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PAPER

A Simple Linear Temperature-to-Frequency Converter Using a Thermistor

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SUMMARY A novel temperature-to-frequency converter consisting of the thermistor-controlled current source, comparator, and monostable multivibrator is developed. Linearization is made by comparing the voltage developed across the current source with an exponentially growing voltage. A prototype converter built using standard components shows an excellent linearity with the residual error less than 0.2 % over the range from 273 K to 353 K. The converter features the simple configuration, high accuracy, and single supply operation.

1. Introduction

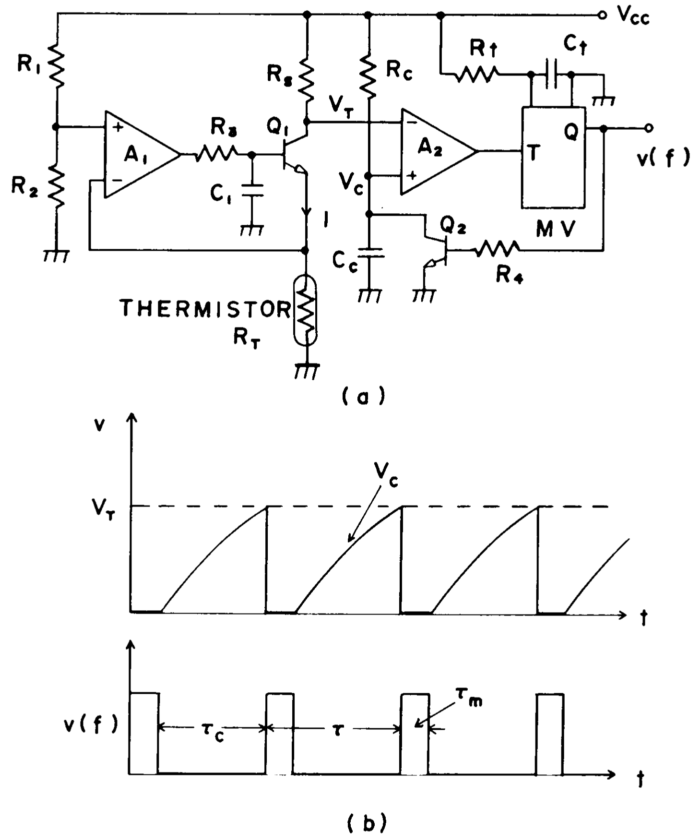
Temperature is one of the physical quantities closely related to human life and thus its measurement and control are eternal engineering problems. To solve the problem, many temperature transducers such as a thermocouple, resistance thermometer, p-n junction diode, and thermistor have been developed. Of these a thermistor is the most inexpensive transducer with the highest sensitivity. Its resistance variation against temperature is, however, highly nonlinear, plagueing the design of the interface between the transducer and a digital system.

A well-acknowledged method for interfacing is the frequency encoding of the thermistor resistance. To linearize the relation between frequency and temperature, two approaches are common; one is to linearize the oscillation frequency of an astable multivibrator or a Colpitts oscillator by means of two resistors connected one in series and the other in parallel with the thermistor (1)-(7). This approach features the simple configuration, but is applicable only to the limited temperature range because of the approximation. The second approach compares the voltage across the thermistor with an exponentially growing or decaying voltage to convert the exponential variation of the thermistor resistance with temperature into the linear change in time(8)-(11). Exact linearization is possible, but the temperature-to-frequency (T/F) converters based on this approach were more complicated than the astable multivibrator and, what is worse, required the bipolar power supply.

A thermistor features, as stated above, its low cost and high sensitivity. In order to make the best use of these merits, its interface should be necessarily simple and low cost. A simple T/F converter based on the second approach of the linearization is developed to meet such requirements. Following this introductory section, Sect. 2 describes its circuit configuration and principles of operation. The practical performance obtainable with the converter calibrated at two temperatures is estimated in Sect. 3. Sect. 4 presents the experimental results. The paper concludes in Sect. 5 with the potential application of the T/F converter.

