RTD Ratiometric Measurements and Filtering Using the ADS1148 and ADS1248 Family of Devices

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ABSTRACT

The ADS1148 and ADS1248 family of devices are highly integrated delta-sigma (ΔΣ) converters that are optimized for the measurement of temperature sensors, including resistance temperature detectors (RTDs), thermocouples, and thermistors. In a typical RTD measurement application, the ADS1148 and ADS1248 are configured in a ratiometric topology using the built-in IDAC current sources feeding through an external reference precision resistor. The ratiometric operation has an advantage because the errors due to the excitation current source drift and noise tend to cancel. In order to maintain good noise cancellation over the input signal range, make sure that the analog-to-digital converter (ADC) external input filter is matched to the filter at the reference input. This document focuses on the external analog low-pass filter implementations and design considerations when performing RTD sensor measurements using the ADS1148 and ADS1248 family of delta-sigma converters in a ratiometric configuration.

NOTE: Although the ADS1248 24-bit device is referenced throughout this document, the ADS1148 16-bit device can also be used. The same concept for filtering applies to both device families, which also include the ADS1147 and ADS1247.

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1 Introduction

Resistance temperature detectors (RTDs) work by correlating the change of the resistance of a metal sensing element versus a temperature change. As the temperature of the RTD element increases, the electrical resistance of the RTD metal increases. When performing the measurement of a resistive sensor, such as an RTD in data acquisition systems, a constant current source excitation is frequently used.

The ADS1148 and ADS1248 family of devices incorporates two programmable current sources that can be used to excite the RTD sensors.Figure 1 shows a typical configuration used to measure an RTD in a four-wire configuration.

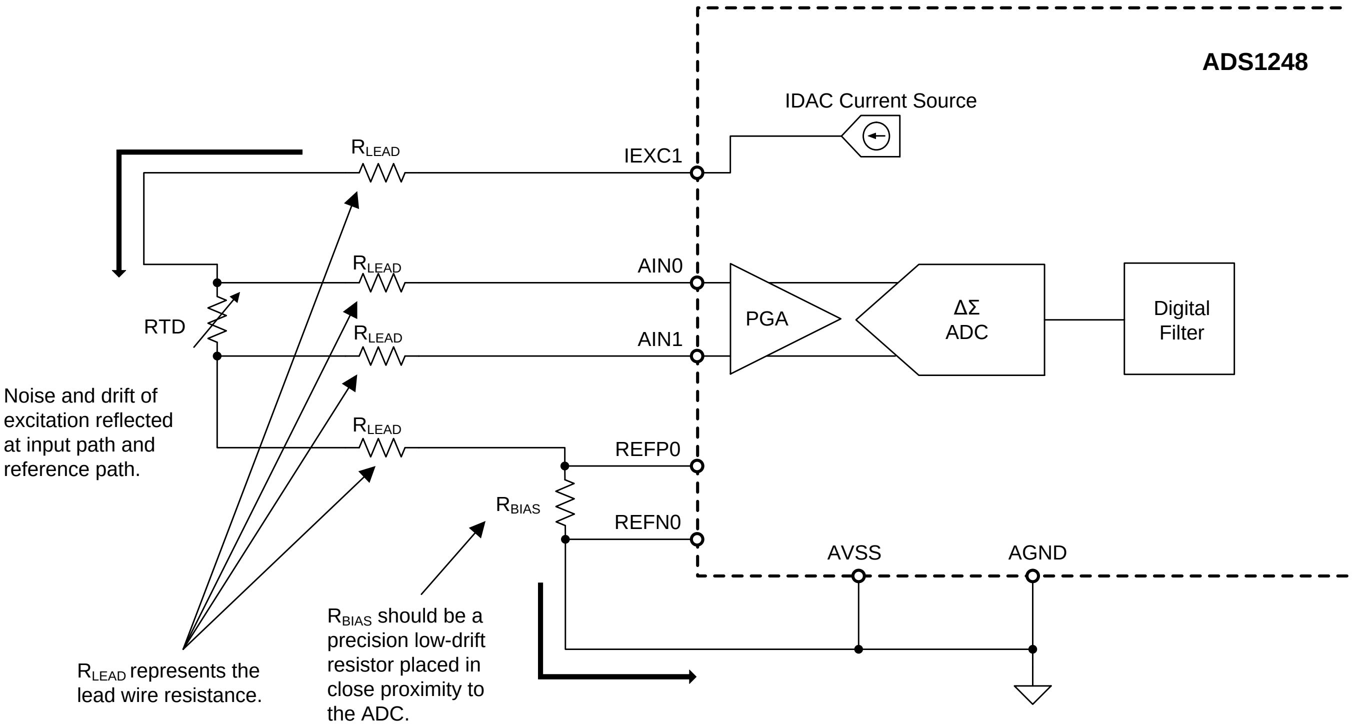

Figure 1. Four-Wire Ratiometric RTD Measurement Using the ADS1248

In the simplified circuit diagram shown in Figure 1 , the current from the IDAC source flows through the RTD sensor and the return current flows through the R_{BIAS} resistor. The R_{LEAD} resistor represents the lead wire resistance connecting the RTD element, generally limited to 10 Ω or less. The voltage generated across the R_{BIAS} resistor is the voltage reference for the ADC. In addition, the R_{BIAS} resistor places the RTD at a voltage greater than the analog negative supply (AVSS) in order for the sensor to be biased in the valid input common-mode voltage range of the ADC.

