096 V, 0 V to +5 V, ±2.5 V, ±5 V±10 V
Sampling Rate:	117/500/600 kSPS, respectively
S/D Supply:	Single, 5 V
Power:	30/85/60 mW typ, respectively
Comments:	8-/8-/1-channel, respectively

Table 7-2. Recommended ADCs for Use with ADI In-Amps (continued)

ADI In-Amp	**AD627AR**
Small Signal BW:	30 kHz
Noise (e_{NI}):	38 nV/$\sqrt{Hz}$
V_{OS}:	200 µV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	±4.9 V
CMR:	77 dB (dc to 60 Hz)
Nonlinearity:	100 ppm max
Supply Voltage:	±5 V
Supply Current:	85 µA max
0.01% Settling Time for 5 V Step:	135 µs
Recommended ADI ADC#1 **AD7923/AD7927**	
Resolution:	12 bits
Input Range:	0 V to V_{REF} or 0 V to 2 × V_{REF}
Sampling Rate:	200 kSPS
S/D Supply:	Single, 2.7 V to 5.25 V
Power:	3.6 mW max @ 200 kSPS with a 3 V supply
Comments:	8-/4-channel ADCs, respectively, with a serial interface and channel sequencer
Recommended ADI ADC#2 **AD7920**	
Resolution:	12 bits
Input Range:	0 to V_{DD}
Sampling Rate:	250 kSPS
S/D Supply:	2.35 V or 5.25 V
Power:	3 mW typ @ 250 kSPS with 3 V supply
Comments:	Single channel, serial ADC in 6-lead SC70

ADI In-Amp JFET In-Amp	**AD8220AR**
Small Signal BW:	1000 kHz
Noise (e_{NI}):	15 nV/$\sqrt{Hz}$
V_{OS}:	1 mV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	±4.8 V
CMRR:	110 dB (dc to 60 Hz)
Nonlinearity:	10 ppm max
Supply Voltage:	Dual, ±5 V
Supply Current:	1 mA max
0.01% Settling Time for 5 V step:	5 ms
Recommended ADI ADC#1 **AD7610/AD7663**	
Resolution:	16 bits
Input Range:	±2.5 V, ±5 V, ±10 V
Sampling Rate:	250 kSPS for both ADCs
S/D Supply:	±5 V to ±15 V and 5 V
Recommended ADC#2 **AD7321, AD7323, and AD7327**	
Resolution:	13 bits
Input Range:	±2.5 V, ±5 V, ±10 V
Sampling Rate:	500 kSPS
S/D Supply:	±5 V to ±15 V and +5 V
Power:	17 mW max at 0.5 MSPS with ±15 V, and 5 V supply
Recommended ADI ADC#3 **AD7898-3**	
Resolution:	12 bits
Input Range:	±2.5 V
Sampling Rate:	220 kSPS
S/D Supply:	5 V
Power:	22.5 mW max at 220 kSPS with 5 V supply

Table 7-2. Recommended ADCs for Use with ADI In-Amps (continued)

ADI In-Amp	**AD8230RZ**
Zero Drift In-Amp	
Small Signal BW:	2 kHz
Noise (e_{NI}):	240 nV/$\sqrt{Hz}$
V_{OS}:	10 mV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	±4.7 V
CMRR:	120 dB (dc to 60 Hz)
Nonlinearity:	20 ppm max
Supply Voltage:	±5 V
Supply Current:	3.5 mA max
Recommended ADI ADC#1	
AD7942	
Resolution:	14 bits
Input Range:	5 V
Sampling Rate:	250 kSPS
S/D Supply:	2.7 V to 5.25 V
Power:	1.25 mW, 2.5 V supply
Recommended ADI ADC#2	
AD7321	
Resolution:	13 bits
Input Range:	±2.5 V
Sampling Rate:	500 kSPS
S/D Supply:	±5 V to ±15 V, 2.7 V to 5.25 V
Power:	17 mW max at 500 kSPS with ±15 V, 5 V supply

NOTE: Specifications are preliminary. Refer to www.analog.com.

