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Uncertainty Analysis of Thermocouple Circuits

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Abstract: In this paper, uncertainty analysis is carried out for the temperature measurement system using thermocouple (K type, with cold junction compensation) as a sensor using interval method and results are compared with worst case analysis and method of moments. *Copyright © 2009 IFSA.*

Keywords: Uncertainty analysis, Thermocouple, Interval method

1. Introduction

Temperature is one of the most widely measured quantities, providing the basis for a variety of control and safety systems. Thermocouples are the most popular sensor for industrial temperature measurement because it is smallest, fastest, accurate, most durable, cost effective and suitable for wide range of temperature measurement. Thermocouple is the most common among temperature sensors, accounting for 37% of the world market [1]. Uncertainty is a static analysis, normally used during the design and development stage to select appropriate instrumentation and measurement technique, as well as in interpreting experimental data. Uncertainty in thermocouple circuits can arise from the purity of thermocouple wires, distance between the measuring junction and readout device, Electro Magnetic Interference (EMI) effect in thermocouple wires, sensor installation effects and calibration. Most of the thermocouple manufacturers define 0.75% as standard uncertainty. Uncertainty of each element in measurement chain influences the measured value. In this work, the temperature is measured by K type thermocouple with operational amplifier based signal conditioning circuit. The uncertainty analysis is carried out by classical and interval method [2]. The measuring circuit with “K” type thermocouple is shown in Fig. 1.

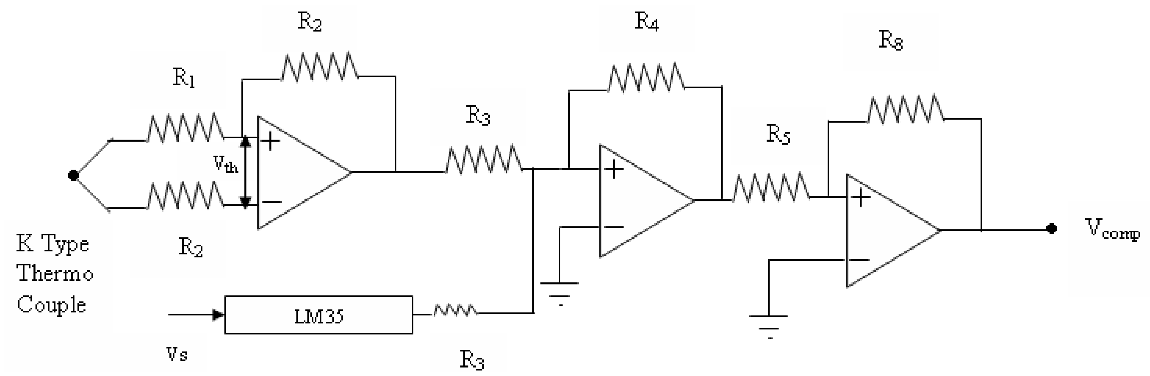

Fig. 1. Thermocouple signal conditioning circuit.

The compensated output voltage (V_{comp}) of thermocouple circuit in Fig. 1 is

$$V_{comp} = \frac{R_2}{R_1} V_{th} + V_C \text{ mV} , \tag{1}$$

where V_{th} is the thermocouple uncompensated voltage, R_1 and R_2 are the fixed general purpose resistors and V_C is the voltage generated by IC LM35 at room temperature [3, 4]. The fixed resistors have 10% tolerance and their representation in interval form is $R_1 = R_3 = R_4 = R_5$ = [900 1100] Ω, R_8 = = [9000 11000] Ω , R_2 = [236.7 289.3] KΩ, and the uncompensated thermocouple output voltage with tolerance of 3.26 x 10^{-4}V is $\boldsymbol{V_{th}}$ = 9.2 x 10^{-5} ± 3.26 x 10^{-4} V = [92 326] µV. [5]

The measured nominal compensated output voltage at 40˚C. is 334.97 mV.

2. Uncertainty Analysis

2.1. Worst Case Analysis

This technique attempt to determine how much change there will be in a function if all the parts are at their extremes and are combined in worst possible manner. If a system passes the worst case analysis it will never fail as long as the inputs parameters are maintained within the tolerance limits established in the analysis. By approximating the performance function by the first few terms of a Taylor series expansion will simplify the problem [6, 7] the general expression for the absolute variation of *u* is given by:

$$|\Delta u| = \sum_{i=1}^{N} \left| \frac{\partial u}{\partial x_i} \right| |\Delta x_i| \tag{2}$$

Then the minimum and maximum values of the function are obtained by

$$u \pm |\Delta u| \tag{3}$$

Using equation (3) and (4), V_{comp} can be written as

$$\left|\Delta V_{comp}\right| = \left|\frac{\partial V_{comp}}{\partial R_2}\right|\left|\Delta R_2\right| + \left|\frac{\partial V_{comp}}{\partial R_1}\right|\left|\Delta R_1\right| + \left|\frac{\partial V_{comp}}{\partial V_{th}}\right|\left|\Delta V_{th}\right| \quad (4)$$

V_{comp} = (334.97, 396.51) mV at 40˚C.

2.2. Method of Moments

Method of moments, in general provides estimators, which are consistent and use very simple computations but not an efficient method. The transformed density function tells the complete information about the problem. In many situations, information about the moments of the distribution is enough. This method assumes that the output parameters have s-normal (Gaussian) distributions [8].

