

SIGNAL PATH | *designer*SM

Tips, tricks, and techniques from the signal-path experts

No. 102

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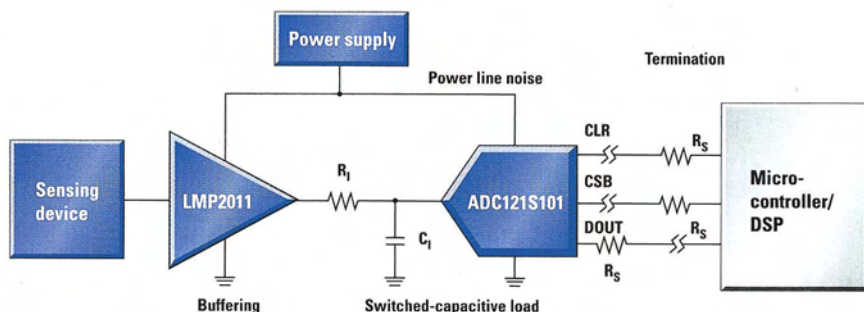
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Maximizing Signal-Path Performance

— By Chuck Sins, Applications Engineer



Precision Signal Path

The signal path offers many opportunities for the system designer. In the analog-to-digital converter (ADC) signal path, making good design choices in buffering a sensing device, charging the switch-capacitive input of an ADC, and minimizing noise sources will maximize performance. All of these examples will be addressed in this issue of the *Signal Path Designer*.

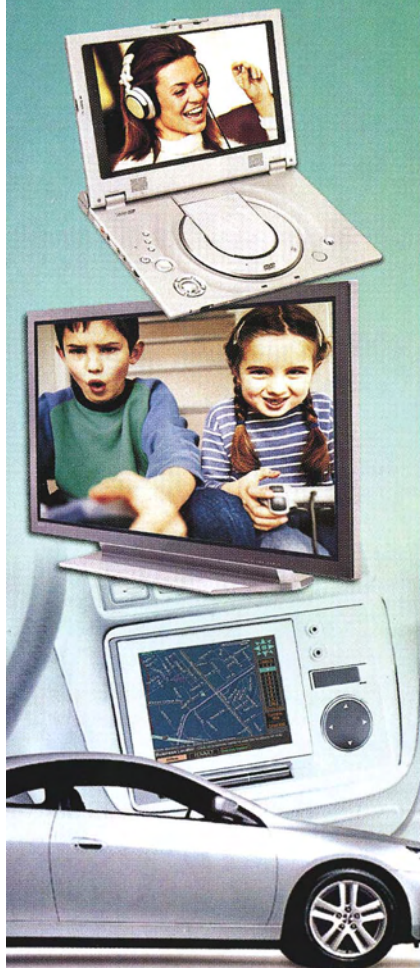
Buffering a Sensing Device

When a sensing device is unable to drive the capacitive load of an ADC, it can be buffered with an operational amplifier (op amp). Since many applications require operation from a single supply, it is important to select an op amp that operates at the same voltage as the ADC. While sharing supply voltages helps reduce system complexity and cost, supply voltages place constraints on the input and output capability of the op amp. For ADCs such as the ADC121S101 where the reference voltage (V_{REF}) is both the supply voltage and the reference, op amps such as the LMP2011 with rail-to-rail output (RRO) capability are preferred. The LMP2011 with RRO capability allows the system designer to utilize the full dynamic range of the ADC, providing access to all of the output codes.

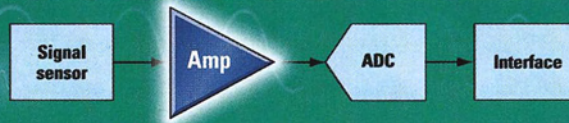
Once an op amp with suitable input/output capabilities has been selected, its gain bandwidth needs to be considered. For cases where the stimulus source's maximum output is less than V_{REF} , gain may be required from the buffering stage. The gain bandwidth product (GBWP) of an op amp specifies its