ADCs produce an output code as a function of the ratio of the input voltage to the reference voltage. In the ratiometric circuit shown in Figure 1, the voltage across the RTD sensor and the R_{BIAS} resistor are generated with the same excitation source. Any changes as a result of the excitation current source drift is reflected across the sensor at the input path of the device, and across the R_{BIAS} resistor at the reference path of the ADC. In this ratiometric configuration, if the RTD and R_{BIAS} resistances remain unchanged, the digital output of the ADC is unaffected by changes of the excitation source.

Performing sensor measurements in a ratiometric configuration provides a significant advantage, where the errors as a result of the absolute accuracy of the excitation current and the errors because of to the excitation drift are virtually eliminated. In addition, when performing measurements in a ratiometric configuration, the noise of the excitation source at the inputs is reflected to the reference path of the ADC; and in this manner, the noise cancels.

In many applications, input RC low-pass filters are employed to improve the end-product immunity to radio frequency interference (RFI) and electromagnetic interference (EMI). However, it is important that the input filter and the reference filter have matched time constants or the cancellation of current source noise can degrade, leading to increasing noise with increasing signal level. Although the ratiometric circuit can work without the use of external RC filters, the addition of low-pass RC filters may prove to be beneficial in noisy environments, where the sensor circuit is prone to noise interference. This document focuses on maintaining noise cancellation of the current source when external RC filters are used.

2 Low-Pass Filter Design Considerations in Ratiometric Measurements

In order for effective ratiometric cancellation to occur, the errors due to the excitation source drift and noise must be equally reflected at the inputs of the ADC, and at the reference inputs of the device. In this configuration, the excitation noise cancels, resulting in a stable, high-resolution measurement. In applications where external filters may be required to eliminate noise interference, make sure to balance the corner frequency of the reference low-pass filter to the corner frequency of the input low-pass filter.

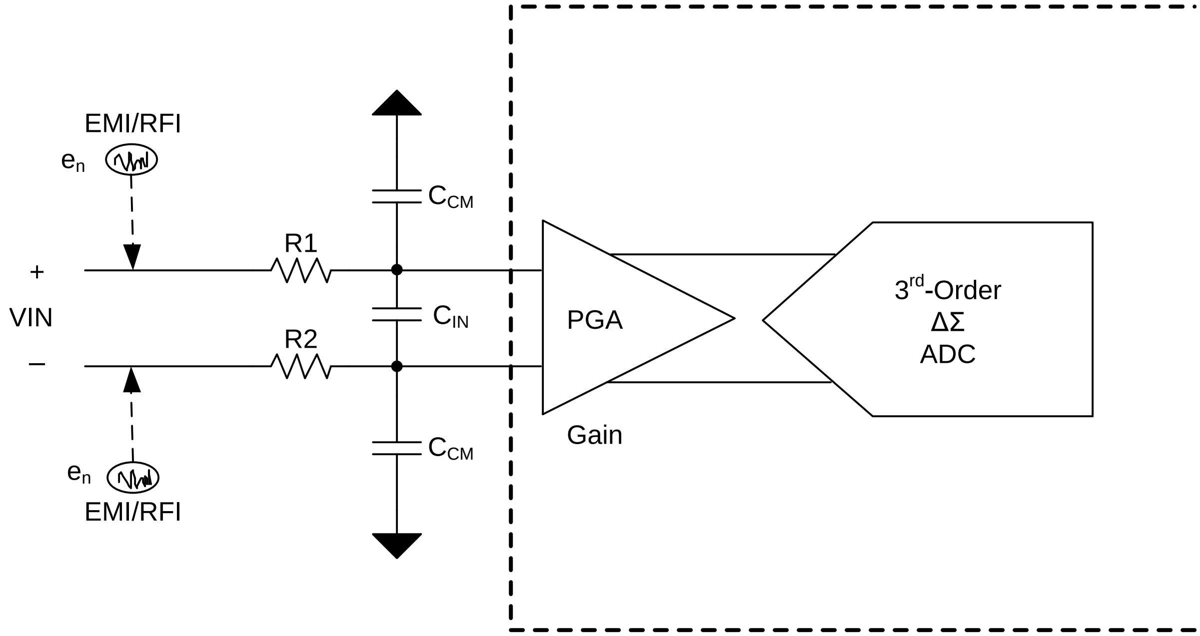

Figure 2. Typical Differential and Common-Mode Filter

The circuit diagram of shows a generic circuit topology frequently used in front of differential amplifiers. The input path RC low-pass filter consists of two matched series resistors, one differential capacitor, and two common-mode capacitors. This passive filter provides a first-order 20-dB/decade roll-off characteristic.

This filter topology provides attenuation for both the differential and common-mode voltage signals. The differential capacitor value is typically chosen to be at least 10 times larger than the common-mode voltage capacitors. By simple inspection, derive Equation 1 and Equation 2 to calculate the corner frequencies:

Differential-Mode Corner Frequency:

$$f_{-3dB} = \frac{1}{2\pi(R1 + R2)(C_{IN} + \frac{C_{CM}}{2})} \quad (1)$$

Common-Mode Corner Frequency:

$$f_{-3dB} = \frac{1}{2\pi(R1C_{CM})} \quad (2)$$

When the C_{DIFF} capacitor value is chosen to be 10 times larger than the common-mode capacitors, the resulting differential filter provides a corner frequency that is 20 times lower than the common-mode filter corner frequency. The differential signals are attenuated at a lower frequency than the common-mode signals. The internal programmable gain amplifier (PGA) of the ADS1248 tends to amplify differential signals and reject the common-mode voltage signals. Providing this ratio of capacitors helps to mitigate the effects due to the mismatch of the common-mode capacitors, where the asymmetric noise attenuation caused by the common-mode capacitor mismatch is attenuated to insignificant levels.