If one assumes independence and if u = g(x) is the performance function, then the expected value and the variance of ‘u’ are given by:

$$E(u) \approx a \quad (5)$$

$$\text{var}(u) \approx \sum_{i=1}^{n} b_i^2 \sigma_i^2 \quad (6)$$

With ‘a’ = g(x), ‘x’ = nominal value,

$$bi = \frac{\partial u}{\partial x_i} \quad (7)$$

$\sigma_i^2 =$ Variance of x_i It is reasonable to assume that ‘a’ is equal to the nominal value and that the tolerance is a certain number of σ units. The exact choice of σ in terms of the tolerance is a matter of judgment when the data are not present. Shooman [8] recommends a value of ‘k’ as 2 or 3. Ranges of ‘u’ can be calculated using:

$$a \pm k\sigma_u, k=2 \text{ or } 3. \quad (8)$$

The variance of components is estimated from extreme values

$$\text{Var (X)} = \left(\frac{X_{max} - X_{min}}{6}\right)^2 \quad (9)$$

Thus, the range of V_{comp} is (303.23, 366.704) for k = 3 at 40˚C.

2.3. Interval Arithmetic

Interval method is an alternative approach to handle uncertainty of electric circuits with inaccurate data. [9] Interval arithmetic is applied to analyze the uncertainty of compensated thermocouple output shown in Fig. 1. The compensated output voltage is calculated as per interval arithmetic rules is [304.19 365.73] mV at 40˚C. The sensitivity analysis is performed using interval arithmetic by assigning bounds to all the input parameters and observing the effect on the final interval outcome, which will contain all possible solution due to variation in input parameters. The Fig. 2 shows the comparison of nominal, minimum and maximum compensated output voltage of thermocouple for the temperature range of 50 to 65˚C. The relative uncertainty is calculated [10] and it increases as the process temperature increases this is due to the variation in the process temperature and increase in the uncertainties of the input parameters (Table 1).

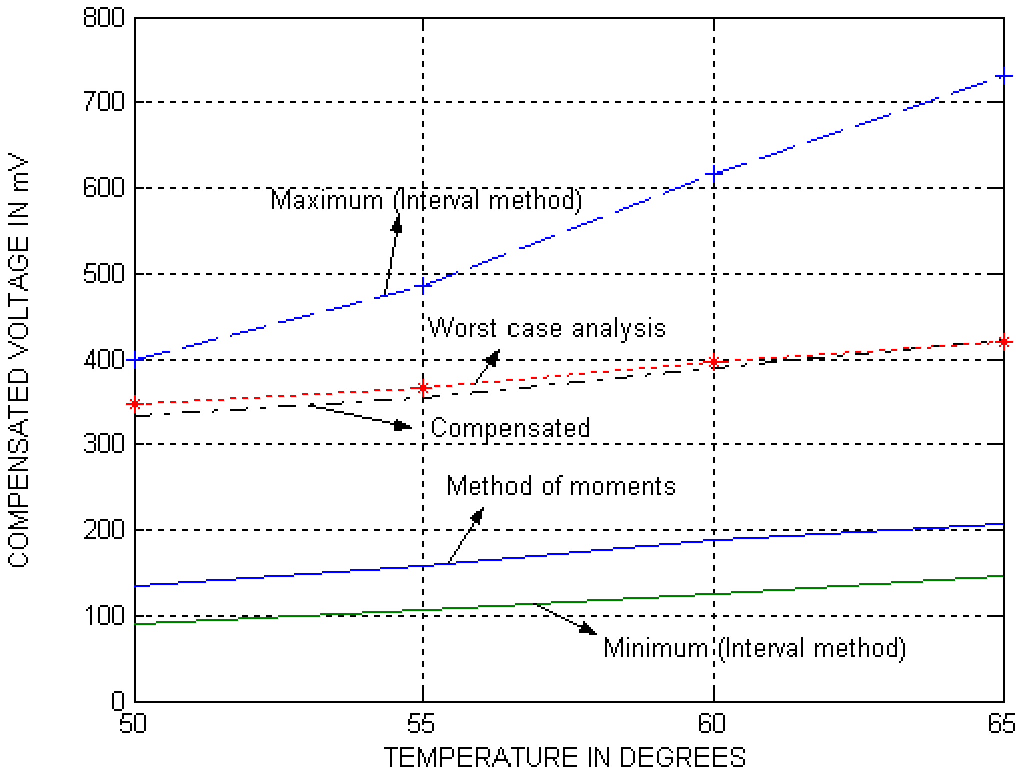

Fig. 2. Uncertainty in compensated voltage.

Table 1. Relative uncertainty.

Temperature(˚C)	**Nominal compensated output voltage (mV)**	**Compensated output voltage using Interval method (mV)**			
		Interval [V]	**Mid-Point $[\hat{V}]$**	**Radius ΔV**	**Relative uncertainty $\Delta V_{relative}$**
50	337.2	[401.8 97.7]	249.75	152.05	0.6088
55	363.8	[493.2 117.6]	305.4	187.8	0.6149
60	412.9	[623.8 146.2]	385.0	238.8	0.6203
65	436.6	[733.5 151.8]	442.65	290.85	0.6571

3. Conclusion

Uncertainty in compensated thermocouple output is analyzed using worst case, method of moments and interval method. Interval method predicts a closed interval output which is more reliable since it does not use statistical methods of error elimination as in the case of worst case analysis and method of moments. The area covered by the interval method will indicate the feasible operating region for thermocouple compensated circuit.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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