

New Rail-to-Rail Output Op Amps Bring Precision Performance to Low Voltage Systems

by Alexander Strong and Gary Maulding

Introduction

Linear Technology has recently released several new high precision op amps for use in low voltage systems. The LT1677, LT1881, LT1882, LT1884 and LT1885 all operate on power supplies from 3V or lower up to 36V and have rail-to-rail output voltage swing. These amplifiers allow high precision circuits to be implemented on low voltage power supplies, including single positive supplies. Rail-to-rail output stages maintain the output signal dynamic range by eliminating the base-emitter voltage drops of conventional emitter-follower output stages. Offset voltages are trimmed to less than 80 μ V, with the low temperature drift and low noise to be expected from bipolar transistor designs. High open-loop voltage gains maintain this accuracy over the output swing range.

The LT1677 is a rail-to-rail input, rail-to-rail output, single-supply version of the industry-standard LT1007. It features the lowest noise available for a rail-to-rail op amp: 3.2nV/ $\sqrt{\text{Hz}}$ and 70nV peak-to-peak 0.1Hz to 10Hz noise. An important feature in low voltage, single-supply applications (as low as 3V) is the ability to maximize the dynamic range. The LT1677's input common mode range can swing

100mV beyond either rail and the output is guaranteed to swing to within 170mV of either rail when loaded with 100 μ A. Low noise is combined with outstanding precision: the CMRR and PSRR are 130dB, the offset voltage is only 20 μ V and the open-loop gain is twenty-five million (typical). The LT1677 is unity-gain stable and has a gain bandwidth product of 7.2MHz. Figure 1 shows the input and output of an LT1677 in follower mode (gain = 1) using a single 3V supply. The output clips cleanly at the rails with no phase reversal, even when the input exceeds the rail by 0.5V. This has the advantage of eliminating lockup in servo systems.

The LT1881 dual and LT1882 quad op amps feature 150pA input bias currents, whereas the similar LT1884 and LT1885 dual and quad op amps trade slightly higher input bias currents of 500pA for three times higher speed. This series of amplifiers brings the performance of the LT1112 to low voltage applications that need the wide rail-to-rail output dynamic range. The graph of Figure 2 shows the input bias currents of the LT1884 over the common mode range of -14V to 14V. This low stable bias current behavior, when coupled with 50 μ V

offset voltage, open-loop gains of over one million and high common mode rejection, allows precision accuracy to be maintained in systems with difficult source impedances.

Table 1 highlights key performance specifications for these amplifiers. Each of these amplifiers provides higher precision operation than was previously available in a rail-to-rail output swing amplifier.

Selecting the Right Amplifier

When choosing one of these amplifiers for an application, it is necessary to consider the signal levels and source impedance of the signal source. Low impedance, low level sources will usually operate best with the LT1677 amplifier. The ultralow 3.2nV/ $\sqrt{\text{Hz}}$ noise of the LT1677 will not obscure low amplitude signals. High gain can be used without introducing DC errors, an important feature in low supply voltage applications. Other natural applications for the LT1677 occur when the input signal range extends to either power supply rail. The LT1677 maintains good DC accuracy and noise performance with the inputs at either power supply rail. As source impedance increases the LT1881 dual or LT1882 quad ampli-

