Fully Differential Amplifier with Rail-to-Rail Outputs Offers 16-Bit Performance at 1MHz on a Single 2.5V Supply

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Introduction

With increasing levels of IC integration, and shrinking transistor geometries, A/D converter supply voltages have decreased and their inputs have been designed to process signals differentially to maintain good dynamic range. These ADCs typically run from a single low voltage supply with an optimal common mode input somewhere near mid-supply. The LT1994 facilitates interfacing to these ADCs by providing differential conversion and amplification, common mode translation of wide band, ground referenced, single-ended or differential input signals. It comes in an 8-pin MSOP or DFN package, which is pin-for-pin compatible with other commercially available fully-differential amplifiers.

What sets the LT1994 apart from other fully- differential amplifiers are its low noise, low distortion, rail-to-rail output, and an input common mode range that extends to ground on power supplies as low as 2.5V. This eliminates the need for a negative power supply, and makes the LT1994 uniquely able to interface to differential input ADCs while sharing the same power supply. This saves the user system cost, and power.

Figure 1. Common mode translation of V_{IN} using the LT1994

Performance of LT1994

The first advantage of the LT1994 is that it can convert and level-shift ground referenced, single-ended or differential signals to V_{OCM} pin referenced, differential output signals. Figure 1 shows how. A single-ended $5V_{P-P}$ ground referenced signal (which swings 2.5V below the supply of both the ADC and the LT1994) is translated by the LT1994 from being a ground referenced signal to a differential mid-supply referenced signal. This is accomplished within the LT1994 by two feedback loops: a differential feedback loop, and a common mode feedback loop. Both loops have high open loop gain, around 100dB. The common mode feedback loop forces the instantaneous average of the two outputs to be equal to the voltage on the V_{OCM} pin. Its feedback loop is internal to the LT1994. The differential feedback loop works similarly to traditional op amps forcing the difference in the summing node voltages to zero. As a result, the differential output is simply governed by the equation:

$$V_{OUT} = V_{OUT+} - V_{OUT-} \approx \frac{R_F}{R_I} \bullet V_{IN}$$

By eliminating the need for a negative supply, the LT1994 gives the user maximum dynamic range at minimal power. Since each output of the LT1994 is capable of swinging rail-to-rail, and with the LT1994's $3nV/\sqrt{Hz}$ input referred voltage noise (see Figure 2 for the LT1994's noise spectral density plot), applications such as the one shown in Figure 1 have a signal-to-noise ratio approaching 96dB in a 10MHz noise bandwidth. This represents a 6dB increase in dynamic range compared to single ended output rail-to-rail amplifiers
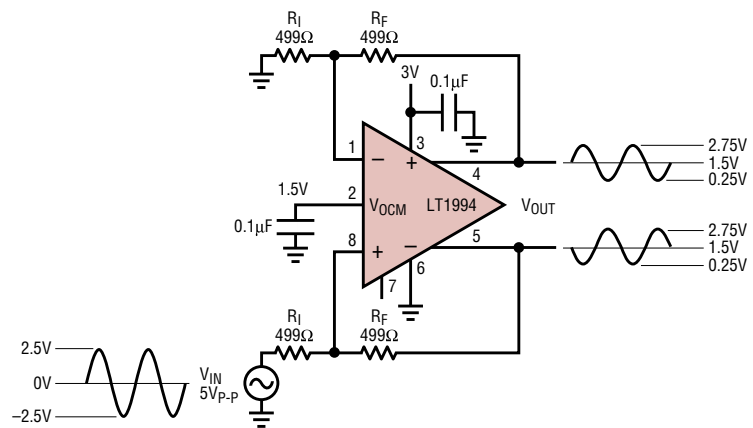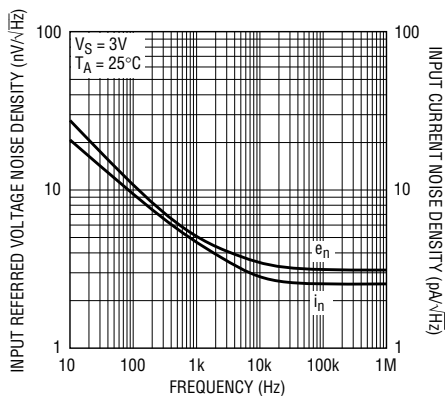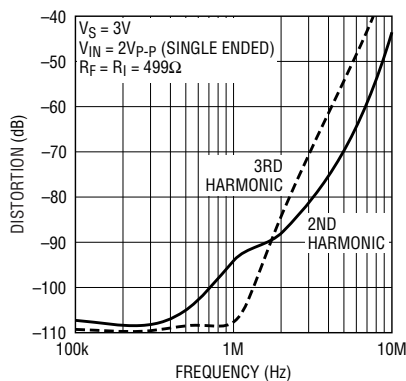
Table 1. LT1994 key specifications

