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Contents

Volume 100
Issue 1
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Editorial

Research Articles

New e-Book

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A Log Amplifier Based Linearization Scheme for Thermocouples

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Abstract: This paper presents a new analog linearization circuit for thermocouple temperature sensors. The proposed circuit employs the linearizing action inherent in logarithmic operation, as well as the ratiometric property of op-amp based logarithmic amplifier compensated against variation in ambient temperature. Numerical and PSPICE simulation studies have been carried out using the standard data for T, J and G type thermocouples. Encouraging results have been obtained. *Copyright © 2009 IFSA.*

Keywords: Thermocouple, Temperature-sensor, Linearization, Log-Amplifier

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1. Introduction

Thermocouples are long being used as temperature sensors in different fields of Science and Technology. In view of the advantages of thermocouples over other temperature sensors [1-3], it is obvious that there should be considerable effort in developing more and more improved techniques for processing thermoelectric signals. Two important issues in the conditioning of thermocouple signals are cold junction compensation (CJC) and Linearization of the transfer relation. While CJC is a problem unique to this class of transducers, the problem of linearization is universal. The problem of cold junction compensation has been given due importance by the investigators over years and a variety of techniques have been developed [4-7].

The generalized software based linearization techniques for transducers [8-10] can also be used for thermocouples, but in the literatures, the results of such applications have seldom been reported. There are however few exceptions [11, 12]. So far as hardware based schemes are concerned, although it is true that there are commercially available hardware modules, e.g. SCM7B47 modules from DATAFORTH, which perform both CJC and linearization for thermocouples, in the research publications one rarely comes across issues in the development of linearizing circuits for thermocouples. Principles of hardware based linearizing schemes developed for other sensors can of course be utilized for thermocouples. It is however worth mentioning that the issue of linearization as applied to thermocouples in general, is further complicated due to the fact that that the refractory metal thermocouples meant for measurement of very high temperatures have transfer characteristics that are not only extremely nonlinear, but are also non monotonic.

Rapid development of digital computer and microprocessor based systems, combined with their dwindling prices, have resulted in wide spread use of computer based measurement systems where the problem of transducer nonlinearity is tackled by software packages. Although it is generally true that computational algorithms for linearization have better performance compared to hardware methods, there are also exceptions [13]. Moreover, even with slashed prices of computer based systems, hardware based linearizers are by and large still cheaper. Hardware linearization methods can also be used to supplement the software techniques. As an example, linearization of a transducer signal by a hardware method followed by a simple form of software linearization, e.g. by means of a ROM look-up table combined with linear interpolation, may yield better results than those obtained solely by some other complex algorithm.

This work presents a newly devised log-amplifier based circuit for linearizing thermocouple signals. It has originated from the knowledge that linearization is inherent in logarithmic operation, and this is why varieties of log- circuits are already in use for linearization of different transducer characteristics [13]. In the present work the task of linearization has been further facilitated by utilizing the ratiometric property of op-amp based temperature-compensated logarithmic amplifier. Computational and PSPICE based studies have been carried out using the manufacturer's data for T and J type thermocouples that have decent linearity, and also for G type thermocouple that has an extremely non-linear transfer characteristic, to assess the performance of the proposed linearizing scheme.

2. Theory for Proposed Linearizing Circuit

The output of the temperature compensated log amplifier [14] shown in Fig. 1, is

$$V_o = A_o \ \ln \frac{V_1}{V_2} \ , \tag{1}$$

where Ao = AKTa /q , q = 1.6 x 10 $^{-19}$ C is the magnitude of the charge of electron, k= 1.38×10^{-23} J / K is the Boltzmann's constant and T_a is the ambient temperature in Kelvin. It is convenient at this point to assume the 'standard' ambient temperature of 25 °C (298 K), which is widely used in specifying semiconductor properties.

To linearize analog transducer signals, equation (1) can be modified as

$$V_o = A_o \ \ln \frac{V_{IN}}{V_{\mathrm{Re}f}} \ , \tag{2}$$

where

$$V_{IN} = V_1 = E\,(T) + E \tag{3}$$

and

$$V_{\mathrm{Re}\,f}(T) = V_2 = \frac{E_r}{1+K} + \frac{K}{1+K}\;E(T)\,. \tag{4}$$

Here, T is the temperature being measured, E(T) is the analog output voltage signal from the thermocouple (after cold junction compensation) and E is the constant dc voltage used to ensure that $V_o(0) = 0$. E_r is a dc voltage and K is a constant. By selecting the appropriate values for linearizing constants 'K' and E_r, the linearity of the signal E(T) can be improved.

