Dynamic Range Expansion Method of Three-component HTc SQUIDs Magnetometer

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Abstract: In view of the small dynamic range of the three-component high-temperature superconducting quantum interference device (HTc SQUID) magnetometer and it is easy to exceed the measurement range when working in the field without magnetic shielding environment. A dynamic range expansion method based on step compensation is proposed. By setting a magnetic compensation coil on each axis of the three-component HTc SQUIDs magnetometer probe, a current is passed to generate a magnetic field opposite to the direction of the external magnetic field to offset most of the magnetic field to be measured. The measured values are calculated and processed to obtain the magnetic field value to be measured. The test results show that the method can greatly improve the dynamic range without reducing the sensitivity of the magnetometer, which can work stably in a non-magnetic shielding environment and meet the requirements of field geophysical magnetic exploration.

1. Introduction

The HTc SQUID magnetometer is a weak magnetic measuring instrument made of a SQUID (Superconducting quantum interferometer device) working in a liquid nitrogen environment (77K) as a sensor, it can detect extremely weak magnetic fields on the order of $10^{-14}$T [1-2]. The three-component HTc SQUID magnetometer is a magnetic measuring instrument composed of three-axis SQUIDs sensor, non-magnetic dewar, signal readout circuit, data acquisition system and magnetic measuring components, it can be used in the fields of geomagnetic navigation, magnetic positioning, archeology and non-explosive detection [3-5].

Three-component HTc SQUIDs magnetometer usually operate in a flux-locked state. The feedback resistance in the locking ring determines the sensitivity and measurement range of the instrument. The feedback resistance is proportional to the sensitivity and inversely proportional to the measurement range [6-7]. The actual sensitivity requirements of the system during field measurements are relatively high, resulting in lower measurement range. When the external magnetic anomaly is large or the attitude of the magnetometer changes greatly, it is easy to exceed the measuring range of the instrument to cause a lock-out situation and affect the measurement effect [8]. To this end, a dynamic range expansion method of three-component HTc SQUIDs magnetometer is proposed in this paper. This method can greatly improve the measuring range of three-component HTc SQUIDs magnetometer without reducing the sensitivity of the system which can work stably in a non-magnetic shielding environment and meet the requirements of field geophysical magnetic method exploration.
2. Compensation principle and method

2.1 Compensation object
The main part of the geomagnetic field is the stable magnetic field. The maximum variation of the measured change magnetic field accounts for about 2% to 4% of the induced intensity of the geomagnetic field. For a geomagnetic field of about 50 000 nT, the changing magnetic field can reach 1000 to 2000 nT [9], it is far beyond the measurement range of the three-component HTe SQUIDs magnetometer, so this changing magnetic field is the compensation object of this method.

2.2 Compensation principle
By setting a magnetic compensation coil in each axial direction at the probe of the three-component HTc SQUIDs magnetometer, a current is passed in to generate a magnetic field opposite to the direction of the external magnetic field to cancel out most of the magnetic field to be measured. The remaining measured magnetic fields in the last three directions are kept within the measuring range of the three-component HTc SQUIDs magnetometer magnetic force. The values of the offset magnetic field and the measured values of the magnetometer are calculated to obtain the magnetic field values to be measured. The magnitude and direction of the current in the magnetic compensation coil are automatically controlled by the compensation system.

Let the external magnetic field values in three directions be $B_{TX}$, $B_{TY}$, $B_{TZ}$ and the dynamic range of the three-component HTc SQUIDs magnetometer be $B_{DX}$, $B_{DY}$, $B_{DZ}$. The corresponding output voltage are $V_{DX}$, $V_{DY}$, $V_{DZ}$. Set two thresholds for $\pm V_{RX}$, $\pm V_{RY}$, $\pm V_{RZ}$, $|V_{RX}|<|V_{DX}|$, $|V_{RY}|<|V_{DY}|$, $|V_{RZ}|<|V_{DZ}|$ in each direction. If the output voltage of the HTS SQUIDs magnetometer in three directions are $|V_{OX}|\leq|V_{RX}|$, $|V_{OY}|\leq|V_{RY}|$, $|V_{OZ}|\leq|V_{RZ}|$, no compensation will be performed; If $|V_{OX}|>|V_{RX}|$, $|V_{OY}|>|V_{RY}|$, $|V_{OZ}|>|V_{RZ}|$, the direction of compensated magnetic field $B_{CX}$, $B_{CY}$, $B_{CZ}$ should be determined according to the positive and negative values of $V_{OX}$, $V_{OY}$, $V_{OZ}$ in the directions of X, Y and Z. The size of the compensation magnetic field is calculated as:

$$|B_{CX}|=K_{IX}K_{JX}|V_{OX}|, |B_{CY}|=K_{IY}K_{JY}|V_{OY}|, |B_{CZ}|=K_{IZ}K_{JZ}|V_{OZ}|$$

(1)

Where $K_{IX}$, $K_{IY}$, $K_{IZ}$ are the current/magnetic field conversion coefficient in the three directions of X, Y and Z; $K_{JX}$, $K_{JY}$, $K_{JZ}$ are the voltage/current conversion coefficient in the three directions of X, Y and Z respectively.

The residual magnetic field after the magnetic field to be measured in three directions cancels out are $|B_{TX}-B_{CX}|<|B_{DX}|$, $|B_{TY}-B_{CY}|<|B_{DY}|$, $|B_{TZ}-B_{CZ}|<|B_{DZ}|$, which are within the dynamic range of the three-component HTc SQUIDs magnetometer and the instrument can work normally and stably. The measured value are $B_{TX}$, $B_{TY}$, $B_{TZ}$, $B_{CX}$, $B_{CY}$, $B_{CZ}$ and the measured value $B_{TX}$, $B_{TY}$, $B_{TZ}$, $B_{CX}$, $B_{CY}$, $B_{CZ}$, $B_{TX}+B_{TY}$, $B_{TY}+B_{TZ}$, $B_{TZ}+B_{CX}$ are calculated. $B_{TX}+B_{TY}+B_{TZ}=B_{TX}$, $B_{CX}+B_{CY}+B_{CZ}=B_{TZ}$ are used to obtain the actual external magnetic field values measured in three directions.

2.3 Compensation method
This paper puts forward the idea of graded compensation in the actual compensation process in order to obtain high precision compensation magnetic field. With 50nT as a file, the system generates a compensating magnetic field of 50nT integer multiples. Fig. 1 shows the structural block diagram of a three-component HTc SQUIDs magnetometer system equipped with a compensation system. The dashed box is the compensation system.
The compensation system of three-component HTc SQUIDs magnetometer consists of signal processing circuit, compensation gear selection circuit, current source and magnetic compensation coil. Wherein, the signal processing circuit preprocesses the magnetic field signals in the three directions output by the SQUID readout circuit respectively. The compensation gear selection circuit selects the appropriate gear according to the result of the signal processing circuit. The current source generates a certain magnitude and direction of current in the magnetic compensation coil according to the control voltage output by the compensation gear selection circuit. The compensation coil generates a compensation magnetic field that is an integer multiple of 50nT. The remaining magnetic field after compensation is collected by the data acquisition system and sent to the microprocessor.

The microprocessor performs arithmetic processing on the measured magnetic field value and the gear state signal to obtain the measured magnetic field value.

3. Compensation system composition

3.1 Signal processing circuit

Fig. 2 is the block diagram of the signal processing circuit in the X direction, the same for Y and Z. The magnetic field signal in the X direction output by the SQUID readout circuit passes through the signal conditioning circuit and is output to two comparison circuits for comparison with the two thresholds set. If the magnetic field value is less than the set negative threshold value, a compensation magnetic field minus pulse signal is output through the trigger; If the magnetic field value is greater than the set positive threshold value, a compensation magnetic field increasing pulse signal is output through the trigger; If the magnetic field value is between two thresholds, no compensation magnetic field pulse signal is output.

3.2 Compensation gear selection circuit

Fig. 3 is the block diagram of compensation gear selection circuit in the X direction, the same for Y and Z. The X direction compensation magnetic field increasing pulse signal output by the signal processing circuit is input to the addition counter and the compensation magnetic field decreasing...
pulse signal is input to the subtraction counter. The digital subtractor subtracts the value of the addition counter and the subtraction counter to obtain the factor that currently needs to compensate the magnetic field, which is a multiple of 50nT. The decoding circuit converts this factor into a 5-digit hexadecimal code, one of which is used as a control signal for the analog switch and the other is output as a gear position signal to the back-end microprocessor. The reference voltage, the resistor network and the analog switch generate a current source control voltage under the control of a control signal output from the decoding circuit. A buffer is connected at the back of the analog switch which is to improve the driving capability of the control voltage.

