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Reference Designs

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Devices Connected/Referenced

| | |
|---------|--|
| AD8495 | Precision Thermocouple Amplifier with Cold Junction Compensation |
| AD7787 | Low Power, 24-Bit Σ - Δ ADC |
| REF194 | Precision Micropower, Low Dropout Voltage Reference |
| ADG1609 | 4.5 Ω R_{ON} , 4-Channel ± 5 V, +12 V, +5 V, and +3.3 V Multiplexer |
| ADR3412 | Micropower, High Accuracy Voltage Reference |
| ADM8829 | Switched Capacitor Voltage Inverter |

Low Power Multichannel Thermocouple Measurement System with Cold Junction Compensation

EVALUATION AND DESIGN SUPPORT

Circuit Evaluation Boards

- [CN-0354 Evaluation Board \(EVAL-CN0354-PMDZ\)](#)
- [System Demonstration Platform \(EVAL-SDP-CB1Z\)](#)
- [SDP-I-PMOD Interposer Board \(PMD-SDP-IB1Z\)](#)

Design and Integration Files

- [Schematics, Layout Files, Bill of Materials](#)

CIRCUIT FUNCTION AND BENEFITS

The circuit shown in Figure 1 is a flexible, 4-channel, low power thermocouple measurement circuit with an overall power consumption of less than 8 mW. The circuit has a multiplexed front end, followed by an instrumentation amplifier that performs

cold junction compensation (0°C to 50°C) and converts the thermocouple output to a voltage with a precise scale factor of $5\text{ mV}/^{\circ}\text{C}$. The error is less than 2°C , over a measurement range of -25°C to $+400^{\circ}\text{C}$, and is primarily due to the thermocouple nonlinearity. A nonlinearity correction algorithm reduces the error to less than 0.5°C over a 900°C measurement range. Noise free resolution is less than 0.1°C .

The signal is then digitized by a 24-bit Σ - Δ ADC, and the digital value is provided on an SPI serial interface. With the PMOD form factor for rapid prototyping, the design requires minimal PC board area and is ideal for applications that require precise thermocouple temperature measurements.

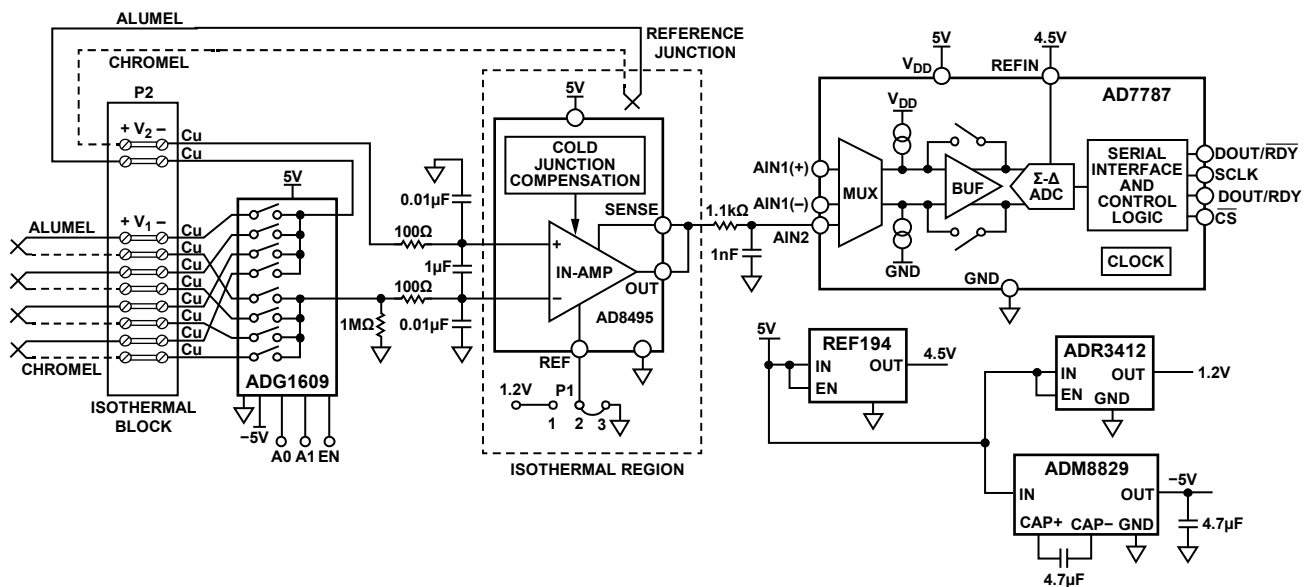


Figure 1. Multichannel K Type Thermocouple Measurement System (Simplified Schematic: All Connections and Decoupling Not Shown)

Rev. B

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CIRCUIT DESCRIPTION

The four thermocouple inputs to the circuit are terminated at the isothermal block, P2. The [ADG1609](#) complementary metal oxide semiconductor (CMOS) analog multiplexer switches the four thermocouple channels to a single signal conditioning block to handle the four thermocouple inputs. The switches exhibit a break-before-make switching action and an inherent low charge injection to minimize transients when switching between channels.

