Overview of Research Methods for Temperature Error Compensation of Sensors

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Abstract

Sensors are widely used in various industrial and agricultural production practices. However, due to factors such as materials and structures used in manufacturing or packaging, their output signals are easily affected by changes in environmental temperature, leading to measurement errors. Sensor temperature error compensation technology is an important means to improve measurement accuracy, which is of great significance for sensors to play a greater role in industrial production. By reviewing relevant literature in recent years, this article summarizes the commonly used hardware compensation methods for sensor error compensation, methods for controlling the working temperature of sensors, methods for optimizing peripheral circuit compensation, and software compensation. With the continuous development of sensor technology, temperature error compensation methods are also constantly innovating and improving. In the future, temperature error compensation for sensors will pay more attention to real-time, adaptive, and intelligent capabilities to meet high-precision measurement requirements in various complex environments. This article helps researchers to gain a deeper understanding of the research methods and current status of sensor temperature error compensation, and also provides some research ideas for researchers in related fields.

Keywords

Temperature; Error; Compensation; Sensor; Accuracy.

1. Introduction

The significance of sensor temperature error compensation is to improve measurement accuracy and precision, ensuring that the sensor can work stably and reliably at different environmental temperatures. Firstly, sensors are inevitably affected by environmental temperature during operation. This influence may lead to deviations in the sensor output signal, thereby affecting the accuracy and precision of the measurement. By compensating for temperature errors, the impact of temperature changes on sensor characteristics can be effectively offset or reduced, ensuring the accuracy of measurement results. Secondly, with the advancement of technology and the development of industry, the demand for sensor measurement accuracy is becoming increasingly high. In many high-precision measurement scenarios, any small measurement error can lead to serious consequences. Therefore, adopting temperature error compensation technology is crucial for improving the measurement accuracy and reliability of sensors[1]. In addition, temperature error compensation can also reduce sensor damage and performance degradation caused by temperature changes, thereby extending the service life of the sensor.

There are various reasons for temperature errors in sensors. The change in environmental temperature will directly affect the output value of the sensor, resulting in temperature errors. In the manufacturing process of sensors, if there is unevenness in the material, such as differences in composition, structure, or density, it can lead to inconsistent response characteristics of the sensor, resulting in temperature errors. The instability of manufacturing processes may lead to deviations in the size, shape, or performance parameters of sensors, thereby affecting their temperature measurement accuracy. The selection of electronic components such as amplifiers and filters in circuits directly affects the output signal quality of sensors. If the performance of the components is unstable or there are deviations, it can lead to temperature errors.

The main methods for compensating temperature errors in sensors currently include hardware compensation, temperature control, optimization of peripheral circuit compensation, and algorithm compensation[2].

2. Current Research Status at Home and Abroad

2.1. Hardware Compensation Method

The hardware compensation method mainly suppresses the temperature error of the sensor by changing the material, structure, processing technology, and improving the packaging quality of the sensor. By optimizing the topology of the sensor, such as installing thermal isolation frames and stress relief anchors, the temperature error of the sensor can be suppressed[3,4]. In theory, the temperature coefficient of silicon and the uneven thermal stress caused by temperature are the main reasons for bias temperature drift. Therefore, researchers have developed isolation frames with single or multiple layers to reduce thermal stress between sensor chips [5,6]. In addition, stress insensitive anchoring also helps to improve the zero bias stability of sensing elements [7]. Researchers have introduced a new type of MEMS accelerometer made using the principle of differential frequency modulation. The sensor eliminates the influence of temperature on sensor output error by building two identical tuning fork resonators made of silicon and using differential methods[8]. Yen introduces a CMOS-MEMS based accelerometer[9]. The sensor reduces the bending of the internal support structure caused by residual stress in the thin film through a symmetrical stack layer design method. The structure consists of three dielectric layers and four metal layers. This construction effectively reduces the deformation of the internal structure caused by thermal errors, thereby further improving the sensor's adaptability to temperature . In addition, using materials that are insensitive to environmental temperature to manufacture sensors is also a hardware compensation method.