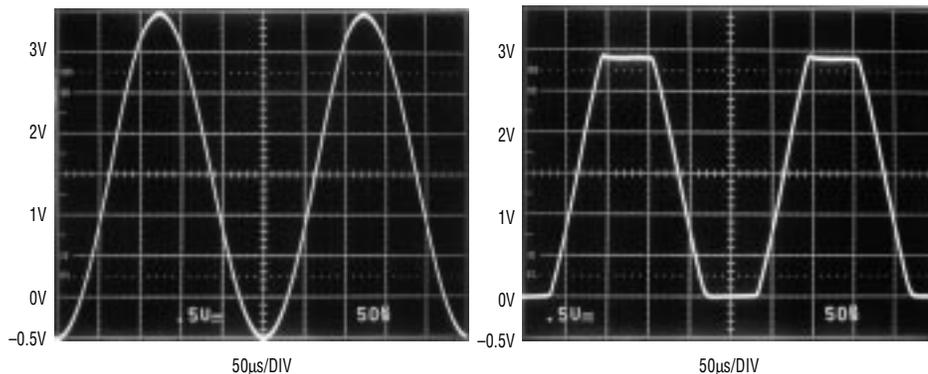


Figure 1. Input (left) and output (right) of an LT1677 configured as a voltage follower with input exceeding the supply voltage ($V_S = 3V$, input = -0.5V to 3.5V)

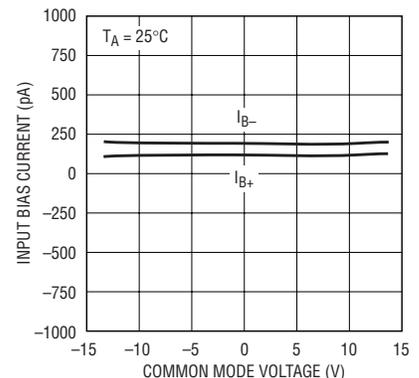


Figure 2. LT1884 input bias current vs common mode voltage

Table 1. Key performance specifications

| Parameter | LT1677 | LT1881 | LT1882 | LT1884 | LT1885 |
|--------------------------------------|--|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| Configuration | Single | Dual | Quad | Dual | Quad |
| Offset Voltage (Max) | 60 μ V | 80 μ V 50 μ V (A grade) | 80 μ V | 80 μ V 50 μ V (A grade) | 80 μ V |
| Input Bias Current (Max) | 20nA | 500pA 200pA (A grade) | 500pA | 900pA 400pA (A grade) | 900pA |
| Input Offset Current (Max) | 15nA | 500pA 200pA (A grade) | 500pA | 900pA 300pA (A grade) | 900pA |
| Input Common Mode Range | $V_{EE} + 1.7V$ to $V_{CC} - 1V$ | $V_{EE} + 1V$ to $V_{CC} - 1V$ | $V_{EE} + 1V$ to $V_{CC} - 1V$ | $V_{EE} + 1V$ to $V_{CC} - 1V$ | $V_{EE} + 1V$ to $V_{CC} - 1V$ |
| (Reduced Precision) | $V_{EE} - 0.1V$ to $V_{CC} + 0.1V$ | | | | |
| Output Swing $I_L = 100\mu A$ | $V_{EE} + 0.170V$ $V_{CC} - 0.170V$ | $V_{EE} + 0.06V$ $V_{CC} - 0.230V$ |
| Input Voltage Noise (Typ) | 3.2nV/ \sqrt{Hz} | 14nV/ \sqrt{Hz} | 14nV/ \sqrt{Hz} | 9.5nV/ \sqrt{Hz} | 9.5nV/ \sqrt{Hz} |
| Input Current Noise (Typ) | 0.3pA/ \sqrt{Hz} | 0.03pA/ \sqrt{Hz} | 0.03pA/ \sqrt{Hz} | 0.05pA/ \sqrt{Hz} | 0.05pA/ \sqrt{Hz} |
| Supply Voltage Range | 2.7V to 40V | 2.7V to 36V | 2.7V to 36V | 2.7V to 36V | 2.7V to 36V |
| Supply Current per Amplifier (Max) | 3.5mA | 0.9mA | 0.9mA | 0.9mA | 0.9mA |
| Gain Bandwidth Product (Typ) | 7.2MHz | 1MHz | 1MHz | 2MHz | 2MHz |
| Slew Rate (Typ) | 1.7V/ μ s | 0.15V/ μ s, -0.11V/ μ s | 0.15V/ μ s, -0.11V/ μ s | 0.5V/ μ s, -0.4V/ μ s | 0.5V/ μ s, -0.4V/ μ s |
| Open Loop Gain, $R_L = 10k$ (Typ) | 25V/ μ V | 1V/ μ V | 1V/ μ V | 1V/ μ V | 1V/ μ V |
| C_{LOAD} , $A_V = +1$ (Max) | 1000pF | 1000pF | 1000pF | 300pF | 300pF |

