AN-1952 Designing With Thermocouples

ABSTRACT

In 1821 Thomas Seebeck discovered the physical phenomenon that when you join two dissimilar metals on both ends and heat one end, a continuous current is created in the thermoelectric circuit . If the other end is broken, a voltage can be measured that is proportional to the temperature difference between the heated junction (measuring or "hot" junction) and the open end (reference or "cold" junction) at which the measurement is taken. This physical property, called the Seebeck effect, is the basis of the thermocouple sensor.

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1 Overview

Thermocouples have several advantages that make them popular in many applications such as industrial, medical, and home appliances. Thermocouples compared to other popular temperature sensors, such as Remote Temperature Diodes (RTDs), thermistors, and IC sensors, are the most rugged, least expensive, and can operate over the largest temperature range. Further, they are passive sensors that do not require an electrical stimulus to operate, thereby minimizing system complexity. Along with their many benefits, it is important to fully understand their electrical characteristics when designing with them.

Thermocouple sensors are categorized into different calibration types (type K, type J, and so forth) based on types of dissimilar metals that are used to form the thermocouple junction. Based on calibration type, the thermocouple will have a sensitivity (µV/°C), a temperature range, and a non-linear voltage curve over that temperature range. For example, a Type K thermocouple has an average sensitivity of approximately 41 µV/°C and an operating range of -200°C to 1250°C. Thermocouple voltage curves are non-linear over their operating temperature ranges, as seen in Figure 1.

When designing with thermocouples, it is important to understand that they are bipolar, which means they can produce a positive or a negative voltage depending on whether or not the measured temperature is higher or lower than the system temperature, respectively.

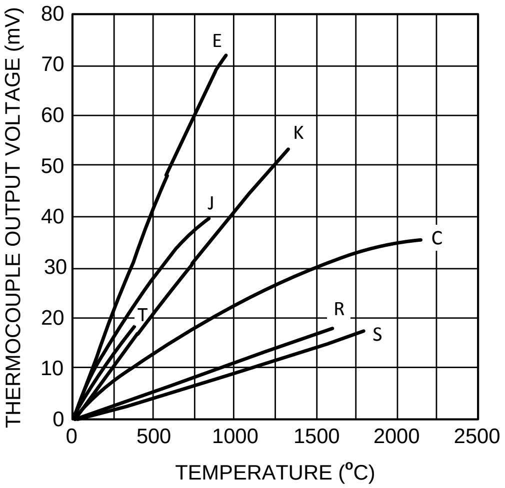

Figure 1. Thermocouple Output Voltage vs. Temperature

As mentioned earlier, the voltage created by a thermocouple is relative to the temperature difference between the measuring junction, which is placed in the measured environment, and the reference junction that is typically at the measuring system environment. This means that the thermocouple is only capable of recognizing a temperature difference between two points and does not have the ability to measure absolute temperature. To determine the absolute temperature of the measured environment, you will need to determine the temperature of the reference junction and factor it in to the absolute temperature calculation. This technique is called "cold junction compensation" and can be handled by having a temperature sensor, such as TI's LM94022, in the measurement system within close proximity of the reference junction. This temperature sensor (temp sensor) should have an isothermal connection to the board to minimize any potential temperature gradients.

One might ask: If the design uses a temp sensor on board, why not just use that in place of the thermocouple? That goes back to the benefits of a thermocouple sensor. A silicon temp sensor cannot be placed in a furnace chamber at 1000°C. Due to their inherit fragility, thermistor elements are not well-suited for rugged industrial environments. The bottom line is that thermocouples have the combination of ruggedness, operating temperature range, and cost that cannot be surpassed by other temp sensors.

Depending on the temperature range and the accuracy requirements of the application, it is often necessary to amplify the thermocouple signal before system processing by an analog-to-digital converter (ADC) or microcontroller. A popular thermocouple amplifier configuration is a differential amplifier (see Figure 2). One of the clear benefits of a differential amplifier is to minimize effects of common-mode pickup, which can be quite significant across a long thermocouple wire in a noisy environment.

