A Low Power Data Acquisition Solution for High Temperature Electronics Applications

By Jeff Watson and Maithil Pachchigar

Introduction

A growing number of applications require data acquisition systems that must operate reliably at very high ambient environments, such as downhole oil and gas drilling, avionics, and automotive. While the end uses in these industries are quite different, there are several common signal conditioning needs. The majority of these systems require precision data acquisition from multiple sensors or require a high sample rate. Furthermore, many of these applications have stringent power budgets because they are running from batteries or cannot tolerate additional temperature rise from self-heating of the electronics. Therefore, a low power analog-to-digital converter (ADC) signal chain that maintains high precision over temperature and can be easily used in a wide variety of scenarios is required. Such a signal chain is shown in Figure 1, which depicts a downhole drilling instrument.

While the number of commercially available ICs rated for 175°C is still small, they are increasing in number in recent years, especially for core functions such as signal conditioning and data conversion. This has enabled electronics engineers to rapidly and reliably design for high temperature applications and achieve performance that was not possible in the past. While many of these ICs are well characterized over temperature, this tends to be limited to the function of that device only. There is clearly a lack of circuit level information for these components that demonstrates best practices to achieve high performance in real-world systems.

In this article, we present a new reference design for high temperature data acquisition, characterized from room temperature to 175°C. This circuit is intended to be a complete data acquisition circuit building block that will take an analog sensor input, condition it, and digitize it to an SPI serial data stream. It is versatile enough to be used as a single channel, or it can be scaled for multiple channel simultaneous sampling applications. Recognizing the importance of low power consumption, the power consumption of the ADC scales linearly with the sample rate. The ADC can also be directly powered from the voltage reference, eliminating the need for an additional power rail and the associated power conversion inefficiencies. This reference design is available off the shelf to facilitate testing by designers and includes all schematics, bill of material, PCB artwork, and test software.

Circuit Overview

The circuit shown in Figure 1 is a 16-bit, 600 kSPS successive approximation analog-to-digital converter system using devices rated, characterized, and guaranteed at 175°C. Because many harsh environment applications are battery-powered, the signal chain has been designed for low power consumption while still maintaining high performance.