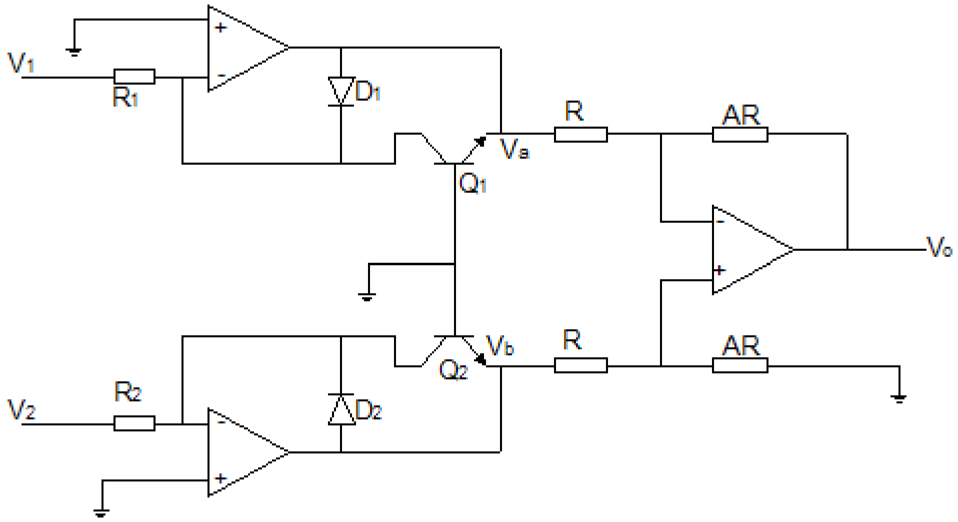

Fig. 1. Practical Form of Logarithmic Amplifier.

Then, equation (2) can be written as

$$\therefore\;\; V_o(T) = A_o\; In\left(\frac{(1+K)\{E(T)+E\}\Big/E_r}{1+KE(T)\Big/E_r}\right) \tag{5}$$

In order to satisfy the condition $V_o(0)=0$, assuming that $E(0)=0$, the value of E should be so selected to fulfill the condition

$$E = \frac{E_r}{1+K} \tag{6}$$

3. Determination of Optimum Values of K and E_r

The normalized deviation of $V_o(T)$ Vs. T characteristic from linearity is defined as

$$D(E_r,K,T)=\frac{V_o(E_r,K,T)}{V_o(E_r,K,T_f)}-\frac{T}{T_f}\ , \tag{7}$$

where T_f denotes the full-scale value of T.

The optimal values of E_r and K can be reached by numerically minimizing the sum-squared deviation 'S', given in equation (8), with respect to E_r and K.

$$S=\sum_{n=1}^{N}D^2(E_r,K,T_n)\ , \tag{8}$$

where N denotes the number of values (T_1,T_2,etc.) of T, considered for computation.

The optimum values of linearizing coefficient K and dc voltage E_r and the values of scaling constant A for the different thermocouples and for different temperature ranges have been determined and tabulated in Table 1. A has been calculated, considering that numerical value of $V_o(T_f)$ in mV should be equal to T_f. It can be seen that the value of K required is negative.

Table 1. Optimum values of 'k' and reference voltage 'e_r' and values of 'a' for different thermocouples.

Thermo-Couple Type	**Temp. Range**	**K**	**E_r mV**	**E mV**	**$V_o(T_f)$ mV**	**$E(T_f)$ mV**	**A**
Copper – Constantan **(T – Type)**	0°C – 300°C	- 0.209	11.1	14.032	300	14.86	10.972
	0°C – 400°C	- 0.198	12.8	15.96	400	20.87	12.548
Iron Constantan **(J – Type)**	0°C – 300°C	- 0.352	18.1	27.932	300	16.32	13.704
	0°C – 760°C	- 0.01	258.1	260.707	760	42.92	189.255
Tungsten – Tungsten 26% Rhenium **(G – Type)**	400°C – 2300°C	- 0.084	3.804	4.15	2300	38.325	21.069
	1000°C – 2300°C	- 0.132	6.515	7.50	2300	38.325	26.744

4. Circuit Diagram

A circuit is proposed that may be used for linearization when the value of K required is negative, and is shown in Fig. 2.