Parameter	Typical Specification
Supply Current at 3V	13.3mA
e_n – Input referred Voltage Noise	$3nV/\sqrt{Hz}$
HD2 at $V_{IN} = 2V_{P-P}$, 1MHz	–94dBc
HD3 at $V_{IN} = 2V_{P-P}$, 1MHz	–108dBc
Gain-Bandwidth	70MHz
Slew Rate	65V/µs
0.01% Settling on a 2V step	120ns

Figure 2. LT1994 input referred noise spectral density

Figure 3. LT1994 disortion vs frequency

with the similar noise floors. Some of the LT1994's key specifications are tabulated in Table 1.

Another benefit of fully-differential signal processing is that interference such as ground noise or power supply noise appear as common mode signals and are rejected by the internal matching and balance of the amplifier. Power supply rejection and common-mode rejection becomes limited primarily by internal transistor matching and are typically around 100dB.

Linearity is enhanced using a fully differential architecture allowing the cancellation of even order harmonics. To see how this works, a pure single tone sine wave input is applied to the LT1994 as shown in Figure 1. The outputs of the LT1994 can be represented by a Taylor series expansion:

$$V_{OUT+} = K_1\left(\frac{V_{IN}}{2}\right) + K_2\left(\frac{V_{IN}}{2}\right)^2 +$$
$$K_3\left(\frac{V_{IN}}{2}\right)^3 + K_4\left(\frac{V_{IN}}{2}\right)^4 +$$

$$V_{OUT-} = K_1\left(-\frac{V_{IN}}{2}\right) + K_2\left(-\frac{V_{IN}}{2}\right)^2 +$$
$$K_3\left(-\frac{V_{IN}}{2}\right)^3 + K_4\left(-\frac{V_{IN}}{2}\right)^4 +$$

V_{OUT} is the difference:

$$V_{OUT} = V_{OUT+} - V_{OUT-}$$
$$= 2K_1\left(\frac{V_{IN}}{2}\right) + 2K_3\left(\frac{V_{IN}}{2}\right)^3 + \quad,$$

leaving just the odd harmonic terms.

Figure 3 shows a plot of distortion vs frequency with the LT1994 configured in the closed-loop unity gain configuration shown in Figure 1. With a $2V_{P-P}$, 1MHz, single-ended input, the 2nd harmonic measures –94dBc, and the 3rd harmonic measures –108dBc.

Getting the best distortion out of the LT1994 requires careful layout, paying close attention to symmetry and balance. In single supply applications, it is recommended that high quality, low ESR, surface mount 1µF and 0.1µF caps be paralleled and tied directly

across the power supplies with short traces with the V⁻ tied directly to a low-impedance ground plane. On split supplies, additional 0.1µF high quality, low ESR, surface-mount bypass caps should be used to bypass each supply separately to a low-impedance ground plane.

Interfacing to ADCs

The sampling process of ADCs create a sampling glitch caused by switching in the sampling capacitor on the ADC front end which momentarily "shorts" the output of the amplifier as charge is transferred between the amplifier and the sampling cap. The amplifier must recover and settle from this load transient before this acquisition period ends for a valid representation of the input signal.

