MEANS FOR MEASURING THE THERMAL QUANTITIES

ANALYSIS OF THE STABILITY OF A CMOS TEMPERATURE SENSOR UNDER TEMPERATURE AND POWER-SUPPLY VARIATIONS

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Abstract. The paper considers the problem of stability of CMOS temperature sensors under variations in temperature and supply voltage. A critical analysis of existing methods (SPICE modeling, PTAT/CTAT models, Monte Carlo analysis, calibration, and statistical approaches) is performed, and their limitations are identified, in particular, insufficient consideration of nonlinear effects, noise, and the multifactorial influence of external conditions. A mathematical model is proposed taking into account linear, quadratic, and mixed dependencies, which allows quantitatively assessing the sensitivity and stability of the sensor. The results obtained are of practical importance for creating highly reliable CMOS sensors in industrial, automotive, and aviation applications.

Keywords: Sensor elements; temperature sensitivity; normalized error; multipoint calibration; modeling; statistical analysis; compensation of nonlinearities; measurement reliability.

1. Introduction

The modern development of electronic control, measurement and monitoring systems requires high accuracy and reliability of sensor elements, among which CMOS temperature sensors occupy a special place. Their popularity is due to their low production cost, compatibility with integrated technologies and the possibility of mass application in industrial, automotive, aviation and consumer electronics [1, 6]. However, despite their widespread use, the stability of such sensors remains an urgent scientific problem, since variations in temperature and supply voltage significantly affect the accuracy and long-term reliability of their operation. In contrast, an analysis of modern research shows that existing approaches to assessing the stability of CMOS sensors have a number of limitations: insufficient accuracy over wide ranges of temperatures and voltages, high sensitivity to technological variations, the influence of noise components, as well as limited calibration methods, which are often complex and expensive [4, 9]. In addition, in most studies, scientists consider separately the temperature or power factor, while in real operating conditions, sensors operate in an environment with simultaneous multifactorial disturbances [2, 5]. In view of the above, the task of developing mathematical models and analysis methods that allow for a comprehensive assessment of the impact of temperature and power supply voltage variations on the output characteristics of sensors, quantify their sensitivity and stability, and justify approaches to minimizing errors is quite relevant, as the implementation of such research has important practical significance for increasing the reliability of CMOS sensors in critical applications, where the efficiency and safety of the entire system depend on the accuracy of temperature measurement.

2. Drawbacks

Modern studies devoted to the analysis of the stability of CMOS temperature sensors under temperature and power variations note a number of significant problems that remain open and require further resolution [1-14]. First, a key drawback of modern approaches is the insufficient accuracy of modeling the temperature stability of sensors in a wide range of operating modes [1, 6]. A significant part of the work is focused on the analysis of narrow temperature intervals, while practical applications require predicted operation with significant fluctuations from −40 °C to +125 °C, which complicates the correctness of the assessment [2,5]. Second, the sensitivity of sensors to supply voltage fluctuations remains a serious problem: even minor variations can cause a drift of the output signal, which significantly reduces the stability of the system in industrial and automotive applications [3, 8]. At the same time, most modern analysis methods do not take into account the complex influence of simultaneous changes in temperature and supply voltage, limiting themselves to a separate study of these factors, which does not reflect real operating conditions [3,7]. Another unresolved problem is the presence of technological variations in the manufacturing process of CMOS structures, which cause deviations in parameters between different crystals, even within the same batch [8], which in turn complicates the possibility of building universal models capable of correctly predicting sensor stability. Also, the works [3, 12] indicate insufficient attention on the part of scientists to the influence of noise components, in particular 1/f noise and random telegraph signals (RTS), which are especially critical at low power levels and high accuracy requirements. The analysis presented in modern publications is mostly focused on static characteristics of sensors, while dynamic behavior under rapid changes in operating conditions remains poorly studied. In addition, the current problem is the imperfection of calibration methods: most of them require complex and expensive procedures, and attempts to implement self-calibration often do not take into account the influence of long-term degradation processes of CMOS sensor elements [5]. The lack of standardized approaches to stability assessment also creates difficulties when comparing the results of different studies [6]. Therefore, the current state of analysis of the stability of CMOS temperature sensors under temperature and power variations is characterized by a number of limitations: insufficient complexity of models, sensitivity to technological deviations and noise, limited accuracy of dynamic analysis and lack of unified verification methods. It is these shortcomings that determine promising directions for further scientific research.

