Analog Front-End Design Considerations for RTD Ratiometric Temperature Measurements

By Barry Zhang and Alex Buda

Introduction

Many system designers use Σ-Δ ADCs together with RTDs (resistance temperature detectors) for temperature measurements, but have difficulties achieving the high performance as specified by the data sheet of the ADC they are using. For example, some designers may only be able to get 12 to 13 noise-free bits from a 16-bit to 18-bit ADC. The front-end techniques introduced in this article will enable designers to achieve 16+ noise-free bits in their system designs.

Using RTDs in a ratiometric measurement has the advantage in that it eliminates sources of error such as the accuracy and drift of the excitation current source. Below is a typical circuit for a 4-wire RTD ratiometric measurement circuit. The 4-wire configuration has the advantage that the error due to lead resistance can be cancelled.

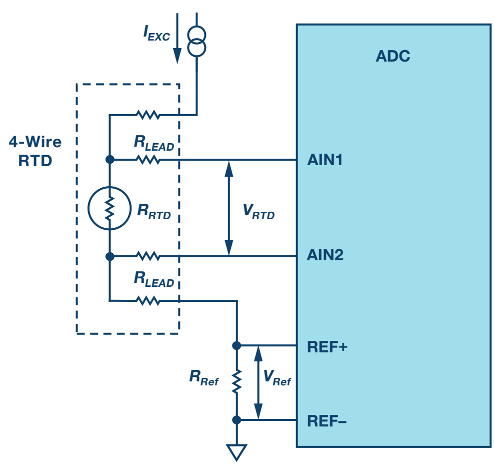

Figure 1. 4-wire RTD ratiometric measurement circuit.

From the circuit above, we can derive the following two equations:

$$V_{RTD} = R_{RTD} \times I_{EXC}$$
$$V_{Ref} = R_{Ref} \times I_{EXC}$$

The general expression used to calculate the RTD resistance (R_{RTD}) when the ADC is operating in bipolar differential mode is given by:

$$R_{RTD} = \frac{Code_{RTD} \times R_{Ref}}{Code_{ADC\_Fullscale}}$$

where:

$Code_{RTD}$ is the ADC code.

$Code_{ADC\_Fullscale}$ is the ADC full-scale code.

The measured resistance value of the RTD is theoretically only related to the precision and drift of the reference resistor. Normally R_{REF} is an accurate and low drift resistor with 0.1% precision.

When engineers design their products using this type of circuit, they will add some resistors and capacitors before the analog input, external reference pins for low-pass filtering, and overvoltage protection as shown in Figure 2. In this article, we will show what should be considered in choosing suitable resistors and capacitors for better noise performance.

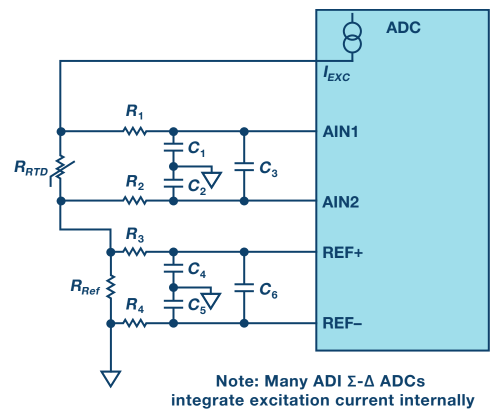

Figure 2. Typical 4-wire RTD ratiometric measurement circuit.

From Figure 2 we can see that R_1, R_2, C_1, C_2, and C_3 are used as a first-order, low-pass RC filter that provides attenuation for both differential and common-mode voltage signals. The values of R_1 and R_2 should be the same and similarly for the values of C_1 and C_2. Similarly, R_3, R_4, C_4, C_5, and C_6 are used as a low-pass filter for the reference path.

Common-Mode Low-Pass RC Filter

Figure 3 shows the common-mode, low-pass filter equivalent circuit.

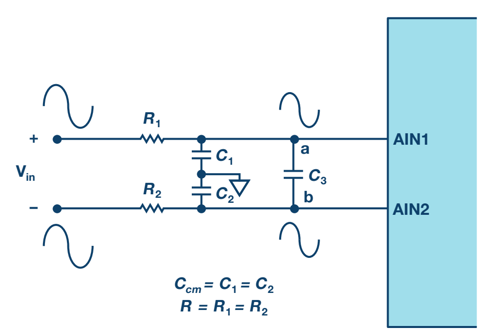

Figure 3. Common-mode low-pass filter.

Because the common-mode voltage at Point a is equal to the voltage at Point b, there is no current flowing through C_3. Therefore, the common-mode cutoff frequency can be expressed as

$$f = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi R C_{cm}}$$

Differential Mode Low-Pass RC Filter

To better understand the low-pass RC filter cutoff frequency for differential signals, the C_3 capacitor in Figure 4 can be thought of as two separate capacitors C_a and C_b in Figure 5.

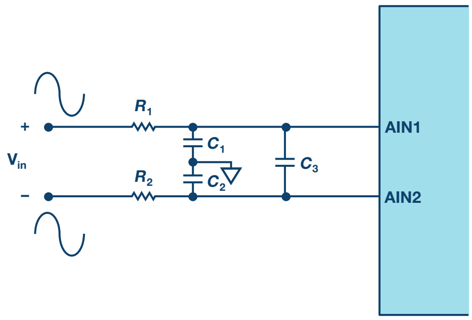

Figure 4. Differential mode low-pass filter.

