ANALOG DEVICES

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Thermocouple Linearization When Using the AD8494/AD8495/AD8496/AD8497

by Reem Malik

INTRODUCTION

The AD8494/AD8495/AD8496/AD8497 thermocouple amplifiers provide a simple, low cost solution for measuring thermocouple temperatures. These amplifiers simplify many of the difficulties of measuring thermocouples. A fixed-gain instrumentation amplifier amplifies the small thermocouple voltage, and an integrated temperature sensor performs cold junction compensation.

The AD849x is optimized to measure and amplify J and K type thermocouple signals for a linear 5 mV/°C response such that

$$V_{OUT} = (T_{MJ} \times 5\ \text{mV/°C}) + V_{REF}$$

where T_{MJ} is the temperature at the measurement junction of the thermocouple.

The AD849x output is accurate to within 2°C across the entire range of measurement and ambient temperatures listed in Table 1. This application note describes ways to achieve even greater accuracy when operating at or measuring temperatures outside the specified ranges using the AD849x.

THERMOCOUPLE NONLINEARITY

The voltage generated by a thermocouple is inherently nonlinear. For example, a J type thermocouple changes by 52 µV/°C at 25°C and by 55 µV/°C at 150°C. K type thermocouples tend to be much more linear, staying fairly near 41 µV/°C when temperatures are above 0°C. The voltage response of a thermocouple to a temperature gradient can be described by a greater than sixth-order polynomial (see Figure 1).

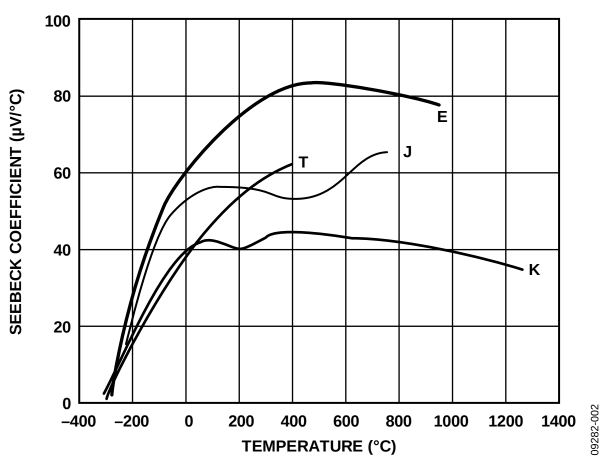

Figure 1. Seebeck Coefficient of Thermocouple vs. Temperature

The AD849x linearly amplifies the (cold junction compensated) thermocouple signal. This means that the output signal is as nonlinear as the input signal from the thermocouple.

An application may require better nonlinearity (meaning greater accuracy) than is provided directly by the thermocouple in that temperature range. In such cases, linearization, or correction, of the thermocouple measurement is required.

Whether a thermocouple measurement needs linearization depends on the type of thermocouple chosen, the required system accuracy, and the temperature range being measured. The nonlinearity of thermocouple signals is well studied and is constant for a specific thermocouple type. Therefore, the measurement system can compensate for it.

AD849x THERMOCOUPLE NONLINEARITY COMPENSATION

Although the AD849x does not actively correct thermocouple nonlinearity, the amplifiers are precision trimmed to match the transfer characteristics of J type and K type thermocouples. This means that the AD849x compensates for nonlinearity by choosing a specific section of the thermocouple curve and performing a linear best fit to this section to create a 5 mV°/C output.

Table 1 shows the temperature ranges chosen, resulting in an error from thermocouple nonlinearity of less than ±2°C. Figure 2 shows the nonlinearity error graphically.