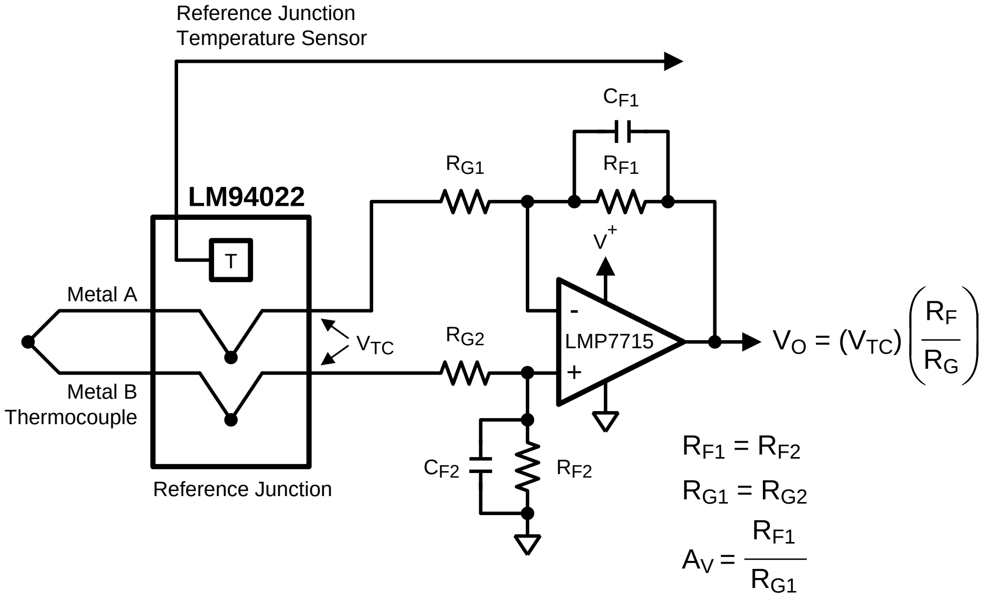

Figure 2. Thermocouple Differential Amplifier

If you set: $R_{F1} = R_{F2} = R_F$ and $R_{G1} = R_{G2} = R_G$, the gain equation for this circuit simplifies to $A_V = R_F / R_G$

Filtering is achieved by adding C_{F1} and C_{F2}. By setting $C_{F1} = C_{F2} = C_F$, you can determine your low-pass filtering frequency with the following equation:

$f = 1/(2\pi R_F C_F)$

Low off-set voltage (V_{OS}), low-voltage noise (e_n), high common-mode rejection ratio (CMRR), and rail-to-rail output are critical amplifier specifications in this application. The typical output of a thermocouple can be in the µV range, so it is crucial that offset voltage and voltage noise remain small and insignificant relative to the measured signal. Having an amplifier with a high CMRR will reduce the potential effects of common-mode pickup, often encountered in the surrounding measurement environment. In addition, a rail-to-rail output amplifier allows designers to match the input full-scale range of the ADC, providing the best opportunity to maximize available codes. An amplifier that provides excellent performance for all of these parameters is TI's PowerWise™ LMP7715 precision, low-noise amplifier. As a precision part, the LMP7715 has a maximum offset voltage of ± 150 µV with a typical off set voltage drift of ± 1 µV/°C. This operational amplifier offers low-voltage noise of 5.8 nV/rtHz and has a high 100 dB CMRR.

For a designer, it is often difficult to measure temperatures that are at or very near the system ambient temperature. This is because at this measurement point, the thermocouple produces close to or zero voltage and the amplifier is in output saturation - as we know, "rail-to-rail output" is not exactly rail to rail. In reality most amplifiers can come within 10s of mV of the output rails. So how do you perform this measurement in the common single-supply system? You can add a negative voltage bias into your system with a charge pump inverter such as TI's LM7705 low-noise negative bias generator (see Figure 3). This chip with its surrounding components will produce -0.23 V and allow you to measure temperatures down to your system temperature.

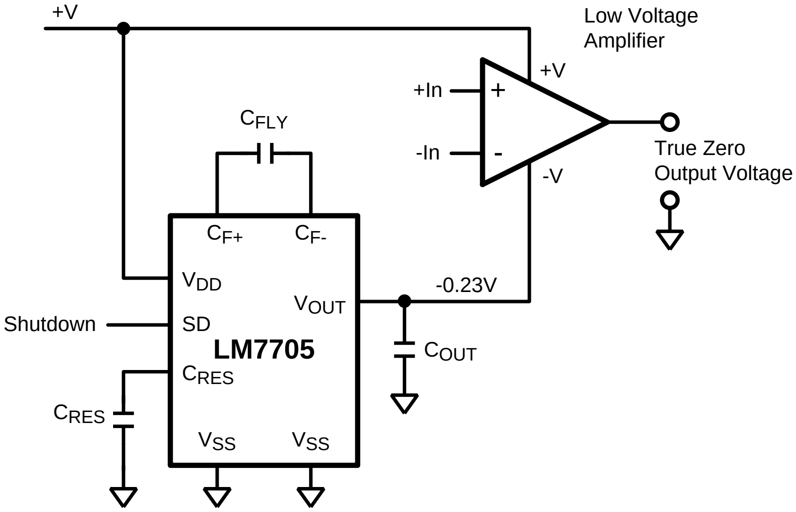

Figure 3. LM7705 Negative Bias Generator

Let's discuss the case when you would like to measure temperatures below your system temperature. As you may recall, a thermocouple is a bipolar device. When the measured temperature is below the system temperature, it will produce a negative voltage that is proportional to the difference in temperature. In order to stay within the input common-mode range of the amplifier and avoid input saturation, level shifting will need to be added to the circuit. One such method is to buffer a resistor divider and connect this circuit to the R_F resistor connected to the non-inverting terminal of the operational amplifier (see Figure 4). The purpose of the buffer is two-fold: first, to utilize the fact that minimal current will travel into the amplifier, thereby, keeping the resistor divider voltage stable, and second, to provide a low-impedance connection to the amplifying circuit. Another single operational amplifier could be used for the buffer, or you can utilize a dual operational amplifier, such as the LMP7716, to cover the buffer and the amplifying operational amplifier in one package.