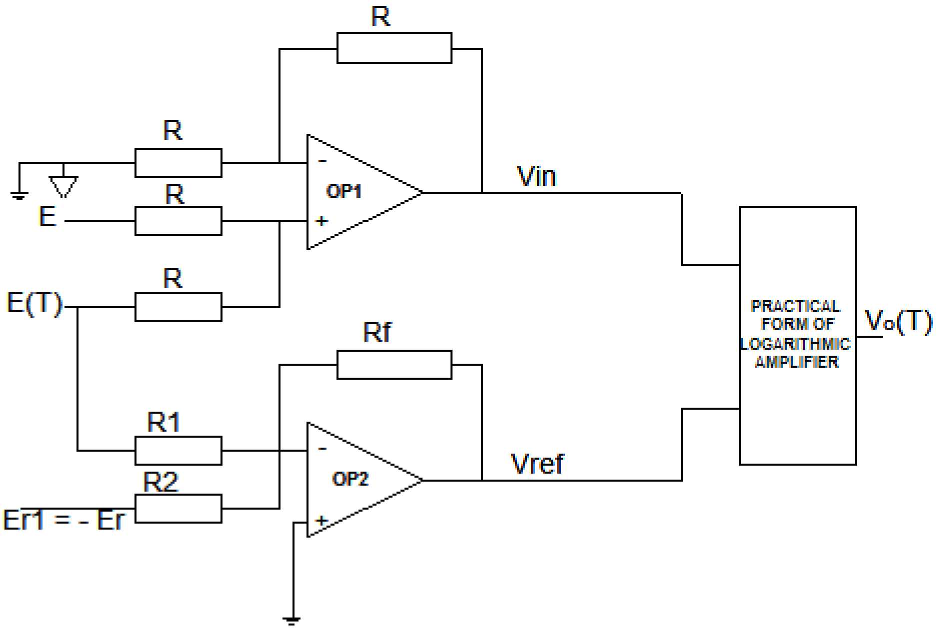

Fig. 2. Block Diagram of Proposed Linearizing Circuit Using Log Amplifier, for negative 'K'.

From the circuit shown, one can obtain the following expressions:

$$V_{IN} = E\,(T) + E \tag{9}$$

and

$$V_{\mathrm{Re}\,f}(T) = \frac{E_r}{1+K} + \frac{KE(T)}{1+K}\ , \tag{10}$$

where $R_f / R_1 = |K| / (1+K)$

and $R_f / R_2 = 1 / (1+K)$

It is to be noted that in the circuit under consideration is only suitable for |K|<1.

Therefore finally

$$V_o\ (T) = A_o \ln\left(\frac{(1+K)\{E(T)+E\} / E_r}{1+K\ \ E(T) / E_r} \right) \tag{11}$$

At the standard ambient temperature of 25°C, A_o= 0.0257 A, where A is the differential amplifier gain which is used to scale the linearized output of the circuit shown in Fig. 2. At first, E_r and K are adjusted to their optimum values and then, setting T = T_f, full scale calibration is carried out by adjusting A until the full scale output voltage V_o (T_f) reaches its desired value.

By virtue of the linearizing action inherent to the logarithmic operation, an improvement in the linearity may be achieved with this method, which may be further augmented by maneuvering the ratiometric property of the log amplifier as discussed above.

5. Investigations and Results

Computational as well as PSPICE simulation studies have been carried out using standard data [1,15] for Copper-.Constantan (T-type), Iron-Constantan (J-type) and Tungsten-Tungsten 26% Rhenium (G-type) thermocouples, to evaluate the performance of proposed circuit, considering different temperature ranges for each type. LF412 operational amplifiers and 2N3707 transistors have been used for PSPICE simulation studies. Among the thermocouples considered the thermo-e.m.f. vs. temperature characteristics of first two are monotonic and that of the last one (refractory metal thermocouple) has an inflection at about 1090ºC. For T-type thermocouple, the temperature ranges covered are 0ºC to 300ºC and 0ºC to 400ºC. The ranges considered for J-type are 0ºC to 300ºC and 0ºC to 760ºC. Since G-type thermocouple is specially used for the measurement of very high temperatures in industries, typically from 400ºC to 2300ºC [6] , linearization for this thermocouple has been carried out over two different temperature ranges, namely 400°C to 2300°C and 1000°C to 2300°C.