The advantage of hardware compensation method is that it improves the robustness of sensors without the need for any calibration experiments, making it suitable for mass production and wide applications. But the residual error that ultimately exists will still affect the accuracy of the sensor. The hardware compensation method has high professionalism, high cost, and usually a long research cycle. In addition, hardware compensation methods are only effective for sensors with partially adjustable structures, and the output errors of sensors cannot be completely eliminated through hardware compensation methods.

2.2. Temperature Control Method

Temperature control method refers to obtaining the working temperature with the highest output accuracy of the sensor through temperature testing. Then, by using a specific external temperature control device or equipment to keep the sensor operating at its optimal temperature, the sensor can avoid output errors caused by temperature changes [10]. Reference [11] reported a resonant accelerometer with epitaxial packaging, which uses on-chip silicon heaters in the packaging layer to maintain the measured temperature at a fixed set point. This can improve the stability of its scaling factor and zero bias. Reference [12] introduces a high-temperature three-axis accelerometer using SOI varistor constant temperature control. Reference [13] designed a high-temperature three-axis accelerometer using SOI varistor constant temperature control. This accelerometer adopts a special structure and is equipped with four Wheatstone bridge piezoelectric resistors to detect three-axis acceleration. A temperature sensor utilizing four Wheatstone bridge integral resistors and a micro heater is integrated on the beam structure, which can maintain stable internal temperature through internal and external heat dissipation balance. This method effectively reduces the temperature drift of the sensor. Reference [14] describes a scheme that utilizes an integrated polycrystalline silicon heater embedded in a micro mechanical sensor structure to maintain the sensor at a constant temperature. The method of thermal isolation between the sensor sampling heating structure and the substrate reduces the power consumption of the system to a certain extent. This technology has been validated on an accelerometer with a nonlinear temperature sensitivity coefficient. After temperature control, the DC bias stability of the accelerometer increased from 1.7g/°C to -42 mg/°C, and the sensitivity change decreased from 60% of the nominal value to 18% within the temperature range of 70 °C.

Operating the sensor at the optimal temperature can effectively reduce the temperature error of the sensor. However, the entire process requires a significant amount of work and requires researchers to possess strong professional knowledge. Adding a temperature control system will also increase the power consumption of the system, and this method is not applicable to all sensors.

2.3. Optimizing Circuit Compensation Methods

The compensation method for optimizing the circuit is to eliminate or suppress the temperature changes of the sensor by optimizing or redesigning the peripheral circuit of the sensor, thereby improving the output accuracy of the sensor. Design appropriate circuits using specific components to eliminate the influence of temperature [15]. Reference [16] proposes a MEMS capacitive gyroscope integrated readout circuit based on a transimpedance amplifier. Design a CMOS variable temperature gain circuit to compensate for MEMS output errors caused by temperature changes. Liu Yidong et al. found that the resonant frequency of MEMS accelerometers varies linearly with temperature[17]. Based on this characteristic, relevant modules were designed using FPGA to compensate for the temperature of the sensor and achieved good results. Due to the high technical difficulty of this method, there are relatively few related research literature.

2.4. Algorithmic Compensation Method

The algorithm compensation method is to study the variation law between the output of the accelerometer and the external temperature. By collecting a large amount of data through multiple experiments, a temperature drift compensation model is established, which essentially compensates for sensor temperature errors through signal processing. Extensive research has been conducted both domestically and internationally on this compensation method. Compensation algorithms typically include methods such as BP neural network, RBF neural network, wavelet neural network, correlation vector machine, ELman neural network, and polynomial fitting.