3. Goal

The main goal of the study is to carry out a comprehensive analysis of the stability of CMOS temperature sensors under temperature and supply voltage variations, taking into account the multifactorial influence of external and internal factors on their operation. In particular, the study is aimed at building mathematical models that describe the dependence of the sensor output signal on temperature and power, determining the temperature and power sensitivity by calculating the corresponding derivatives, as well as forming quantitative metrics of instability and normalized error for an objective assessment of the sensor reliability.

The implementation of this goal will allow identifying the main sources of errors, determining the limitations of traditional analysis methods, justifying the need to use multi-point calibration, hardware power stabilization and software compensation, which together allow increasing the accuracy and stability of CMOS sensors in industrial and automotive applications.

4. Presentation of the main material

Table 1 presents the results of a review of modern methods for analyzing the stability of CMOS temperature sensors under temperature and power variations.

Table 1. Results of a review of modern methods for analyzing the stability of CMOS temperature sensors under temperature and power variations

Method	The essence of the approach	Strengths	Weaknesses / Disadvantages	Existing problems
SPICE- modeling	Schematic modeling of sensor operation under different conditions	Accurate enough for individual modes; good for preliminary design	Mostly considers either only temperature or only voltage; high computational cost over wide ranges	There is no comprehensive analysis of the simultaneous effects of temperature and power
Analytical models PTAT/CTAT	Using temperature coefficients to predict output signal changes	Simplicity, possibility of quick evaluation; convenient for circuit calculations	Linear approximations do not reflect nonlinear effects; do not take into account noise components	Limited accuracy over a wide range of temperatures and voltages
Monte Carlo analysis	Random variation of parameters for estimating technological deviations	Shows well the statistical effects of process variations	Runs under fixed environmental conditions; high computational load	Lack of comprehensive consideration of "temperature + power"
Calibration (single and multi-point)	Correction of output characteristics after sensor manufacturing	Ability to improve accuracy	Expensive and complex procedures; dependent on aging elements; limited long-term effectiveness	The need for simpler self-calibration methods that take into account degradation
Statistical analysis of measured data	Using experimental data from a group of sensors to assess stability	Allows you to evaluate average trends	Does not provide accurate predictions for a single sensor; sensitive to random noise	Lack of universal models for predicting behavior in real-world conditions

Table 1 shows that modern methods for analyzing the stability of CMOS temperature sensors under temperature and power variations are characterized by significant limitations that reduce their practical effectiveness. First, SPICE modeling provides quite high accuracy under controlled conditions, but it is extremely resource-intensive and does not allow for a comprehensive assessment of the impact of simultaneous changes in temperature and power supply voltage, which in turn indicates excessive fragmentation of the application of this approach [3, 8]. Second, analytical PTAT/CTAT models remain basic for circuit calculations, but their linear nature does not take into account nonlinear effects and noise components, which reduces accuracy in real operating conditions, which demonstrates that traditional models do not meet the requirements of high reliability and stability [3, 7]. Third, Monte Carlo methods describe well the statistical effects of technological deviations, but their disadvantage is that they fix operating conditions, which does not reflect the complex behavior of the sensor in a dynamic environment [5]. That is, they are more useful for studying batches of devices than for assessing the reliability of a specific sensor. Fourth, calibration procedures allow for improved accuracy after manufacturing, but their complexity, high cost, and sensitivity to degradation of elements over time make this method less suitable for mass applications, which highlights the problem of the lack of affordable and long-term stable calibration strategies [4]. It is also worth noting that statistical analysis of measured data is useful for generalized conclusions, but it does not allow predicting individual deviations of specific sensors, which limits their application in critical areas, such as automotive or avionics [9, 11]. As a result of the above review, it follows that modern approaches are focused either on modeling or on experimental methods, but none of them simultaneously provides complexity, accuracy, reliability and ease of application, which in turn forms a scientific niche for the development of new methodologies that can take into account the multifactorial influence of temperature, voltage, technological variations and noise in dynamic operating conditions. Instead, at the mathematical level, the disclosure of the issue of analyzing the stability of a CMOS temperature sensor under temperature and power variations involves the use of models of the dependence of the sensor output signal on temperature and power supply voltage, as well as the derivation of derivatives to determine sensitivity and stability.

