Sensorless Temperature Measurement Based on ADC Input Noise Measurement

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***Abstract*—All published temperature sensors convert temperature into an intermediate signal from which temperature is extracted. Nonlinearity is introduced in all steps. Researchers have focus on improve accuracy of temperature measurement, which makes the circuit more and more complicated. This paper develops a new method for measuring temperature based on thermal noise measurement. Input noise of a low resolution ADC is measured in digital domain, in which little nonlinearity is introduced. Profit from inherently proportional relation between noise and temperature, the method has very good linearity. The method has been validated by MATLAB simulations.**

I. INTRODUCTION

Requirement of integrated smart temperature sensor is growing in applications such as die temperature and power consumption control and environment temperature monitor and control. Starting from bipolar technology, on chip temperature sensors have been built based on temperature dependent characteristics of the PN junction and resistors. After CMOS technology becoming more popular, researchers have focused on parasitic, lateral or substrate bipolar transistors in CMOS process [1-3]. Some temperature sensors have been built based on temperature dependence of two main parameters of MOS transistor, threshold voltage and mobility [4]. In addition, ring oscillator based temperature sensor and time to digital converter based temperature sensor are also reported in literatures [5, 6].

All reported approaches attempt to measure die temperature in three steps. Firstly, a sensing element generates an electrical signal (voltage, current, impedance, delay, frequency, and so on) that carries temperature information. Then a data acquisition element captures the electrical signal. Finally, temperature information is extracted from the captured signal. All three steps are inherently nonlinear due to nonideality of silicon devices. In order to overcome the nonlinearity, techniques have been proposed to increase linearity such as trimming, calibration, offset cancellation, dynamic element matching, etc [1, 7]. All these techniques make circuit more complicated and expensive.

In the area of very accurate thermodynamic temperature measurement, Johnson noise thermometry (JNT) is widely used to measure temperature. The technique is based on measurement of thermal noise of a resistor which is proportional to the absolute temperature. Once thermal noise is accurately measured and characterized, an intrinsically linear temperature measurement is obtained. This opens up the door to significantly improve the accuracy and area efficiency of on-die temperature measurement.

This paper develops a novel methodology for measuring temperature based on noise measurement. No sensing element or extraction will be needed. The input referred noise of a low resolution ADC is computed from its digital output codes. Most tasks are carried out in digital domain so that little nonlinearity will be introduced. The ADC speed is set to be much higher than the refresh speed of temperature so that enough number of points can be sampled for noise computation. The ADC conversion speed is set to be 50MS/s which is not difficult to be realized for 4 or 5 bits resolution. The characteristic that temperature changes slowly is also used to improve the measurement accuracy.

The rest of this paper is organized as following. In Section II, the architecture of the temperature measurement is described. In Section III, methods of efficiently and accurately measuring noise power are discussed. To further improve measurement accuracy from the same number of points, a 1^{st} order digital lowpass filter is applied to measurement results. MATLAB simulation results are given in Section IV.

II. MEASURING TEMPERATURE FROM NOISE

Noise exists in all electronic devices. In an integrated ADC, resistor thermal noise, MOS transistor channel noise, and flicker noise are key contributors of input referred noise. The thermal noise is shown by (1), where k is the is the Boltzmann constant, T is absolute temperature, Δf is the interested bandwidth, R is the resistor value. From (1), we can see that no matter how the noise is generated, the noise power is always proportional to absolute temperature. This relation indicates that measurement of temperature is intrinsically linear if noise can be measured accurately.

$$\overline{V_n^2} = 4kT\Delta f \cdot R \tag{1}$$

In temperature sensors that have been published, temperature is converted into an intermediate signal such as current, voltage, time, etc. Then the intermediate signal is processed and converted into digital signal which provides

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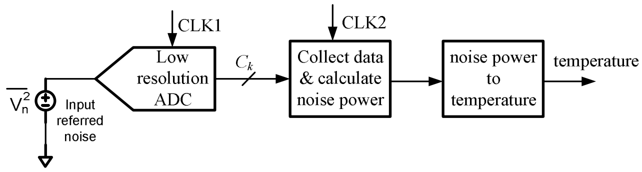


Fig.1. Diagram of temperature sensor

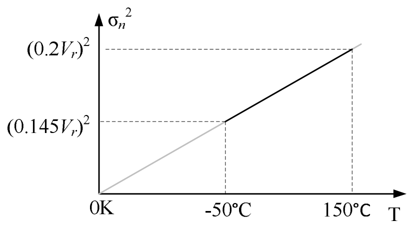


Fig.2. Relation of noise power and temperature

temperature value. From real temperature to measured temperature, all processes are nonlinear. First, sensing cell converts temperature to intermediate signal nonlinearly. And then the intermediate signal is processed nonlinearly.