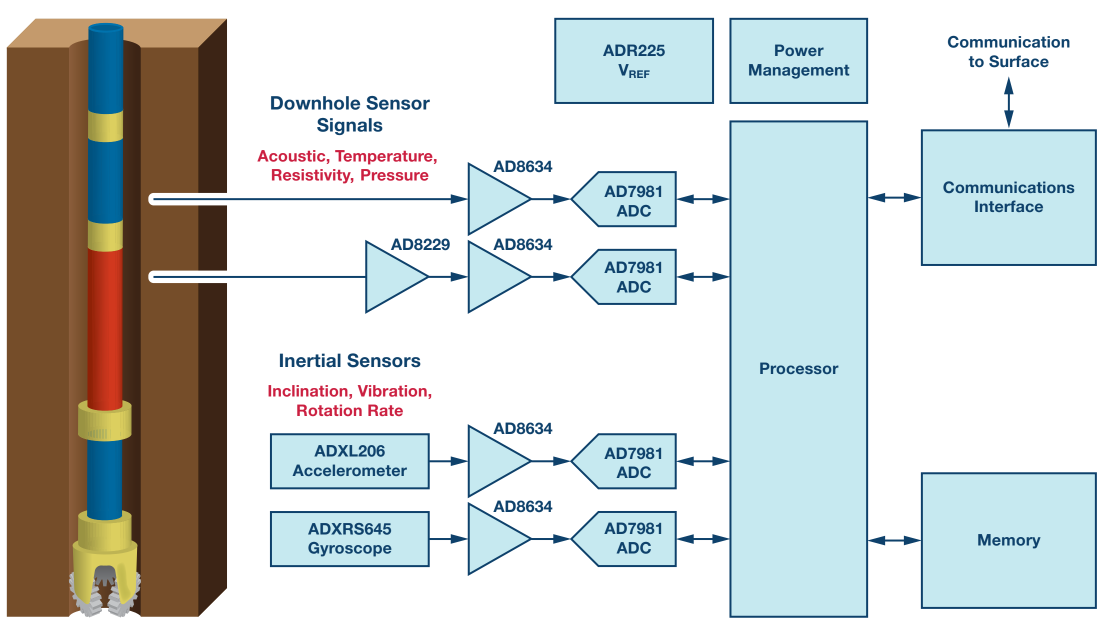

Figure 1. Downhole instrument data acquisition signal chain.

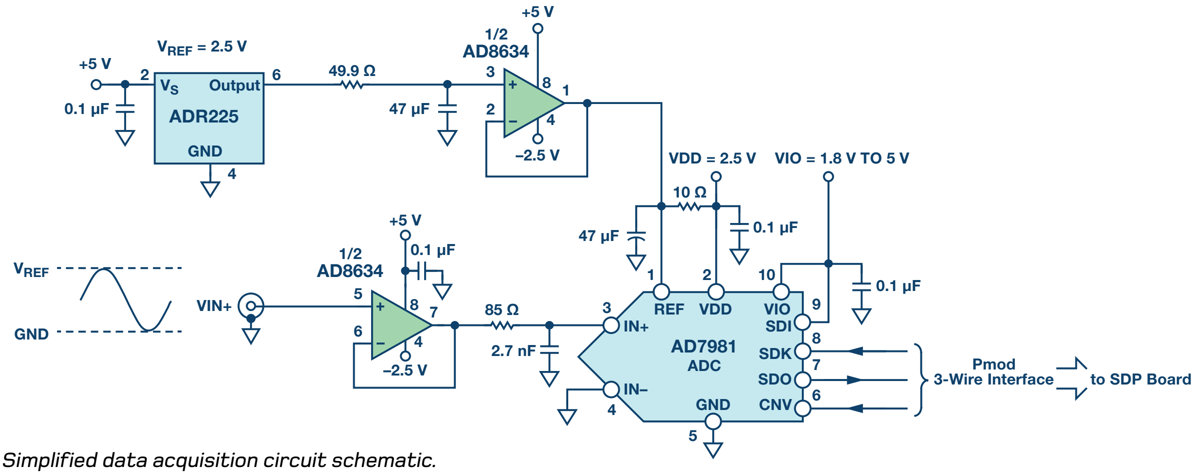

Figure 2. Simplified data acquisition circuit schematic.

This circuit uses the AD7981, a low power (4.65 mW @ 600 kSPS), high temperature PulSAR® ADC, driven directly from the AD8634 high temperature, low power op amp. The AD7981 ADC requires an external voltage reference between 2.4 V and 5.1 V, and in this application, the voltage reference chosen is the micropower ADR225 precision 2.5 V reference, which is also qualified for high temperature operation and has a very low quiescent current of 60 µA maximum at 210°C. All of the ICs in this design have packaging specially designed for high temperature environments, including monometallic wire bonds.

Analog-to-Digital Converter

The heart of this circuit is the AD7981, a 16-bit, low power, single-supply ADC that uses a successive approximation architecture (SAR), capable of sampling up to 600 kSPS. As shown in the diagram in Figure 1, the AD7981 uses two power supply pins: a core supply, VDD, and a digital input/output interface supply, VIO. The VIO pin allows a direct interface with any logic between 1.8 V and 5.0 V. The VDD and VIO pins can also be tied together to save on the number of supplies needed in the system, and they are independent of power supply sequencing. A simplified connection diagram is shown in Figure 3.

The AD7981 typically consumes only 4.65 mW at 600 kSPS and powers down automatically between conversions in order to save power. Therefore, the power consumption scales linearly with the sampling rate, making the ADC well suited for both high and low sampling rates—even as low as a few Hz—and enables very low power consumption for battery-powered systems. Additionally, oversampling techniques can be used to increase the effective resolution for low speed signals.

