

AN INHERENTLY LINEAR TRANSDUCER USING THERMAL SIGMA-DELTA MODULATOR

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Abstract – The aim of this article is to describe a feedback circuit with thermoresistive sensor based on thermal sigma-delta modulator. The circuit uses 1-bit first order sigma-delta modulator in which a considerable part of conversion functions is performed by the sensor. This transducer circuit is able to measure digital physical quantities that interact with the sensor: temperature, thermal radiation and fluid velocity. In this study, it is used to measure environment temperature, on which digital output is linearly dependent. Equations that support circuit behaviour, simulation results and experimental results are shown. Two architectures are presented, one completely analogue and other with some parts digitally implemented using microcontroller. In addition, it is presented a thermal radiation architecture version in which digital output is intrinsically linear to the thermal radiation measure.

Keywords: sigma-delta modulation; temperature transducer; thermal radiation transducer

1. INTRODUCTION

Negative feedback system configurations with thermoresistive sensor using the power balance principle have been employed in measurement of thermal radiation, H [1], fluid velocity, U [2], and temperature, T_a [3]. Constant temperature is the most used method, in which the sensor is heated by Joule effect to a chosen temperature and the thermal radiation (or fluid velocity, or temperature) variation is compensated by a change in electrical heating due to the negative feedback employed. Thus the sensor is kept at an almost constant temperature.

Some configurations to implement a measurement system with a sensor heated to a constant temperature have been studied. The most usual is the configuration that uses a Wheatstone bridge with the sensor in one of its branches [4]. It was observed that in that configuration, the relation between the output signal and input physical quantity was not linear.

Another attractive possibility is the use of sigma-delta configurations [5], in which the sensor is a part of the feedback loop. One-bit sigma-delta modulation is already a feedback configuration in which output signal is an oversampled version of the analogue input signal [6].

Sigma-delta modulator has been employed in signal processing to convert an analogue quantity to a digital quantity using simple analogue circuitry. Sigma-delta converters were recognized to be robust and to have high performance A/D converters.

This work presents a temperature circuit meter composed of a one-bit sigma-delta modulator in which some of its block functions are performed by the thermoresistive sensor itself. This architecture idea is presented with simulation results in [7] for thermal radiation measurement. The result from circuit simulation and some experiments for environment temperature measurement are presented in this study. It was used one version with discrete components and an analogue filter; and other version with some parts digitally implemented by using microcontroller and digital filter. It will be also shown the thermal radiation circuit version in which digital output is also intrinsically linear with the thermal radiation measure.

2. TEMPERATURE METER

2.1. Circuit Topology

The circuit in Fig. 1 depicts a sigma-delta modulator. The sum and integration functions were replaced by a negative temperature coefficient sensor (NTC sensor) which operated at constant temperature T_{s0} .

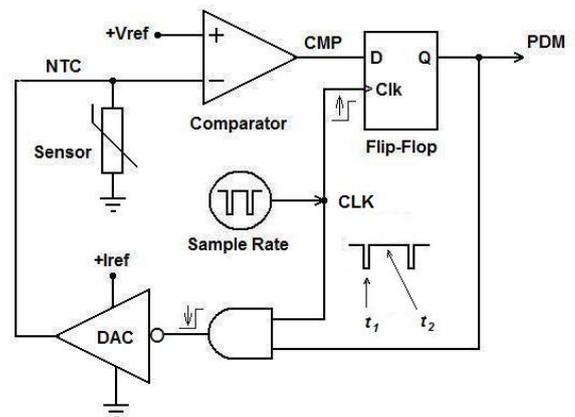


Fig. 1. Proposed circuit topology.

In this circuit, V_{ref} is the sensor voltage when it is operating at reference temperature T_{s0} . The *PDM* (Pulse Density Modulation) signal at flip-flop output is an oversampled digital version of *CMP* signal at comparator output, and *NTC* is the voltage between sensor terminals. *PDM* signal is level “1” when sensor temperature is greater than T_{s0} and level “0” when sensor temperature is less than T_{s0} . This signal is used to estimate environment temperature after filtering. It also feeds the digital to analogue current converter (*DAC*) at modulator feedback path to maintain the sensor temperature constant.