Table 1. AD849x ±2°C Accuracy Temperature Ranges

Part	Thermocouple Type	Max 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

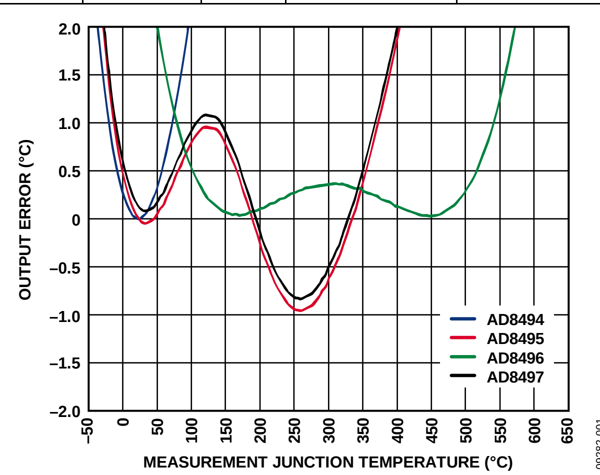

Figure 2. AD849x Output Error due to Thermocouple Nonlinearity

Each part in the AD849x family is precision trimmed to optimize a linear operating range for a specific thermocouple type and for specific measurement and ambient temperature ranges. The following three parameters are trimmed to achieve a 5 mV/°C output with minimal errors:

- Gain of the amplifier
- Offset of the amplifier (error voltage at 0°C to achieve 125 mV at 25°C)
- Scale factor of the temperature sensor/cold junction compensator

The thermocouple voltage, V_{TC}, is a function of the thermocouple type, the measurement junction temperature (T_{MJ}), and the reference junction temperature (T_{RJ}).

$$V_{TC} \propto T_{MJ} - T_{RJ} = (T_{MJ} - 0) - (T_{RJ} - 0)$$

The following transfer function should be used to determine the actual thermocouple voltages being measured by the AD849x (see Table 2 for specific values for each part).

$$V_{TC} = \frac{V_{OUT} - (T_{RJ} \times CJC) - V_{OFFSET} - V_{REF}}{Gain}$$

where:
CJC is the cold junction compensation scale factor.
V_{OFFSET} is the error voltage at 0°C to achieve 125 mV at 25°C.
V_{REF} is the user input voltage.
Gain is the gain of the amplifier.

Table 2. Transfer Function Values for the AD8494, AD8495, AD8496, and AD8497

Part	Gain	CJC Factor (mV/°C)	Offset (mV)
AD8494	96.7	5	0
AD8495	122.4	4.95	1.25
AD8496	90.35	4.8	20.2
AD8497	122.4	5.0392	−0.98

LINEARITY CORRECTION ALGORITHMS

Thermocouple nonlinearity is typically corrected with a microcontroller in the digital domain. One of two correction algorithms can be used.

AD849x Output Lookup Table

The first method is to use Table 3, which lists the ideal AD849x output voltages as a function of the temperature for J type and K type thermocouples with the specified junction temperatures.

For example, an AD8495 at room temperature (25°C) with a grounded reference pin connected to a K type thermocouple outputs 1 V. Using the 5 mV/°C transfer function, 1 V represents 200°C. For greater accuracy, the user must calculate the temperature that corresponds to the 1 V output as follows:

1. Table 3 indicates that at a measurement junction temperature of 200°C, the actual AD8495 output is 0.999 V, and at a measurement junction temperature of 220°C, it is 1.097 V.
2. Linear extrapolation between these two points yields an answer of 200.2°C at 1 V.

NIST Thermoelectric Voltage Lookup Tables

The second method is to use the following equations, where T_{MJ} is the temperature at the thermocouple measurement junction, and f_{NIST} is a millivolt-to-temperature function based on the standard lookup tables or on equations published by the National Institute of Standards and Technology (thermocouple databases can be found at http://srdata.nist.gov/its90/main).

Recall that $V_{TC} \propto T_{MJ} - T_{RJ}$, such that

$$V_{TC} = f_{NIST}(T_{MJ} - 0) - f_{NIST}(T_{RJ} - 0)$$

Output values for intermediate temperatures can be interpolated or calculated using the AD849x output equations and the NIST thermoelectric voltage tables referred to 0°C.