Fig. 3 Block diagram of X-direction compensation shift selecting circuit.

The compensation magnetic field value corresponding to the hexadecimal code of the gear state is shown in Table 1. The range of the designed compensated magnetic field value is -14000 ~ +14000nT.

Table 1. Compensation magnetic field values corresponding to hexadecimal code of gear state.

| Gear status hexadecimal code | Compensated magnetic field value (nT) |
|-----------------------------|-------------------------------------|
| 06D60                       | 14000                               |
| 06D5F                       | 13950                               |
| ...                         | ...                                 |
| 00001                       | 50                                  |
| 00000                       | 0                                   |
| 10001                       | -50                                 |
| ...                         | ...                                 |
| 16D6F                       | -13950                              |
| 16D60                       | -14000                              |

3.3 Current source

The current source generates a certain magnitude and direction of current according to the current source control voltage output by the compensation gear selection circuit and supplies the magnetic compensation coils in the X, Y and Z directions to generate the required compensation magnetic field. The current source circuit adopts a closed-loop system in this paper. The output current value is collected through a sampling resistor, it is compared with the current source control voltage to obtain an error signal after the conditioning circuit is converted to a voltage. The output of the constant current source is controlled by a PI regulator. Fig. 4 is a block diagram of a current source.

Fig. 4 Block diagram of current source.
In the figure, $V_{in}$ is the current source control voltage and the range is $-2 ~ + 2V$. The sampling resistance is $8\Omega$. $I_{out}$ is the output current and the range is $-300 ~ + 300mA$. A large-diameter winding resistor with a temperature coefficient of $1\times10^{-6}\degree C$ is used as a sampling resistor to reduce the effect of temperature drift and improve the linearity of the output current and the control voltage of the current source in the closed-loop system. The output current error caused by the temperature drift of the sampling resistor is

$$\Delta I = \frac{V_{in}}{R_s} \frac{V_{in}}{R_{s}+R_s \times T \times 1 \times 10^{-6}}$$

(2)

Where $T$ is the temperature change value; $R_s$ is the sampling resistance value. When $V_{in} = 2V$, $\Delta I = 0.25\mu A/\degree C$ is the maximum error.

3.4 Compensation coil

As shown in Fig. 5, there is a single-turn circular coil with a current $I$ and a radius $R$. According to Biot-Savart law, the magnetic induction intensity generated by any current element $Idl$ on a circular current at a point $P$ on the $yoz$ plane is

$$dB = \frac{\mu_0 Idl \sin 90^\circ}{4\pi r^2} = \frac{\mu_0 Idl}{4\pi r^2}$$

(3)

Where $\mu_0$ is vacuum permeability; $r$ is the position vector of point $P$.

![Fig. 5 Single-turn circle coil with current.](image)

From the symmetry of the circular energized coil, it can be known that all components of the magnetic field $dB$ generated by all current elements on a circular current in the direction perpendicular to the $z$-axis cancel each other and there are only components in the $z$-direction. The integral of Equation (5) can be obtained

$$B = \int dB = \frac{\mu_0}{4\pi} \int \frac{dl \sin \varphi}{r^2} = \frac{\mu_0 IR^2}{2r^2} = \frac{\mu_0 IR^2}{2(R^2+z^2)^{1/2}}$$

(4)

If the number of coil turns is $N$, the magnetic induction intensity at point $P$ is

$$B = \frac{\mu_0 IR^2 N}{2(R^2+z^2)^{1/2}}$$

(5)

The magnetic compensation coils in each direction are composed of two 6-turn circles with a radius of 110 mm, which are placed in parallel with the axis of the sensor as the center of the circle. The distance between the two coils is equal to the coil radius which is designed as a Helmholtz coil. As shown in Fig. 6, it is connected in series to pass the same current in the same direction. The coil holders are made of non-magnetic PTFE.