When the *PDM* signal is level “1”, the sensor needs to be cooled so a slight current pulse with amplitude I_{ref} , period $t_1 + t_2$ and width t_1 is generated at sensor terminal by the *DAC* and the sensor is cooled by dissipation. On the other hand, when the *PDM* signal is level “0”, the sensor needs to be heated so a pulse current with amplitude I_{ref} , period $t_1 + t_2$ and width $t_1 + t_2$ is generated at sensor terminal by the *DAC* and the sensor is heated by Joule effect.

The environment temperature variation is obtained by sensor resistance variation, which is proportional to the voltage at sensor terminals. If the medium peak voltage at sensor terminals is maintained constant at V_{ref} value (Fig.1), the medium sensor resistance is maintained constant at V_{ref}/I_{ref} . Consequently, sensor temperature is also maintained constant.

2.2. Circuit Analysis

The circuit from Fig. 1 is able to maintain sensor temperature constant and to provide a pulse density modulated power to the sensor. In steady state, the electric power provided to the sensor is given by [7]:

$$P_i = G_{th}(T_{s0} - T_a) \quad (1)$$

In which T_a is the environment temperature and G_{th} is the sensor thermal conductance.

When the environment temperature is equal to T_{min} the power provided to the sensor is (Fig. 2):

$$P_{max} = G_{th}(T_{s0} - T_{min}) \quad (2)$$

When the environment temperature is equal to T_{max} the power provided to the sensor is:

$$P_{min} = G_{th}(T_{s0} - T_{max}) \quad (3)$$

In which T_{max} and T_{min} are the environment temperature limits to be measured.

The maximum power provided to the sensor is given by:

$$P_{max} = V_{ref} I_{ref} \quad (4)$$

The minimum power provided to the sensor is given by:

$$P_{min} = P_{max} \left(\frac{\rho_t}{\rho_t + 1} \right) \quad (5)$$

In which $\rho_t = t_1/t_2$ and $t_1 + t_2$ is the oversampling period.

From (2), (3) and (5):

$$T_{s0} = T_{max} + \rho_t \Delta T \quad (6)$$

$$P_{max} = G_{th} \Delta T (\rho_t + 1) \quad (7)$$

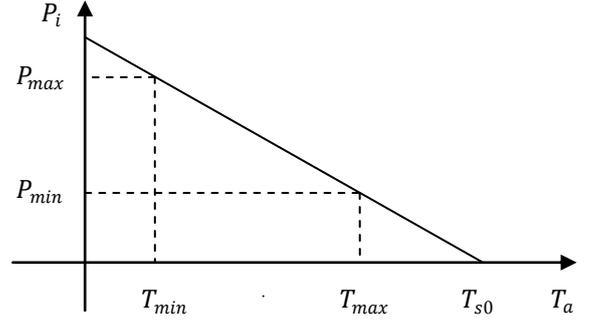


Fig. 2. Electric power provided to the sensor versus environment temperature in steady state.

In which, $\Delta T = T_{max} - T_{min}$

The voltage in sensor terminals is given by:

$$V_{ref} = I_{ref} R_{s0} \quad (8)$$

From (4), (7) e (8):

$$V_{ref} = \sqrt{G_{th} \Delta T (\rho_t + 1) R_{s0}} \quad (9)$$

$$I_{ref} = \sqrt{G_{th} \Delta T (\rho_t + 1) / R_{s0}} \quad (10)$$

V_{ref} and I_{ref} are dependent on sensor characteristics, environment temperature range, sensor operation point (R_{s0}, T_{s0}) and the relation between t_1/t_2 .

2.3. Linearity

The objective here is to establish relationship between medium output transducer signal and environment temperature.

The electrical power given to the sensor is (Fig. 1):

$$P_{NTC} = I_{ref} V_{ref} (1 - CLK.PDM) \quad (11)$$

In which the *AND* function was substituted by the product *CLK.PDM* and the *NOT* function by the subtract operation.