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High-Speed Signals,
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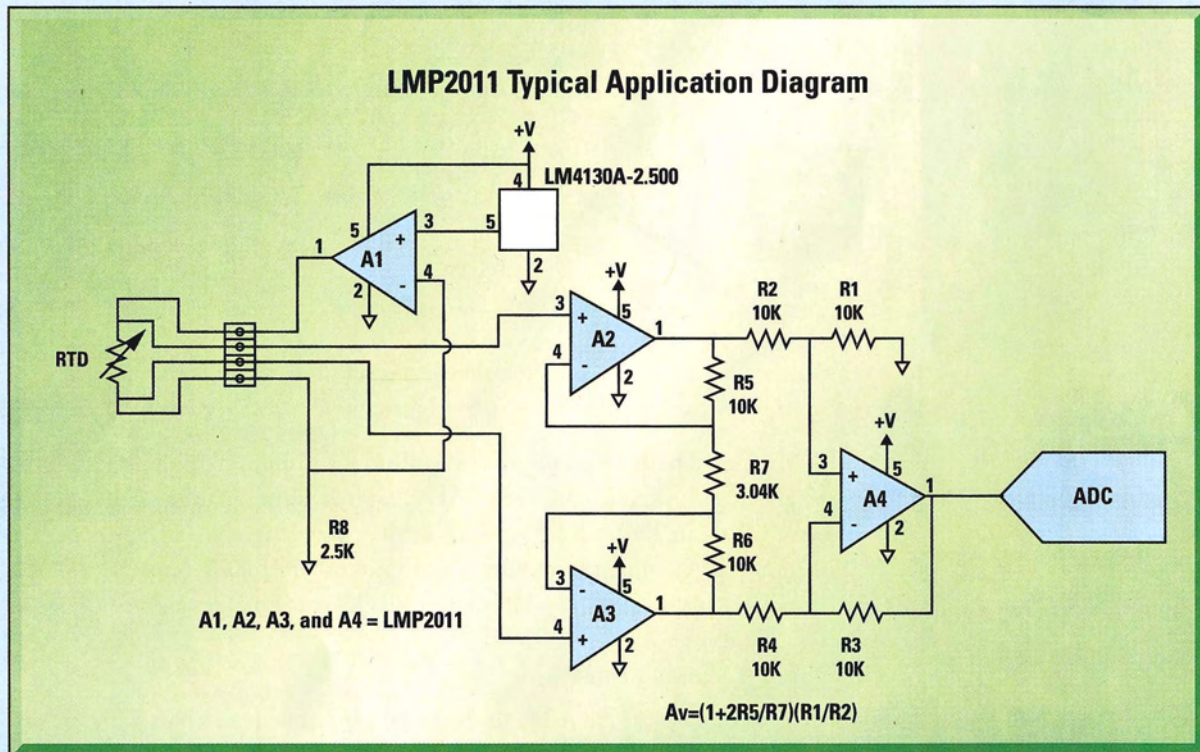
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The Sight & Sound of Information



High Precision-Rail-to-Rail Output Amplifiers



Delivering High Precision Over Time and Temperature



LMP2011/12/14 Key Features

- 60 μV V_{OS} max over temp (- 40°C to +125°C)
- Low voltage noise (35 $\text{nV}/\sqrt{\text{Hz}}$) and no 1/f
- High CMRR (130 dB), PSRR (120 dB)
- Gain (130 dB) and 3 MHz GBW product

System Benefits

- Offers high accuracy measurements with continued accuracy over temperature
- Increase signal accuracy during low frequency measurements
- High accuracy across voltages
- Wide frequency range at higher gains

Maximizing Signal-Path Performance

bandwidth (-3 dB frequency) when configured as a unity gain amplifier. Since GBWP remains constant for a given op amp, a closed loop configuration with a gain of A_{CL} lowers the bandwidth by a factor of A_{CL} : $BW = \frac{GBWP}{A_{CL}}$

For example, the LMP2011 with a GBWP of 3 MHz will have a bandwidth of 300 kHz when configured with an A_{CL} of 10 V/V.