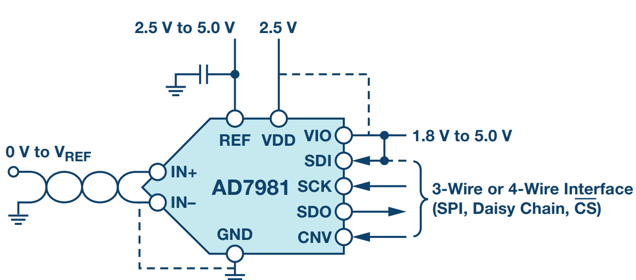

Figure 3. AD7981 application diagram.

The AD7981 has a pseudo differential analog input structure that samples the true differential signal between the IN+ and IN− inputs and rejects the signals common to both inputs. The IN+ input can accept the unipolar, single-ended input signal from 0 V to V_{REF}, and the IN− input has a restricted range of GND to 100 mV. The pseudo differential input of AD7981 simplifies the ADC driver requirement and lowers power dissipation. The AD7981 is available in a 10-lead MSOP rated for 175°C.

ADC Driver

The input of AD7981 can be driven directly from low impedance sources, but high source impedances significantly degrade the ac performance, especially total harmonic distortion (THD). Therefore it is recommended to use an ADC driver or op amp, such as AD8634, to drive the input of the AD7981 as shown in Figure 4. At the start of the acquisition time the switch closes, and the capacitive DAC injects a voltage glitch (kickback) on the ADC input. The ADC driver helps to settle this kickback as well as isolate it from the signal source.

The low power (1 mA/amplifier) AD8634 dual precision op amp is suited for this task because its excellent dc and ac specifications are a good fit for sensor signal conditioning and elsewhere in the signal chain. While the AD8634 has rail-to-rail outputs, the input requires 300 mV headroom from the positive and negative rails. This necessitates the negative supply, which was chosen to be –2.5 V. The AD8634 is available in an 8-lead SOIC rated for 175°C and an 8-lead flatpack rated for 210°C.

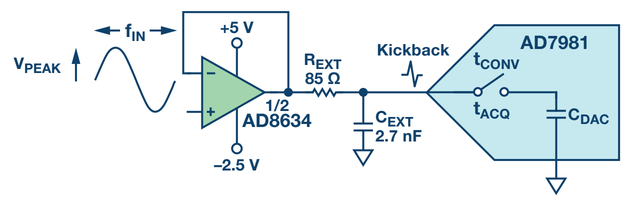

Figure 4. ADC front-end amplifier circuit.

The RC filter between the ADC driver and AD7981 is used to attenuate the kickback injected at the input of the AD7981 and band limits the noise coming to its input. However, too much band limiting can increase settling time and distortion. Therefore, it is very important to find the optimal RC values for this filter. The calculation is primarily based on the input frequency and throughput rate.

From the AD7981 data sheet, internal sampling cap C_{IN} = 30 pF and t_{CONV} = 900 ns, so as described, for a 10 kHz input signal, assuming the ADC is running at 600 kSPS and C_{EXT} = 2.7 nF, the voltage step for a 2.5 V reference would be:

$$V_{STEP} = \frac{2\pi f_{IN} V_{PEAK} t_{CONV} C_{IN}}{C_{EXT} + C_{IN}}$$

$$V_{STEP} = 7.768e - 4 \text{ V}$$

Therefore, the number of time constants required to settle to ½ LSB at 16 bits is:

$$N_{TC} = \ln\left(\frac{V_{STEP}}{\frac{V_{REF}}{2^{N+1}}}\right) = \ln\left(\frac{7.768e-4}{\frac{2.5\text{ V}}{2^{16+1}}}\right) = 3.707$$

The acquisition time of AD7981 is

$$t_{ACQ} = \left(\frac{1}{f_S}\right) - t_{CONV} = \left(\frac{1}{600\ kSPS}\right) - 900\text{ ns} = 7.67e-7$$