Waveforms obtained from those signals can be observed in Fig. 5.

The medium value in both sides of (1) is obtained by:

$$P_i = P_{max} (1 - \overline{pdm_c} \overline{pdm}) \quad (12)$$

In which P_i is the medium power given to the sensor in other to maintain the sensor at constant temperature, $\overline{pdm_c}$ is a constant and \overline{pdm} represents the medium normalized clock signal value and \overline{pdm} is the medium normalized output signal which is dependent on environment temperature.

Substituting (1) and (7) in (12) we have:

$$T_{s0} - T_a = \Delta T (\rho_t + 1) (1 - \overline{pdm_c} \overline{pdm}) \quad (13)$$

In accordance with Fig. 1 we obtain:

$$\overline{pdm_c} = \frac{1}{\rho_t + 1} \quad (14)$$

Substituting (14) in (13):

$$T_{s0} - T_a = \Delta T(\rho_t + 1) \left(1 - \frac{\overline{pdm}}{\rho_t + 1}\right) \quad (15)$$

Substituting (6) in (15):

$$T_{max} + \rho_t \Delta T - T_a = \Delta T(\rho_t + 1) \left(1 - \frac{\overline{pdm}}{\rho_t + 1}\right) \quad (16)$$

Finally:

$$T_a = T_{min} + \Delta T \overline{pdm} \quad (17)$$

Equation (17) shows that the medium output circuit signal has an intrinsic linear relationship with the measurand which, in this case, is the environment temperature.

This linearity has no sensor or circuit parameter dependency and is valid for any temperature in the range between T_{min} and T_{max} . With the defined environment temperature range, we only need to calculate V_{ref} and I_{ref} values with (9) and (10), fit those values to the circuit and the medium circuit output, obtained using a low-pass filter, will obey (17).

2.4. Verification Circuit

The proposed circuit was implemented using discrete components and the *NTC* sensor. The same circuit was simulated in a circuit simulator using the same conditions of the implemented circuit.

Fig. 3 shows the *DAC* circuit, a constant current generator that can drive transistor T_1 current to the output (sensor terminal) or to ground depending on the input signal.

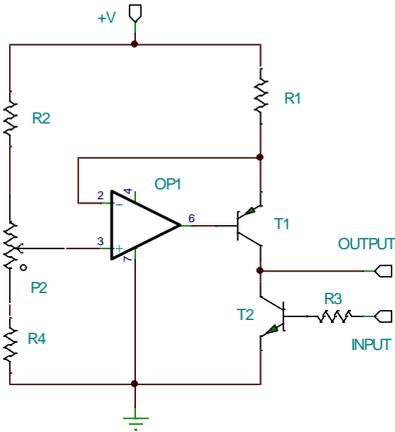


Fig. 3. Digital to analogue current converter.

Some simulated results can be observed in Fig.4 and Fig.5.

Figure 4 shows transient and steady state of signals: *CMP* (comparator output), *NTC* (sensor voltage) and *PDM* (modulator output digital voltage) (Fig. 1).

During 5 sec, *PDM* signal remains in zero voltage commanding the sensor to initial heating. When the sensor reaches T_{s0} , the *PDM* signal alternates to maintain sensor temperature at the constant value T_{s0} .

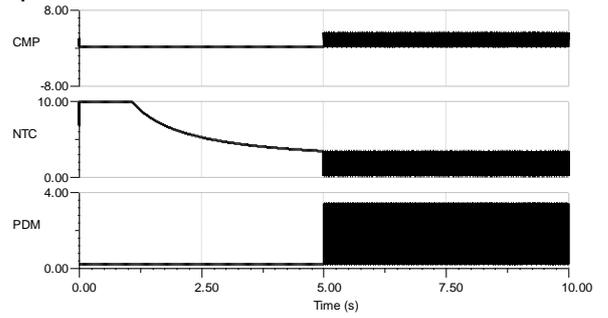


Fig. 4. Transient and steady state *CMP*, *NTC* and *PDM* signals.