Because the closed-loop bandwidth is the -3 dB frequency of the amplifier, it is the frequency where the amplifier output is 70.7% of its input value. So at the -3 dB frequency there is a 29.3% error in output amplitude. Errors in ADCs are measured in units of least significant bits (LSBs). One LSB is defined as $V_{REF}/2^n$ where V_{REF} is the reference voltage and n is the ADC resolution. For example, 1 LSB of an 8-bit ADC is $V_{REF}/256$. For a system requiring $1/2$ LSB of accuracy from its ADC, the input stimulus must have gain accuracy of $(1-1/2^{n+1})$ or 99.8% for an 8-bit ADC. To guarantee that the op amp has sufficient gain accuracy for a given system requirement, it is necessary to calculate the maximum operating frequency (f_{max}) for the op amp. This is accomplished by approximating the frequency response of an op amp to be that of a single pole filter. The curve shown in *Figure 1* has the gain (A_V) and -3 dB frequency (f_0) normalized to 1.

The expression for this curve is

$$A_V = \frac{1}{\sqrt{1+(f)^2}}$$

or solving for f ,

$$f = \sqrt{\frac{1}{A_V^2} - 1}$$

To achieve $1/2$ LSB of error from an 8-bit system, the normalized f_{max} of an op amp is

$$f = \sqrt{\frac{1}{(0.998)^2} - 1} = 0.062$$

Therefore, for an 8-bit ADC with a $1/2$ LSB accuracy requirement, the op amp's effective bandwidth is $0.062 \times GBWP$. The LMP2011 with a GBWP of 3 MHz would have an effective bandwidth of 186 kHz when configured for unity gain. The effective bandwidth is further reduced if a gain greater than unity is required. The normalized f_{max} for

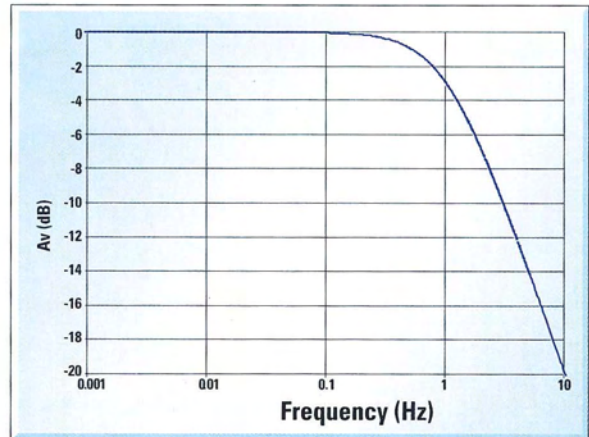


Figure 1. Op-Amp Frequency Response

$1/2$ LSB of error for ADCs of various resolutions can be calculated as:

$$\text{Normalized } f_{max} = \sqrt{\frac{1}{\left(1 - \frac{1}{2^n}\right)^2} - 1}$$

Transferring Charge to a Switched-Capacitive Load

The op amp was added to the ADC signal path to drive the capacitive load. However, the ADC's input is a switched-capacitive load (see *Figure 2*).

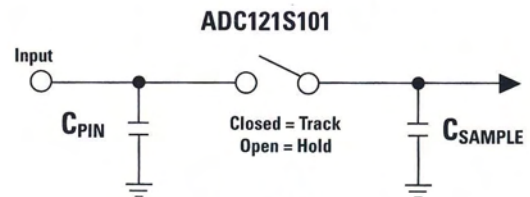
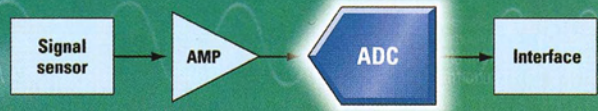