We can then calculate the bandwidth of the RC filter using the following equation:

$$\tau = \left(\frac{t_{ACQ}}{N_{TC}}\right) = \left(\frac{7.67e-7}{3.707}\right) = 2.068e-7$$

$$f_{-3dB} = \left(\frac{1}{2\pi\tau}\right) = 769.5\text{ kHz} \rightarrow R_{EXT} = 76.6\ \Omega$$

This is a theoretical value with first-order approximation that should be verified in the lab. We determined through testing that the optimum values were R_{EXT} = 85 Ω and C_{EXT} = 2.7 nF (f_{-3dB} = 693.48 kHz), which gave excellent performance over the extended temperature range to 175°C.

In the reference design, the ADC driver is in unity-gain buffer configuration. Adding gain to the ADC driver will reduce the bandwidth of the driver and lengthen the settling time. In this case, the throughput of the ADC may need to be reduced or an additional buffer as a driver should be used after the gain stage.

Voltage Reference

The ADR225 2.5 V voltage reference uses only 60 µA maximum of quiescent current at 210°C and has a very low drift of 40 ppm/°C typical, making it an ideal part for this low power data acquisition circuit. It has an initial accuracy of ±0.4% and can operate over a wide supply range of 3.3 V to 16 V.

The voltage reference input of the AD7981, like other SAR ADCs, has a dynamic input impedance and should therefore be driven by a low impedance source with efficient decoupling between the REF pin and GND as shown in Figure 5. The AD8634 is well suited as a reference buffer in addition to its ADC driver application.

Another advantage to using a reference buffer is that the noise on the voltage reference output can be further reduced by adding a low-pass RC filter, as shown in Figure 5. In this circuit, a 49.9 Ω resistor and 47 µF capacitor gives a cutoff frequency of approximately 67 Hz.

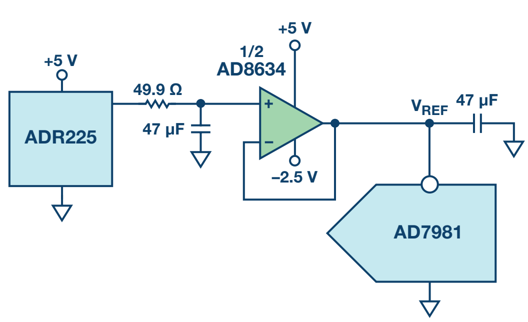

Figure 5. SAR ADC reference buffer and RC filter.

During conversions, current spikes as high as 2.5 mA can occur on the AD7981 reference input. A high value reservoir capacitor is placed as close as possible to the reference input to supply that current and keep the reference input noise low. Typically, a low ESR—10 µF or more—ceramic capacitor is used, but for high temperature applications this is problematic due to the lack of availability of high value, high temperature ceramic capacitors. For this reason, a low ESR 47 µF tantalum capacitor was chosen that has minimal impact to the performance of the circuit.

Digital Interface

The AD7981 offers a flexible serial digital interface compatible with SPI, QSPI, and other digital hosts. The interface can be configured for a simple 3-wire mode for the lowest I/O count, or 4-wire mode that allows options for the daisy-chained readback and busy indication. The 4-wire mode also allows independent readback timing from the CNV (convert input), which enables simultaneous sampling with multiple converters.

The Pmod-compatible interface utilized on this reference design implements the simple 3-wire mode with SDI tied high to VIO. The VIO voltage is supplied externally from the SDP-PMOD interposer board. The interposer board connects the reference design board to the Analog Devices System Development Platform (SDP) board and allows connection to a PC through USB in order to run software to evaluate performance.

Power Supplies

This reference design requires external low noise power supplies for the +5 V and –2.5 V rails. Because the AD7981 is low power, it can be supplied directly from the reference buffer. This eliminates the need for an additional power supply rail—saving power and board space. The proper configuration to power the ADC from the reference buffer is shown in Figure 6. VIO can also be supplied if logic levels are compatible. For the reference design board VIO is supplied externally through the Pmod-compatible interface for maximum flexibility.