Reference [18] established the relationship between the scale factor and temperature, as well as the relationship between zero bias and temperature, for fiber optic gyroscopes using BP neural networks. After compensation, the output accuracy of the gyroscope was improved by one level. References [19] and [20] respectively established error compensation models for a torsion pendulum silicon micro accelerometer using BP neural networks and explored the number of layers in the neural network. The output accuracy of the sensor was improved through error compensation. Reference [21] established a model of the variation of MEMS gyroscope bias voltage with temperature using BP neural network, and improved the output accuracy of gyroscope angular acceleration through compensation. Considering that BP neural networks are prone to getting stuck in local minima, many literature have optimized the initial weights and thresholds of BP neural networks through other auxiliary algorithms [22,23]. RBF is a neural network that can converge to the global minimum. Reference [24] compensated for the temperature drift of MEMS accelerometers using an improved RBF neural network method. Reference [25] also used RBF neural network to model and compensate for the temperature drift of gyroscope, and achieved good results through RBF neural network compensation. Wavelet neural network is a type of neural network proposed based on wavelet analysis. This neural network is a novel neural network model with hierarchical structure and multi-resolution constructed on the basis of wavelet transform and wavelet analysis. A model based on genetic algorithm and Elman neural network is proposed for the temperature drift characteristics of MEMS gyroscopes in reference [26]. The output signals of the gyroscope and temperature sensor were obtained through temperature experiments, and a temperature drift model based on temperature, temperature change rate, and coupling term was proposed on this basis. Finally, genetic algorithm was used to optimize the parameters of Elman neural network and improve the accuracy of compensation. Reference [27] studied a temperature compensation algorithm without temperature sensors based on gyroscope arrays. The gyroscope data fusion adopts Elman deep learning neural network to directly compensate for the output error of the gyroscope. The experimental results show that this method can significantly reduce the error of the gyroscope. Reference [28] addresses the issue of temperature drift in gyroscopes by compensating for it through polynomial fitting. Finally, it is demonstrated through sports car experiments that polynomial modeling compensation improves the positioning accuracy of sports cars. When there are many and complex factors affecting the temperature drift of sensors, the compensation effect of polynomials is often not ideal, and many literature also shows the disadvantage of low fitting accuracy of polynomials [29,80]. Reference [31] established the relationship between zero bias, temperature, and temperature rise rate of MEMS acceleration sensors through the predictive ability of correlation vector machines, and ultimately compensated for the temperature drift error of MEMS acceleration sensors to improve their output accuracy. The previous text listed some mainstream compensation algorithms, and there are also other algorithms used for temperature error compensation of sensors.

The algorithm compensation method usually requires a short cycle, relatively simple operation, and is relatively economical, so it is a commonly used method by researchers in related fields. There are relatively more research literature in related fields, which is also a hot topic of concern for researchers.

3. Conclusion

Sensor temperature error compensation is an important research area in sensor technology, aimed at reducing or eliminating the impact of temperature changes on sensor measurement accuracy. With the continuous development of technology, significant progress has been made in temperature error compensation methods.

At present, sensor temperature error compensation can be generally divided into two categories: hardware compensation and software compensation. The hardware compensation method mainly uses temperature compensation components to offset sensor zero drift. These methods introduce temperature sensitive components into the sensor circuit to measure and adjust the sensor output in real-time, in order to offset errors caused by temperature changes. The software compensation method mainly utilizes microprocessors to analyze and process the temperature data collected by sensors. Calculate the temperature compensation value through a pre-set compensation algorithm and superimpose it onto the original measurement data to achieve accurate measurement. Common software compensation methods include multi-point calibration method, curve fitting method, and polynomial consistency method. These methods process sensor outputs through mathematical algorithms to compensate for zero drift. In addition to traditional hardware and software compensation methods, there have been some improved compensation methods in recent years, such as adaptive compensation methods, neural network compensation methods, and fuzzy logic compensation methods. These methods have better performance in real-time, dynamics, and accuracy, providing new ideas for compensating temperature errors in sensors.

In practical applications, appropriate compensation methods or a combination of multiple methods can be selected according to specific situations to improve the accuracy and stability of sensor temperature measurement. For example, in situations where high-precision measurement is required, a combination of hardware compensation and software compensation can be used to achieve better compensation results.

Overall, temperature error compensation for sensors is an indispensable part of sensor technology. With the continuous development of technology, temperature error compensation methods will be further improved and innovated, providing strong guarantees for high-precision measurement of sensors in various complex environments.

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