2. Circuit Description

Figure 1 (a) shows the circuit diagram of the T/F converter. OP-amp A_1 and transistor Q_1 constitute the



(a)

(b)

Fig. 1 The circuit diagram (a) and waveforms (b) of the T/F converter.

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thermistor-controlled current source, producing the temperature-dependent voltage V_T at the collector of Q_1. The R_3C_1 low-pass filter is incorporated to prevent the current source from oscillating. The voltage V_T is then compared with the exponentially growing voltage V_c across C_c by the comparator A_2. When the capacitor voltage V_c reaches V_T, as shown by the waveform in Fig. 1 (b), the comparator A_2 triggers the monostable multivibrator (MV). The output pulse of the MV with duration τ_m makes, in turn, the transistor Q_2 on to discharge the capacitor C_c. After τ_m, C_c is charged toward the supply voltage V_{cc} until it reaches V_T. Repeating this process, the circuit produces the rectangular pulse train whose frequency depends on temperature.

Referring to Fig. 1 (a), the voltage V_T is given by

$$V_T = V_{cc}(1 - kR_s/R_T), \tag{1}$$

where $k = R_2/(R_1 + R_2)$ and R_T is the thermistor resistance expressed as

$$R_T = R_o \exp B\left(\frac{1}{T} - \frac{1}{T_o}\right), \tag{2}$$

where R_o is the resistance at the reference temperature T_o and B is the constant determined by the thermistor material. The capacitance C_c is charged through R_c until its voltage reaches V_T. The charging time τ_c is thus given by

$$\tau_c = C_cR_c\left(\ln \frac{R_o}{kR_s} + \frac{B}{T} - \frac{B}{T_o}\right). \tag{3}$$

Setting the output pulse width τ_m of the MV such that

$$\tau_m = C_cR_c\left(\frac{B}{T_o} - \ln \frac{R_o}{kR_s}\right) \tag{4}$$

hold, one can get the linear relation between the oscillation frequency and temperature T ;

$$f = \frac{1}{\tau_c + \tau_m} = \frac{T}{C_cR_cB} = S_cT, \tag{5}$$

where S_c denotes the conversion sensitivity.

3. Measurement Accuracy and Range

3.1 Calibration

The divider ratio k is determined by the allowable internal power dissipation of the thermistor. The load resistor R_s of the current source is then chosen such that V_T be in the range appropriate for the comparator A_2. With k and R_s thus fixed, R_c of known value, and C_c, R_t, and C_t roughly selected, the T/F converter is calibrated by the following procedure.

First, the oscillation frequencies f_1 and f_2 are measured at two temperatures T_1 and T_2 ;

$$\frac{1}{f_{1,2}} = C_cR_c'\left(\ln \frac{R_o}{kR_s} + \frac{B}{T_{1,2}} - \frac{B}{T_o}\right) + \tau_m', \tag{6}$$

where a prime denotes the component to be trimmed. Manipulating Eq. (6), one can obtain the relation

$$S_c' = \frac{1}{C_cR_c'B} = \frac{T_1^{-1} - T_2^{-1}}{f_1^{-1} - f_2^{-1}}. \tag{7}$$

Trim R_c' at this stage such that the conversion sensitivity S_c fit the specified value. Next, trim the resistor R_t such that the oscillation frequency, say f_1, meet Eq. (5). This completes the calibration.

3.2 Accuracy

The above description assumes that B is constant over the measurement temperature range. In fact, it is a bilinear function of temperature, causing the nonlinear error. Expanding B into a Taylor series, we have

$$\begin{aligned} B &= B_0 + B_1(\Delta T) + B_2(\Delta T)^2 + B_3(\Delta T)^3 + \cdots \\ &= B_0 + B_1(\Delta T) + O(\Delta^2), \end{aligned} \tag{8}$$

where

$$\Delta T = T - T_o,$$

$$B_n = \frac{1}{n!}\frac{d^nB}{d(\Delta T)^n},$$

$$(n = 1, 2, \cdots)$$

$$\text{and } O(\Delta^2) = \sum_{i=2} B_i(\Delta T)^i. \tag{9}$$

The practical oscillation frequency f' is then given by

$$f' = \frac{1}{C_cR_c[B_0/T - \{B_1\Delta T + O(\Delta^2)\}\Delta T/TT_o]} \tag{10}$$

