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A Temperature Difference-to-Frequency Converter Using Resistance Temperature Detectors

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Abstract—A novel temperature difference-to-frequency (TD/F) converter using two platinum resistance temperature detectors (RTD's) has been developed. The resistance difference of two RTD's is converted into a dc current to control the simulated inductor which is designed so that its inductance is inversely proportional to the square of the current. The simulated inductor forms the resonant circuit of a Colpitts oscillator and hence the oscillation frequency becomes directly proportional to the resistance difference.

A conversion sensitivity of 16 Hz/°C and a residual nonlinearity of less than 2% over the temperature difference range of 35°C to 155°C are obtained by the prototype converter which oscillates at 667 Hz at a 51°C temperature difference. The minimum detectable temperature difference is estimated to be $\pm 0.013^\circ\text{C}$. The power dissipations in the RTD's are about 2 μW . The proposed converter, except for the RTD's, can be fabricated in a monolithic IC form.

I. INTRODUCTION

The expanding use of microprocessors in measurement systems requires transducers with digital outputs. This is true of a low-cost and high-resolution temperature difference measuring system. Several sensing elements are available for measuring the temperature difference, but the platinum resistance temperature detector (RTD) is most suitable for precision work because of its small manufacturing tolerance, wide temperature range, and high accuracy. The straightforward approach of encoding the resistance difference of two RTD's into a digital number is first to convert it into an intermediate form, such as a voltage or current, and then digitally convert this via voltage or current-controlled relaxation oscillators [1], [2]. This type of temperature difference-to-frequency (TD/F) converter features a simple configuration, but its temperature resolution is poor. This is because the oscillation frequency depends not only on the resistances of the RTD's, but also on temperature-sensitive transistor parameters.

A tuned sinusoidal oscillator has better frequency stability than a relaxation oscillator [3], [4]. Therefore, the temperature resolu-

tion can be improved by replacing the relaxation oscillator with such an oscillator. Based on this concept, a new TD/F converter has been developed. In this converter, the temperature difference sensed by two RTD's is first converted into a dc current. The current is then encoded into its equivalent frequency via a current-controlled tuned oscillator based on a simulated inductor.

II. CIRCUIT DESCRIPTION AND OPERATION

Fig. 1 shows the circuit diagram of the TD/F converter using platinum RTD's. Here, R_{T1} and R_{T2} are RTD resistances at temperatures T_1 and T_2 , respectively. Their difference is converted into a dc current by the operational transconductance amplifier (OTA₁). The output current of OTA₁ is given by

$$I_0 = g_{m1} \left(\frac{R_{T1}}{R_1 + R_{T1}} - \frac{R_{T2}}{R_1 + R_{T2}} \right) V_r \quad (1)$$

where g_{m1} is the transconductance of OTA₁ and V_r is the reference voltage that excites the RTD-resistor network (series combination). Choosing R_1 so that $R_1 \gg R_{T1}$ and R_{T2} , (1) is simplified to

$$I_0 \approx g_{m1} \left(\frac{R_{T1} - R_{T2}}{R_1} \right) V_r \quad (2)$$

This current is used to bias two matched OTA's, OTA₂ and OTA₃, thereby controlling their transconductances. Since OTA₂ and OTA₃ in conjunction with capacitor C form the simulated inductor [5], [6], its equivalent inductance L_{eq} is related to I_0 as follows:

$$L_{eq} = \frac{(4V_T)^2 C}{I_0^2 \cdot l} \quad (3)$$

where V_T represents the thermally induced voltage and $l = R_b / (R_a + R_b)$. It is noted that the simulated inductance is inversely proportional to the square of the bias current I_0 .

