High-temperature digital circuit design for fluxgate sensor

Chenhao Zhang\textsuperscript{1a*}, Yiming Zhang\textsuperscript{1b}, Junxia Gao\textsuperscript{1c*}, ZhongZheng Li\textsuperscript{1d}

\textsuperscript{1}Faculty of Information Technology, Beijing University of Technology, Beijing 100124, China

\textsuperscript{a*}zhangchenhao@emails.bjut.edu.cn, \textsuperscript{b}ymzhang@bjut.edu.cn, \textsuperscript{c}gaojunxia@bjut.edu.cn, \textsuperscript{d}lizhongzheng123@163.com

Abstract—With the continuous development of integrated electronics and the increasing demand for downhole resource exploration, it has become important to develop a small size, high temperature resistant, high-performance digital fluxgate sensor. Due to the strict size limitation of downhole exploration equipment, some high-temperature devices are generally large in size and have a different performance of the same type of devices, so it is necessary to select the devices that meet the temperature requirements through high-temperature experiments. In this paper, by simplifying the circuit structure and selecting devices through high-temperature experiments, the usability of the circuit structure at 175°C and the stable performance in long-time operation at high temperature were verified.

1. Introduction

For downhole exploration, fluxgate sensors generally use analog circuit structure, which has the advantages of simple structure and good temperature resistance, but its performance is limited by noise interference\textsuperscript{[1]}. With the continuous development of integrated circuit technology, the temperature resistance of digital circuits has been able to meet the temperature requirements of downhole exploration\textsuperscript{[2]}. At the same time, the digital circuit has a strong anti-interference capability, and the addition of feedback signals can substantially improve the performance of fluxgate sensors\textsuperscript{[3]}. A temperature sensor can be added to the digital circuit to reduce the drift of magnetic field data at high temperatures and improve the overall performance of the fluxgate sensor through temperature compensation by the master control chip according to the temperature\textsuperscript{[4]}. In previous studies, the temperature performance of fluxgate sensors is improved by selecting different core materials, and resistors are connected in series to the pick-up coil to obtain the best linearity at different temperatures. This method is only appropriate to improve the temperature performance at industrial temperatures\textsuperscript{[5]}. With the development of integrated circuits, devices were selected for higher temperature resistance, but this solution is less applicable due to the limitations of analog circuit characteristics and size\textsuperscript{[6]}.

The closed-loop digital fluxgate sensor circuit designed in this paper contains a control chip, linear power supply chips, a driver chip, digital-to-analog converters (DAC), analog-to-digital converters (ADC), operational amplifiers (OP), a thermistor, and a temperature-compensating crystal. However, the general high-temperature devices are large in size and cannot meet the size requirements of downhole equipment, so it is necessary to select a small size device that is close to the temperature and select a device that can meet the temperature requirements through high-temperature testing, and the device can also meet the small size requirements. In this paper, the designed digital circuit was tested several times in a high-temperature chamber in the laboratory to select a device that meets both the
size and temperature requirements, and the stability of the circuit design at high temperatures was verified by reducing the data drift at high temperatures through temperature compensation.

2. Structure and Design of Circuit

The principle of fluxgate sensors is the law of electromagnetic induction, which is used to measure weak static magnetic field signals. The fluxgate sensor usually contains a probe and a circuit part, but the high-temperature circuit studied in this paper does not involve the probe part. The fluxgate circuit is a three-axis structure, and the circuit corresponding to each axis is basically the same except for the different resistor and capacitor configurations, so this paper only describes the single-axis structure to simplify the structure. Fig.1 shows the structure of the fluxgate sensor studied in this paper, which contains the excitation circuit, the sensing circuit, and the feedback circuit.

![Fig.1 Circuit structure of fluxgate sensor](image)

The operating temperature of the fluxgate sensor studied in this paper is 175°C or higher, so the selected device needs to operate stably for a long time under the operating temperature. However, most of the high-temperature devices cannot meet the PCB size of 20mm wide and 170mm long. Under the premise of meeting the size requirements, the core high-temperature chip, as shown in Fig.2, is selected.

![Fig.2 Operating temperature of high temperature devices](image)

Although the better the temperature resistance of the power supply chip is often the greater the noise and size, but the voltage instability in the high-temperature operating environment will lead to poor system stability, especially for analog devices sensitive to voltage stability, so the first to meet
the temperature requirements of the power supply chip. Second, the stability of analog devices directly affects the performance of the fluxgate sensor, so it is necessary to choose the analog devices that meet the operating temperature requirements as much as possible, but the fluxgate studied in this paper is a three-axis structure, requiring four ADCs and six DACs, so the analog devices need to be as small as possible. High-temperature analog devices that can fully meet the temperature requirements, size does not meet the PCB size specified in this paper, so choose the smallest package of commercially available analog devices in Fig.2. After selecting the power supply chip and analog devices, there is little PCB area left. At the same time, digital processing chips and driver chips are often larger in size at room temperature chips, so we can only choose a smaller package and can work properly at high temperatures. The devices in the circuit need to be tested and replaced in a high-temperature environment to select the same type of devices that can operate at high temperatures.

3. Results and Discussions

The high-temperature circuit was placed in a separate high-temperature chamber for linear heating and cooling tests, and the probe was placed in a magnetically shielded cylinder to verify the overall performance. The magnetic field data of the x-axis and PCB temperature are recorded in real-time by the upper computer, and the magnetic field data before and after temperature compensation are also compared. The test results are shown in Fig.3, in which all high-temperature devices on the circuit board have been individually tested at high temperatures shown as Fig.4.

![Fig.3 Magnetic field data in the shielded cylinder before and after compensation](image)

The test results show that when the probe is in a magnetic field environment at room temperature of 25°C within 1nT, and the circuit is placed in a high-temperature environment, the magnetic field data measured by all the devices together have two data drifts with temperature changes. The measured magnetic field data has a brief data drift until the temperature is 125°C but then is able to return to near zero magnetic fields and remain stable for a period of time. When the temperature varies between 125°C and 180°C, the measured magnetic field data also follows the temperature change regularly within a specific error. Repeating the same temperature test with a specific circuit, the magnetic field data and temperature data show a similar variation relationship with each other. Based on the relationship of the data change after the temperature change, the corresponding data compensation is performed to compensate the magnetic field data to the actual value of the magnetic field. The results show that the compensated magnetic field data can be maintained near-zero magnetic
field during the whole period of temperature change, and the magnetic field data fluctuates within 50nT. The above test data show that the high-temperature digital circuit designed in this paper, with a core chip selected to meet the size and high-temperature requirements, can meet the operating conditions of continuous high temperatures downhole with linear temperature drift. Based on the data from the high-temperature tests, the measured magnetic field data is linear and stable in operation after linear compensation, meeting the high-temperature operating conditions downhole.

![Fig.4 High-temperature experimental environment in the laboratory](image)

4. Conclusion
Fluxgate sensors for downhole exploration are limited by size and temperature and usually use analog circuit solutions, but their overall performance is average, and they cannot compensate magnetic field data according to temperature, which can no longer meet the growing demand of downhole exploration. In this paper, both size and temperature factors are considered, and the core devices are reasonably selected, and the PCB layout is assigned according to the magnitude of device impact on the circuit. The same type of chip that meets the downhole operating temperature is selected through high-temperature tests, and the high-temperature circuit is placed in a high-temperature chamber for high-temperature experiments under a constant magnetic field. The experimental results show that the high-temperature digital circuit designed in this paper can work stably at 175°C, and the linearity of the magnetic field data is improved after temperature compensation.

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