In the noise measurement based architecture, input referred noise of an ADC is directly measured in digital domain. Therefore no nonlinearity is introduced at all. Fig.1 shows block diagram of this new architecture. First, a low resolution ADC converts the noise into digital signal. 4 or 5 bits ADC is enough for converting noise into digital signal. To achieve small area and low power, SAR ADC is a good choice. The noise $\overline{V_n^2}$ not only stands for noise from the ADC but also from other parts, and even is generated intentionally. Since noise variance is a statistical variable, it is computed after collecting a number of output codes. The computation can be real-time so that large memory is not needed. Clock of ADC CLK1 has higher frequency than CLK2 number of collected output codes is large enough for accurate noise variance computing.

The relation between noise power and temperature is expressed in a general formula (2).

$$\sigma_n^2 = \beta \cdot (T + 273) \tag{2}$$

In (2), σ_n^2 is the noise variance and also noise power, β is a parameter determined in design, T is Celsius temperature. Assume reference voltage of the ADC is ±Vr, and the interested temperature range is from -50°C to 150°C which is enough for most applications. In order to avoid clipping, circuits can be designed so that σ_n changes from $0.145V_r$ to $0.2V_r$ when temperature changes from -50°C to 150°C. The probability of noise voltage exceeds input range of ADC is so small that it will not affect noise measurement.

The temperature needs to be measured changes with the power consumed by circuit which can be monitored by other circuit. The relation between temperature and power consumption can be expressed by (3).

$$C_{th}\frac{dT(t)}{t} = -R_{th}\left(T(t) - T_{amb}\right) + P_i(t) \tag{3}$$

in which $P_i(t)$ is the power consumption at time t, $T(t)$ is the temperature, T_{amb} is the ambiance temperature, C_{th} is , and R_{th} is . Assume the power consumption is

$$P_i(t) = A\sin(\omega t) \tag{4}$$

The solution of (3) is (5) which relate temperature to power consumption.

$$T(t) = T_{amb} + \frac{A\left(R_{th}\sin(\omega t) - \omega C_{th}\cos(\omega t)\right)}{\omega^2 C_{th}^2 + R_{th}^2} \tag{5}$$

III. Accurate Measurement of Noise

Assume temperature within -50˚C and 150˚C needs to be measured at 0.2˚C level, which is about 10-bit accuracy. From the relation between noise power and temperature, the noise variance should also be measured at 10-bit accuracy. When M samples are collected and used to estimate the noise variance, the estimated variance value is

$$\hat{\sigma}_n^2 = \frac{1}{M-1}\sum_{i=1}^{M} y_i^2 - \frac{M}{M-1}\bar{y}^2 \tag{6}$$

in which y_i is the i^{th} sample of noise voltage. $\hat{\sigma}_n^2$ is also a random variable, and its expected value is the true noise variance. Standard deviation of $\hat{\sigma}^2$ is

$$std\left(\hat{\sigma}_n^2\right) = \sqrt{\frac{2}{M-1}}\sigma_n^2 \tag{7}$$

To achieve 10-bit accuracy and 1-σ yield, the following condition should be satisfied.

$$\sqrt{\frac{2}{M-1}} \le \frac{1}{2^{10}} \tag{8}$$

From (8), M should be larger than 2097153. If the temperature needs to be measured every 1ms, the sampling speed needs to be 2GS/s which is difficult to be realized with low cost. The required number of samples is too large to be realized. A method making use of low frequency characteristic of temperature will be introduced to reduce the required number of samples.

The input noise variance is computed from digital output codes of the ADC. There are three simple methods to calculate noise variance. The first one is given by (9)

$$\hat{\sigma}_n^2 = \frac{1}{M}\cdot\sum_{k=1}^{M} C_k^2 - \left(\frac{1}{M}\cdot\sum_{k=1}^{M} C_k\right)^2 \tag{9}$$

The second one is given by (10)

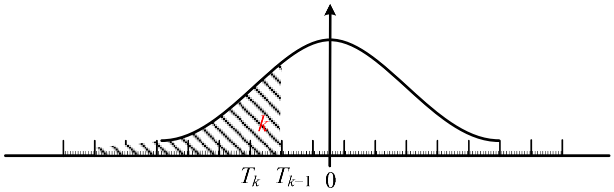


Fig.3. Probability of output equal to *k*

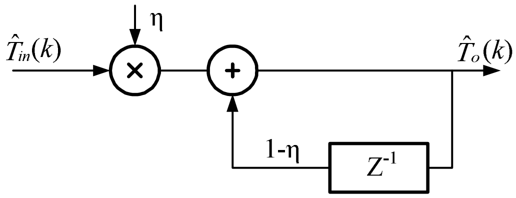


Fig.4. 1st order filter for temperature

$$\hat{\sigma}_n^2 = \sqrt{\frac{\pi}{2}} \cdot \overline{|C_k|} \tag{10}$$

The third one is based on the Gaussian distribution of noise. Fig.3 shows the distribution of output codes of ADC when noise is the only input. The total number of samples is M, from the input noise distribution, the probability of output code smaller than k+1 is

$$P_k = \frac{1}{2}\left[1 + erf\left(\frac{T_k}{\sigma\sqrt{2}}\right)\right] \tag{11}$$