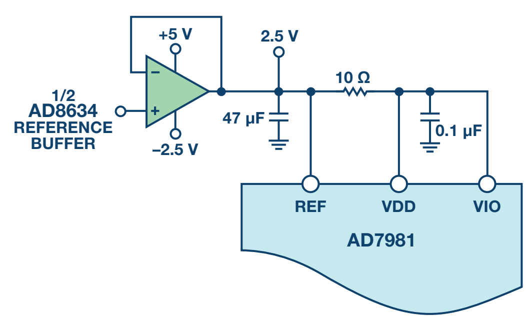

Figure 6. Supplying ADC from reference buffer.

The typical total power consumption for an entire data acquisition solution at 175°C can be calculated as follows:

ADR225: 30 µA × 5 V = 0.15 mW

AD8634: (1 mA × 2 amplifiers) × 7.5 V = 15 mW

AD7981: 4.65 mW @ 600 kSPS

Total power consumption = 19.8 mW

IC Packaging and Reliability

Devices in the Analog Devices high temperature portfolio go through a special process flow that includes design, characterization, reliability qualification, and a production test. Part of this process includes special packaging designed specifically for extreme temperatures. A special material set is used for the 175°C plastic packages in this circuit.

One of the major failure mechanisms in high temperature packaging is the bond wire-to-bond pad interface, particularly when gold (Au) and aluminum (Al) metals are mixed, as is typical in plastic packages. Elevated temperature accelerates the growth of AuAl intermetallic compounds. It is these intermetallics that are associated with bond failures, such as brittle bonds and voiding, which can occur in a few hundred hours as shown in Figure 7.

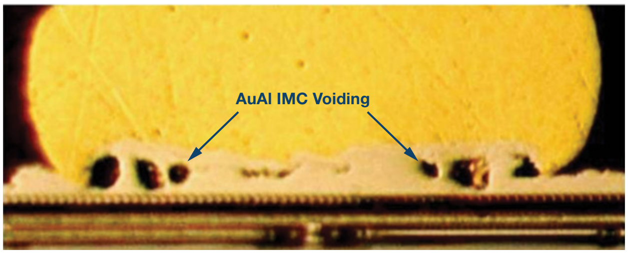

Figure 7. Au ball bond on Al pad, post 500 hours at 195°C.

In order to avoid these failures, Analog Devices uses an over pad metallization (OPM) process to create a gold bond pad surface for the gold bond wire to attach. This monometallic system will not form intermetallics and has been proven reliable in qualification testing with over 6000 hours soak at 195°C, as shown in Figure 8.

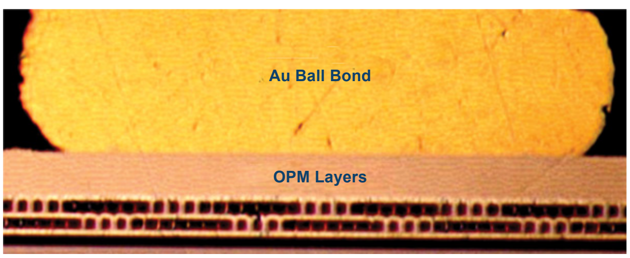

Figure 8. Au ball bond on OPM pad, post 6000 hours at 195°C.

Although Analog Devices has shown reliable bonding at 195°C, the plastic package is rated for operation only to 175°C due to the glass transition temperature of the molding compound. In addition to the 175°C rated products used on this circuit, 210°C rated models are also available in a ceramic flatpack package. Known good die (KGD) are also available for systems that require custom packaging.

Analog Devices has a comprehensive reliability qualification program for high temperature (HT) products that includes high temperature operating life (HTOL), with the parts biased at the maximum operating temperature. HT products are data sheet specified for a minimum of 1000 hours at the maximum rated temperature. Full production testing is the last step required to guarantee performance for each device that is manufactured. Each device in Analog Devices' high temperature portfolio is production tested at elevated temperature to ensure performance is met.