For the AD8494, the equation is as follows:

$$T_{MJ} = f_{NIST}((V_{OUT} - V_{REF})/96.7)$$

For the AD8495, the equation is as follows:

$$T_{MJ} = f_{NIST}((V_{OUT} - V_{REF} - 1.25\text{ mV})/122.4)$$

For the AD8496, the equation is as follows:

$$T_{MJ} = f_{NIST}((V_{OUT} - V_{REF} - 20.2\text{ mV})/90.35)$$

For the AD8497, the equation is as follows:

$$T_{MJ} = f_{NIST}((V_{OUT} - V_{REF} + 0.98\text{ mV})/122.4)$$

Using the same example as for the first method (an AD8495 at room temperature with a grounded reference pin connected to a K type thermocouple that reads 1 V), the correction procedure is as follows:

$$T_{MJ} = f_{NIST}((1\text{ V} - 1.25\text{ mV})/122.4) = f_{NIST}(8.158\text{ mV})$$

1. Consulting a standard K type thermocouple table indicates that at a measurement junction temperature of 200°C, the thermoelectric voltage of the thermocouple is 8.138 mV, and at a measurement junction temperature of 201°C, the thermoelectric voltage is 8.178 mV.
2. Linear extrapolation yields a final answer of 200.5°C.

Table 3. Actual AD849x Results Reflecting Thermocouple Nonlinearity

Measurement Junction Temperature (°C)	AD8494/AD8495 Output, $T_A = T_{RJ} = 25°C$			AD8496/AD8497 Output, $T_A = T_{RJ} = 60°$		
	Ideal Output (V)	Actual Output (V)		Ideal Output (V)	Actual Output (V)	
	AD8494/ AD8495	AD8494 Output with J Type	AD8495 Output with K Type	AD8496/ AD8497	AD8496 Output with J Type	AD8497 Output with K Type
−260	−1.3		−0.786	−1.3		−0.785
−240	−1.2		−0.774	−1.2		−0.773
−220	−1.1		−0.751	−1.1		−0.751
−200	−1		−0.719	−1		−0.718
−180	−0.9	−0.714	−0.677	−0.9	−0.642	−0.676
−160	−0.8	−0.658	−0.627	−0.8	−0.590	−0.626
−140	−0.7	−0.594	−0.569	−0.7	−0.530	−0.568
−120	−0.6	−0.523	−0.504	−0.6	−0.464	−0.503
−100	−0.5	−0.446	−0.432	−0.5	−0.392	−0.432
−80	−0.4	−0.365	−0.355	−0.4	−0.315	−0.354
−60	−0.3	−0.278	−0.272	−0.3	−0.235	−0.271
−40	−0.2	−0.188	−0.184	−0.2	−0.150	−0.184
−20	−0.1	−0.095	−0.093	−0.1	−0.063	−0.092
0	0	0.002	0.003	0	0.027	0.003
20	0.1	0.100	0.100	0.1	0.119	0.101
25	0.125	0.125	0.125	0.125	0.142	0.126
40	0.2	0.201	0.200	0.2	0.213	0.200
60	0.3	0.303	0.301	0.3	0.308	0.301
80	0.4	0.406	0.402	0.4	0.405	0.403
100	0.5	0.511	0.504	0.5	0.503	0.505
120	0.6	0.617	0.605	0.6	0.601	0.605
140	0.7	0.723	0.705	0.7	0.701	0.705
160	0.8	0.829	0.803	0.8	0.800	0.804
180	0.9	0.937	0.901	0.9	0.900	0.902
200	1	1.044	0.999	1	1.001	0.999
220	1.1	1.151	1.097	1.1	1.101	1.097
240	1.2	1.259	1.196	1.2	1.201	1.196
260	1.3	1.366	1.295	1.3	1.302	1.296
280	1.4	1.473	1.396	1.4	1.402	1.396
300	1.5	1.580	1.497	1.5	1.502	1.498
320	1.6	1.687	1.599	1.6	1.602	1.599
340	1.7	1.794	1.701	1.7	1.702	1.701
360	1.8	1.901	1.803	1.8	1.801	1.804
380	1.9	2.008	1.906	1.9	1.901	1.907
400	2	2.114	2.010	2	2.001	2.010
420	2.1	2.221	2.113	2.1	2.100	2.114
440	2.2	2.328	2.217	2.2	2.200	2.218
460	2.3	2.435	2.321	2.3	2.300	2.322
480	2.4	2.542	2.425	2.4	2.401	2.426
500	2.5	2.650	2.529	2.5	2.502	2.530
520	2.6	2.759	2.634	2.6	2.603	2.634
540	2.7	2.868	2.738	2.7	2.705	2.739
560	2.8	2.979	2.843	2.8	2.808	2.843
580	2.9	3.090	2.947	2.9	2.912	2.948
600	3	3.203	3.051	3	3.017	3.052
620	3.1	3.316	3.155	3.1	3.124	3.156
640	3.2	3.431	3.259	3.2	3.231	3.259
660	3.3	3.548	3.362	3.3	3.340	3.363
680	3.4	3.666	3.465	3.4	3.451	3.466