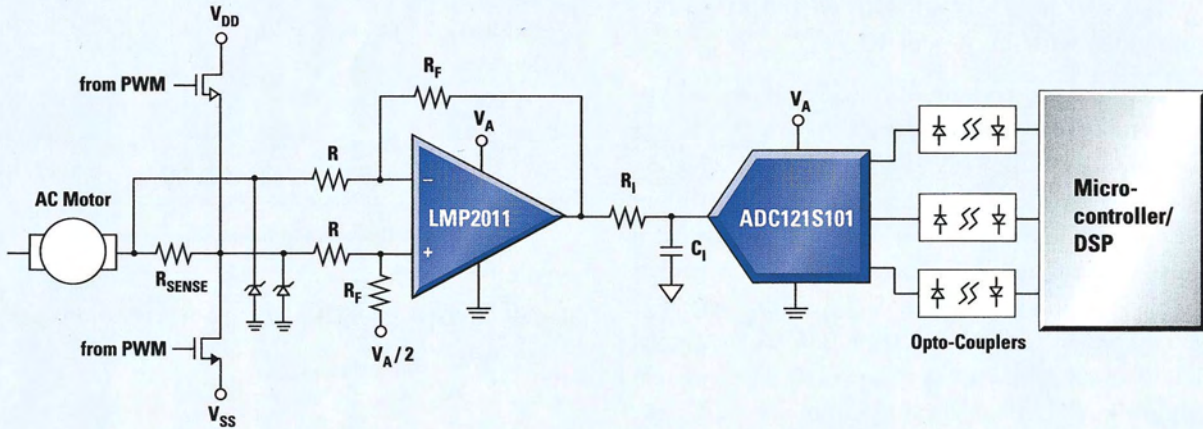
Figure 2. ADC121S101 Input

The ADC121S101 in "hold" mode has an input capacitance, C_{PIN} , of less than 4 pF, and in "track" mode has an input capacitance, C_{SAMPLE} plus C_{PIN} , of less than 30 pF. To minimize the error caused by the changing input capacitance, a capacitor (C_1) is connected from the input pin to ground. The C_1 , which is much larger than the input capacitance of the ADC when in "track" mode, provides the current to quickly charge the ADC's sampling capacitor. An isolation resistor is generally added to isolate the additional load capacitance from the op-amp output (see *Figure 3*).

Low power, high precision 8/10/12-bit, 1 MSPS ADCs



ADC121S101 Typical Application Diagram

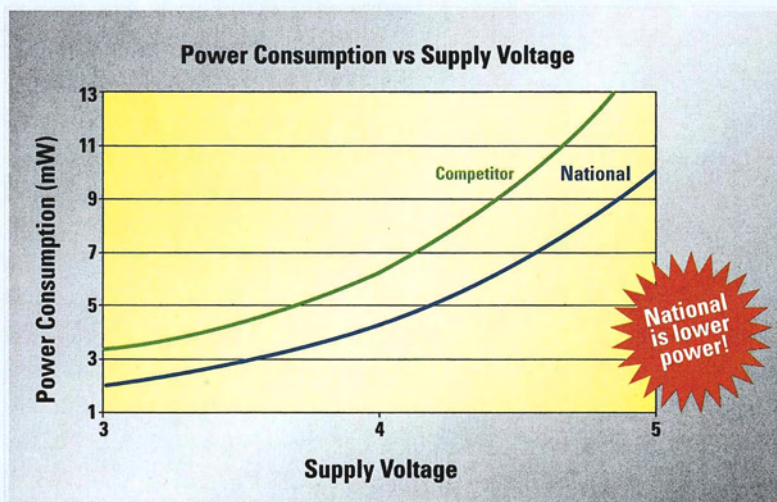


ADC121S101, ADC101S101, and ADC081S10 Features (typical)

- Speed range: 500 KSPS to 1 MSPS
- Integral non-linearity (INL): ± 0.4 LSB
- Differential non-linearity (DNL): ± 0.5 LSB
- Signal-to-noise ratio (SNR): 72.5 dB
- Signal-to-noise and distortion ratio (SINAD): 72 dB
- Spurious free dynamic range (SFDR): 82 dB
- Power consumption: 2 mW at 3V
- Supply voltage: 2.7 to 5.25V

Family Benefits

- Guaranteed performance over speed
- Pin and function compatible family
- Excellent static and dynamic performance
- Extremely low power
- Miniature packages reduce board space



