may save fault information, the spare processing time might also be used to extend the relay's operation or for self-diagnostic testing.

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REFERENCES

- [1] C. A. Gross, *Power Systems Analysis*. New York: Wiley, 1979.
- [2] R. J. Marttila, "Directional characteristics of distance relay mho elements: Part I—A new method of analysis," *IEEE Trans. Power App. Syst.*, vol. PAS-100, pp. 96-102, 1981.
- [3] —, "Directional characteristics of distance relay Mho elements: Part II—Results," *IEEE Trans. Power App. Syst.*, vol. PAS-100, pp. 103-113, 1981.
- [4] L. R. Rabiner and G. Gold, *Theory and Application of Digital Signal Processing*. Englewood Cliffs, NJ: Prentice-Hall, 1975, ch. 6, section 10.

A Linear Temperature-to-Frequency Converter Using An Integrable Colpitts Oscillator

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Abstract—A novel temperature-to-frequency (T/F) converter using a thermistor has been developed. The resistance of the thermistor is converted into its equivalent inductance to form the resonant circuit of the Colpitts oscillator. To linearize the T/F conversion, two resistors, one in series and the other in parallel with the thermistor, are used and their values are determined so that the resultant resistance, and hence the equivalent inductance, is proportional to the square of a temperature in a specified temperature range.

The conversion sensitivity of 59 Hz/°K and the residual nonlinearity less than 2.85 percent over the temperature range from 253 to 333°K are obtained by the prototype converter which oscillates at 6 kHz at 298°K. The minimum detectable temperature variation is estimated to be $\pm 8.5 \times 10^{-3}$ °K. The power dissipation in the thermistor is quite low, being 28 μ W at 273°K and 23 μ W at 323°K. The proposed converter, except for the thermistor, can be fabricated in monolithic IC form.

I. INTRODUCTION

THE digital process control made possible by the spread of microprocessors requires transducers with digital outputs. This is true of a low-cost temperature measuring system using a thermistor. Several methods are available for converting the temperature-sensitive resistance into the digital form [1], [2], but the relaxation oscillator which incorporates the thermistor into the frequency determining network is most common [3]–[5]. This type of temperature-to-frequency (T/F) converter features a simple configuration, but its temperature resolution is poor. This is because the oscillation frequency depends not only on the thermistor resistance, but also on the temperature-sensitive transistor parameters. A large power dissipation in

the thermistor is another factor which limits the sensitivity [6].

A tuned sinusoidal oscillator has better frequency stability than a relaxation oscillator. Therefore, a higher temperature resolution can be expected by replacing the relaxation oscillator with such an oscillator. Based on this concept, a new T/F converter was developed. Two methods are available for controlling the oscillation frequency of a tuned oscillator by the thermistor; one is to apply the voltage across the thermistor to the voltage-controlled oscillator. The other is to convert the thermistor resistance to its equivalent inductance to form the resonant circuit of the oscillator. The latter approach is adopted here, because a wider dynamic range seems possible with a simpler configuration.

The impedance converter is described in Section II. The practical T/F converter and the experimental results are presented in Sections III and IV, respectively. The paper concludes in Section V by suggesting its advantages and application.

II. IMPEDANCE CONVERSION

The gyrators or generalized immittance converters are well-acknowledged circuits for converting resistance into its equivalent inductance [7]. A transfer function approach, however, is used here for the systematic design of the converter [8]–[10].

A block diagram for synthesizing the impedance converter is shown in Fig. 1. Here, R_T is the thermistor resistance and the active two-port marked $T(s)$ is assumed to have an infinite input impedance and a transfer function

$$T(s) = \frac{V_0(s)}{V_i(s)} \quad (1)$$

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Fig. 1. A block diagram for synthesizing the impedance converter.

Fig. 2. Circuit diagrams of impedance converters. (a) The grounded capacitor realization. (b) The floating capacitor realization.

The input current is

$$I_i(s) = [V_i(s) - V_o(s)]/R_T = [1 - T(s)]V_i(s)/R_T. \quad (2)$$

The input impedance of the circuit will be that of an inductance, if

$$\frac{V_i(s)}{I_i(s)} = \frac{R_T}{1 - T(s)} = sL. \quad (3)$$

The transfer function $T(s)$ should be

$$T(s) = 1 - \frac{R_T}{sL}. \quad (4)$$

Equation (4) indicates that the converter can be realized by an integrator and a differential amplifier.