In general, the LT1994 settles faster from these periodic load impulses than from a 2V input step, but it is a good idea to place a small RC filter network between the output of the LT1994 and the input of the ADC to help absorb the charge injection that comes out of the ADC from the sampling process (Figure 4 shows an example of this). The capacitance of this decoupling network serves as a charge reservoir to provide high frequency charging during the sampling process, while the two resistors of the decoupling network are used to dampen and attenuate any charge kickback from the ADC.

The selection of the RC time constant is trial and error for a given ADC, but the following general guidelines are recommended: Too large a resistor in the decoupling network leaving
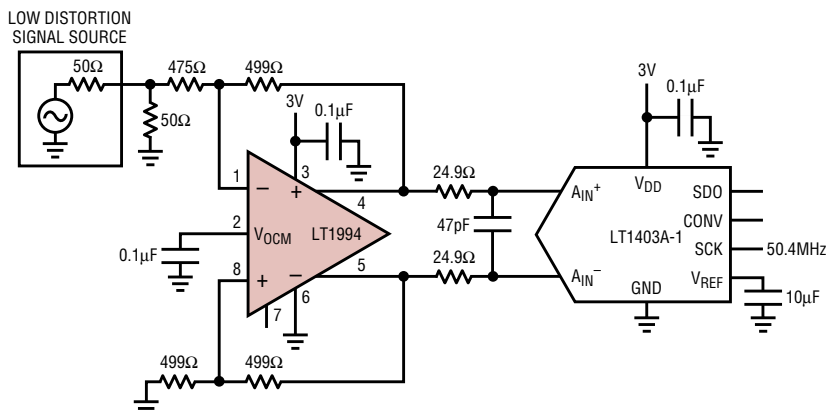
Figure 4. ADC buffering with common mode translation and differential conversion
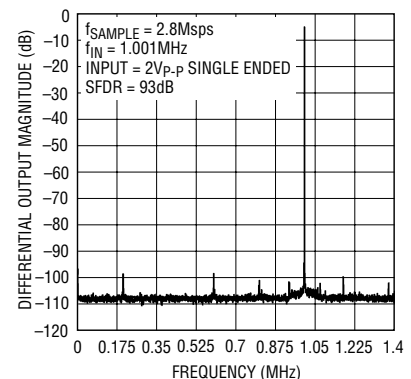
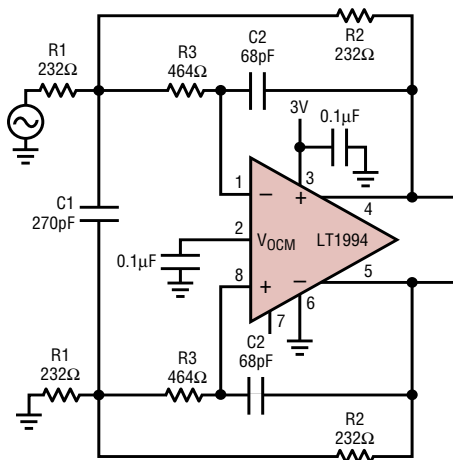Figure 5. 4096 sample FFT of the LT1994 driving a 14-bit ADC

Figure 6. Low noise differential active RC filter

insufficient settling time creates a voltage divider between the dynamic input impedance of the ADC and the decoupling resistors. Too small of a resistor possibly prevents the resistor from properly dampening the load transient caused by the sampling process, prolonging the time required for settling.