fiers become the better choice. These amplifiers have an input noise current that is less than one tenth of the LT1677's. The input bias currents are as low as those of most FET input devices and they maintain their low I_B at high temperatures where FET leakage currents increase exponentially. The input offset voltage and temperature drift are far superior to those of JFET input amplifiers. The LT1881 and LT1882 also operate at only 1mA supply current per amplifier.

The LT1884 dual and LT1885 quad amplifiers have input bias and offset currents almost as low as the LT1881 and LT1882, but have approximately three times faster AC response. These amplifiers can be employed in the same types of applications as the LT1881/LT1882, where AC response

has greater value and the cost in DC accuracy is minimal. Supply current is the same 1mA per amplifier.

Low Noise Remote Geophone Amplifier

Small signal applications require high gain and low noise, a natural for the LT1677. Its 1kHz noise is 100% tested and is guaranteed to be less than 4.5nV/ \sqrt{Hz} . Figure 3 is a 2-wire remote geophone preamp that operates on a current-loop principle and, as such, has good noise immunity. A low noise amplifier is desired in this application because the seismic signals that must be resolved are extremely small and require high gain. The LT1677 amplifies the geophone signal by one hundred and transmits it back to the

operator by modulating the current through R12. U2 is an LT1635 micro-power rail-to-rail op amp and reference configured as a stable current source of 5mA, which powers the LT1677 and another LT1635, this time configured as a 3V shunt regulator. The idling current through R10 is set up from the voltage at the emitter of Q2 (3V) and the voltage at the emitter of Q3 (1.85V from the ratio of R6 and R7). This places about 1.15V (zero TC, since Q1 temperature compensates Q2) across R10, thereby pulling an additional 7mA from the main supply through Q2. Of the total 12mA across the receiver resistor R12, 7mA is being modulated by allowing a peak signal of $\pm 1.5V$ about the 3V bias point across R12.