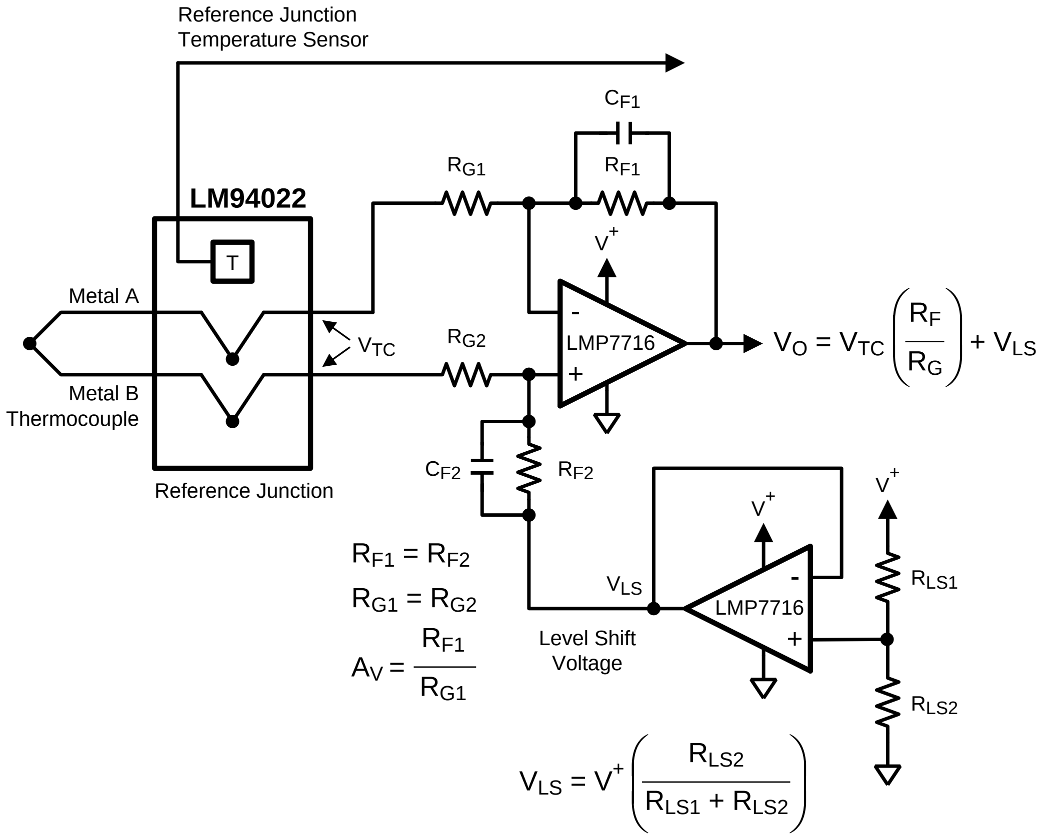

Figure 4. Level-Shifting Circuit

TI's WEBENCH® Sensor Designer online tool and supporting evaluation boards employ all of the techniques discussed in this application report. Use the Sensor Designer tool to select an existing thermocouple sensor, or create your own design, and the tool will provide a circuit catered to your sensor and measurement temperature range of interest. The tool then provides the error calculations, Bill of Materials (BOM), component documentation, and the ability to order supporting evaluation boards. The tool allows for easy optimization of your design by giving you the ability to change sensors, amplifiers, and ADCs while immediately providing new error calculations based on your new selections. Designing a circuit that meets your specifications is simple and fast. For more information and to build your own design, visit the WEBENCH Sensor Designer tool at: http://www.ti.com/ww/en/analog/webench/sensors/index.shtml.

Thermocouples are popular because they are inexpensive, rugged, and operate over an extended temperature range. When designing with thermocouples, keep in mind the specific type, associated sensitivity, and the fact that they are bipolar devices.

A differential amplifier configuration is a popular circuit that allows good CMRR performance. Depending on your specific measurement needs, you may need to add a negative bias generator or level shifting to the circuit. Due to its low noise, low-off set voltage, high CMRR, and rail-to-rail output capability, TI's PowerWise LMP7715 amplifier makes a good fit in a thermocouple amplifier application. To help expedite the thermocouple design process, TI's WEBENCH Sensor Designer tool allows you to effortlessly design from concept to simulation to prototype. (1)

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(1) OMEGA Temperature Measurement Handbook (2007): Z-21

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