A similar filter topology may be applied to the RTD ratiometric measurement circuit. Make sure to match the corner frequency of the RTD filter at the input path and the corner frequency at the reference path.

The RTD sensor resistance along with the R_{BIAS} resistor affect the time constants of the filters. In order to analyze the circuit in Figure 3, a zero-value time constant technique approach [1] may be used to obtain an estimate of the differential and common-mode corner frequencies involved.

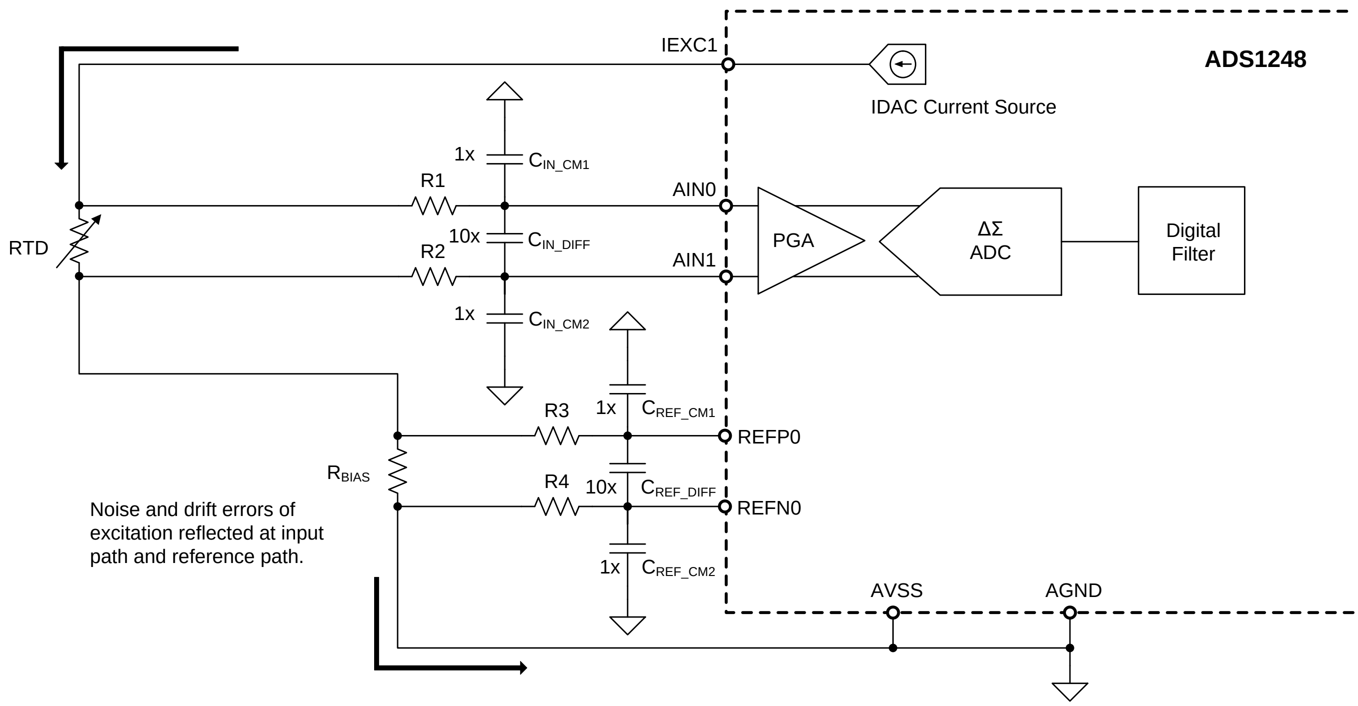

Figure 3. Four-Wire Ratiometric RTD Measurement with Filters (R_{LEAD} Removed for Simplicity)

Start by considering the differential filter corner frequency at the inputs of the ADC. The signal sources are set to zero by replacing the current excitation source with an open circuit, as shown in Figure 4. Replace differential input capacitor C_{IN_DIFF} with a test voltage source and the rest of the capacitors with open circuits.

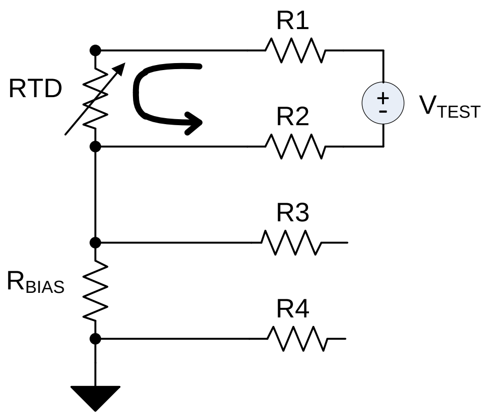

Figure 4. Simplified RC Circuit to Find the Corner Frequency of the Differential-Mode Input Filter

The effective resistance seen by the test voltage source is RTD + R1 + R2. Therefore, the RC constant seen by this filter is approximately C_{IN_DIFF} (RTD + R1 + R2), resulting in an approximate corner frequency of:

$$f_{-3dB} = \frac{1}{2\pi C_{IN\_DIFF}(RTD + R1 + R2)} \quad (3)$$

The same approach is used to determine the corner frequencies of the common-mode filters, as shown in Figure 5.