In deriving Eq. (10), Eq. (4) with B replaced by B_0 is assumed. The nonlinear error is thus

$$\varepsilon = \frac{f - f'}{f} = \frac{B_1(\Delta T)^2 + \Delta T_o(\Delta^2)}{B_0T_o} \tag{11}$$

Typical values of B_i's for the thermistor with $R_o = 20$ kΩ and $B_0 = 3884$ at $T_o = 323$ K are : $B_1 = 2.04$, $B_2 = -7.06 \times 10^{-3}$, $B_3 = 1.22 \times 10^{-5}$, $B_4 = -7.05 \times 10^{-9}$. Using these values, ε is estimated to be less than 0.34 % for $\Delta T = \pm 50$ K.

Another error source is the temperature variation $\Delta\tau_m$ of the output pulse width τ_m[(10)]. The relative frequency deviation δ due to $\Delta\tau_m$ is given by

$$\delta = \frac{\Delta f}{f} = -\frac{\Delta\tau_m}{\tau_m} \cdot \frac{\tau_m}{\tau} \tag{12}$$

A typical temperature coefficient of $\Delta\tau_m/\tau_m$ is 100 ppm/°C. The ratio τ_m/τ falls within 1/2 if the oscillation frequency is below 10 kHz. The maximum frequency deviation over the temperature range 100 K is thus estimated to be −0.5%. Fortunately, the frequency deviation δ tends to cancell the deviation ε. Therefore, an excellent

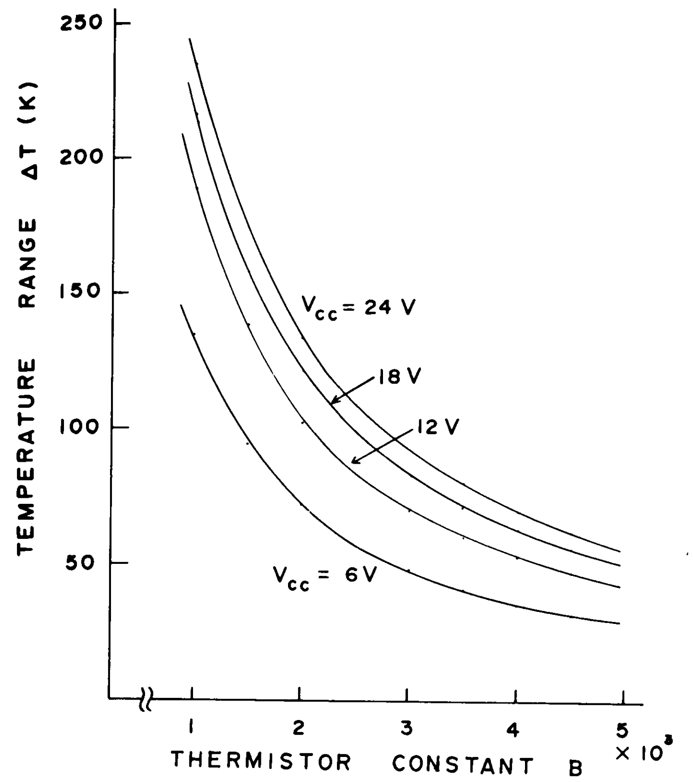

Fig. 2 The measurable temperature range ΔT versus the thermistor constant B with the supply voltage V_{cc} as a parameter.