Based on (4), several circuits have been designed for the impedance conversion [10]. Two of them are shown in Fig. 2(a) and (b). In these realizations, the operational transconductance amplifier (OTA) forms, in conjunction with the capacitor C , the integrator while the op amp (OA) forms the differential amplifier. The amplifier marked B is a unity-gain buffer with high-input and low-output impedance. Each circuit presents the simulated inductance L_{eq} given by

$$L_{eq} = \frac{CR_T R_1}{g_m R_2} \quad (5)$$

where g_m is the transconductance of the OTA. Since g_m is proportional to the bias current of the OTA, the simulated inductance L_{eq} is electrically variable. The grounded capacitor configuration in Fig. 2(a) is less sensitive to par-

Fig. 3. The circuit diagram of the T/F converter.

asitic capacitances, but requires matched resistors, while the floating capacitor configuration in Fig. 2(b) does not require the matched resistors. Hence, the latter is used hereafter for the impedance conversion.

The stray capacitance C_p accompanying the thermistor probe and the finite gain-bandwidth product (GB) of the OA introduces a lossy component r_{eq} into the simulated inductance. Modeling the OA gain by $A(s) = GB/s$, one can derive the following expression of r_{eq} :

$$r_{eq} = \omega^2 L_{eq} \left(C_p R_T - \frac{1}{GB} \left(1 + \frac{R_2}{R_1} \right) \right). \quad (6)$$

When the time constant $C_p R_T$ of the thermistor probe is small, r_{eq} becomes negative. This is preferable to the oscillator application.

III. T/F CONVERTER

The circuit diagram of the T/F converter is shown in Fig. 3. The impedance converter described in Section II forms, in conjunction with C_1 and C_2 , the resonant circuit of the Colpitts oscillator. The thermistor resistance is highly sensitive to temperature, and so is the resonant frequency. Two resistors, R_s in series and R_p in parallel with the thermistor R_T , are used to linearize the relation between the temperature and the resonant frequency.

The oscillation conditions are given by

$$\omega_0^2 = \frac{(C_1 + C_2)(R_f R_{ss} g - (R_f + R_{ss})) - C_1 r_{eq}}{L_{eq} C_1 C_2 (R_f R_{ss} g - (R_f + R_{ss}))} \quad (7)$$

$$g R_{ss} = \frac{(C_1 + C_2)}{L_{eq}} ((R_f + R_{ss}) - R_f R_{ss} g) r_{eq} + \frac{C_1}{C_2} \quad (8)$$

where g is the transconductance of the FET. Usually r_{eq} is so small that the terms including it can be neglected. Then, (7) and (8) are simplified to

$$f_0 = \frac{1}{K \sqrt{(R_T + R_s) R_p}} \quad (9)$$

$$g R_{ss} = \frac{C_1}{C_2} \quad (10)$$

where

$$K = 2\pi \left(\frac{CR_1}{g_m R_2} \cdot \frac{C_1 C_2}{C_1 + C_2} \right)^{1/2}. \quad (11)$$

The thermistor resistance R_T at $T^\circ\text{K}$ can be expressed as

$$R_T = R_{T_0} \cdot \exp B \left(\frac{1}{T} - \frac{1}{T_0} \right) \quad (12)$$

where R_{T_0} is the thermistor resistance at the reference temperature $T_0^\circ\text{K}$ and B is a constant depending on the thermistor material. Substituting (12) into (9), one can obtain the explicit expression of the oscillation frequency as a function of temperature

$$f_0(T) = \frac{1}{K} \left[\frac{R_s + R_{T_0} \cdot \exp B \left(\frac{1}{T} - \frac{1}{T_0} \right)}{1 + \frac{R_s}{R_p} + \frac{R_{T_0}}{R_p} \cdot \exp B \left(\frac{1}{T} - \frac{1}{T_0} \right)} \right]^{-1/2} \quad (13)$$

The term in the brackets in (13) represents the resultant resistance of the thermistor-resistor network. Linearization of the frequency $f_0(T)$ against T can be accomplished by selecting R_s and R_p so that the resultant resistance is proportional to the square of the temperature in the specified range. The least square method using a computer may be the best choice for determining the optimum values of R_s and R_p . The oscillation frequency at a given temperature can be adjusted independently as desired by the bias current, and hence by the transconductance g_m , of the OTA.

IV. EXPERIMENTAL RESULTS

A prototype T/F converter was built using 741 OA's and LM13600 OTA. The OTA was biased so that its transconductance g_m is 0.1 mS. The resistance and the B constant of the thermistor used were 134.3 k Ω at 293 $^\circ\text{K}$ and 3290, respectively. For these thermistor parameters and the temperature range from 253 $^\circ\text{K}$ to 333 $^\circ\text{K}$, the optimum values of R_s and R_p were found to be 51 k Ω and 1 M Ω , respectively. The other circuit elements were: $C = C_1 = C_2 = 1$ nF, $R_1 = R_2 = 10$ k Ω , $R_f = 24$ k Ω , $R_{ss} = 1.6$ k Ω , and $R_{DD} = 2$ k Ω . Fig. 4(a) and (b) show the typical oscillation waveform and its spectrum. A sinusoidal waveform with low harmonic distortion can be seen. The relation between frequency and temperature was measured in the specified range. The result is plotted in Fig. 5, indicating that the conversion sensitivity is 59 Hz/ $^\circ\text{K}$ and the linearity error is less than 2.85 percent. This sensitivity is 1.5 to 6 times higher than those of the T/F converters reported so far [1], [2].