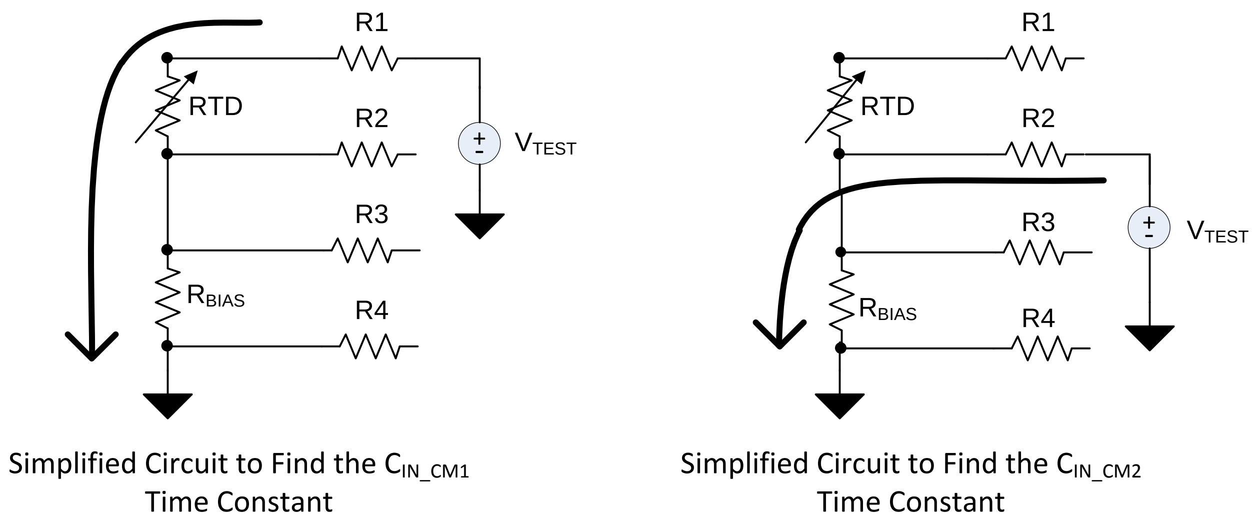

Figure 5. Simplified RC Circuit to Find the Corner Frequency of the Common-Mode Input Filter

When replacing C_{IN_CM1} with a test source, the resistance seen by C_{IN_CM1} is R1 + RTD + R_{BIAS}, yielding a corner frequency of:

$$f_{-3dB} = \frac{1}{2\pi C_{IN\_CM1}(R1 + RTD + R_{BIAS})} \quad (4)$$

In similar fashion, the corner frequency provided by C_{IN_CM2} is given as:

$$f_{-3dB} = \frac{1}{2\pi C_{IN\_CM2}(R2 + R_{BIAS})} \quad (5)$$

The resistance of the RTD sensor changes with temperature measurement, and thus changes the frequency response of the differential filter. It also causes a mismatch on the corner frequencies of the input common-mode filters, but the impact of noise cancellation caused by the common-mode filters is not as significant as the differential filters. Scale the R1 and R2 resistors to be larger than the RTD sensor in order to help mitigate this effect.

Using the same approach, the corner frequencies for the differential reference path circuit may be calculated as:

$$f_{-3dB} = \frac{1}{2\pi C_{REF\_DIFF}(R3 + R_{BIAS} + R4)} \quad (6)$$

And the common-mode filters at the reference path may be calculated as:

$$f_{-3dB} = \frac{1}{2\pi C_{REF\_CM1}(R3 + R_{BIAS})} \quad (7)$$

$$f_{-3dB} = \frac{1}{2\pi C_{REF\_CM2}(R4)} \quad (8)$$

Although it is not always possible to exactly match the corner frequencies of all the filters, a good compromise is to attempt to balance the corner frequencies of the input path differential filter and the reference path differential filter because these filters have a dominant effect in the performance.

2.1 Resistor and Capacitor Component Selection

Another consideration in the RC filter design is selecting resistor and capacitor components. The ADS1248 incorporates a low-noise, high input impedance PGA. This PGA allows for the use of series filter resistors up to a few kΩ; however, avoid using exceedingly high resistor values.

The differential input bias current of the ADS1248 is typically in the order of 100 pA. Use 1% resistors with resistances below 20 kΩ to make the dc errors due to the differential input bias current negligible. In addition, the thermal noise contribution of the resistors is negligible when the resistor values are kept below 20 kΩ.

Among ceramic surface-mount capacitors, COG (NPO) ceramic capacitors provide the best capacitance precision. The type of dielectric used in COG (NPO) ceramic capacitors provides the most stable electrical properties over voltage, frequency, and temperature changes.

3 Noise Performance Using the ADS1248 in the Ratiometric Configuration

Using matched RC filters at the input path and the reference path results in a better ratiometric cancellation over the entire signal range. The following subsections illustrate the effect on noise performance when the device is set up using unmatched filters, and also provide several ratiometric circuit examples using matched filters. The noise versus input signal plots are also shown.

3.1 Noise Performance Using Mismatched RC Filters

To illustrate increasing noise when using unmatched filters in the ratiometric circuit, ADS1248 noise-measurement tests are performed using mismatched input and reference filters. In this experiment, the measurements are performed applying a low-pass filter in the reference path while no filter is used at the inputs of the PGA. Different C_{REF_DIFF} capacitors are used to implement a low-pass filter at the reference with corner frequencies of 130 Hz, 13 Hz, and 1.3 Hz, respectively.