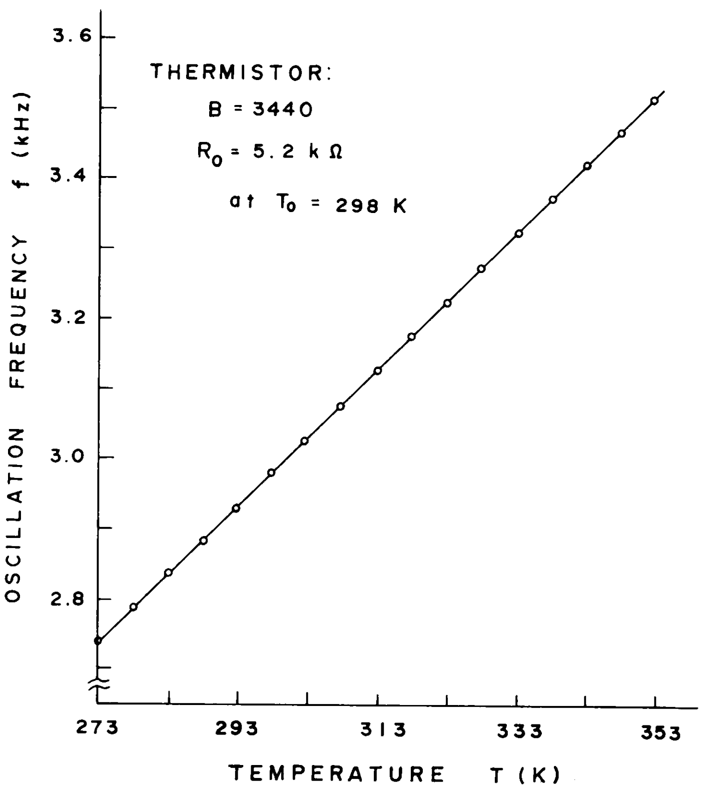

Fig. 3 The oscillation frequency f versus temperature T measured by a prototype converter.

linearity can be expected from the present T/F converter.

3.3 Measurement Range

The measurable temperature range ΔT is limited by the allowable input voltage range of the comparator A_2. Let $V_{\max}$ and $V_{\min}$ be the maximum and minimum voltages, respectively, that can be applied to the camparator. Then, from Eqs. (1) and (2), we have

$$\frac{\Delta T}{(T_o-\Delta T/2)(T_o+\Delta T/2)}=\frac{1}{B}\ln\frac{V_{cc}-V_{\min}}{V_{cc}-V_{\max}}. \quad (13)$$

The relation between ΔT and B is plotted in Fig. 2 with V_{cc} as a parameter. Here, $T_o=300$ K, $V_{\min}=1$ V, and $V_{\max}=V_{cc}-1$ (V) are assumed. Referring to this figure, one can select the thermistor and the supply voltage appropriate for a given temperature range.

4. Experimental Results

A prototype T/F converter was built using the thermistor with $B=3440$ and $R_o=5.2$ kΩ at $T_o=298$ K. The relevant circuit parameters were: $k=0.01$, $V_{cc}=24$ V, $R_s=100$ kΩ, $C_c=5.6$ nF, and $C_t=23$ nF. The small divider ratio k eliminates the self-heating problem of the thermistor. The calibration was performed at two temperatures $T_1=273$ K and $T_2=323$ K, to trim R_c so that the conversion sensitivity be 10 Hz/K. The output pulse width τ_m was adjusted by means of R_t so that the oscillation frequency be 3.23 kHz at $T_2=323$ K.

The relation between the oscillation frequency f and temperature T was then measured by immersing the thermistor into a temperature-controlled oil bath. The results thus obtained are plotted in Fig. 3. An excellent linearity can be seen. The residual linearity error and the correlation between T and f were calculated to be less than 0.2 % and 0.9984, respectively. These results confirm the principles of operation and the accuracy estimate. The measurable temperature range was about 80 K, which also fits the measurement range plotted in Fig. 2.

5. Conclusions

A linear T/F converter using a thermistor was described. It features a low cost made possible by the small component-count and the single supply operation. Therefore, it can find a wide applicability as a digital thermometer. Another salient feature of being accurate makes it feasible to implement a low cost and high precision digitally programmable temperature controller based on the phase-lock loop, which is now under development.

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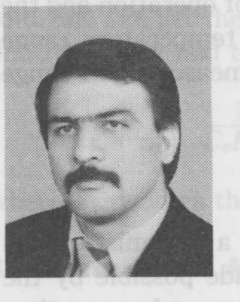

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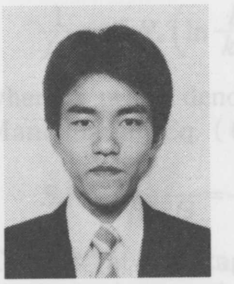

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