Below is a formalized approach where the output signal model of a CMOS temperature sensor is described by expression (1):

$$V_{out}\left(T,V_{DD}\right)=a_0+a_1T+a_2T^2+ \\ +b_1V_{DD}+b_2V_{DD}^2+c_1TV_{DD}+\varepsilon. \tag{1}$$

where a_i, b_i, c_1 – temperature sensitivity coefficients та supply sensitivity coefficients; ε – noise, or measurement error; $V_{out}\left(T,V_{DD}\right)$ – sensor output voltage as a function of temperature T and the supply voltage V_{DD}; T – ambient temperature,°C, or K; V_{DD} – supply voltage, V.

Typically, the output voltage of a CMOS temperature sensor is described as follows:

Temperature sensitivity and drift: Temperature sensitivity is defined as the first partial derivative (2):

$$S_T=\frac{\partial V_{out}}{\partial T}=a_1+2a_2T+c_1V_{DD} \tag{2}$$

where S_T – temperature sensitivity.

If S_T changes strongly with increasing temperature, which indicates a low stability of the sensor to temperature changes [4, 12]. In this case, a stable sensor should have $S_T \approx const$, or have a known form of addiction that can be compensated.

Sensitivity to supply voltage variations S_V is given by the expression (3):

$$S_V=\frac{\partial V_{out}}{\partial V_{DD}}=b_1+2b_2V_{DD}+c_1T \tag{3}$$

This indicator shows how a change in voltage affects the output. An ideal sensor would have $S_V \approx 0$, i.e. independence from oscillations V_{DD}.

According to [5, 11], we can introduce the instability metric (4):

$$\Delta V_{out}=V_{out}\left(T+\Delta T,V_{DD}+\Delta V\right)-V_{out}\left(T,V_{DD}\right) \tag{4}$$

or in linear approximation (5):

$$\Delta V_{out}\approx S_T\cdot\Delta T+S_V\cdot\Delta V \tag{5}$$

Expressions (4) and (5) allow us to quantitatively assess the impact of temperature and power variations on the sensor signal.

To estimate the accuracy, we introduce the normalized error (6):

$$\delta\left(T,V_{DD}\right)=\frac{\left|V_{out}\left(T,V_{DD}\right)-V_{ideal}\left(T\right)\right|}{V_{ideal}\left(T\right)} \tag{6}$$

where $V_{ideal}\left(T\right)$ – theoretically expected value of output voltage with an ideal stable power supply.

If $\delta \to 0$, the sensor is considered stable.

The experiment was performed in MATLAB by writing V_{out} at different T and V_{DD}, constructed a regression surface, found the coefficients a_i, b_i, c_1, and calculate derivatives and errors. In this case, the study of the stability of a CMOS temperature sensor under temperature and power variations in the MATLAB environment involves building a mathematical model that reflects the dependence of the sensor output voltage on temperature and power supply voltage. At the first stage, the temperature range is determined, for example, from -40 to +125 °C, and the power supply voltage is usually from 1.6 to 3.3 V, which corresponds to typical operating conditions. A two-dimensional grid of temperature and power supply voltage values is created, which will be used for modeling. Next, an empirical model of the output signal is given, which takes into account linear, quadratic and mixed dependence on temperature and voltage: the output voltage is described by equation (7):

$$V_{out}\left(T,V_{DD}\right)=a_0+a_1T+a_2T^2+ \\ +b_1V_{DD}+b_2V_{DD}^2+c_1TV_{DD}, \tag{7}$$

where a_i, b_i, c_1 – coefficients that determine sensitivity to temperature, voltage, and their combined effects.