According to the Biot-Savart law superposition principle, it can be known that the magnetic induction intensity on the coil axis in each direction is
\[ B = \frac{\mu_0 I R^2 N}{2\left( R^2 + \left( \frac{R}{2} + z \right)^2 \right)^{3/2}} + \frac{\mu_0 I R^2 N}{2\left( R^2 + \left( \frac{R}{2} - z \right)^2 \right)^{3/2}} \]  

(6)

When 100, 150, 200, 250 and 300mA currents are respectively fed into the compensation coil, the magnetic induction intensity distribution on the coil axis is shown in Fig. 7. When the magnetic compensation coil and the non-magnetic dewar are installed together, the three directions SQUIDs are located at the center points \( O \) of the respective compensation coils.

![Fig. 7 Distribution of the magnetic induction.](image)

![Fig. 8 X, Y and Z test magnetic field strength curve.](image)

4. Test results and analysis

It was tested to verify the compensation effect of the compensation system. A test magnetic field is generated at each of the three high-temperature SQUID probes. The magnetic field frequency is 10Hz and the amplitude gradually increases from 0. The peak value of the magnetic field is 11323nT and the valley value is -13283nT. The strength curves of the tested magnetic field in X, Y and Z directions are shown in Fig. 8. The voltage output range of the SQUID readout circuit is ±10 V. The magnetic field measurement range of each channel can be obtained according to the voltage / magnetic field calibration coefficients of each channel. The SQUID calibration coefficients and measurement ranges in the three directions of X, Y and Z are shown in Table 2. The magnetic field measurement ranges of the three channels are all within ±600nT.

| Calibration coefficient (mV/nT) | Measurement range (nT) |
|---------------------------------|------------------------|
| X                               | ±443.7                 |
| Y                               | ±599.5                 |
| Z                               | ±394.2                 |

The test result of the magnetic field measurement using a three-component HTc SQUIDs magnetometer without a compensation system is shown in Fig. 9, it can be seen from the test results that when the test magnetic field strength value exceeds the measurement range, the high-temperature SQUIDs lose lock and cannot work normally. SQUID thresholds in X, Y and Z directions can be set as ±430nT, ±590nT and ±370 nT respectively according to Fig. 9. After the compensation system is adopted, the compensation system will start to work when the strength of the magnetic field is tested beyond the threshold value in each direction. The compensation magnetic field intensity is set in steps of 50 nT and is automatically adjusted by the compensation system according to the change of the measured magnetic field intensity. The compensation magnetic field intensity curves in the three directions of X, Y and Z are shown in Fig. 10 (a), (b) and (c).
Fig. 9 Test results of three-component HTc SQUIDs magnetometer without compensation system.

As can be seen from the Fig. 10, the compensation systems in the X, Y and Z directions started to work at 1.948s, 1.998s and 1.898s, the corresponding test magnetic field strengths were -430nT, -590nT and 370nT respectively.

After the compensation system works, the measurement results after high temperature SQUIDs compensation in the X, Y and Z directions are shown in Fig 11 (a), (b) and (c). The remaining measured magnetic field strength after compensation is within the measurement range of the three-component HTc SQUIDs magnetometer and the instrument can work in a normal locked state for a long time.

Fig. 10 (a) X direction.

Fig. 10 (b) Y direction.

Fig. 10 (c) Z direction.

Fig. 11 (a) Test result after X direction compensation.

Fig. 11 (b) Test result after Y direction compensation.
The measured values of the three high-temperature SQUIDs and the compensation magnetic field values are processed. The results are shown in Fig. 12, compared with Fig. 8, the calculation results of the three directions are consistent with the test magnetic field intensity curve, compared with Fig. 9, the measurement range of the instrument was increased from ±500nT to ±14000nT, which greatly improved the measurement range and could meet the requirements of field geophysical magnetic exploration after compensation.

5. Conclusion
This paper proposes a three-component HTc SQUIDs magnetometer dynamic range expansion method. Experimental results show that this method can increase the measurement range from ±500 nT to ±14000 nT without reducing the sensitivity of the magnetometer (0.1pT/√Hz (@ 100Hz)). The magnetometer can work stably in field magnetic fields up to 80000 nT and also can work for more than 6 hours under the temperature of -10 °C to + 50 °C which meets the requirements of field geophysical magnetic method exploration work.

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