Passive Components

Passive components chosen should be rated for high temperatures. For this design, >175°C thin film, low TCR resistors were used. COG/NPO capacitors were used for low value filter and decoupling applications and have a very flat coefficient over temperature. High temperature rated tantalum capacitors are available in larger values than ceramic and are commonly used for power supply filtering. The SMA connector used on this board is rated for 165°C, so it should be removed for long duration testing at elevated temperatures. Similarly, the insulation material on the 0.1" header connectors (J2 and P3) is only rated for short durations at high temperature but should also be removed for prolonged high temperature testing. For production assemblies, there are a number of options for HT rated connectors from multiple vendors, such as Micro-D style connectors.

PCB Layout and Assembly

The PCB for this circuit is designed so that the analog signals and digital interface are on separate sides of the ADC, with no switching signals running under the ADC IC or near analog signal paths. This design minimizes the amount of noise that is coupled into the ADC die and supporting analog signal chain. The pin out of the AD7981, with all its analog signals on the left side and all its digital signals on the right side, eases this task. The voltage reference input, REF, has a dynamic input impedance and should be decoupled with minimal parasitic inductances, which is achieved by placing the reference decoupling capacitor as close as possible to the REF and GND pin and making the connection to the pin with a wide, low impedance trace. The layout of this board was purposely designed with components only on the top side of the board in order to facilitate testing over temperature where heat would be applied from the bottom of the board. A photo of the complete assembly is shown in Figure 9. For further layout recommendations, see the AD7981 data sheet.

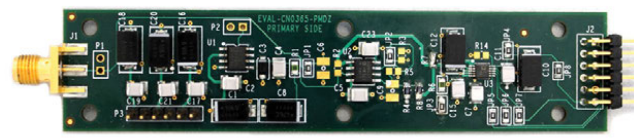

Figure 9. Reference design circuit assembly.

For high temperature circuits, special circuit materials and assembly techniques should be used to ensure reliability. FR4 is a common material used for PCB laminates, but commercial grade FR4 has a typical glass transition temperature around 140°C. Above 140°C, the PCB will begin to break down, delaminate, and cause stress on components. A widely used alternative for high temperature assemblies is polyimide, which typically has a glass transition temperature of greater than 240°C. A four layer polyimide PCB was used in this design.

The PCB surface is also a concern, especially when used with solders containing tin because of the tendency to form bronze intermetallics with copper traces. A nickel-gold surface finish is commonly used, where the nickel provides a barrier, and the gold provides a good surface for the solder joint bonding. High melting point solder should also be used with a good margin between the melting point and maximum operating temperature of the system. SAC305 lead free solder was chosen for this assembly. With a melting point of 217°C, there is a margin of 42°C from the highest operational temperature of 175°C.

Performance Expectations

The AD7981 is specified for typical SNR of 91 dB with a 1 kHz input tone and a 5 V reference. However, when using low reference voltages such as 2.5 V, as is common in low power/low voltage systems, some degradation in SNR is expected. We can calculate the theoretical SNR based on the specifications of the components used in the circuit. From the AD8634 amplifier data sheet, its input voltage noise density is 4.2 nV/$\sqrt{\text{Hz}}$ and current noise density is 0.6 pA/$\sqrt{\text{Hz}}$. Since the noise gain of AD8634 in buffer configuration is 1, and assuming negligible series input resistance for the current noise calculation, the equivalent output noise contribution from the AD8634 would be:

$$\sqrt{(4.2e-9)^2 + 0 \times (0.6e-12)^2} = 4.2\ \text{nV}/\sqrt{\text{Hz}}$$

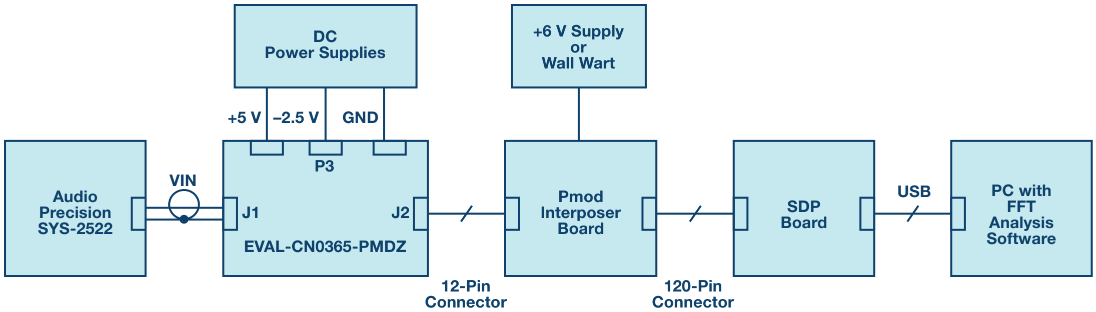

Figure 10. Characterization test setup.

The total integrated noise at the ADC input

(after RC filter $\left(\dfrac{1}{2\pi(85)(2.7e-9)}\right)$) would be:

$$4.2\ \text{nV}/\sqrt{\text{Hz}} \times \sqrt{(693.48e3 \times \tfrac{\pi}{2})} = 4.38\ \mu\text{V rms}$$

The rms noise of AD7981 can be calculated from its data sheet typical SNR of 86 dB for a 2.5 V reference.

$$e_{AD7981} = 10^{\left(-\frac{SNR}{20}\right)} \times V_{signal\text{-}rms} =$$

$$10^{\left(-\frac{86}{20}\right)} \times 0.884\ \text{V} = 44.3\ \mu\text{V rms}$$

The total rms noise of the complete data acquisition system can be calculated by using root-sum-square (RSS) of AD8634 and AD7981 noise sources:

$$V_{noise\text{-}rms} = \sqrt{(4.38e-6)^2 + (44.3e-6)^2}$$

$$= 44.51\ \mu\text{V rms}$$

So, the theoretical SNR of the data acquisition system at room temp (25°C) can be estimated as shown below:

$$SNR = 20 \times \log\left(\frac{V_{signal-rms}}{V_{noise-rms}}\right)$$

$$= 20 \times \log\left(\frac{0.884\ \text{V}}{44.51\ \mu\text{V rms}}\right) = \sim 86\ \text{dB}$$

Test Results

The ac performance of the circuit was evaluated over temperature from 25°C to 185°C. It is critical to use a low distortion signal generator to characterize performance. For this test, the Audio Precision SYS-2522 was used. In order to facilitate testing in an oven, extension harnesses were assembled so that only the reference design circuit was exposed to an elevated temperature. The block diagram of the test setup is shown below in Figure 10.

From our calculations in the previous setup, we expect to achieve approximately 86 dB SNR at room temperature. This compares well to our measured value of 86.2 dB SNR at room temperature as shown in the FFT summary in Figure 11.

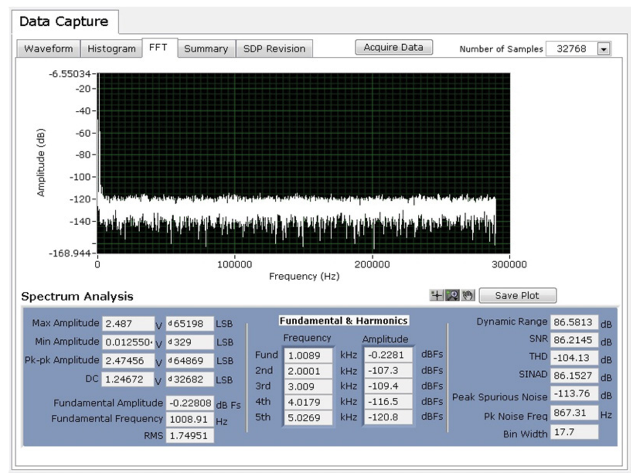

Figure 11. AC performance with 1 kHz input tone, 580 kSPS, 25°C.