Figure 5 shows a zoom in Fig. 4 from 9.05 sec to 9.10 sec. The *CMP* signal shows the progressive sensor cooling during each sample time while the *PDM* signal is kept at level “1”. When the *PDM* signal is level “0” the *CMP* signal shows the continuous sensor heating.

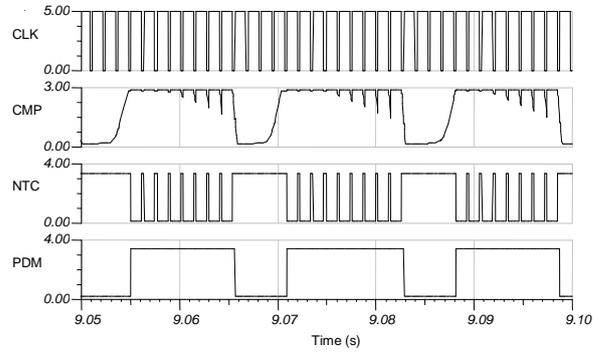


Fig. 5. Steady state *CMP*, *NTC* and *PDM* signals.

Test conditions:

NTC sensor characteristics:

$$A = 0.01366 \Omega \quad B = 3334 \text{ K}$$

$$C_{th} = 10.73 \text{ mJ/K} \quad G_{th} = 0.841 \text{ mW/K}$$

Environment temperature range:

$$T_{min} = 0.0 \text{ }^\circ\text{C} \quad T_{max} = 68.6 \text{ }^\circ\text{C}$$

Sensor steady state operation point:

$$T_{s0} = 83.4 \text{ }^\circ\text{C} \quad R_{s0} = 163.3 \Omega$$

Oversampling frequency:

$$F_s = 755 \text{ Hz} \quad \rho_t = t_1/t_2 = 21.5\%$$

$$V_{ref} = 3.38 \text{ V} \quad I_{ref} = 20.69 \text{ mA}$$

The medium value of *PDM* signal at filter output was measured with a 6 1/2 digits voltmeter and 0.0035% basic DC accuracy.

The experimental tests were done with the *NTC* sensor near the sensor element of a 4 1/2 digits thermometer with 0.01°C of accuracy together in a laboratory heater. The heater was kept at constant temperature by a controller.

An analogue Butterworth filter with 60 dB/decade of attenuation in rejection frequency band and cut-off frequency of 1 Hz was used to obtain medium value of *PDM* signal due to implementation and test facilities.

Figure 6 shows the linearity between circuit simulation results and experimental results.

Linearity between environment temperature and medium *PDM* signal was 100% in simulated circuit results and 99.93% in experimental circuit results.

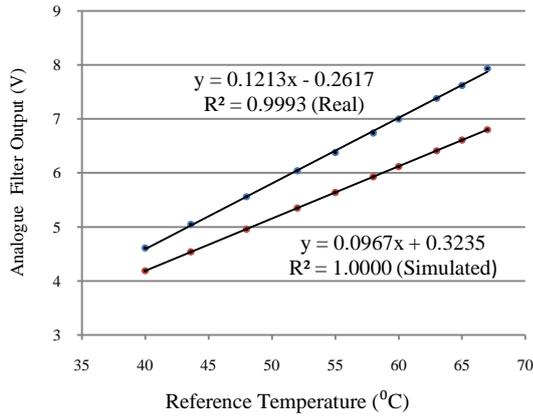


Fig. 6. Analogue filter output voltage versus environment temperature.

3. PROPOSED TRANSDUCER USING DSP

A digital filter and a *LCD* display were joined to the circuit of Fig. 1 resulting in the circuit of Fig. 7. Every function is shown on the right side of the dotted line (except for the *LCD* display) was implemented using the *TMS320F2812 DSP* [9]. The *DAC*, on the left side of the dotted line, was implemented with the circuit of Fig. 3.