The simulated inductor together with C_1 and C_2 forms the resonant circuit of a Colpitts oscillator. At low frequencies, its oscillation frequency is given by

$$f_0 = K(R_{T1} - R_{T2}) \quad (4)$$

where

$$K = \frac{g_{m1} V_r}{8\pi R_1 V_T} \left(\frac{C_1 C_2}{C_1 + C_2} \frac{C}{l} \right)^{-1/2} \quad (5)$$

The temperature-resistance characteristic of the RTD at $T^\circ\text{C}$ can be approximately expressed as

$$R_T \approx R_{T0} (1 + \alpha T + \beta T^2) \quad (6)$$

where R_{T0} is the resistance at 0°C and α and β are temperature coefficients of resistance. Assuming the temperature-resistance characteristics of two RTD's to be identical, the relation between the oscillation frequency and the temperature difference can be written as

$$f_0 = KR_{T0} \alpha (T_1 - T_2) [1 + \beta/\alpha (T_1 + T_2)]. \quad (7)$$

Since $|\beta/\alpha| \ll 1$, the term including β can be neglected for the case of small temperature differences and thus the oscillation frequency becomes linearly proportional to the temperature difference.

III. EXPERIMENTAL RESULTS

A prototype TD/F converter was built using CA3080 OTA's. OTA₁ was biased so that its transconductance g_m is 7 mS. The RTD's used were PA-50-8 with $R_{T0} = 100 \Omega$, $\alpha = 3.9733 \times 10^{-3}/^\circ\text{C}$, and $\beta = -5.8611 \times 10^{-7}/(^\circ\text{C})^2$. The reference voltage V_r was set to +14 V. The other circuit elements were: $C = 10$ nF, $C_1 = C_2 = 500$ pF, $R_1 = R_a = 100$ k Ω , and $R_b = 100 \Omega$. Fig. 2 shows the oscillation waveform when the temperature difference

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Fig. 1. The circuit diagram of the TD/F converter using platinum RTD's.

Fig. 2. Experimentally observed oscillation waveform when the temperature difference is 55°C. Horizontal scale: 1 ms/div. Vertical scale: 1 V/div.

is 55°C. The relation between the oscillation frequency and the temperature difference was measured by fixing R_{T2} at 96 Ω (-5°C) and varying R_{T1} from 109 Ω to 161 Ω ($30^{\circ}\text{C} \sim 150^{\circ}\text{C}$). The result is plotted in Fig. 3. From this, it appears that the oscillation frequency is linearly dependent upon the temperature difference over the range $35\text{--}115^{\circ}\text{C}$ with a sensitivity amounting to 16 Hz/ $^{\circ}\text{C}$. However, if a deviation of 2% is to be tolerated, the linear range extends to 155°C . The linearity error is mainly due to the β term of (7) and can be compensated by means of a correction table stored in a ROM.

The frequency drift of the oscillator itself was measured by operating it for a few hours at a constant temperature. The measured drift was ± 0.5 Hz. Thus the minimum detectable temperature difference of the converter can be estimated to be $\pm 0.031^{\circ}\text{C}$. It should be mentioned here that since the transconductance g_m of the OTA's is itself dependent on temperature, its stabilization is essential in the realization of the higher resolution TD/F converter, particularly under varying environmental conditions. This can be achieved by using improved OTA's with on-chip diode linearization networks, like LM13600 and CA3280. In such OTA's, temperature independent transconductance can be obtained by biasing the diode with a constant current source [7].

Fig. 3. The oscillation frequency versus temperature difference obtained by the prototype converter.

The power dissipation in each RTD was about $2 \mu\text{W}$. Since the internal power dissipation is quite small, the self-heating problem in the detectors is avoided.

IV. CONCLUSIONS

A new TD/F converter based on a current-controlled tuned oscillator is described. It features good linearity with relatively high temperature difference resolution. The whole circuit, except for the RTD's, can be fabricated in a monolithic IC form by scaling the component values. This converter can be applied to industrial temperature controllers and chemical process controllers as a low cost and precise temperature difference measuring device. Because of its sinusoidal output, remote sensing is also possible.

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