The numerical studies portray the performance of the circuit according to equation (11), i.e. considering ideal devices to constitute the circuit. Although PSPICE is also a computational software package, it takes into account the characteristics of practical devices. Hence the results obtained using PSPICE can be expected to be more realistic, thereby revealing the feasibility of actually implementing the scheme envisaged and also its performance.

The percentage deviation from linearity (i.e. non-linearity error) is given by,

$$D\% = \frac{V_o(T) - \frac{T}{T_f} V_o(T_f)}{V_o(T_f)} \times 100 \tag{12}$$

So far as computation of non-linearity prior to linearization is concerned, it has been assumed that the thermocouple signal has been adequately amplified so that the numerical value of full-scale amplifier output is equal to that of T_f.

The non-linearity error vs. temperature plots for the three varieties of thermocouples are shown in Figs. 3, 4 and 5. In these figures the results have been plotted considering only one range for each type of thermocouple.

The limits of % non-linearity error and RMS % non-linearity error of the quasi – linearized thermocouple signal obtained by the method under consideration, for the three types considered, are given in Table 2. It is clear from the plots mentioned above as well as from the tabulated data that there is no marked departure of the error-characteristics obtained by PSPICE simulation from those obtained by computation.

For the sake of comparison, the maximum % error and R.M.S % error of the thermocouple signals before and after linearization, are shown in Table 3.

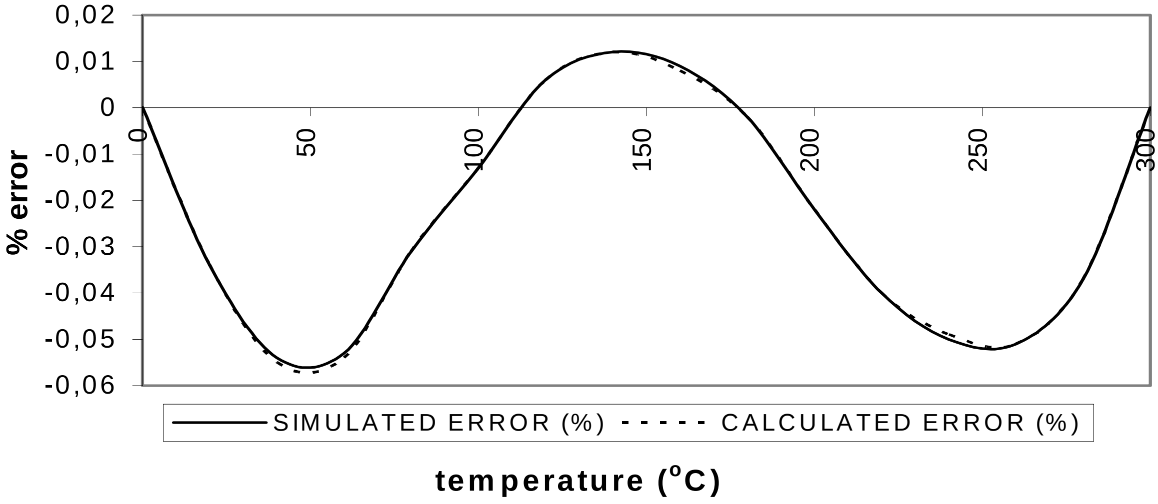

Fig. 3. Non-linearity error curve for Copper-Constantan thermocouple over 0°C to 300°C.