This implementation was done in order to validate the theoretical approach and the following step would be the implementation of this circuit in a mixed integrated circuit.

A decimator and a Blackman window low-pass digital filter [10] with cut frequency at 50 mHz were implemented using the *DSP* to obtain the medium value of *PDM* signal. The medium value of *PDM* signal at filter output was observed using a *LCD* display.

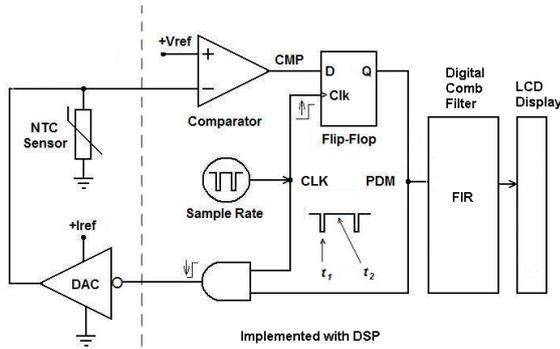


Fig. 7. Circuit with a microcontroller.

Test conditions:

NTC sensor characteristics:

$$A = 0.01366 \Omega \quad B = 3334 \text{ K}$$

$$C_{th} = 10.73 \text{ mJ/K} \quad G_{th} = 0.841 \text{ mW/K}$$

Environment temperature range:

$$T_{min} = 33.6 \text{ }^\circ\text{C} \quad T_{max} = 82.7 \text{ }^\circ\text{C}$$

Sensor steady state operation point:

$$T_{s0} = 88.7 \text{ }^\circ\text{C} \quad R_{s0} = 137.1 \Omega$$

Oversampling frequency:

$$F_s = 1000 \text{ Hz} \quad \rho_t = t_1/t_2 = 11.1\%$$

$$V_{ref} = 2.70 \text{ V} \quad I_{ref} = 19.70 \text{ mA}$$

The experimental tests were carried out with the *NTC* sensor near the sensor element of a 4 ½ digits thermometer with 0.01°C of accuracy together in a laboratory heater. The heater was kept at constant temperature by a controller.

Figure 8 shows the linearity obtained with this approach. Linearity between environment temperature and medium *PDM* signal was 99.98%.

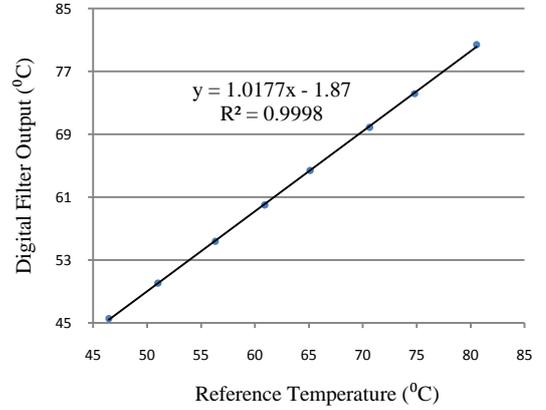


Fig. 8. Digital filter output versus environment temperature.

4. THERMAL RADIATION MEASUREMENT

The idea to measure thermal radiation is to use the circuit of Fig. 1 in a differential format with two sensors. One sensor will be able to measure thermal radiation and surrounding temperature, the other sensor will be protected from thermal radiation and will measure surrounding temperature. This architecture is shown in Fig. 9.

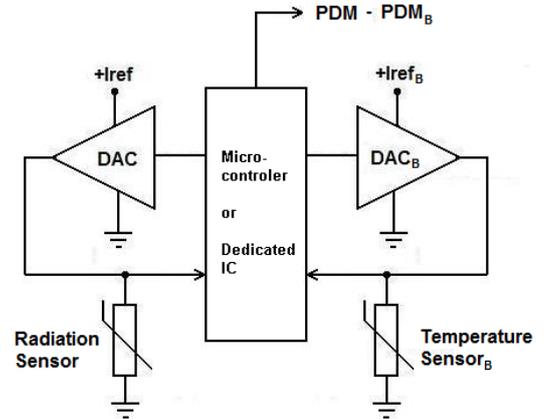


Fig. 9. Proposed circuit for thermal radiation measurement.