The ADS1248 IDAC current is set to 1000 µA, producing a voltage reference of 2 V across the 2-kΩ R_{BIAS} resistor. The ADS1248 is configured at a data rate of 20 SPS with PGA gain of 8 V/V, allowing a full-scale voltage of 250 mV. The RTD sensor in this case was simulated using a resistance decade box. The resistance at the input was swept from 0 Ω to 250 Ω in order to produce an input voltage of 0 mV to 250 mV.

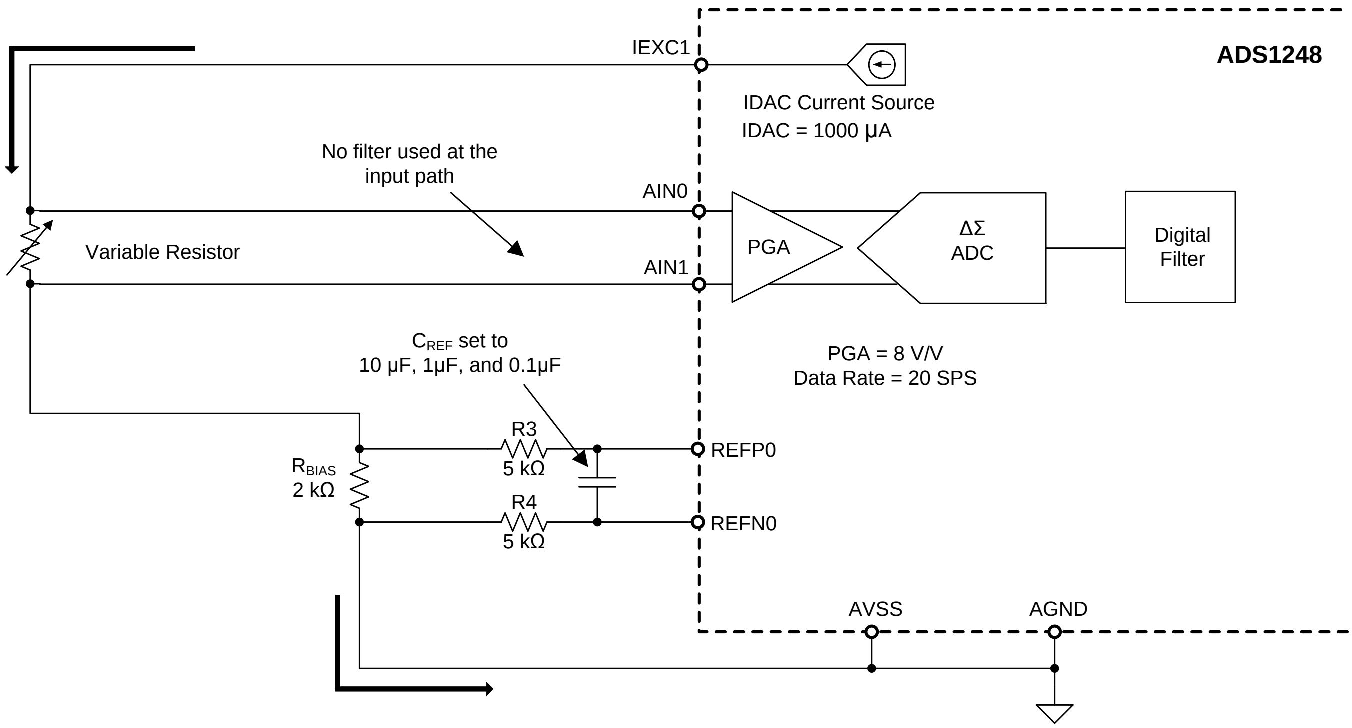

Figure 6. Circuit for Noise Measurement Experiment with Mismatched RC Filters

Figure 7 shows experimental noise measurements using the ADS1248 with the different reference input filters, but no signal input filter. The noise measurements show a pattern, where the conversion noise in the measurement increases as the input differential voltage increases. There is no filter in the ADC input path; therefore, the noise produced by the excitation source is reflected at the ADC inputs. However, the RC filter at the reference path attenuates noise components seen at the reference inputs. The noise signals seen by the reference inputs and the ADC are not attenuated equally; therefore, ratiometric noise cancellation is not effective.