Maximizing Signal-Path Performance

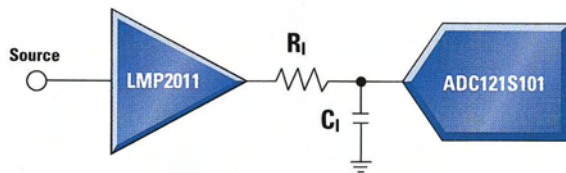


Figure 3. Quick-Charge Circuit

There are three important factors to consider in choosing appropriate values for the RC network. First, the designer needs to be aware that the RC network forms a low pass filter in the signal path. Therefore, the network can attenuate the sampled signal as the input frequency approaches the pole defined by $\frac{1}{2\pi RC}$. This is extremely critical for applications where ADC gain is important and no gain-calibration scheme is employed. Second, refrain from making the series resistor too large. While an increased resistance value decreases the phase delay at the output of the op amp (maintaining op-amp stability), it prevents the parallel combination of internal and external capacitance at the ADC input from fully charging during the ADC “track” time. Typical resistor values are less than 100 ohms. Third, make the external capacitor many times larger than the input capacitance while in “track” mode. Achieving this will minimize the drop in voltage on the capacitor when the ADC switches from “hold” to “track” mode.

The settling-time requirement of the op amp is determined by the amount of time the ADC spends in “track” mode. This is the amount of time that the op amp has to replenish the charge and reestablish the voltage on the capacitor prior to the ADC switching to “hold” mode. The time constant for recharging the capacitance at the input pin is defined by the series resistance value and the parallel combination of the internal and external capacitances. If the op amp fails to stabilize the voltage at the input by the time the ADC enters “hold” mode, inconsistent and erroneous conversions will result.

As a starting point for selecting values for R_1 and C_1 , the pole of the RC network may be set to the sampling frequency of the ADC. If this causes too

much attenuation for the highest input frequency, the designer can decrease the capacitance or resistance values accordingly. The minimum resistor value should be set by the output drive capability of the op amp. Smaller resistor values are preferred since they limit distortion. However, the amplifier stability must be guaranteed over the full input frequency range, amplitude, and temperature of the application.

Managing Component Tolerance

If an inverting amplifier is used for the amplifier configuration (see Figure 4), it is easy to calculate the error coefficient due to component tolerance. Since the gain is defined as $-R_F/R_G$, the maximum deviation from the ideal will occur when R_F is maximum and R_G is minimum or when R_F is minimum and R_G is maximum. If resistors with a tolerance of 1% are used, the maximum error will be 2%.

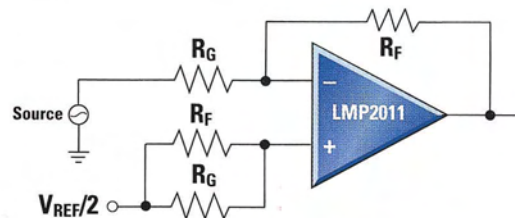


Figure 4. Inverting Amplifier Configuration

Applications where gain calibration schemes are not utilized must limit the dynamic range of the ADC. For an 8-bit ADC, 1 LSB represents 0.39% of V_{REF} ($V_{REF}/2^n$). Therefore, a 2% gain error due to resistor tolerance equates to a 12 LSB loss in dynamic range, 6 LSB (rounded up from 5.13) from the maximum output code and 6 LSB from the minimum.