Sensor behavioural, under thermal radiation and surrounding temperature must be modelled by [1]:

$$P_i + A_{th}H = G_{th}(T_s - T_a) + C_{th} \frac{dT_s}{dt} \quad (18)$$

In which, $A_{th} = \alpha S$, α is the absorb thermal radiation coefficient, S is the sensor surface area and H is the thermal radiation.

As the sensor operates at constant temperature in this case, (18) can be written as:

$$P_i + A_{th}H = G_{th}(T_s - T_a) \quad (19)$$

Substituting (7), (12) and (14) in (19):

$$G_{th}\Delta T(\rho_t + 1)\left(1 - \frac{\overline{pdm}}{\rho_t + 1}\right) + A_{th}H = G_{th}(T_s - T_a) \quad (20)$$

Supposing that both sensors were submitted to the same surrounding temperatures to operate in the same temperature range, and protect them from forced thermal conduction (reminder: the sensor B in Fig. 9 is protected from thermal radiation) (17) can be used in (20). After simplifications, H can be expressed by:

$$H = \frac{G_{th}\Delta T}{A_{th}}(\overline{pdm} - \overline{pdm}_B) \quad (21)$$

Equation (21) shows that thermal radiation to be measured is intrinsically linear with the difference of the medium of the two PDM signals at modulator output and that the sensors parameters do not need to be the same to guarantee the linearity of this architecture.

As PDM and PDM_B signals are at the same oversampling frequency, thermal radiation can be expressed also by:

$$H = \frac{G_{th}\Delta T}{A_{th}}(\overline{pdm} - \overline{pdm}_B) \quad (22)$$

Equation (22) shows that there is no need to filter the two PDM signals but only the difference between them using one filtering routine.

Equation (21) shows that the maximal thermal radiation that can be measured happens when $\overline{pdm} = 1$ and that it is dependent on the surrounding temperature and the worst case happens when the surrounding temperature is equal to $T_{a(max)}$.

$$H_{max} = \frac{G_{th}}{A_{th}}(T_{max} - T_{a(max)}) \quad (23)$$

5. CONCLUSIONS

We presented a circuit architecture based on sigma-delta modulation applied to environment temperature and thermal radiation measurements. This circuit architecture can be extended to fluid velocity measurement.

The thermal sigma-delta transducer circuit for environment temperature application measurement was implemented to validate the architecture. The linear relationship between environment temperature or thermal radiation and the average signal value at the thermal sigma-delta output was demonstrated by (17) and (22).

The methodology for sensor reference voltage and sensor reference current calculations was developed for any temperature range supported by the sensor. The thermal sigma-delta architecture topology applied to thermal radiation measurement was theoretically developed.

The experimental results show the intrinsic linearity between variable to be measured and circuit response. Thus they are in accordance with the simulation results and the

developed theory in the case of surround temperature measurement.

This architecture, based on sigma-delta modulation, has the advantage of transforming the physical greatness directly to digital form, without the need to pass it through intermediate voltage or current value. In addition, the analogue part of this architecture is easy to implement in an integrated circuit because it is reduced to the sensor polarization circuit and a comparator circuit. Another advantage is the linear relationship between the measure variable and the estimated greatness for the thermal radiation and temperature meter cases.

The disadvantage of this architecture is that the resolution is poor, given that it is based on a first order sigma-delta architecture [8]. To obtain better resolution it is necessary to use a high oversampling rate or thermal sigma-delta architecture of higher order.

The power consumed by the circuit to maintain sensor temperature above environment temperature is another disadvantage.

The improvement suggestions would be: a) the proposed thermal sigma-delta architecture circuit implementation for thermal radiation application; b) a study on thermal sigma-delta architecture of higher order in order to improve resolution; c) a study about others sensors to improve frequency response and d) to implement thermal sigma-delta architecture using integrated mixed circuit technology.

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