ADI In-Amp	**AD8250/AD8251**
High Speed Programmable Gain In-Amp	
Small Signal BW:	10 MHz
Noise (e_{NI}):	13 nV/$\sqrt{Hz}$
V_{OS}:	100 mV
In-Amp Gain:	10
Maximum Output Voltage Swing:	V_{CC} – 1.2 V, V_{CC} + 1.2 V
CMRR:	100 dB (dc to 60 Hz)
Nonlinearity:	40 ppm max
Supply Voltage:	Dual, ±5 V to ±12 V
Supply Current:	3 mA typ
0.01% Settling Time for 5 V step:	0.5 µs
Recommended ADI ADC#1	
AD7685, AD7687	
Resolution:	16 bits
Input Range:	5 V
Sampling Rate:	250 kSPS
S/D Supply:	Single, 2.5 V to 5 V
Power:	4 mW at 0.1 kSPS, 5 V supply
Recommended ADI ADC#2	
AD7327, AD7323, and AD7321	
Resolution:	13 bits/12 bits
Input Range:	±2.5 V
Sampling Rate:	0.5 MSPS
S/D Supply:	±5 V to ±15 V, single, 5 V
Power:	17 mW max at 500 kSPS with ±15 V, 5 V supply

Table 7-2. Recommended ADCs for Use with ADI In-Amps (continued)

ADI In-Amp **Zero Drift In-Amp**	**AD8553RM**
Small Signal BW:	1 kHz
Noise (e_{NI}):	150 nV/√Hz
V_{OS}:	50 mV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	0.075 V to 4.925 V
CMRR:	120 dB (dc to 60 Hz)
Nonlinearity:	600 ppm max
Supply Voltage:	Single, 5 V
Supply Current:	1.3 mA max
Recommended ADI ADC#1 **AD7476**	
Resolution:	12 bits
Input Range:	0 to V_{DD}
Sampling Rate:	1 MSPS
S/D Supply:	2.35 V to 5.25 V
Power:	3.6 mW max at 1 MSPS with 3 V supply 15 mW max at 1 MSPS with 5 V supply
Recommended ADI ADC#2 **AD7466**	
Resolution:	12 bits
Input Range:	0 to V_{DD}
Sampling Rate:	100 kSPS
S/D Supply:	1.6 V to 3.6 V
Power:	0.62 mW max at 100 kSPS with 3 V supply 0.12 mW max at 100 kSPS with 1.6 V supply

ADI In-Amp **Zero Drift In-Amp**	**AD8555AR/AD8556ARZ**
Small Signal BW:	150 kHz
Noise (e_{NI}):	32 nV√Hz
V_{OS}:	10 mV max
In-Amp Gain:	10
Maximum Output Voltage Swing:	30 mV to 4.94 V
CMRR:	100 dB (G = 70, dc to 200 Hz)
Nonlinearity:	1000 ppm typ
Supply Voltage:	Single, 5 V
Supply Current:	2.5 mA max
0.1% Settling Time for 4 V step:	8 ms
Recommended ADI ADC#1 **AD7685**	
Resolution:	16 bits
Input Range:	5 V
Sampling Rate:	250 kSPS
S/D Supply:	Single, 2.5 V to 5 V
Power:	4 mW at 0.1 SPS with 5 V supply
Recommended ADI ADC#2 **AD7476**	
Resolution:	12 bits
Input Range:	0 to V_{DD}
Sampling Rate:	1 MSPS
S/D Supply:	2.35 V to 5.25 V
Power:	3.6 mW max at 1 MSPS with 3 V supply 15 mW max at 1 MSPS with 5 V supply
Recommended ADI ADC#3 **AD7476A**	
Resolution:	12 bits
Input Range:	0 to V_{DD}
Sampling Rate:	1 MSPS
S/D Supply:	2.7 V to 5.25 V
Power:	3.6 mW max at 1 MSPS with 3 V supply 12.5 mW max at 1 MSPS with 5 V supply