Minimizing Power Line Noise

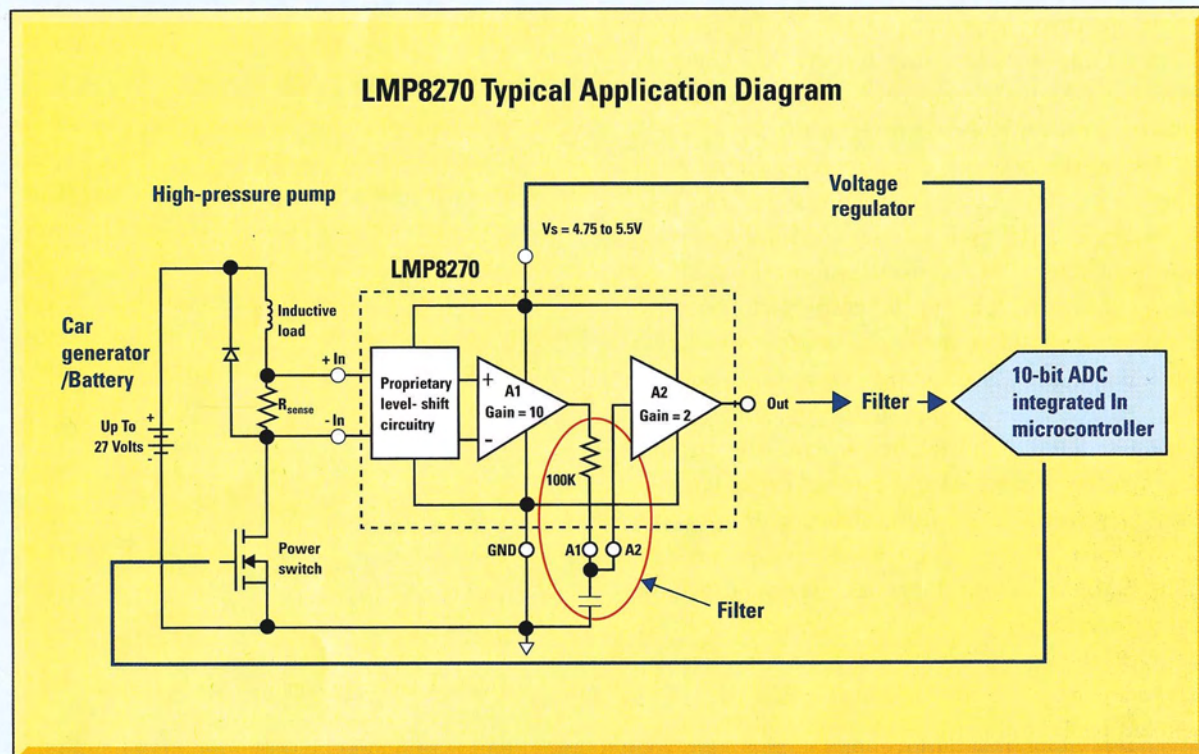
While component tolerance is one source of error in the ADC signal path, noise on power lines due to digital circuitry is another. Noise can couple into an ADC and an op amp through their supply pins. Typically, devices such as the LMP2011 have excellent power supply rejection ratios (PSRR) and will not be affected. However, ADCs such as the

High Common Mode, Voltage-Difference Amplifier



Precision Current Measurement in Automotive and Industrial Environments

LMP8270 Typical Application Diagram



LMP8270 Key Features

- Input offset voltage 1 mV max
- TCVo's 15 $\mu\text{V}/^\circ\text{C}$ max
- CMRR 80 dB min
- Extended CMVR -2V to 36V
- Output voltage swing rail-to-rail
- Supply voltage 4.75V to 5.5V
- Temp range -40°C to 125°C
- Supply current 1 mA

System Benefits

- • Initial system accuracy
- • Continued accuracy over temperature
- • Accurate under wide dynamic input currents
- • Supports a wide range of input voltages
- • Supports ADC input voltage levels
- • Compatible with ADC voltage supplies
- • Supports most automotive/industrial applications
- • Minimum power consumption

Maximizing Signal-Path Performance

ADC121S101 whose supply voltage is also the V_{REF} have a PSRR value of 0 dB (no PSRR). The output drivers of the ADC itself have fast edge rates that cause the ADC to draw varying amounts of current. The noise introduced on the supply line can upset the ADC and other analog circuitry connected to it. A dual capacitor decoupling scheme with the smallest capacitor, typically 0.1 μ F, placed within 1 cm of the supply pin and a 1.0 μ F to 10 μ F capacitor placed nearby is an excellent starting place for limiting supply noise. If analog and digital supply pins are connected to the same voltage source, a choke may be used between the pins. The choke will appear as a short at DC and a resistor at the higher frequencies where isolation is desired.