This probability can be also calculated from M samples

$$\hat{P}_k = \frac{H_k}{M} \tag{12}$$

In which H_k is the number of codes that smaller than k. From (11) and (12), the input noise variance can be expressed by (13)

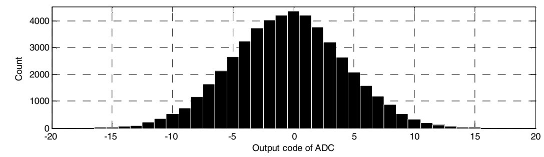
$$\hat{\sigma}_n^2 = \frac{T_k^2}{2erf^{-1}\left(2\frac{H_k}{M} - 1\right)^2} \tag{13}$$

All three method of calculating noise variance have the same accuracy which is only determined by number of samples. But the number given by (8) is too large to be realized on chip. Usually, temperature changes very slowly, which means the output of temperature sensor is low frequency signal. Based on this information, we can apply a low pass filter to the measured temperature. As shown in Fig.4, the temperature which is calculated measured noise variance $\hat{\sigma}_n^2(k)$ is filtered and the output value is determined by both the new value and previous results. The filtered temperature is given by (11), in which η filter factor. The smaller η is, the more temperature is determined by previous results.

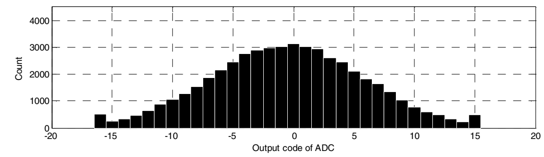
$$\hat{T}_o(k) = (1-\eta)\cdot\hat{T}_o(k-1) + \eta\cdot\hat{T}_{in}(k) \tag{14}$$

In order to achieve accurate measurement with smaller number of samples, we want η to be small. But small η makes the filter lag so that another error appears in estimated noise variance while estimation variance decreases. Fortunately, this error caused by heavy filter is deterministic and can be compensated. According to the temperature model given by equation (5), error due to filter lag can be expressed by (15). Values of coefficients a1, a2, and a3 can be calculated according to the temperature model which is combination sine and cosine function.

$$\hat{T}_{in}(k) - \hat{T}_o(k) = a_1(1-\eta)^k + a_3\cos(\omega_0 k) + \left(a_3\cos(\omega_0) + a_2\right)\frac{\sin(\omega_0 k)}{\sin\omega_0} \tag{15}$$



(a). Distribution of output code when temperature is -50°C



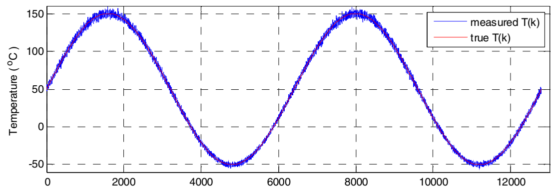
(b). Distribution of output code when temperature is 150°C

Fig.5

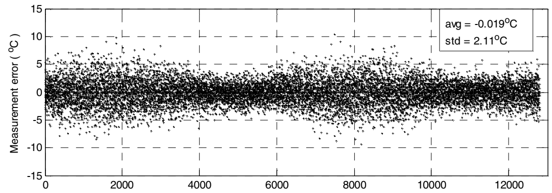
IV. Simulation Results

The new method has been validated by Matlab simulations. Temperature is generated according to the model shown in equation (5). The input noise power is generated according to the relation shown in Fig.2. The coefficient is chosen to be a certain value so that noise standard deviation changes within a range can be easily computed from output code. Fig.5 shows the distribution of ADC output codes when temperature is -50°C and 150°C. The noise power changes within a range so that all codes are activate and a few codes are out of range. The noise variance which is also noise power is computed by comparing distribution of output code to ideal distribution.