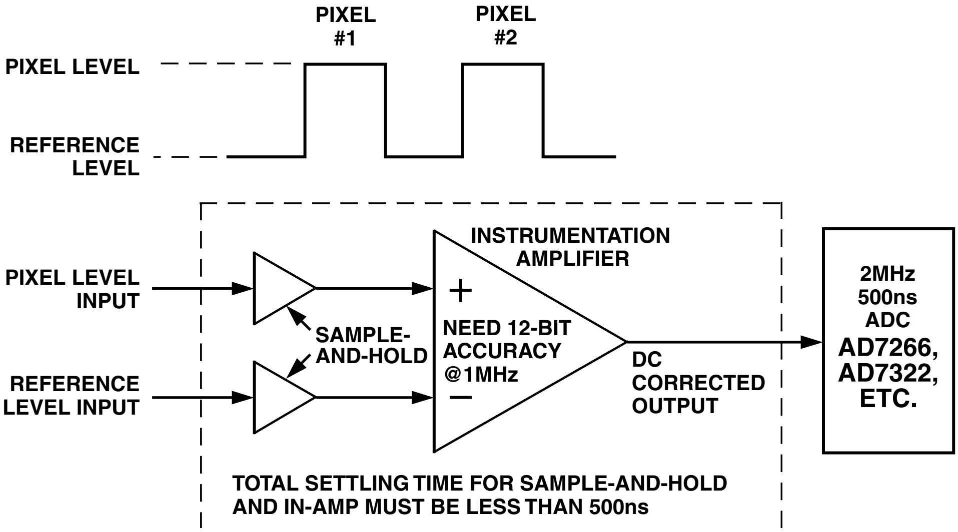


Figure 7-1. In-amp buffers ADC and provides dc correction.

High Speed Data Acquisition

As the speed and accuracy of modern data acquisition systems have increased, a growing need for high bandwidth instrumentation amplifiers has developed—particularly in the field of CCD imaging equipment where offset correction and input buffering are required. Here, double-correlated sampling techniques are often used for offset correction of the CCD imager. As shown in Figure 7-1, two sample-and-hold amplifiers monitor the pixel and reference levels, and a dc-corrected output is provided by feeding their signals into an instrumentation amplifier.

Figure 7-2 shows how a single multiplexed high bandwidth in-amp can replace several slow speed nonmultiplexed buffers. The system benefits from the common-mode noise reduction and subsequent increase in dynamic range provided by the in-amp.

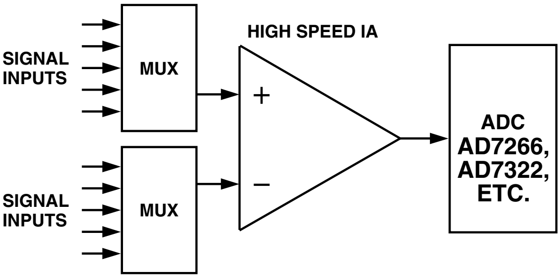


Figure 7-2. Single high speed in-amp and mux replace several slow speed buffers.

Previously, the low bandwidths of commonly available instrumentation amplifiers, plus their inability to drive 50 Ω loads, restricted their use to low frequency applications—generally below 1 MHz. Some higher bandwidth amplifiers have been available, but these have been fixed-gain types with internal resistors. With these amplifiers, there was no access to the inverting and noninverting terminals of the amplifier. Using modern op amps and employing the complementary bipolar (CB) process, video bandwidth instrumentation amplifiers that offer both high bandwidths and impressive dc specifications may now be constructed. Common-mode rejection may be optimized by trimming or by using low cost resistor arrays.