Measurement Junction Temperature (°C)	AD8494/AD8495 Output, $T_A = T_{RJ} = 25°C$			AD8496/AD8497 Output, $T_A = T_{RJ} = 60°$		
	Ideal Output (V)	Actual Output (V)		Ideal Output (V)	Actual Output (V)	
	AD8494/ AD8495	AD8494 Output with J Type	AD8495 Output with K Type	AD8496/ AD8497	AD8496 Output with J Type	AD8497 Output with K Type
700	3.5	3.786	3.568	3.5	3.562	3.569
720	3.6	3.906	3.670	3.6	3.675	3.671
740	3.7	4.029	3.772	3.7	3.789	3.773
760	3.8	4.152	3.874	3.8	3.904	3.874
780	3.9	4.276	3.975	3.9	4.020	3.976
800	4	4.401	4.076	4	4.137	4.076
820	4.1	4.526	4.176	4.1	4.254	4.176
840	4.2	4.650	4.275	4.2	4.370	4.276
860	4.3	4.774	4.374	4.3	4.486	4.375
880	4.4	4.897	4.473	4.4	4.600	4.474
900	4.5	5.018	4.571	4.5	4.714	4.572
920	4.6	5.138	4.669	4.6	4.826	4.670
940	4.7	5.257	4.766	4.7	4.937	4.767
960	4.8	5.374	4.863	4.8	5.047	4.863
980	4.9	5.490	4.959	4.9	5.155	4.960
1000	5	5.606	5.055	5	5.263	5.055
1020	5.1	5.720	5.150	5.1	5.369	5.151
1040	5.2	5.833	5.245	5.2	5.475	5.245
1060	5.3	5.946	5.339	5.3	5.581	5.339
1080	5.4	6.058	5.432	5.4	5.686	5.433
1100	5.5	6.170	5.525	5.5	5.790	5.526
1120	5.6	6.282	5.617	5.6	5.895	5.618
1140	5.7	6.394	5.709	5.7	5.999	5.710
1160	5.8	6.505	5.800	5.8	6.103	5.801
1180	5.9	6.616	5.891	5.9	6.207	5.891
1200	6	6.727	5.980	6	6.311	5.981
1220	6.1		6.069	6.1		6.070
1240	6.2		6.158	6.2		6.158
1260	6.3		6.245	6.3		6.246
1280	6.4		6.332	6.4		6.332
1300	6.5		6.418	6.5		6.418
1320	6.6		6.503	6.6		6.503
1340	6.7		6.587	6.7		6.588
1360	6.8		6.671	6.8		6.671
1380	6.9		6.754	6.9		6.754

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