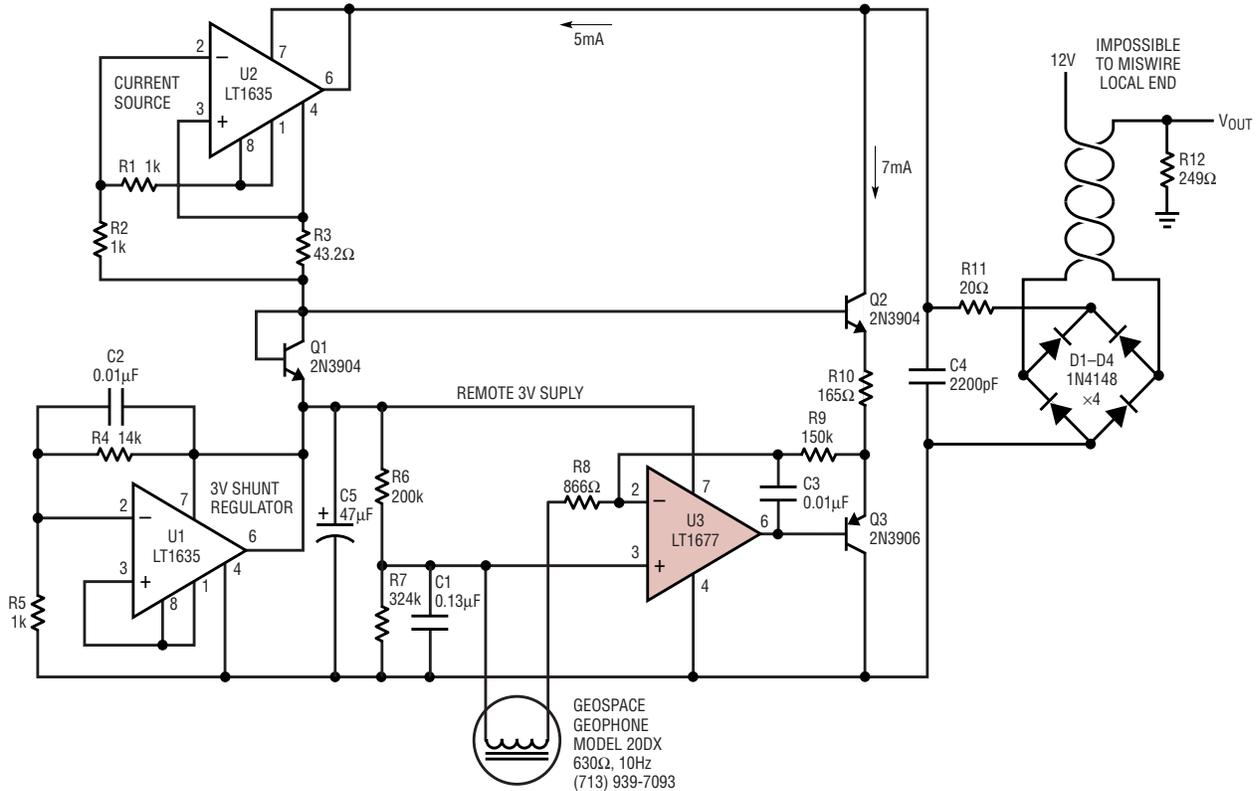


Figure 3. Geophone amplifier

Buffered Precision Voltage Reference

Figures 4a and 4b, respectively, show the gain (V_{OUT}/V_{IN}) and gain linearity for the LT1677 sinking or sourcing current into a 600Ω load with a single 5V supply. A horizontal trace indicates high gain; a straight trace indicates constant gain vs output voltage—this is excellent gain linearity. The trace for the ground-referenced load is more horizontal; this indicates higher loop

gain, due to the additional gain of the PNP output stage. Gain and gain linearity are improved by increasing the load resistor. Figure 4c shows the gain for a higher load resistance at a ±15V supply (note the change of vertical scale).

When teamed up with a precision shunt voltage reference such as the LT1634 (Figure 5), the LT1677, used

as a precision buffer, can enhance the reference voltage without significantly increasing the error budget. The LT1677 is used to make a 2.5V voltage source from a single 5V supply. The tolerance of the LT1634BCS8-2.5 is ±1.25mV (0.05%); the LT1677 adds only a ±60μV offset voltage. The output impedance of the voltage source for a wide range of sourcing or