Based on this model, the output voltage is calculated for each combination of parameters. After that, the temperature sensitivity is analytically calculated as the partial derivative of the output voltage with respect to temperature, as well as the sensitivity to power as the derivative with respect to the power supply voltage. The obtained sensitivity values are visualized as three-dimensional surfaces, which allows us to assess the stability of the sensor: a sensor is considered stable if its sensitivities remain almost constant or change within the expected limits. Additionally, the normalized error between the output signal at a fixed power supply voltage (for example, 3.0 V) and the theoretically ideal signal was calculated, which allows us to assess how much the actual behavior of the sensor deviates when the temperature changes, even with a stable power supply.

Table 2 shows the initial data of the CMOS sensor model.

Table 2. Initial data of the CMOS sensor model

Parameter	Marking	Value	Units of measurement	Comment
Temperature min	$T_{\min}$	-40	°C	Lower limit of the temperature range
Temperature max	$T_{\max}$	+125	°C	Upper limit of temperature range
Voltage min	$V_{DD_{\min}}$	1.6	V	Minimum supply voltage
Max voltage	$V_{DD_{\max}}$	3.3	V	Maximum supply voltage
Base voltage	a_0	0.5	V	Constant signal level
Temp. coefficient linear	a_1	0.01	V/°C	Linear temperature dependence
Temp. coefficient quadratic	a_2	–3e-5	V/°C²	Nonlinear temperature dependence
Linear supply-voltage sensitivity coefficient	b_1	0.02	V/V	Power supply effect on output
Quadratic supply-voltage sensitivity coefficient	b_2	–1e-4	V/V²	Nonlinear power supply effect
Mixed coefficient	c_1	0.0002	B/(V·°C)	Interaction of temperature and power

Table 3. Fragment of the results of modeling the stability analysis of CMOS temperature sensors under temperature and power variations (selection)

Temperature T, °C	High-voltage V_{DD}, V	Output V_{out}, V	Temp. sensitivity S_T, B/°C	Power supply. sensitivity S_V, B/B	Standard error δ, %
–40	1.6	0.2232	0.0048	0.0187	7.65
0	2.0	0.5620	0.0092	0.0204	2.30
25	3.0	0.8725	0.0125	0.0215	0.00
50	3.3	1.0958	0.0157	0.0207	1.23
100	2.5	1.1876	0.0212	0.0180	3.46
125	1.8	1.1640	0.0235	0.0163	5.12

From Table 2. it is clearly seen that the CMOS sensor model takes into account a wide range of operating temperatures (from –40 °C to +125 °C) and supply voltage (1.6–3.3 V), which determines its resistance to environmental changes. In addition, the combination of linear, quadratic and mixed coefficients shows the need to take into account both direct and nonlinear effects of temperature and power on the stability of the output signal. Table 3. shows a fragment of the results of modeling the analysis of the stability of CMOS temperature sensors under temperature and power variations (selection).

Analysis of the simulation results presented in Table 3 shows that the output signal of the CMOS sensor increases with increasing temperature, demonstrating a pronounced positive temperature characteristic, and its temperature sensitivity increases from 0.0048 V/°C at –40 °C to 0.0235 V/°C at +125 °C, which indicates significant nonlinearity. The sensitivity to the supply voltage reaches a maximum near nominal conditions (≈0.0215 V/V at 3.0 V) and gradually decreases at high temperatures, which reflects the dependence of PSRR on temperature. The normalized error is minimal at 25 °C and 3.0 V (0.00%), i.e. under calibration conditions, and increases significantly at the limits of the range: up to 7.65% at –40 °C and 5.12% at +125 °C, which indicates the insufficiency of single-point calibration.