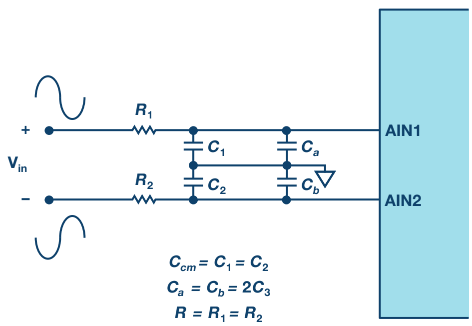

Figure 5. Differential mode low-pass filter equivalent circuit.

From Figure 5, the differential mode cutoff frequency is:

$$f = \frac{1}{2\pi R_1 (C_1 + C_a)} = \frac{1}{2\pi R (C_{cm} + 2C_3)}$$

Normally the value of C_3 is 10× larger than the value of C_{cm}. The purpose of this is to decrease the effects that are introduced by the mismatch of C_1 and C_2. For example, with an analog front-end design used in the Analog Devices circuit note CN-0381 as seen in Figure 6, the cutoff frequency for differential signals is around 800 Hz and the cutoff frequency for common-mode signals is 16 kHz.

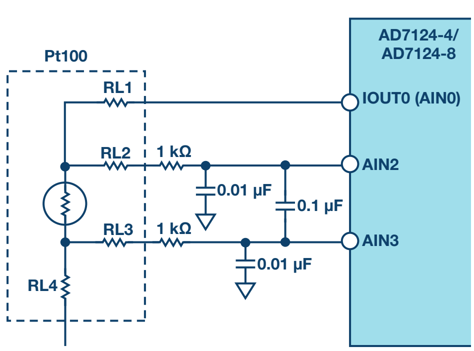

Figure 6. Analog input configuration for RTD measurement using AD7124.

Resistor and Capacitor Considerations

Other than being part of the low-pass filter, R_1 and R_2 can also provide overvoltage protection. If 3 kΩ resistors are used before the AD7124-4 A_{IN} pins in Figure 6, these can protect against up to 30 V miswiring. It's not recommended to use larger resistors before the A_{IN} pins for the following two reasons. First of all, they will generate more thermal noise. Secondly, the A_{IN} pins will have input currents that will flow across these resistors and introduce errors. These input currents do not have a constant value and when combined with a mismatch between them they will generate noise that will increase with the size of the resistors.

The resistor and capacitor values play a vital role in determining the performance of the final circuit. Designers need to understand their field requirements and calculate the resistor and capacitor values according to the equations above. For ADI Σ-Δ ADC parts and precision analog microcontrollers with an integrated excitation current source, it is recommended to use the same resistor and capacitor values before the A_{IN} and reference pins. This design ensures that the analog input voltage remains ratiometric to the reference voltage and any errors in the analog input voltage due to the temperature drift and noise of the excitation current are compensated by the variation of the reference voltage.

Measured Noise Performance on ADuCM360 with Ratiometric Measurement

The ADuCM360 is a fully integrated, 3.9 kSPS, 24-bit data acquisition system that incorporates dual high performance, multichannel Σ-Δ ADCs, a 32-bit ARM® Cortex®-M3 processor, and Flash/EE memory on a single chip. It also integrates programmable gain instrumentation amplifiers, a precision band gap reference, programmable excitation current sources, a flexible multiplexer, and many other features. It allows a direct interface to resistive temperature sensors.

When using the ADuCM360 for RTD measurements, the REF– pin is normally connected to ground so R_4 and C_5 from Figure 2 can be removed as there is no current flowing across them. C_4 and C_6 are in parallel so these two can be added together. However, because C_4 is much smaller than C_6, it can be ignored. This results in the simplified analog front-end circuit as shown in Figure 7.

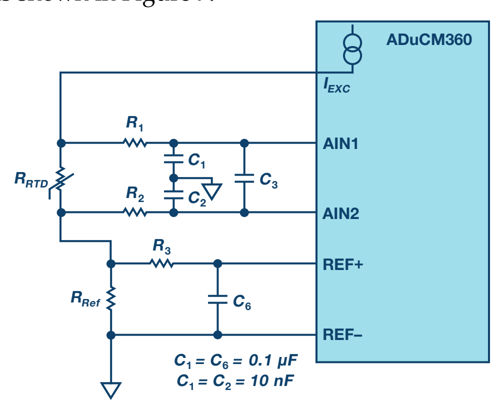

Figure 7. ADuCM360 analog front-end circuit for RTDs measurement.

Table 1 shows the noise level with matched and unmatched filters in front of the analog and reference input paths. A 100 Ω precision resistor is used instead of R_{RTD} to measure the noise voltage on the ADC input pins. The value of R_{Ref} is 5.62 kΩ.

Table 1. Noise Test Results

ADC Gain	I_{SOURCE} (μA)	Noise Voltage on 100 Ω Resistor (μV)	
		$R_1 = R_2 = R_3 = 1k$	$R_1 = R_2 = 10k$, $R_3 = 1k$
16	100	1.6084	1.8395
16	200	1.6311	1.7594
16	300	1.6117	1.9181
16	400	1.6279	1.9292

From Table 1 we can see that using a matched analog front-end circuit where the values of R_1 and R_2 are the same as R_3, the noise decreases by around 0.1 μV to 0.3 μV as compared to the unmatched circuit, which means that the number of ADC noise-free bits increases by about 0.25 bit to 16.2 bits with an ADC PGA gain of 16.

Conclusion

Using matched RC filter circuits and choosing the right resistor and capacitor values based on field requirements according to the considerations introduced in this article, the RTDs in ratio-metric measurement applications can achieve optimum results.

References

CN-0381 Circuit Note. "Completely Integrated 4-Wire RTD Measurement System Using a Low Power, Precision, 24-Bit, Sigma-Delta ADC." Analog Devices, Inc.

CN-0267 Circuit Note. "Complete 4 mA to 20 mA Loop-Powered Field Instrument with HART Interface." Analog Devices, Inc.

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