The frequency stability of the oscillator itself was also measured by replacing the thermistor with a fixed resistor. The value of a fixed resistor was then so chosen that the oscillation frequency range agreed with that of the T/F converter. The result is shown in Fig. 6. The stability is found to be $10^{-3}/^\circ\text{K}$, which is 2 times worse than that of a conventional Colpitts oscillator. When the OA was used

(a)

(b)

Fig. 4. (a) Experimentally observed oscillation waveform. Horizontal scale: 0.1 ms/div. Vertical scale: 1 V/div. (b) The frequency spectrum of (a). Horizontal scale: 5 kHz/div. Vertical scale: 10 dB/div.

Fig. 5. The oscillation frequency versus temperature of the T/F converter.

Fig. 6. The frequency stability of the Colpitts oscillator.

in place of the OTA to form the integrator in the impedance converter, frequency stability comparable to that of a conventional Colpitts oscillator was obtained. Therefore, the poor stability of the present circuit was attributed to the variation of the transconductance g_m of the OTA.

The frequency drift of the oscillator itself was also measured by operating it for a few hours at a constant temperature. The measured drift was ± 0.5 Hz. Thus the minimum detectable temperature variation of the converter can be estimated to be $\pm 8.5 \times 10^{-3}^\circ\text{K}$.

The power dissipation in the thermistor was $28 \mu\text{W}$ at 273°K and $23 \mu\text{W}$ at 323°K . Since the internal power dissipation is quite small, the self-heating problem in the thermistor is eliminated.

V. CONCLUSIONS

A new T/F converter based on the inductance simulation was described. It features very high temperature resolution and small power dissipation in the thermistor. Furthermore, the whole circuit, except for the thermistor, can be fabricated in a monolithic IC form by scaling the component values. As a low-cost and precise temperature measuring device, the proposed converter can be applied to chemical process controllers, air conditioners, refrigerators, and even to conventional and clinical thermometers. Because of the sinusoidal output, remote sensing is also possible.

REFERENCES

- [1] B. Sundqvist, "Simple, wide range, linear temperature-to-frequency converters using standard thermistors," *J. Phys. E: Sci. Instrum.*, vol. 16, pp. 261-264, 1983.
- [2] B. Ž. Djordjevich, "Wide range temperature/frequency converter," *Electron. Lett.*, vol. 12, pp. 627-628, Nov. 1976.
- [3] M. Ikeuchi, T. Furukawa, and G. Matsumoto, "A linear temperature-to-frequency converter," *IEEE Trans. Instrum. Meas.*, vol. IM-24, pp. 233-235, Sept. 1975.
- [4] S. Natarajan, "Widely linear temperature-to-frequency converters," *IEEE Trans. Instrum. Meas.*, vol. IM-24, pp. 235-239, Sept. 1975.
- [5] D. Stanković and J. Elazer, "Thermistor multivibrator as the temperature-to-frequency converter and as a bridge for temperature measurement," *IEEE Trans. Instrum. Meas.*, vol. IM-26, pp. 41-46, Mar. 1977.
- [6] A. A. Khan and R. SenGupta, "A new approach to reducing power dissipation in the thermistor probe for temperature/frequency converter based on astable multivibrator," *IEEE Trans. Instrum. Meas.*, vol. IM-31, pp. 278-279, Dec. 1982.
- [7] G. C. Temes and J. W. Lapatra, *Introduction to Circuit Synthesis and Design*. New York: McGraw-Hill, 1977.
- [8] T. S. Rathore and B. M. Singhi, "Network transformation," *IEEE Trans. Circuits Syst.*, vol. CAS-27, pp. 57-59, Jan. 1980.
- [9] J. A. Nossek and G. C. Temes, "Switched-capacitor filter design using bilinear element modeling," *IEEE Trans. Circuits Syst.*, vol. CAS-27, pp. 481-491, June 1980.
- [10] W. S. Chung and K. Watanabe, "Active-RC circuit synthesis for the simulation of a grounded inductor," *Electron. Lett.*, vol. 20, no. 14, pp. 610-612, July 1984.