Experimental Research on the Directivity of Overhauser Magnetometer

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Abstract: Overhauser magnetometer with the advantages of high sensitivity and low power consumption is widely used in different fields. As an important part of the system, the sensor is responsible for the performance of the whole system. In this paper, the influences of sensor orientation on the performance of Overhauser magnetometer are investigated. The Larmor signal and the system sensitivity have been measured and analyzed when sensor in different directions. The experimental results show that the JOM-3 magnetometer sensor has no dead zone but poor omnidirection. Factors affected directivity of the sensor are discussed in this paper.

1 INTRODUCTION

Overhauser magnetometer, based on dynamic nuclear polarization (DNP) effect, is widely used in volcano surveillance, mineral prospecting , geophysical exploration, weapons detection and arch eology (Duret,1995). Compared to the traditional proton precession magnetometer, Overhauser magnetometer can achieve higher sensitivity with lower power consumption, (Maly,2008). The sensitivity of the Overhauser magnetometer GSM-19 made by GEM reaches up to 0.015-0.022nT and power consumption as low as 2W. Overhauser magnetometer researched by Zhang Shuang and other scholars has also made great progress (Ge,2016).

After a long period of research, we have developed a series of Overhauser magnetometers, the newly one is named JOM-3 Overhauser magnetometer. Compared with the JOM-2 Overhauser magnetometer, the system sensitivity has been improved by optimizing the design of the preamplifier circuit (Zhang,2017). With the new digital architecture of ARM + CPLD in the JOM-3 Overhauser magnetometer, the frequency measurement is more accurate and power consumption is reduced (Fan,2016).

Sensitivity is an important parameter to evaluate the performance of the instrument. It indicates the repeatability of the instrument measurement. In addition, the sensitivity of the magnetometer system can be affected by many factors, such as signal-to-noise ratio, frequency measurement accuracy and surrounding environment (Hovde,2013). The influences on the instrument performance caused by the sensor orientation will be investigated in this paper.

2 PRINCIPLE OF OPERATION

Overhauser magnetometer sensor is filled with free radical solution. In the absence of external field, the hydrogen proton orientation is random, total magnetic moment is zero. In the geomagnetic field, randomly oriented proton magnetic moments are oriented along the geomagnetic field, and the total magnetic moment is M0, as shown in Fig.1(a). With the radio frequency excitation, the phenomenon of the double resonance of electrons and nuclei occurs in solution, and the total magnetic moment M1 has been greatly enhanced on geomagnetic field direction, as shown in Fig.1(b). In the presence of DC polarization field, the total magnetic moment M2 deflects away from the geomagnetic field, as shown in Fig.1(c). After the DC signal is turned off, total magnetic field revert to geomagnetic field, and

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the hydrogen proton will rotate around direction of geomagnetic field to M0, as shown in Fig.1(d).

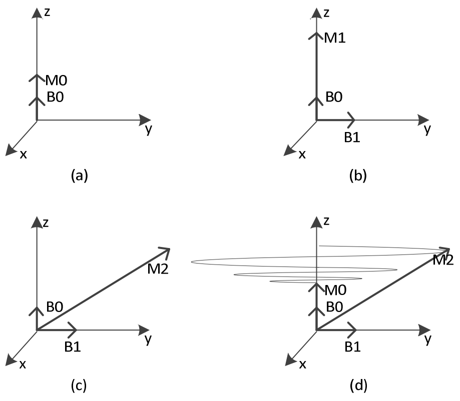


Figure 1: Principle of Overhauser magnetometer.

In the procession to the geomagnetic field, magnetic moment cutting receiving coils. The Larmor signal induced in the coils can be expressed as:

$$V(t) = A\omega_0 e^{-t/T} \sin \omega_0 t \qquad (1)$$

Where ω_0 is Larmor frequency, T is the time constant of signal attenuation. Larmor signal frequency is proportional to the magnetic field strength:

$$f = \gamma_p B_0 / 2\pi \qquad (2)$$

Where *f* is the Larmor frequency of the proton precession signal, γ_p is the gyromagnetic ratio and the value is $2.67512 \times 10^8 T^{-1} S^{-1}$, B_0 is the magnitude of the external magnetic field. Magnetic field strength can be expressed as:

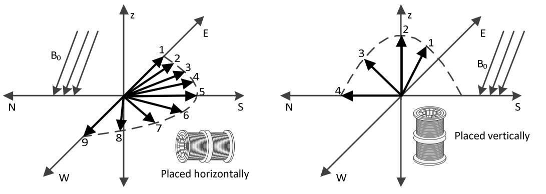
$$B_0(nT) = 23.4874 f(Hz) \qquad (3)$$

Therefore, the magnetic field strength can be calculated by measuring the frequency of the Larmor signal.