The thermocouple voltage generated at the output of the isothermal block is proportional to the difference between the temperature at the measurement thermocouple and the temperature of the isothermal block (cold junction).

The signal is amplified by the [AD8495](#), a precision instrumentation amplifier that is laser trimmed to provide a precise 5 mV/°C output for a K type thermocouple. The [AD8495](#) also provides cold junction compensation over a range of 0°C to 50°C.

The fifth thermocouple, shown in Figure 1, can be added to cancel the voltage generated by any temperature differential that exists between the isothermal block and the [AD8495](#) cold junction compensation circuit. With the multiplexer enabled, the constantan (alumel) copper junction, formed by the thermocouple connection at the isothermal block, is in series with a copper constantan (alumel) junction, formed by the reference thermocouple connection. This series combination contributes equal but opposite voltages because the block is isothermal. In this condition, the [AD8495](#) internal cold junction compensation compensates for the reference junction at the IC, which must remain between 0°C and 50°C. Therefore, the fifth thermocouple connection option eliminates the requirement of mounting the [AD8495](#) directly on the isothermal block, as is normally the case. If the fifth thermocouple is not connected, Pin 5 and Pin 6 of P2 must be connected with a short wire. Because of the proximity of P2 to the [AD8495](#), the error produced is minimal.

The output of the [AD8495](#) is filtered by the 1.1 kΩ/1 nF single-pole filter that has a -3 dB cutoff frequency of 145 kHz. This filter minimizes broadband noise at the [AD7787](#) ADC input.

The [AD7787](#) is a 24-bit, low noise, low power Σ - Δ ADC for low frequency measurement applications, such as thermocouple measurement systems. Its internal clock eliminates the need for an external clock and makes the output data rate user configurable, which can reduce current consumption because it functions at a lower internal clock frequency. It contains a Σ - Δ ADC with one differential input and one single-ended input, either of which can be buffered or unbuffered after passing through the multiplexer.

The [AD7787](#) operates from an internal clock. Therefore, the user does not have to supply a clock source to the device. The output data rate from the device is software programmable and can be varied from 9.5 Hz to 120 Hz, with the rms noise equal to 1.1 μ V at the lower update rate. The [AD7787](#) operates at an update rate of 9.5 Hz in this circuit. The internal clock frequency

can be divided by a factor of 2, 4, or 8, which leads to a reduction in the current consumption. The update rate, cutoff frequency, and settling time all scale with the clock frequency.

The [AD7787](#) operates with a power supply from 2.5 V to 5.25 V. When operating from the 3 V supply, the power dissipation for the device is 225 μ W maximum. It is packaged in a 10-lead MSOP.

Thermocouple Signal Conditioning

Thermocouples are used in temperature measurements requiring high temperature ranges. They are preferred over resistance temperature detectors (RTDs) for this reason, as well as for their lower cost. However, thermocouples are nonlinear, which means that the voltage generated by a thermocouple changes at different rates and at different temperatures. For example, a J type thermocouple changes by 52 μ V/°C at 25°C and by 55 μ V/°C at 150°C. K type thermocouples tend to be more linear, at approximately 41 μ V/°C, when temperatures are above 0°C. The voltage response of a thermocouple to a temperature gradient is generally described by a polynomial of greater than the sixth-order.

Figure 2 shows the Seebeck coefficient of the different types of thermocouples over their operating temperature ranges. Figure 2 shows that the K type thermocouple has the widest temperature range and can measure temperatures up to 1250°C.