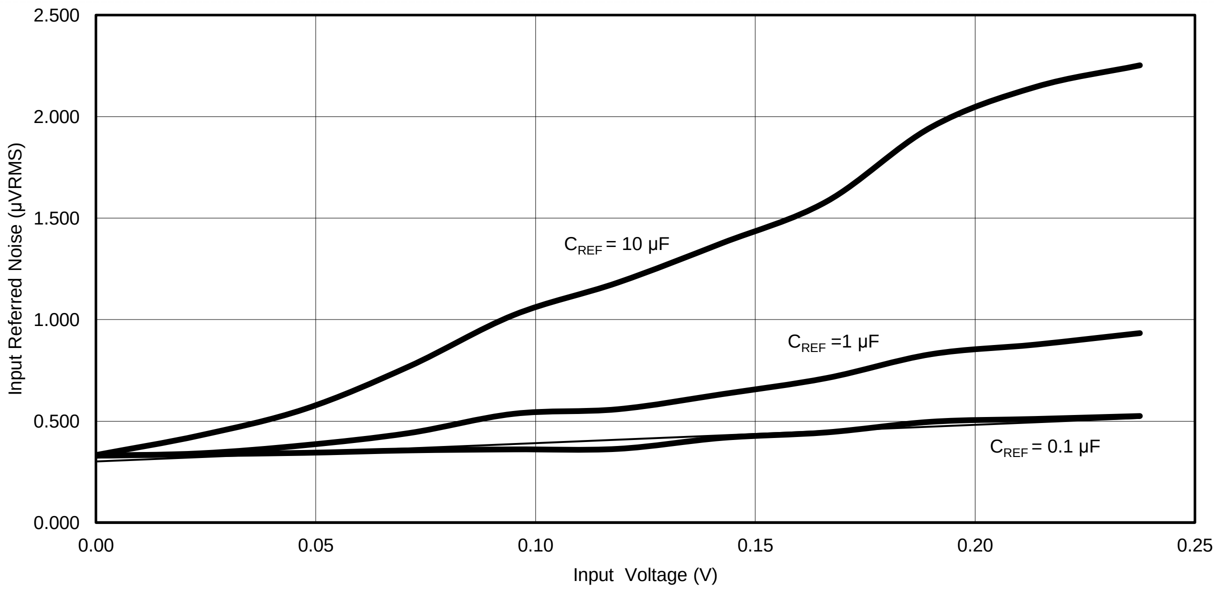

Figure 7. Input Referred Noise vs Input Voltage Using Mismatched RC Filters

The input referred noise of the ADS1248 is approximately 350 nVrms when the device is configured with a PGA gain of 8 V/V at 20 SPS. In the case where C_{REF} = 10 µF, where a 1.3-Hz heavy low-pass filter is present in the reference path, the increased noise due to the mismatched RC filters is the most severe. The input referred noise changes from 350 nVrms to 1 µVrms as the differential input voltage approaches the full-scale range.

When the reference input time constant is smaller (C_{REF} = 0.1 µF), the increasing noise versus input level is not as severe.

The ADC output conversion results are proportional to V_{IN} / V_{REF}. As the input signal increases, uncorrelated noise present on either V_{IN} or V_{REF} results in increased measurement noise. When the filters are matched, the noise is correlated and the measurement noise remains constant. This configuration is described next.

3.2 Noise Performance Using The Four-Wire Configuration with Matched RC Filters

In this noise measurement experiment, filters with closely-matched time constants at the reference path and at the input path are used. The diagram in Figure 8 shows a typical four-wire configuration using matched RC filters.

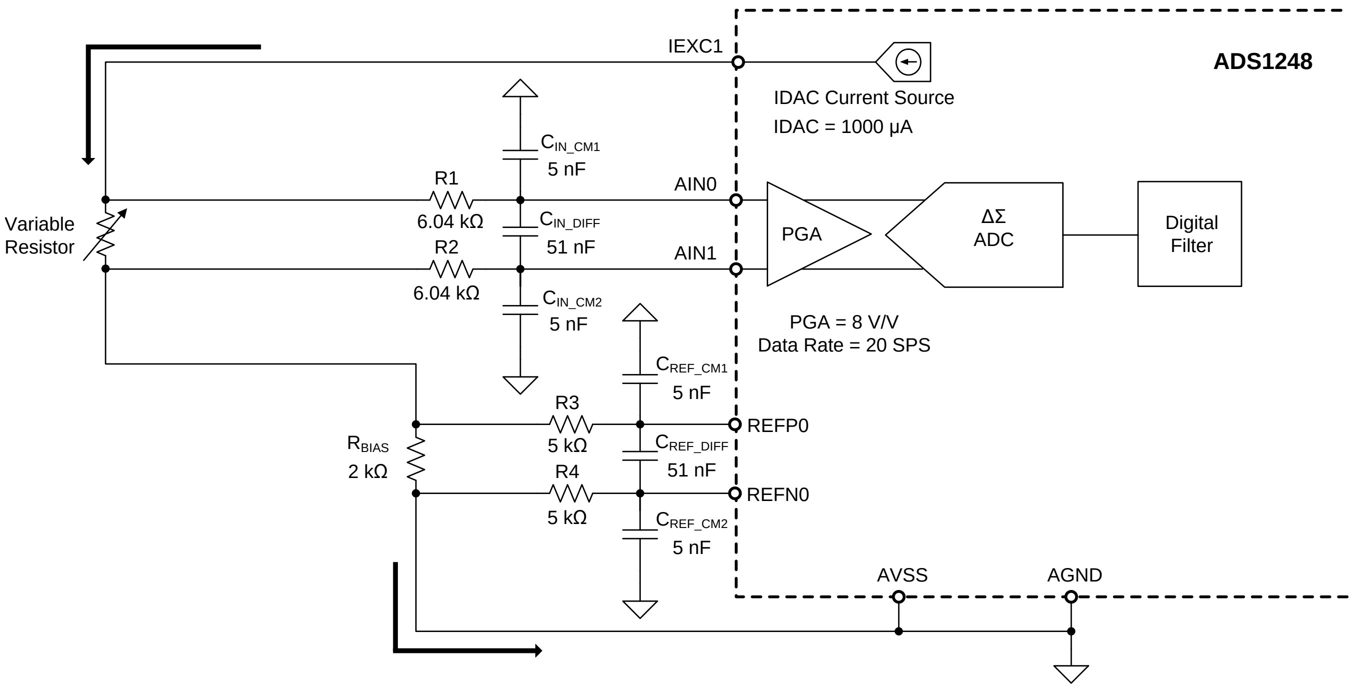

Figure 8. Example of a Four-Wire Ratiometric Configuration with RC Filters (R_{Lead} Removed for Simplicity)