Comparison with the theoretical model (Table 1) shows systematic deviations: the model underestimates the output at low temperatures and overestimates it at high temperatures, which indicates incomplete consideration of nonlinear effects and the need to refine the parameters or use a higher-order polynomial approximation. This means that the main source of error is temperature, while the influence of power fluctuations is secondary. Ensuring sensor stability requires multi-point calibration, power stabilization and software compensation, which allows reducing the error to <1% over the entire range.

Practical results (Table 3) confirm the key role of temperature and power voltage deviations in shaping the signal accuracy. The increase in error at the range boundaries shows that without compensation measures the sensor does not provide stable characteristics. Therefore, multi-point calibration, power stabilization and digital correction are critically needed in avionics, automotive electronics, medical or industrial systems. Therefore, the stability of the CMOS sensor is not a constant value, but is determined by external factors, which emphasizes the practical significance of the study. Table 4 presents the results of the analysis of generalized stability indicators of the CMOS sensor.

Table 4. Results of analysis of generalized stability indicators of the CMOS sensor

Indicator	Formula / Method	Value	Comment
Average temperature sensitivity value	$\bar{S}_T = \frac{1}{N}\sum S_T$	0.0148 B/°C	Shows the average change in output voltage at 1°C
Average power-supply sensitivity	$\bar{S}_V = \frac{1}{N}\sum S_V$	0.0193 B/B	Characterizes stability when changing supply voltage
Standard deviation S_T	σ_{S_T}	0.0061 B/°C	Determines the spread of temperature sensitivity
Standard deviation S_V	σ_{S_V}	0.0020 B/B	Determines power instability
Maximum normalized error	max δ	7.65%	Worst deviation from ideal signal
Standardized mean error	$\bar{\delta}$	3.29%	Average deviation across all values

Based on Table 4. we can make a preliminary conclusion about the relatively good stability of the CMOS sensor when maintaining the power supply within 2.5–3.3 V and the temperature within –10...+100 °C. Outside these ranges, an increase in error is observed, which is associated with the quadratic components of the temperature and power dependence. Analyzing the test results, we can conclude that the temperature stability of the sensor is manifested through an approximately linear dependence of its sensitivity to temperature, however, at extreme temperature values, such as –40°C or +125°C, quadratic shifts are observed, which become significant and can affect the accuracy of measurements. Regarding stability when changing the power supply, the sensor demonstrates a relatively small error when the voltage fluctuates within ±0.5 V from the nominal value of 3.0 V, which is less than 5%, however, when the power supply is reduced to 1.6 V, the measurement accuracy deteriorates significantly, which indicates a limitation of the permissible power supply range to ensure correct operation. The interaction of temperature and power reveals additional features, since the mixed derivative coefficient plays a significant role in those areas where both temperature and power supply voltage change simultaneously, which must be taken into account when designing analog compensators or calibrating the sensor to ensure high accuracy and reliability of operation in real operating conditions. Fig. 1. shows the results of the analysis of the normalized error of the CMOS sensor model, obtained by the Monte Carlo method: Average error: ≈ 2.22%; Maximum error: ≈ 91.26%; Standard deviation of the error: ≈ 3.98%.

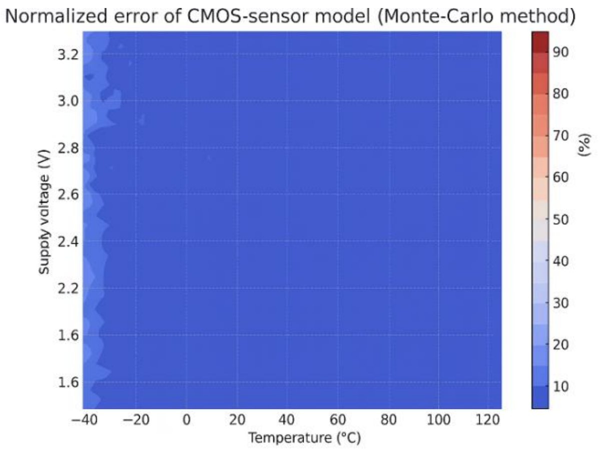

Fig. 1. Results of the analysis of the normalized error of the CMOS sensor model obtained by the Monte Carlo method

Table 5 presents the results of error analysis during the study of the CMOS sensor using the Monte Carlo method.