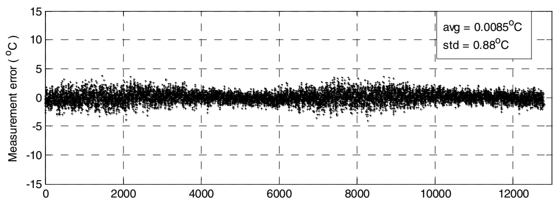
Temperature is generated every 1ms according to (5), so that 50000 points are sampled by ADC and used for measuring the temperature. It is also assumed that the rate of temperature changing is always smaller than 100˚C/s which is reasonable in most applications. Fig.6.a shows the temperature needs to be test which is shown in red curve



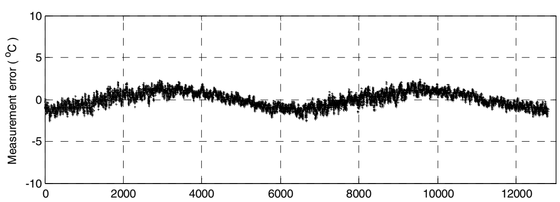
(a). Temperature



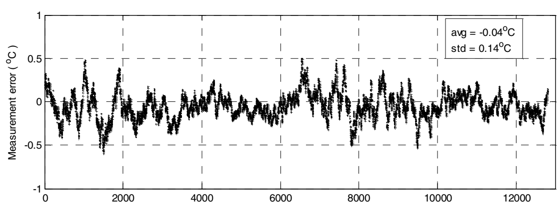
(b). Temperature measurement error



(c). Temperature measurement error after filter (η=0.3)



(d). Temperature measurement error after filter (η=0.1)



(e). Temperature measurement error after filter (η=0.01) and deterministic error compensated

Fig.6

and the measured temperature from ADC output codes which is shown in blue curve. Fig.6.b shows the measurement error, in which we can see that the higher the temperature the larger the error. And the error standard deviation is 2.11˚C.

In order to improve the accuracy, we take the advantage of knowing that temperature changes very slowly. A 1st order digital filter is applied to measured temperature values. The measurement error can be reduced as shown in Fig.6.c. And the error standard deviation is reduced to 0.88˚C. Fig.6.d shows the measurement error when temperature is more heavily filtered which introduces deterministic component. This deterministic component is caused by filter lag which can be compensated by equation (15). Fig.6.e shows the temperature measurement error when η in the filter is set to be 0.01 and deterministic component is removed. From the plot we can see that the standard deviation of temperature measurement inaccuracy is only 0.14˚C.

V. ONCLUSION

Most existing approaches of smart temperature sensor try to convert temperature into an analog intermediate signal and then extract temperature from it. The process is vulnerable to process nonideality so that most researches focus on improve linearity which makes circuit more complicated and expensive. The paper proposes a sensorless temperature sensor based on measuring input noise of a low resolution ADC. Profit from the inherently linear relation between temperature and noise and most tasks are finished in digital, the temperature can be measured very accurately.

REFERENCES

[1] A. Bakker and J. H. Huijing, "Micropower CMOS temperature sensor with digital output", IEEE J. Solid-State Circuits, vol. 31, pp. 933 - 937, 1996.

[2] P. Chen et al., "A Time-Domain SAR Smart Temperature Sensor With Curvature Compensation and a 3σ Inaccuracy of -0.4°C ~ +0.6°C Over a 0°C to 90°C Range", IEEE J. Solid-State Circuits, vol. 45, pp.600 - 609, 2010.

[3] V. Szekely et al., "CMOS temperature sensors and built-in test circuitry for thermal testing of IC's", Sensors and Actuators A, vol. 71, nos. 1–2, pp. 10–19, 1998.

[4] M. K. Law and A. Bermak, "A 405-nW CMOS Temperature Sensor Based on Linear MOS Operation", IEEE Trans. Circuits Syst. II, vol. 56, no. 12, pp. 891–895, Dec. 2009.

[5] B. Dattta and W. Burleson, "Low-Power and Robust On-Chip Thermal Sensing Using Differential Ring Oscillators", pp. 29-32, August 2007 .

[6] P. Chen, C. Chen, C.Tsai, and W. Lu, "A Time-to-Digital-Based CMOS Smart Temperature Sensor", IEEE Journal of Solid State Circuits, vol. 40, pp. 1642-1648, 2005.

[7] M. A. P. Pertijs, K. A. A. Makinwa, and J. H. Huijsing, "A CMOS Smart Temperature Sensor with a 3← Inaccuracy of ±0.1°C From -55 oC to 125 oC," IEEE Journal of Solid-State Circuits, vol. 40, no. 12, pp. 2805–2815, 2005.

[8] E. Isosaari et al., "Thermometry by micro and nanodevices," The European Physical Journal - Special Topics vol:172, pp:323-332, 2009.

[9] L. Callegaro, V. D'Elia, M. Pisani, and A. Pollarolo, "A Johnson noise thermometer with traceability to electrical standards," Metrologia, vol:46, pp:409-415, 2009.