The resistance at the input is swept from 0 Ω to 250 Ω to produce a full-scale voltage of 250 mV. Resistors R1 and R2 are selected to be 6.04 kΩ in order to reduce the effect of the resistance change of the RTD on the input frequency. Using Equation 3, the differential-mode filter corner frequency at the input path can be calculated as:

$$f_{-3dB} = \frac{1}{2\pi * 51nF(RTD + 6.04k\Omega + 6.04k\Omega)} \quad (9)$$

The differential-mode input corner frequency changes very little (258 Hz to 253 Hz) as the sensor resistance changes from 0 Ω to 250 Ω (full-scale). Using Equation 6, the differential mode filter corner frequency at the reference path can be calculated as:

$$f_{-3dB} = \frac{1}{2\pi * 51nF(2k\Omega + 5k\Omega + 5k\Omega)} \quad (10)$$

The differential mode filter corner frequency at the reference path is approximately 260 Hz.

The input-referred noise of the ADS1248 is typically 0.350 µVrms when the device is configured with a PGA gain of 8 V/V with a data rate of 20 SPS. The full-scale range in this case is 250 mV. The reference path and input path filter corner frequencies are closely matched; therefore, the input-referred noise remains constant as the differential voltage increases. Figure 9 shows the input-referred noise in the measurement versus input differential voltage.

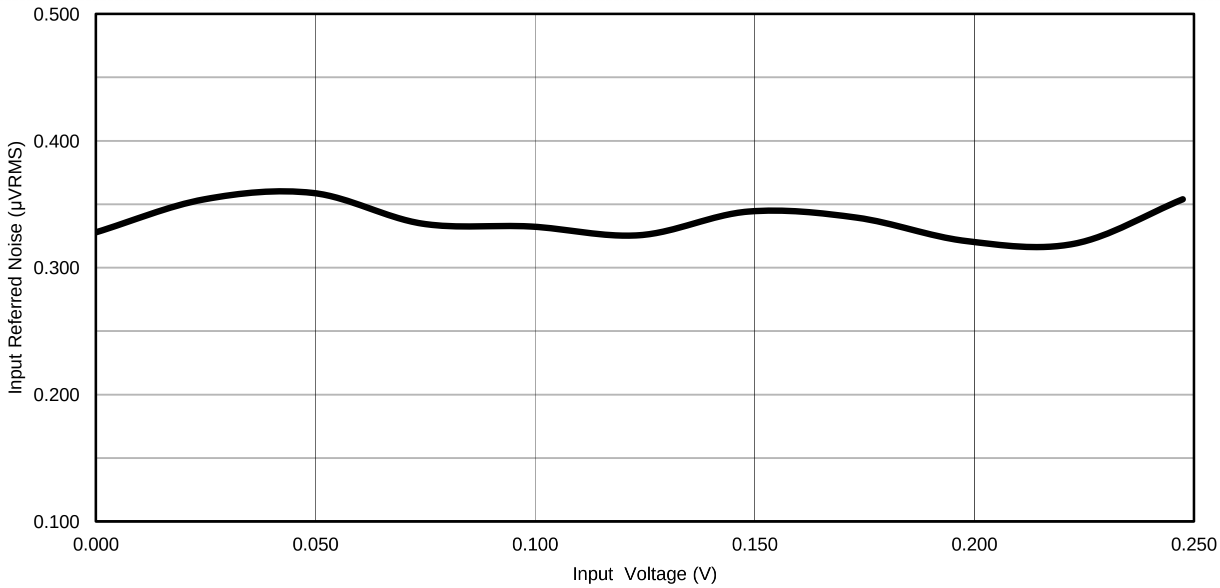

Figure 9. Input-Referred Noise vs Input Voltage Using Matched RC Filters

3.3 Noise Measurements Using the Three-Wire Configuration with Matched RC Filters

In the three-wire configuration, the matched IDAC1 and IDAC2 excitation currents flow though the wire resistances connecting the RTD sensor to the inputs of the ADC. Given that typically the lead wire resistances are equal, and the excitation current sources are closely matched, the errors due to the line series resistance cancel; this configurations allows the RTD sensor to be remotely placed away from the ADC.

In noisy industrial environments, where the sensor wiring is prone to noise interference, the addition of low-pass RC filters can be beneficial. However, when adding the filter resistors in the excitation current path, the input common-mode range is exceeded and the drift and mismatch of the resistors results in errors. The solution is to connect the IDAC excitation current in the configuration as shown in Figure 10. The IDAC current is sourced from another set of unused input channels or in the case of the ADS1248, from the IEXC1 and IEXC2 pins. In this configuration, the series resistors of the low-pass filter are outside the excitation current path.