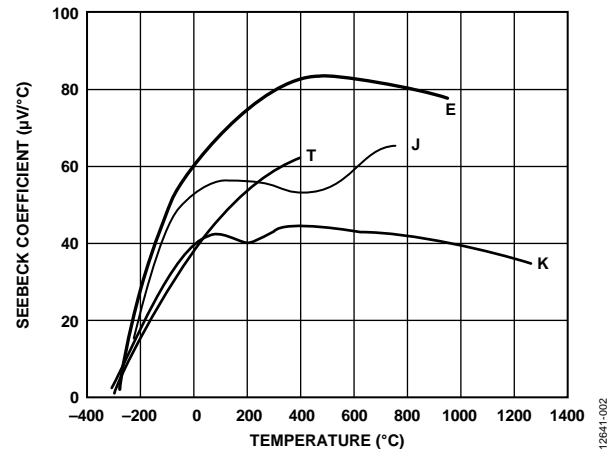


Figure 2. Seebeck Coefficient of Thermocouple vs. Temperature

Due to the nonlinear characteristic of thermocouples, complex signal processing and signal conditioning are required to obtain a precise temperature reading, and the [AD8495](#) provides an ideal solution.

The [AD8495](#) is trimmed to provide cold junction compensation over a reference junction range of 0°C to 50°C and provides a linear 5 mV/°C transfer function. Over a measurement range of -25°C to +400°C, the maximum output error is $\pm 2^\circ$ C. To calculate the output voltage, use the following equation:

$$T_{MJ} = \frac{V_{OUT} - V_{REF}}{5 \text{ mV}/^\circ\text{C}}$$

The [AD8495](#) operates on a single 5 V supply in the circuit. Because of the PNP transistor input structure, the input voltage

can be as low as -200 mV, thereby allowing the measurement of negative temperatures. However, the output voltage must be offset to process negative temperatures, which is accomplished using the reference voltage input pin (REF).

With the REF pin grounded using the P1 jumper, the minimum temperature that the system can measure is 5°C . The P1 jumper also allows the REF pin bias voltage to connect to a 1.2 V ADR3412 reference, thereby allowing measurement temperatures as low as -235°C . The corresponding temperature range for either condition is specified in Table 1. In both cases, the temperature span is 875°C . It is important to drive the REF pin with a low impedance source, such as a voltage reference or a buffer amplifier, to prevent errors.

Table 1. Measurement Ranges for REF = 0 V and 1.2 V with Single 5 V Supply

| REF Pin Voltage | Temperature Range |
|-----------------|--|
| 0V or Grounded | 5°C to 880°C |
| 1.2V | -235°C to $+640^{\circ}\text{C}$ |

Open Thermocouple Detection

The AD8495 can detect an open or broken thermocouple. The inputs of the AD8495 are the bases of PNP transistors; therefore, the bias current always flows out of the inputs. If either input is open, the output goes to one of the supply rails. Connecting the negative input to ground through a 1 M Ω resistor causes the AD8495 output to rail high in an open thermocouple condition. In cases where any of the four channels are not used, short the inputs to prevent the AD8495 from railing to the positive supply if that channel is connected. The 1 M Ω resistor also provides a bias current return path to ground.

The AD8495 has a high common-mode rejection, thereby minimizing the common-mode noise picked up by long thermocouple leads. The high impedance inputs of the amplifier make it easy to add extra filtering for additional electromagnetic interference/radio frequency interference (EMI/RFI) protection.

Power Considerations

The circuit in Figure 1 is powered from a single 5 V supply that powers the ADG1609, the AD8495, the VDD pin of the AD7787, the REF194, the ADR3412, and the ADM8829.

The REF194 supplies the 4.5 V reference for the AD7787. The ADR3412 provides the 1.2 V optional offset voltage for the REF input of the AD8495. Jumper P1 allows the REF pin to be connected either to 1.2 V or to ground.

The ADM8829 switched capacitor voltage inverter provides the -5 V required by the ADG1609 multiplexer to accommodate negative temperatures.

Table 2 shows the current consumed by each device in the circuit, based on the data sheet specifications. The design consumes a maximum of 1.56 mA. Note that the maximum current consumption is due to the ADM8829 switched capacitor voltage inverter. This inverter can be eliminated if a negative supply is available to drive the VSS pin of the ADG1609, thereby reducing the total current to approximately 556 μA .

Table 2. Circuit Current Consumption

| Part Number | Maximum Current Consumption |
|-------------|-----------------------------|
| AD8495 | 250 μA |
| AD7787 | 160 μA |
| ADG1609 | 1 μA |
| REF194 | 45 μA |
| ADR3412 | 100 μA |
| ADM8829 | 1000 μA |

Note that the total current is 1556 μA .