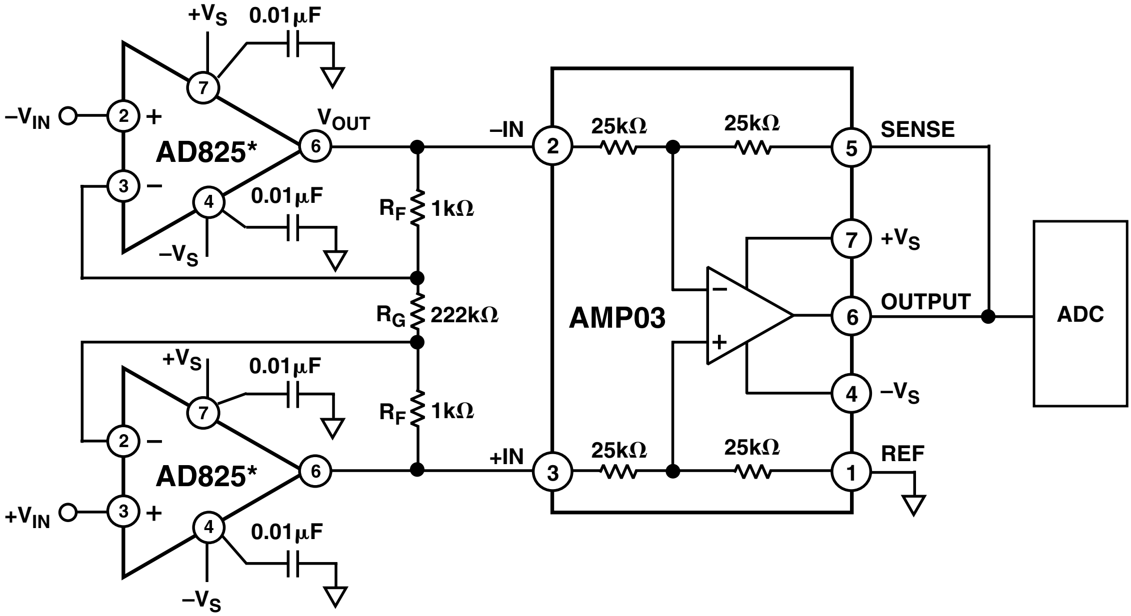
The bandwidth and settling time requirements demanded of an in-amp buffering an ADC, and for the sample-and-hold function preceding it, can be quite severe. The input buffer must pass the signal along fast enough so that the signal is fully settled before the ADC takes its next sample. At least two samples per cycle are required for an ADC to unambiguously process an input signal (FS/2)—this is referred to as the *Nyquist criteria*. Therefore, a 2 MHz ADC, such as the **AD7266** or **AD7322**, requires that the input buffer/sample-and-hold sections preceding it provide 12-bit accuracy at a 1 MHz bandwidth. Settling time is equally important: the sampling rate of an ADC is the inverse of its sampling frequency—for the 2 MHz ADC, the sampling rate is 500 ns. This means that for a total throughput rate of less than 1 µs, these same input buffer/sample-and-hold sections must have a total settling time of less than 500 ns.

A High Speed In-Amp Circuit for Data Acquisition

Figure 7-3 shows a discrete in-amp circuit using two **AD825** op amps and an AMP03 differential (subtractor) amplifier. This design provides both high performance and high speed at moderate gains. Circuit gain is set by resistor R_G where gain = $1 + 2\ R_F/R_G$. The R_F resistors should be kept at around 1 kΩ to ensure maximum bandwidth. Operating at a gain of 10 (using a 222 Ω resistor for R_G) the –3 dB bandwidth of this circuit is approximately 3.4 MHz. The ac common-mode rejection ratio (gain of 10, 1 V p-p common-mode signal applied to the inputs) is 60 dB from 1 Hz to 200 kHz and 43 dB at 2 MHz. And it provides better than 46 dB CMRR from 4 MHz to 7 MHz. The RFI rejection characteristics of this amplifier are also excellent—the change in dc offset voltage vs. common-mode frequency is better than 80 dB from 1 Hz up to 15 MHz. Quiescent supply current for this circuit is 15 mA.

For lower speed applications requiring a low input current device, the **AD823** FET input op amp can be substituted for the AD825.

This circuit can be used to drive a modern, high speed ADC such as the **AD871** or **AD9240**, and to provide very high speed data acquisition. The AD830 can also be used for many high speed applications.



*REFER TO ANALOG DEVICES WEBSITE AT WWW.ANALOG.COM FOR THE LATEST OP AMP PRODUCTS AND SPECIFICATIONS.

Figure 7-3. A High performance, high speed in-amp circuit.