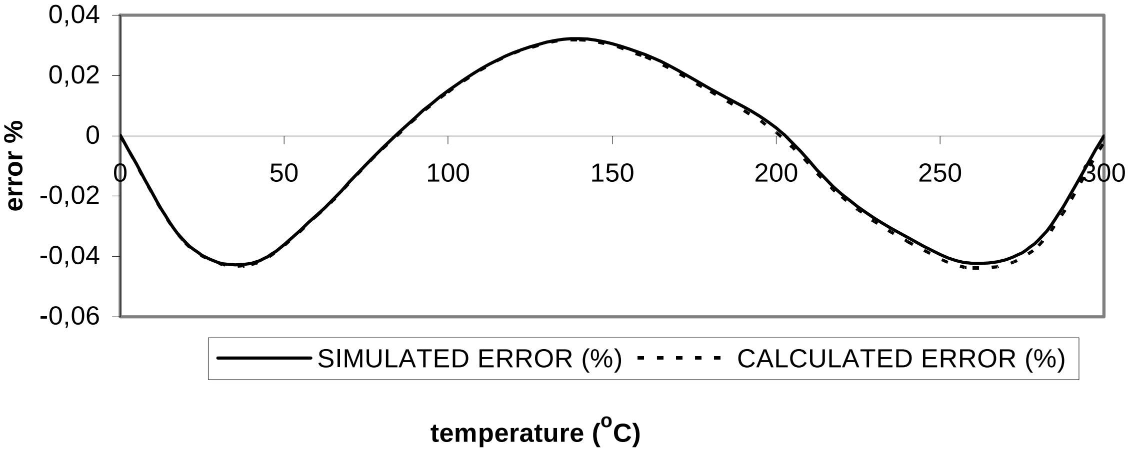

Fig. 4. Non-linearity error curve for Iron-Constantan thermocouple over 0°C to 300°C.

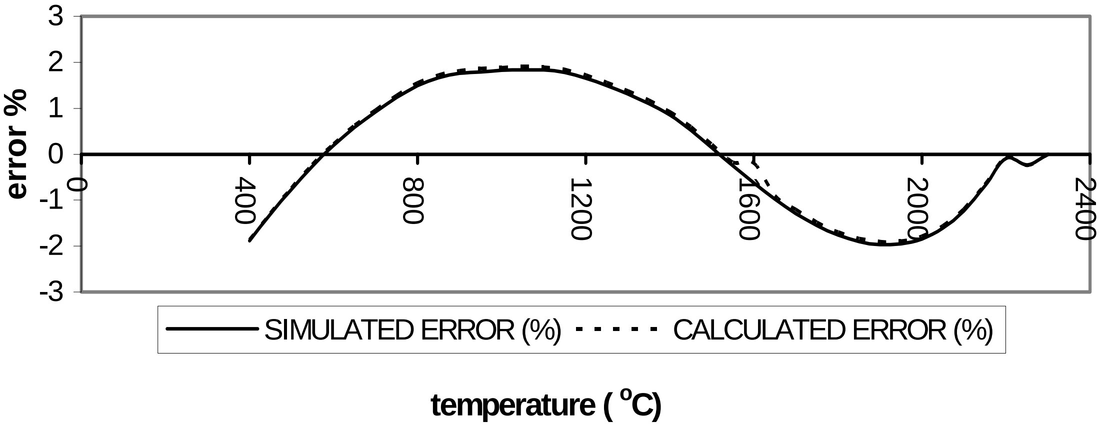

Fig. 5. Non-linearity error curve for Tungsten-Tungsten 26% Rhenium thermocouple over 400 °C to 2300 °C.

Table 2. Limits of % nonlinearity error and rms % nonlinearity error.

Thermocouple Type	**Temperature Range**	**By PSPICE Simulation**		**By Computation**	
		Limits of % error	**RMS % error**	**Limits of % error**	**RMS % error**
Copper – Constantan (*T – Type*)	0°C – 300°C	0.012 at 140°C and - 0.054 at 40°C	0.033	0.012 at 140°C and - 0.055 at 40°C	0.033
	0°C – 400°C	0.052 at 200°C and - 0.102 at 60°C	0.051	0.050 at 200°C and - 0.103 at 60°C	0.051
Iron Constantan (*J – Type*)	0°C – 300°C	0.032 at 140°C and - 0.042 at 260°C	0.026	0.032 at 140°C and - 0.044 at 260°C	0.027
	0°C – 760°C	0.359 at 280°C and - 0.554 at 620°C	0.301	0.352 at 280°C and - 0.569 at 620°C	0.306
Tungsten – Tungsten 26% Rhenium (*G – Type*)	400°C – 2300°C	1.836 at 1050°C and - 1.968 at 1900°C	1.347	1.900 at 1050°C and - 1.903 at 1900°C	1.340
	1000°C – 2300°C	0.876 at 1350°C and - 0.961 at 1850°C	0.637	0.943 at 1350°C and - 0.894 at 1850°C	0.637

Table 3. Maximum % nonlinearity error and rms % nonlinearity error before and after linearization.