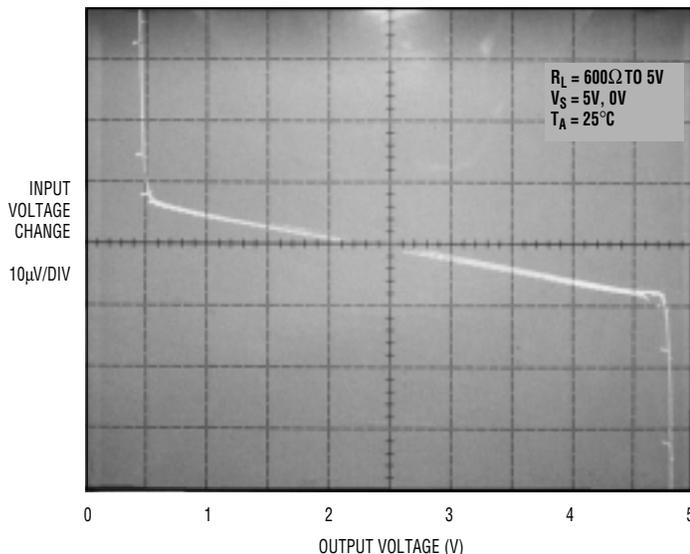


Figure 4a. Gain linearity of the LT1677 sinking current

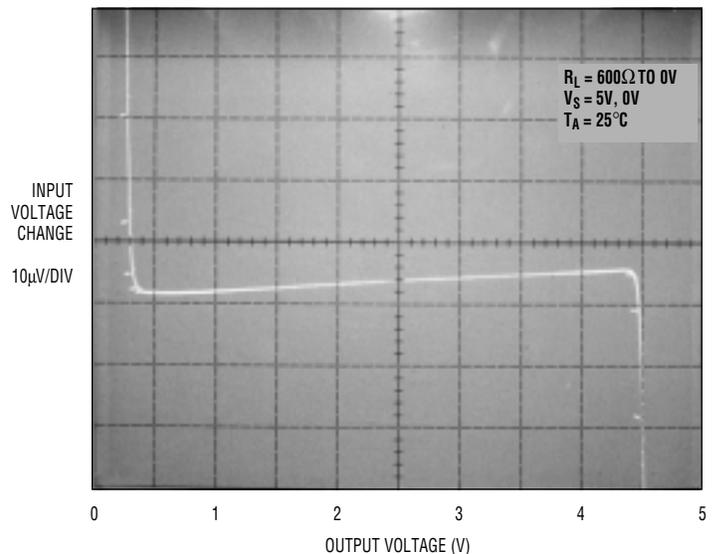


Figure 4b. Gain linearity of the LT1677 sourcing current

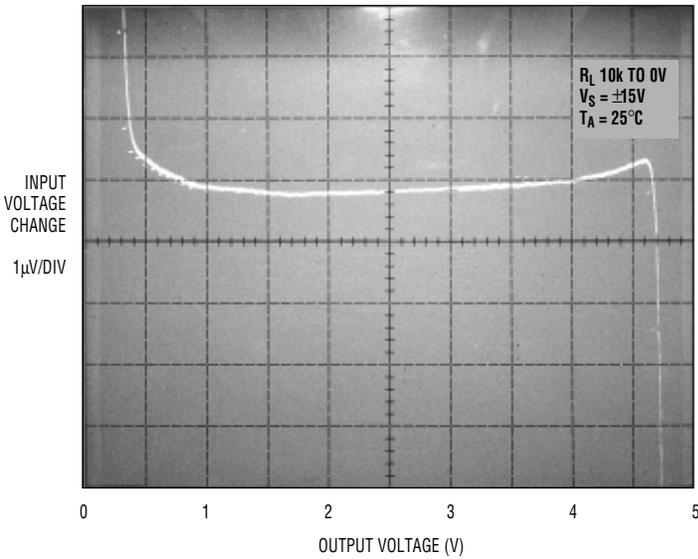


Figure 4c. LT1677 gain linearity with a higher load resistance and supply voltage

sinking currents can be calculated by dividing the LT1677's 80Ω open-loop resistance by its loop gain. This results in an output impedance of less than 1mΩ. The dynamic impedance at 10kHz drops from 20Ω (LT1634) to less than 0.01Ω (LT1677). The change in output voltage due to die temperature is reduced thirty times by shifting the load current to the LT1677. The temperature coefficient of the LT1677, 2µV/°C max, is negligible compared to the 62.5µV/°C TC (25ppm/°C • 2.5V) of the LT1634.

High-Side Current Sensing

Figure 6 is a precision high-side current sense amplifier that can operate on a single supply from 3V to 40V. The current flowing into the load produces a voltage drop across the line resistor R_{LINE} . The LT1677 forces a current through R_{IN} , which dupli-

cates the voltage drop across R_{LINE} . This current is then converted back to a voltage across R_{OUT} . By selecting appropriate values for these three resistors, the transfer function can be tailored to fit any application. Since the LT1677 can operate from either rail, a low-side current sense circuit can also be realized.