While good supply decoupling is always recommended, it is best to try and minimize the load capacitance seen by the output of the ADC so less current is required. Charging load capacitance causes noise spikes on the supply line while discharging load capacitance adds noise to the ADC substrate. There are several techniques to minimize load capacitance. The easiest way is to drive only a single device and place it as close as possible to the ADC output. It is also helpful to limit the effect of driving load capacitance by using series resistors, which limit the current required to charge or discharge the load capacitance and reduce the slew rate of the output. Limit the value of the series resistance to less than 100 Ω to avoid violating the timing requirements of the digital circuitry. High-frequency systems may not tolerate the use of series resistors. Thus, it is essential that the driven circuitry be very close to the ADC output.

Maximizing Clock Integrity

Similar to ADC outputs, the ADC clock line can add noise to the system. The clock line should be treated as a transmission line when its length exceeds its rise time divided by 6 times the trace delay:

$$\text{line length} > \frac{t_{\text{rise}}}{6 \times t_{\text{delay}}}$$

Trace delay is typically 150 ps per inch on an FR4 board. Treating a trace as a transmission line involves making the trace a controlled impedance with proper termination. This will help avoid signal reflection

that can cause distortion. Distortion of the clock waveform leads to changes in the cycle-to-cycle clock period, better known as jitter. As the clock timing changes, there is variation in the exact point an ADC samples the waveform. With jitter, the ADC samples a point higher or lower on the signal than it ideally would. The net result of the time variation in the signal sampling point is noise. The maximum amount of jitter allowed for 1 LSB of error is $\frac{1}{2\pi f_{in}}$. For half an LSB of error, replace n with $n+1$.

Another technique for avoiding line reflection is line termination. There are two methods for terminating traces, near-end and far-end termination. Near-end termination requires a resistor in series with the line located close to the output of the signal source. The signal source resistance plus this series resistor should equal the characteristic impedance of the line. When near-end termination is insufficient, far-end termination is required. Far-end termination requires a resistor to ground at the clock input to the ADC. The terminating resistor is placed very close to the ADC input pin and the value should equal the characteristic impedance of the line.

When the clock source is required to drive multiple inputs, far-end termination alone may not be satisfactory. Far-end termination attenuates the signal level. Driving several inputs, each with a terminating resistor, may attenuate the clock voltage to the point that the logic thresholds are no longer met. For this instance, AC-termination is more appropriate. AC-termination requires a resistor in series with a capacitor to ground at the input to the ADC. This attenuates the AC component but not the DC component. For example, a signal that swings from 0 to 5V would remain centered around 2.5V in a system that is AC-terminated. The clock would still be attenuated but would be optimally centered between the CMOS trip points, allowing minimum signal swing to meet logic level-specifications.

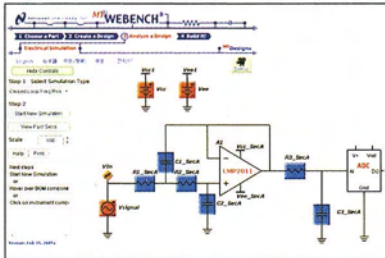
Summary

By making smart design choices in buffering a sensing device, charging the switch-capacitive input of an ADC, and minimizing noise sources, the performance of the analog signal path is maximized. ■

Design Tools

INTRODUCING...

Signal-Path Design Tool



National's newest online innovation is the Signal-Path Designer toolset on the WEBENCH platform. This unique analog design tool allows you to synthesize an anti-aliasing filter, amplifier selection, and analog-to-digital converter combination that is precisely tailored to your needs.

Once you select a filter, it allows you to choose a matching ADC. Or, you can select an ADC first, then have the tool guide you to selecting the optimal filter to fit the ADC. This fast and easy tool allows you to select the best combination of components that are designed to work together and achieve your system goals for cost and performance.

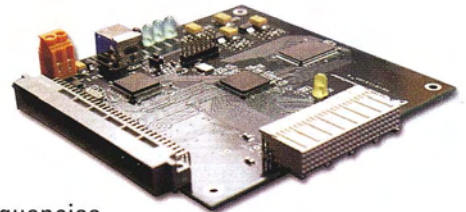
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