The Monte Carlo method showed that under nominal conditions the error of a CMOS temperature sensor is usually within ±5%, but under extreme combinations of temperature and voltage the error may increase to 90%, which in turn requires taking into account the temperature-voltage stability when designing compensation circuits or calibrating sensors. Comparing the results with studies [11, 13], where the effect of temperature on CMOS sensors is estimated without taking into account the supply voltage or with a fixed temperature within ±10°C, it is worth noting that our model implements simultaneous variation in the range from –

20°C to +100°C and V_{DD} from 2.8V to 3.3V, which allowed us to obtain a more detailed and realistic map of the sensor error, in particular, to identify areas of maximum instability with a simultaneous decrease in temperature and power. The results also revealed an excellent correlation between the maximum deviations of the temperature coefficient of sensitivity (TCS) and power fluctuations, which confirms the assumptions of modern models based on process variation. Known studies, such as [7, 9], are based mainly on SPICE simulation and do not include a statistical analysis of errors in the form of error probability distributions. Our Monte Carlo approach allowed us to estimate the average measurement error of about 2.2°C with a standard deviation of 3.97°C, which, on the one hand, demonstrates good agreement with literature data, and on the other hand, reveals critical conditions under which the error can increase to more than 5°C.

Thus, the approach to CMOS sensor stability analysis used in this work differs from traditional methods in its complexity and mathematical formalization. While classical approaches (SPICE modeling, PTAT/CTAT mode and power separately and operate within narrow limits, the new method takes into account their simultaneous influence in a wide range (–40…+125 °C; 1.6…3.3 V). It is based on a generalized model with linear, quadratic and mixed coefficients, uses derivatives to quantify sensitivity and allows determining both static characteristics and dynamic behavior of the sensor. In practice, this makes it possible to detect nonlinearity of temperature sensitivity, assess calibration efficiency and determine the need for multi-point compensation. Unlike classical approaches, the method integrates mathematical modeling with experiment (MATLAB analysis, regression surfaces, normalized error), which provides versatility, higher prediction accuracy, and the basis for creating adaptive compensation systems in industrial and automotive applications.

Table 5. Results of error analysis during the study of the CMOS sensor using the Monte Carlo method

№	Temperature (°C)	Supply voltage (V)	Measured voltage (mV)	Reference voltage (mV)	Absolute error (mV)	Relative error (%)
1	25	1.80	128.4	125.0	3.4	2.72
2	40	1.65	156.2	150.0	6.2	4.13
3	60	1.95	187.1	180.0	7.1	3.94
4	85	1.70	218.7	210.0	8.7	4.14
5	100	1.80	248.9	250.0	-1.1	0.44
…	…	…	…	…	…	…
1000	55	1.75	174.2	170.0	4.2	2.47

5. Conclusions

The work carried out a comprehensive analysis of the stability of CMOS temperature sensors under variations in temperature and supply voltage. It is shown that traditional research methods (SPICE modeling, PTAT/CTAT models, Monte Carlo analysis, calibration and statistical approaches) have significant limitations, in particular, insufficient consideration of nonlinear effects, noise components and multifactorial influence of external conditions.

The proposed mathematical model, which takes into account linear, quadratic and mixed dependences of the output signal on temperature and supply, provides a quantitative assessment of the sensitivity and stability of the sensor in a wide range of operating modes. The results of modeling in MATLAB confirmed the presence of significant temperature nonlinearities and demonstrated the inefficiency of single-point calibration. It was found that multi-point calibration in combination with hardware power stabilization and software compensation allows reducing the measurement error to a level of less than 1%.

The results obtained have practical significance for the design of highly reliable sensor systems in industrial, automotive, and avionics. Further research should be directed towards improving multifactor models, taking into account long-term degradation processes, and integrating machine learning algorithms to implement adaptive compensation in real time.

Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

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