Low Input Bias Currents Fit Other Applications

The applications described above benefit from the LT1677's low input noise and rail-to-rail inputs, but other applications require high DC accuracy with low input bias currents. The LT1881/LT1882/LT1884/LT1885 provide the appropriate answer in these applications. Circuits that have high source impedances make the input bias current and input offset current characteristics of the ampli-

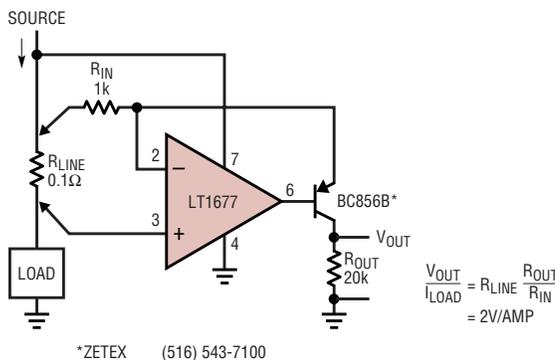


Figure 6. Precision high-side current sense amplifier

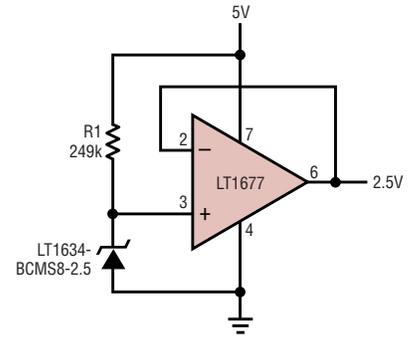


Figure 5. 2.5V reference from a 5V supply

fier important considerations. The amplifiers' input currents, acting on the source impedance, generate a DC offset error, limiting precision sensing of the source signal. The input voltage noise of the amplifier becomes a less important parameter because the noise generated by the high source impedance will typically be larger than the op amp's input noise. Input current noise is now the more important amplifier noise characteristic. The LT1881/LT1882/LT1884/LT1885 have very low input noise current, as shown in Table 1. Figure 7 graphs the total system noise due to amplifier input noise voltage, input noise current and the source resistance Johnson noise. The graph shows that the LT1677 is the correct amplifier when source resistance is below 20k. Above 200k an LT1881, LT1882, LT1884 or LT1885 are the best choices for minimizing system noise. In the

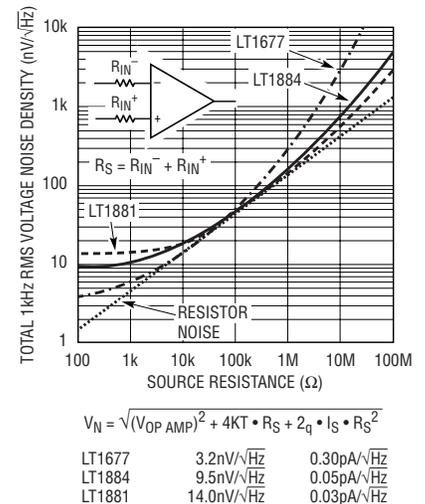


Figure 7. 1kHz noise voltage vs source resistance

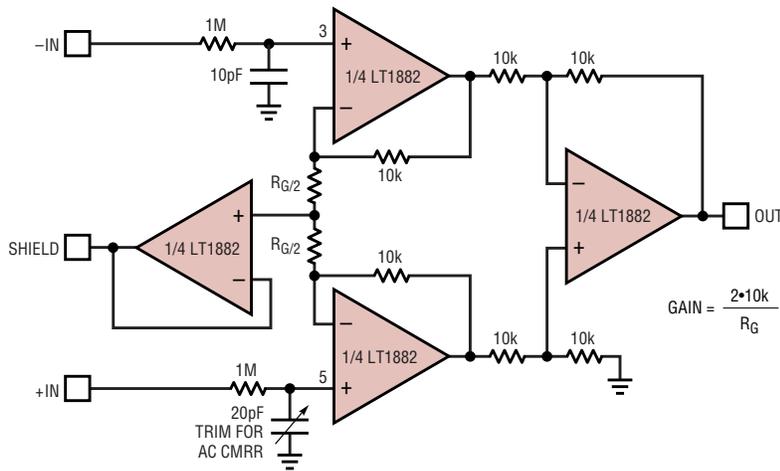


Figure 8. Input-fault-protected instrumentation amplifier

intermediate range of 20k to 200k, the source resistor's noise dominates and all of the amplifiers will give nearly equal system noise performance.