When this circuit is evaluated over temperature, SNR performance only degrades to approximately 84 dB at 175°C as shown in Figure 12. THD remains better than –100 dB, as shown in Figure 13. The FFT summary for the circuit at 175°C is shown in Figure 14.

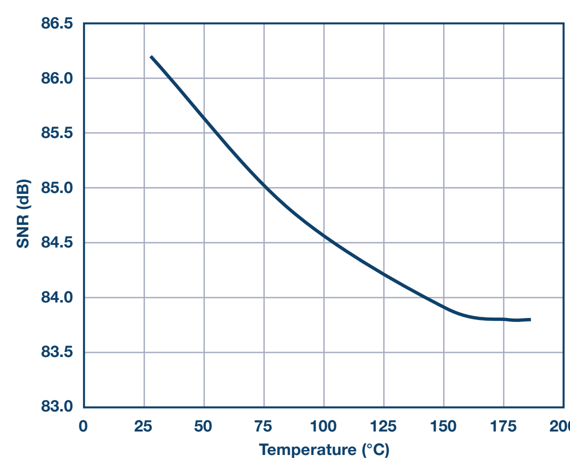

Figure 12. SNR over temperature, 1 kHz input tone, 580 kSPS.

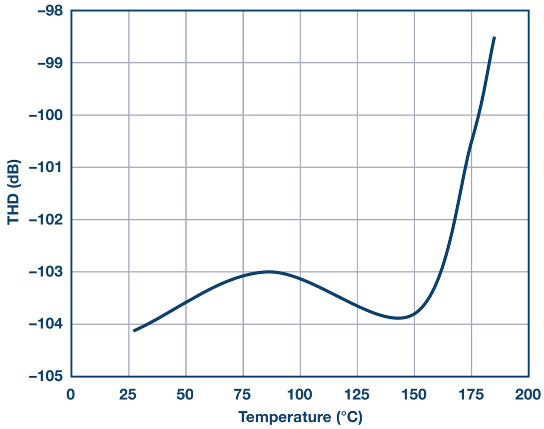

Figure 13. THD over temperature, 1 kHz input tone, 580 kSPS.

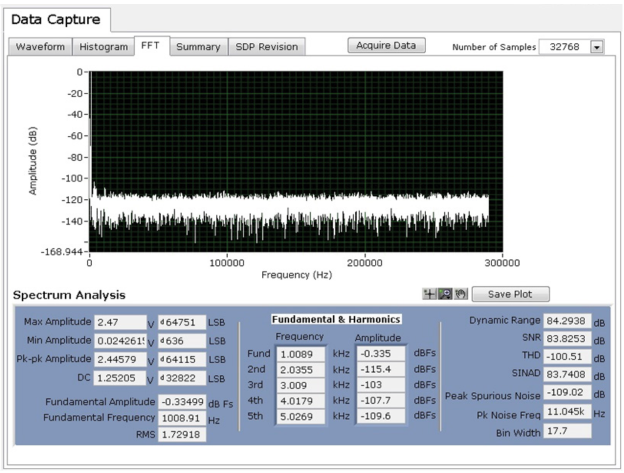

Figure 14. AC performance with 1 kHz input tone, 580 kSPS, 175°C.

Summary

In this article we presented a new reference design for high temperature data acquisition, characterized from room temperature to 175°C. This circuit is a complete low power (<20 mW) data acquisition circuit building block that will take an analog sensor input, condition it, and digitize it to an SPI serial data stream. This reference design is available off the shelf to facilitate testing by designers and includes all schematics, bill of materials, PCB artwork, test software, and documentation.

For more information on this reference design, please visit analog.com/CN0365. For more information on ADI's high temperature portfolio, please visit analog.com/hightemp.

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