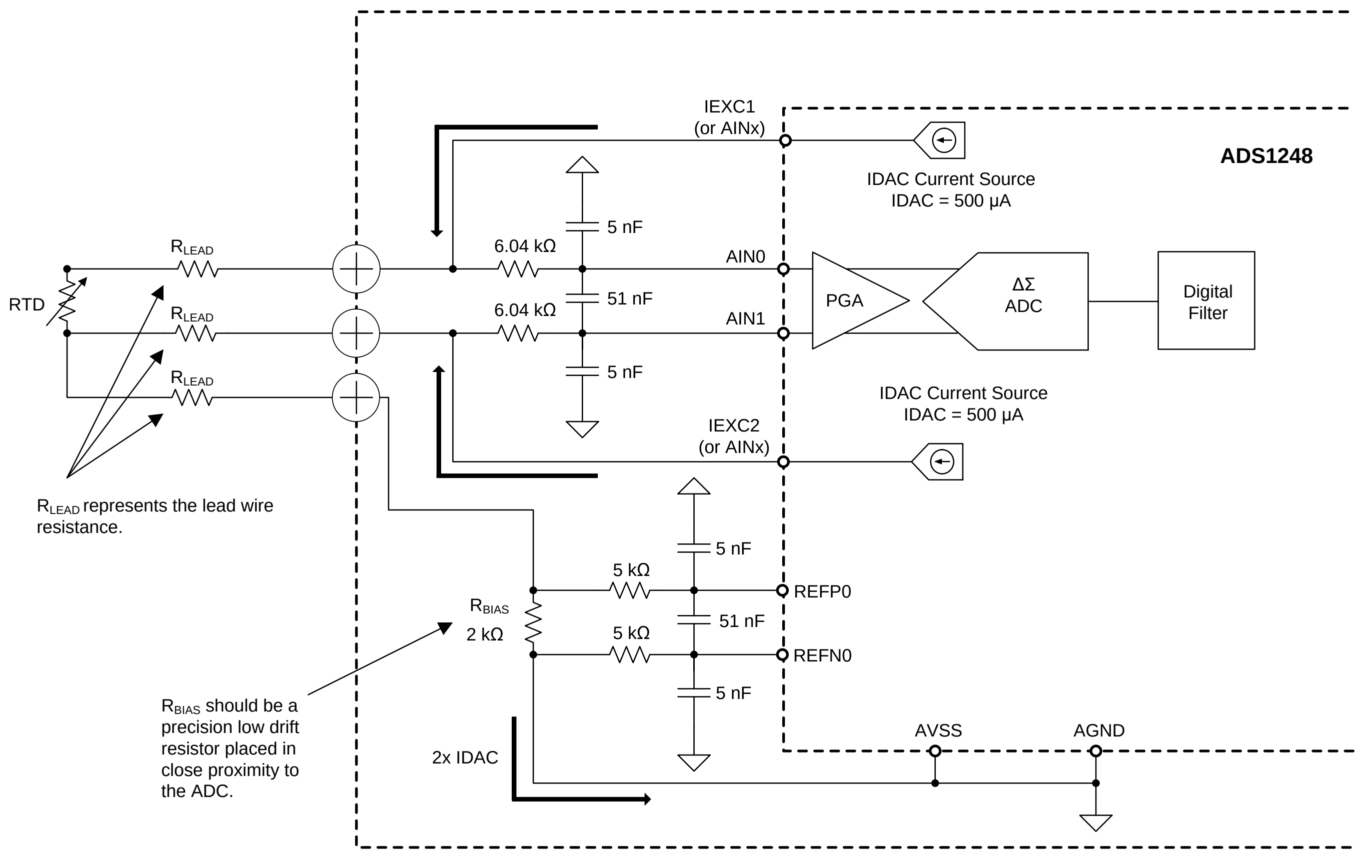

Figure 10. Example of a Three-Wire Ratiometric Configuration with RC Filters

3.4 Other Considerations

When selecting the corner frequency of the RC filters, make sure to account for both the noise signals present in the environment, and the timing constraints of the application. In many cases, the signal produced by the RTD may be treated as essentially a dc signal. The analog filter must be allowed to completely settle after activating the current source, but before the sensor measurement takes place. On high-resolution applications, when initially biasing the RTD, the user may have to wait several time constants for the filter to settle. For example, when performing a 20-bit resolution measurement, after initially biasing the sensor, the user must wait up to 14 RC filter time constants for the measurement to settle within ½ an LSB. Table 1 shows the required RC filter time constants to settle to ½ LSB resolution.

Table 1. Required RC Filter Time Constants to Settle to ½ LSB Resolution

Resolution (Bits)	Time Constants to ½ LSB
16	11.78
18	13.17
20	14.56
22	15.94
24	17.33

4 Conclusion

Performing sensor measurements in a ratiometric configuration provide a significant advantage, where the voltage reference used for the analog-to-digital conversion is derived from the excitation source, and the errors due to the absolute value of the excitation and excitation drift are virtually eliminated. In addition, when performing measurements in a ratiometric configuration, the noise of the excitation source is reflected at the inputs of the ADC device and the reference path, and in this manner the noise cancels.

Although external RC filters are not required to achieve a ratiometric measurement, the addition of external filters may prove to be beneficial in noisy environments, where sensors are prone to RFI or EMI. In addition, appropriate printed circuit board (PCB) layout, shielding, and grounding techniques are essential in the design to mitigate interference. When adding RC filters to combat RFI noise, make sure to balance the input path low-pass filter and the reference path low-pass filter. The preceding discussion shows some of the trade-offs and design considerations to balance the filters using the ADS1248 in RTD ratiometric circuits. The information is provided to assist the design engineer when implementing the filter design and testing according to the specific application needs.

5 References

1. Paul R. Gray, Paul J Hurst, Stephen H Lewis, Robert G Meyer (2001). Analysis and design of analog integrated circuits (Fourth Edition). New York: Wiley. p. §7.3.2 pp. 517–520.
2. Robert Burnham and Nagaraj Ananthapadamanabhan, “Example Temperature Measurement Applications Using the ADS1247 and ADS1248” SBAA180, January 2011.

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