Input-Fault-Protected Instrumentation Amplifier

Figure 8 is a fault-protected instrumentation amplifier with shield drive. The 1M input resistors allow high voltage faults to be tolerated without damaging the amplifiers. An AC line fault will result in only 180μA of peak current flowing into the LT1882's input pins. Normally, such a high input resistance would result in huge DC offsets due to the input bias currents from the amplifiers. The LT1882's I_B is a low 500pA max. In addition, by using the guaranteed matching of I_B between amplifiers A and B or C and D, a worst-case I_B mismatch of 700pA is guaranteed. This results in a worst-case offset error of 700μV; typically this error would be less than 200μV. A pair of LT1881 "A" grade devices may be used to ensure a worst-case error less than 300μV.

The LT1882's input noise current working against the 1M source resistance generates a noise voltage of 42nV/√Hz. This compares to the protection resistors' Johnson noise of 182nV/√Hz and the amplifier's input noise voltage of 14nV/√Hz. Hence, the 1M protection resistors dominate the system's input noise. It is interesting to note that the LT1677 would contribute 420nV/√Hz of input noise

due to its input noise current, dominating the system noise level. In high source impedance applications, the LT1677 low noise amplifier will generate more system noise than an LT1882, which has a higher input voltage noise level. This underscores the need for proper amplifier selection based upon the application. In high source impedance applications, input current noise is a more important parameter than input voltage noise.

Low Voltage -50°C to 600°C Digital Thermometer

The circuit of Figure 9 is a digital thermometer which uses a 1k RTD sense element in a linear-output, single-leg bridge configuration. An LT1881 dual amplifier is used to provide the negative bridge excitation as well as output amplification and buffering. An LTC1287 A/D converter

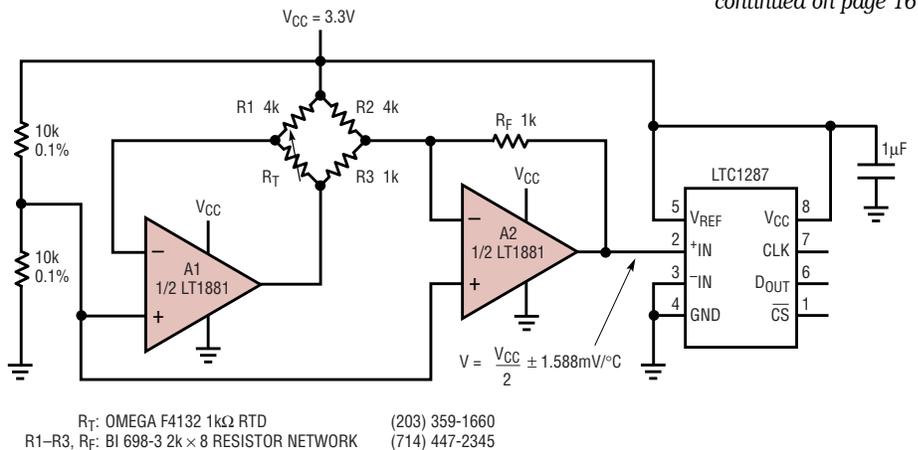
digitizes the output. No reference is needed; the bridge excitation and A/D reference are the power supply. The fixed bridge elements and output gain resistor are made with series and parallel combinations of an 8 × 2k resistor pack to get the best precision at a reasonable price.