Thermocouple Type	**Temperature Range**	**Maximum % Error**		**RMS % Error**	
		Before Linearization	**After Linearization**	**Before Linearization**	**After Linearization**
Copper – Constantan (*T – Type*)	0°C – 300°C	- 4.917 at 140°C	- 0.054 at 40°C	3.351	0.033
	0°C – 400°C	- 5.540 at 180°C	- 0.102 at 60°C	3.990	0.051
Iron Constantan (*J – Type*)	0°C – 300°C	- 1.065 at 110°C	- 0.042 at 260°C	0.725	0.026
	0°C – 760°C	- 1.998 at 530°C	- 0.554 at 620°C	1.412	0.306
Tungsten – Tungsten 26% Rhenium (*G – Type*)	400°C – 2300°C	- 9.118 at 530°C	- 1.968 at 1900°C	4.872	1.340
	1000°C – 2300°C	- 5.574 at 1000°C	- 0.961 at 1850°C	2.056	0.637

The salient features of the findings of the study undertaken, are summarized below:

1. From Table 3, it can be observed that for T-type, the maximum % error and RMS % error are substantially reduced to about 1/50 of their original values in the two different temperature ranges 0°C to 300°C and 0°C to 400°C. In the case of J-type, for the temperature range 0°C to 300°C, these quantities are reduced to same extent as in T-type. However in the range 0°C to 760°C, the reduction in the interested quantities are small (1/4 of the original values) due to the wide range of temperature considered for computation. For G-type, it can be seen that the maximum and RMS% deviation can be reduced approximately to 1/5 of their original values for 400ºC to 2300°C. Over the range 1000°C to 2300°C, the reduction is approximately to 1/10 of the original values.

2. The performance of the log-amplifier based linearizing circuit is excellent when used for T-type thermocouple. The non-linearity with the present scheme is within. ± 0.01% over 0°C to 300°C and ± 0.1% over 0°C to 400°C. The performance is substantially better than that of a software method introduced by Bolk [11] which yields a nonlinearity of ± 0.36% over 0°C to 300°C. It is noteworthy that Bolk had proved that his method gives better results than the interpolation techniques.

3. The performance of the log-amplifier based linearizing circuit is excellent when used for T-type thermocouple. The non-linearity with the present scheme is within. ± 0.01% over 0°C to 300°C and ± 0.1% over 0°C to 400°C. The performance is substantially better than that of a software method introduced by Bolk [11] which yields a nonlinearity of ± 0.36% over 0°C to 300°C. It is noteworthy that Bolk had proved that his method gives better results than the interpolation techniques.

4. When used for type-J thermocouple, the performance of the proposed linearizer is also brilliant. The non-linearity is within ±0.04% and ±0.55% over 0 °C to 300 °C and 0 °C to 760 °C respectively. The error value achieved with Bolk's method lies within ±0.29% over 0 °C to 300 °C.

5. When applied to type-G thermocouple, the logarithmic circuit, as expected, yields inferior results. The results with the proposed log-amplifier based contender are not satisfactory compared to the software methods indicated below. From 1000 °C to 2300 °C, the non-linearity with the present scheme lies within ±0.53% of full-scale, which is ±12.2 °C. The RMS deviation is 0.365%, which corresponds to 8.28 °C. It is worth mentioning that the RMS deviations obtained by Attari et al. [12] using linear interpolation, quadratic interpolation, polynomial interpolation and by an ANN method, are 2.11 °C, 1.27 °C, 10.54 °C and 1.06 °C respectively even over a wider temperature range of 250ºC to 2150ºC.

6. Conclusion

A low-cost log-amplifier based linearizing circuit has been proposed for thermocouple temperature sensors. It has been shown that its performance when employed for thermocouples with monotonic thermo-emf vs. temperature characteristics is better than some of the common software linearizers used for these thermocouples.

For the G-type thermocouple, the performance of the proposed linearizer is not satisfactory compared to that of software methods. Therefore, for temperature measurement using G-type thermocouple, the log circuit can be used only for high temperature applications, provided that linearity of transfer characteristic can be sacrificed to a certain extent, in exchange of the low cost of the linearizer. For computer based measurement systems employing G-type thermocouple sensor, the log circuit may also be used as a first stage linearizer, and the final linearization may be carried out by some simple software method. This hybrid combination may result in improved performance compared to the purely software-based methods.

The obvious source of error of the proposed arrangement is the temperature-dependence of the scaling factor Ao which makes the calibration of the set-up dependent on the ambient. This may not be a serious problem when the signal conditioning circuit is located in an air-conditioned control room. Otherwise the same scheme can be implemented by replacing the op-amp based log-amplifier with commercially available two-input log module e.g. Model 756 from Analog Devices. Such a circuit will be free from the above-mentioned error. However the cost will increase considerably.

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- Sensor instrumentation;
- Virtual instruments;
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- Signal processing;
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- Nanosensors;
- Microsystems;
- Applications.

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