Start with 25Ω on each output to decouple the ADC input capacitance. Then choose a capacitance (taking account of the sampling capacitance), which gives the amplifier time to settle to desired accuracy during the acquisition period. In 16-bit applications, this typically requires a minimum of 11 RC time constants. The capacitor chosen should have a high quality dielectric (for example, C0G multi-layer ceramic). Figure 4 shows the LT1994 driving the LTC1403A-1, a 14-bit ADC, sampling at 2.8MHz on a single 3V supply. Figure 5 shows its 4096-point FFT. The spurious free dynamic range is about 93dB and is limited by the non-linearities of the ADC rather than the LT1994 (The SFDR of the LTC1403A-1 is specified around 86dB at 1.4MHz). This shows that the LT1994 has no problem settling and accommodating the LTC1403A's 39ns acquisition times.

Single 3V Supply, 2.5MHz, 2nd Order Fully Differential Butterworth Filter
Figure 6 shows a low noise, single supply, butterworth active filter with a 2.5MHz bandwidth suitable for anti-aliasing applications. The differential output spot noise at 50kHz is about $7nV/\sqrt{Hz}$, and the amplifier provides about 40dB of stopband rejection at 25MHz. The filter's frequency response is shown in Figure 7. The filter's low frequency gain is set by the ratio of R2 to R1. If a different cutoff frequency is desired, the capacitors C1, and C2 can easily be scaled inversely with cutoff frequency.

Gain-of-2 Amplifier (No resistors required)
Figure 8 shows the LT1994 configured in circuit configuration in which the output consists of an in-phase and an out-of-phase representation of the input signal. The circuit has the benefit of having high input impedance. The input-to-output transfer function is governed by the equation:
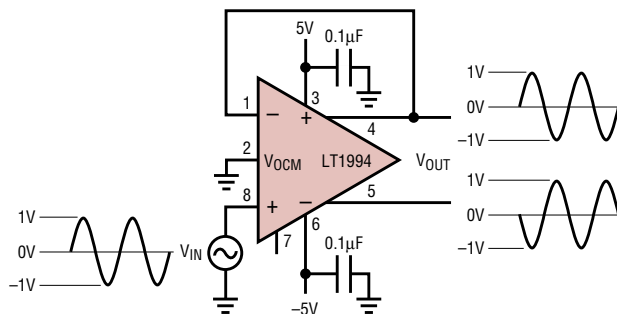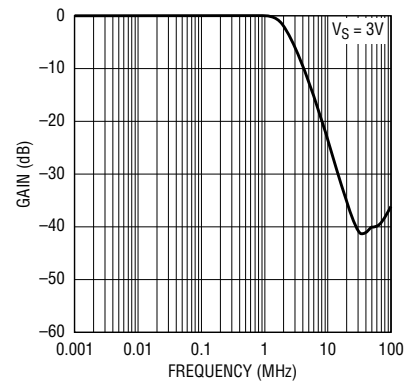$V_{OUT} = 2 \cdot V_{IN}$

Figure 7. Differential filter response

The circuit works well enough, but the consequence of such a configuration is that it reflects the performance of the common mode path, rather than the differential path. Because of this, the output does not have the benefit of the differential noise ($3nV/\sqrt{Hz}$), but rather is swamped by the common mode noise of $15nV/\sqrt{Hz}$ gained up by a factor of two ($30nV/\sqrt{Hz}$). This is a consequence of mismatch in feedback factors from the LT1994 outputs to their respective inputs. In fact, whenever the two feedback paths from the output to the input mismatch, and to the degree they mismatch, common mode noise is converted to differential noise at the output.

$$e_{NO(DIFF)} = 2e_{N(VOCM)} \frac{(\beta_{F1} - \beta_{F2})}{(\beta_{F1} + \beta_{F2})}$$

where β_{F1}, and β_{F2} are the two feedback factors from each output to their respective input.

Conclusion
The LT1994's low noise, low distortion, and high performance make it an ideal amplifier for interfacing with single supply ADCs. Its rail-to-rail outputs, low distortion, and $3nV/\sqrt{Hz}$ input referred voltage noise maximize dynamic range, and its ability to common mode to ground eliminates the need for a negative supply in single supply systems, saving cost and power. $\boldsymbol{\mathcal{LT}}$

Figure 8. Gain of two (no resistors required)

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