The LT1884's low offset voltage and rail-to-rail output swing enable the circuit to function properly. The first amplifier, A1, is used to drive the negative side of the bridge to force a constant current excitation of the variable resistance element. The constant current drive results in the output voltage being perfectly linear with respect to the variable resistance. Since the LT1884 is able to swing to within to 50mV of the negative supply, the full dynamic range of the transducer is available even when operating on low voltage supplies. The second amplifier provides voltage gain to the bridge output to use the full-scale range of the A/D converter. The LT1884's low offset voltage is an important attribute of the gain amplifier.

±4.096V Swing 16-Bit Voltage Output DAC on a ±5V Supply

The final application, Figure 10, shows an LT1881 dual amplifier used as an I/V converter with the 16-bit LTC1597 DAC. The first amplifier is used to invert and buffer the LT1634 reference. This amplifier has no trouble swinging to -4.096V even with low supply voltages. The LT1881's exceptionally low I_B and offset voltage

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R1-R3, RF: BI 698-3 2k × 8 RESISTOR NETWORK (714) 447-2345

Figure 9. -50°C to 600°C digital thermometer runs on 3.3V

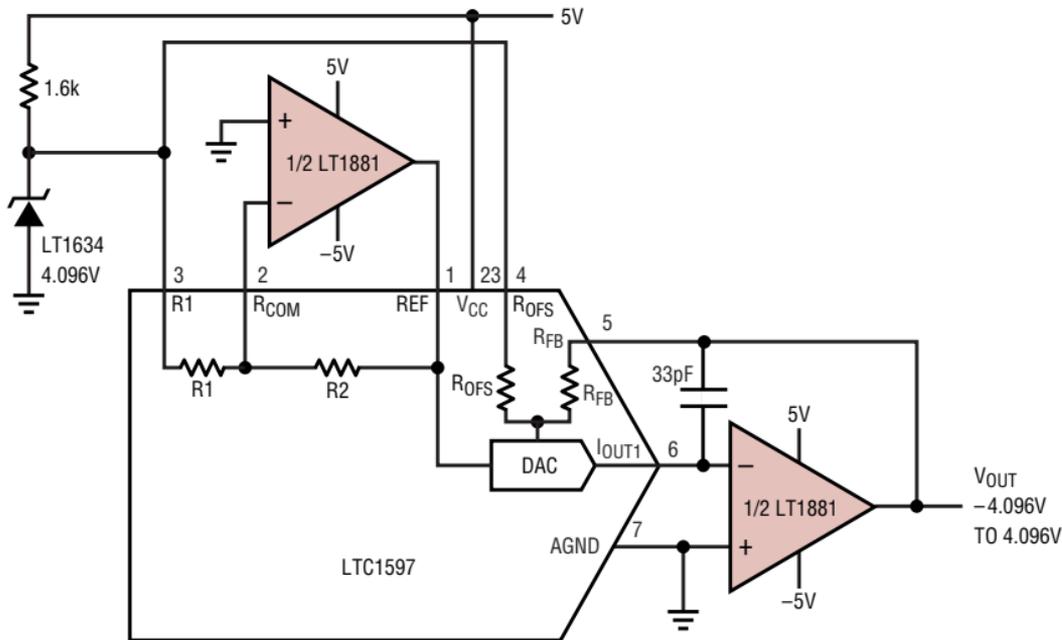


Figure 10. 16-bit voltage-output DAC on a $\pm 5V$ supply

minimize the introduction of errors due to the amplifiers. This is especially important when operating the DAC at low supply voltages. An LSB of DAC output current is only 3nA. The low I_B of the LT1881 keeps this error to less than 0.2LSB of zero-scale offset.

Conclusion

Linear Technology's new rail-to-rail output precision operational amplifiers provide the proper amplifier for any low voltage, high precision application. The user must understand the requirements of the application, particularly the source impedance, to make the proper choice as to whether the LT1677, LT1881/LT1882 or LT1884/LT1885 is the best amplifier for a given application. 