Test Results

The AD8495 has a maximum temperature error due to the thermocouple nonlinearity of $\pm 2^{\circ}\text{C}$ from -25°C to $+400^{\circ}\text{C}$, for a reference junction temperature of 0°C to 50°C . Wider temperature ranges or better accuracy requires a linearity correction algorithm that can be implemented in the software. Nonlinearity correction is discussed in the AN-1087 Application Note, *Thermocouple Linearization When Using the AD8494/AD8495/AD8496/AD8497*. Figure 3 shows the linearity error of the circuit, with and without the correction algorithm implemented.

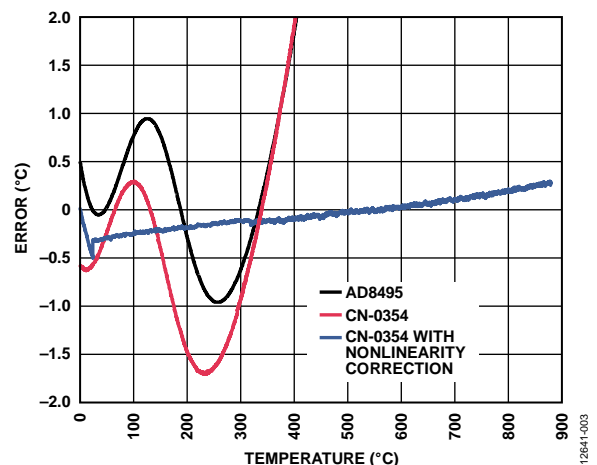


Figure 3. Linearity Error with and Without the Correction Algorithm Implemented

The noise of the system was tested in a controlled temperature environment to check the noise free code resolution of the system. Figure 4 shows the noise distribution, which spans approximately 1098 codes. For a 24-bit resolution and a span of 900°C, 1 LSB = 900°C/224 = 0.07°C resolution.

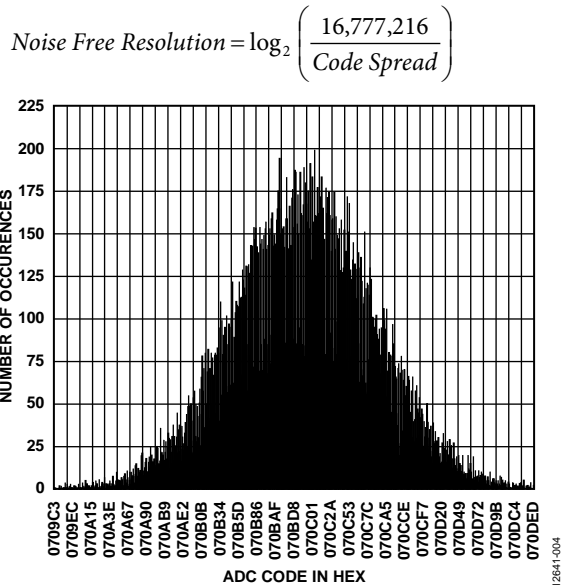


Figure 4. Noise Distribution Histogram of Circuit with the AD7787 Input Buffer Disabled, Output Data Rate = 9.5 Hz

Calculate the noise free code resolution as follows:

$$\text{Noise Free Resolution} = \log_2 \left(\frac{16,777,216}{1098} \right) = 13.9 \text{ Bits}$$

COMMON VARIATIONS

The CN-0354 circuit was proven to work with good stability and accuracy with the devices selected for the design.

This design can also be implemented using the AD594/AD595, which are also single chip thermocouple, signal conditioning amplifiers, with an output of 10 mV/°C.

The AD8495 has other variants, such as the AD8494, the AD8496, and the AD8497, for different thermocouple types, different ambient temperature ranges, and different measurement temperature ranges, as shown in Table 3.

Table 3. AD849x with ±2°C Accuracy Temperature Ranges

| Device | Thermocouple Type | Maximum Error | Ambient Temperature Range | Measurement Temperature Range |
|--------|-------------------|---------------|---------------------------|-------------------------------|
| AD8494 | J | ±2°C | 0°C to 50°C | -35°C to +95°C |
| AD8495 | K | ±2°C | 0°C to 50°C | -25°C to +400°C |
| AD8496 | J | ±2°C | 25°C to 100°C | 55°C to 565°C |
| AD8497 | K | ±2°C | 25°C to 100°C | -25°C to +295°C |

CIRCUIT EVALUATION AND TEST

Equipment Required

The following equipment is needed:

- The EVAL-CN0354-PMDZ evaluation board
- The EVAL-SDP-CB1Z system demonstration platform
- The PMD-SDP-IB1Z, SDP-I-PMOD, interposer board
- Short piece of Type K thermocouple wire if additional temperature compensation is desired. Otherwise, connect a short wire between Screw Terminal 5 and Screw Terminal 6 of P2.
- The CN0354 Evaluation Software
- 6 V wall wart power supply
- PC (Windows 32-bit or 64-bit)

Software Installation

The CN-0354 evaluation kit includes self installing software on a CD. The software is compatible with Windows® XP (SP2), Windows Vista (32-bit and 64-bit), and Windows 7 (32-bit and 64-bit). If the setup file does not run automatically, run the setup.exe file from the CD. Install the evaluation software before connecting the evaluation board and the SDP board to the USB port of the PC to ensure that the evaluation system is correctly recognized when connected to the PC. The software allows full configuration of the serial interface. It is important that the configurations of the masters and the slaves match for proper operation.

Software operation is described in the CN-0354 Software User Guide.

Power Supply Requirements

The EVAL-CN0354-PMDZ evaluation board must be powered by a 5 V power supply. It is recommended that the supply provide at least 2 mA. If powered directly from the PMD-SDP-IB1Z interposer board, ensure that the supply is well filtered and free of digital noise.

Test Setup Functional Diagram

A functional diagram of the test setup is shown in Figure 5, and a photo of the EVAL-CN0354-PMDZ board is shown in Figure 6.

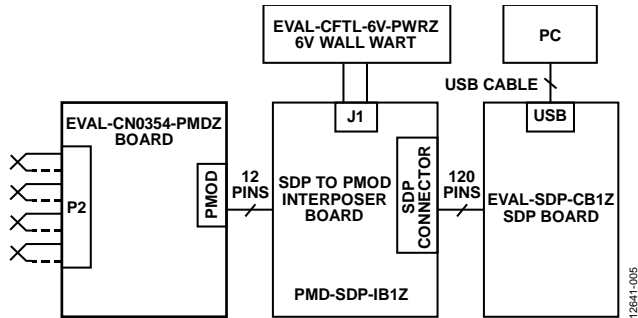


Figure 5. Test Setup Functional Diagram



Figure 6. EVAL-CN0354-PMDZ Evaluation Board

LEARN MORE

- CN0354 Design Support Package:
<http://www.analog.com/CN0354-DesignSupport>
- Corrigan, Theresa. AN-1024. *How to Calculate Settling Time and Sampling Rate of a Multiplexer*. Analog Devices.
- Duff, Matthew and Towey, Joseph. *Two Ways to Measure Temperature Using Thermocouples Feature Simplicity, Accuracy, and Flexibility*. Analog Dialogue, 44-10, October 2010.
- Kester, Walt, et. al. "Temperature Sensors", Chapter 7 in *Sensor Signal Conditioning*. Analog Devices, 1999.
- MT-022 Tutorial. *ADC Architectures III: Sigma-Delta ADC Basics*. Analog Devices.

- MT-023 Tutorial. *ADC Architectures IV: Sigma-Delta ADC Advanced Concepts and Applications*. Analog Devices.
- Malik, Reem. AN-1087. *Thermocouple Linearization When Using the AD8494/AD8495/AD8496/AD8497*. Analog Devices.
- Marcin, Joe. AN-369. *Thermocouple Signal Conditioning Using the AD594/AD595*. Analog Devices.
- MT-035 Tutorial. *Op Amp Inputs, Outputs, Single-Supply, and Rail-to-Rail Issues*. Analog Devices.
- MT-031 Tutorial. *Grounding Data Converters and Solving the Mystery of AGND and DGND*. Analog Devices.
- MT-101 Tutorial. *Decoupling Techniques*. Analog Devices.
- NIST (National Institute of Standards and Technology) Table for Type K Thermocouple.

Data Sheets and Evaluation Boards

- [AD8495 Data Sheet](#)
- [AD7787 Data Sheet](#)
- [ADG1609 Data Sheet](#)
- [REF194 Data Sheet](#)
- [ADR3412 Data Sheet](#)
- [ADM8829 Data Sheet](#)

REVISION HISTORY

| | |
|---|---|
| 3/2017—Rev. A to Rev. B | |
| Changes to Circuit Descriptions Section | 2 |
| Changes to Equipment Required Section | 4 |
| 2/2015—Rev. 0 to Rev. A | |
| Change to Circuit Function and Benefits Section | 1 |
| Change to Table 1 | 3 |
| 9/2014—Revision 0: Initial Version | |

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