3 EXPERIMENTAL RESULTS

3.1 Experimental program

Two sets of experiments are designed to study the directivity of the sensor in this paper. Direction of the geomagnetic field in Changchun, Jilin Province, is vertical to the south 30 degrees pointing to the ground. Considering that the experiments are carried out in both horizontal and vertical planes.



(a) (b)

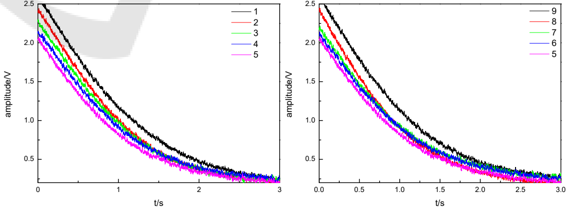
Figure 2: (a) Schematic of direction in horizontal plane, (b) Schematic of direction in vertical plane.

As shown in Figure 2(a), nine directions numbered 1-9 were set from east to west for experiment in the horizontal plane. The nine directions are the east direction, 20 degrees east to south, 40 degrees east to south, 60 degrees east to south, south direction, 20 degrees south to west, 40 degrees south to west, 60 degrees south to west and west direction. As shown in Figure 2 (b), four directions numbered 1-4 were set for experiment in the vertical plane. The four directions are the geomagnetic field direction, the vertical direction, vertical 45 degrees north direction and the north direction, respectively.

3.2 Effect of Sensor Orientation on the Larmor Signal

3.2.1 Experimental results when sensor in horizontal plane

When sensor is placed in different directions as shown in Figure 2(a), the envelopes of the Larmor signals received are shown in Figure 3.



(a) (b)

Figure 3: (a) The test resaults when sensor in direction numbered 1~5, (b) The test resaults when sensor in direction numbered 5~9.

It can be seen from Figure 3 that the amplitude of the Larmor signal is largest up to 2.50V when the sensor is placed in east direction and west direction. As the sensor's major axis approaches the south, the amplitude of the Larmor signal decreases. When the sensor is placed in the south direction, the amplitude of the signal is the smallest, as low as 2.03V.

3.2.2 Experimental results when sensor in vertical plane

When sensor is placed in different directions as shown in Figure 2(b), the envelopes of the Larmor signals received are shown in figure 4.

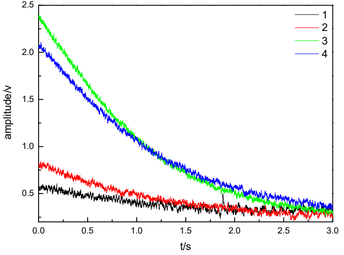


Figure 4: Test resaults when sensor in vertical plane.

It can be seen from Figure 4 that the amplitude of the Larmor signal is the smallest as low as 0.57V when the sensor is placed in direction 1. Direction 1 represent the direction of the geomagnetic field in Changchun. In the other three directions, the amplitude of the Larmor signal gradually increases, when the angle between the sensor's major axis and the geomagnetic field increases.

3.3 System sensitivity

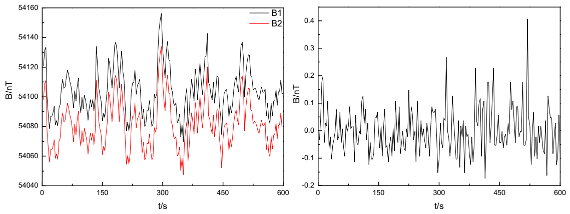
3.3.1 System sensitivity experiment

The sensitivity of a magnetometer is expressed by the standard deviation of multiple measurements. In this experiment, two sensors are placed in the same direction with a spacing of 1.5m and perform their measurements at the same time. The relative uncertainty of the two sensors is taken as the sensitivity of the instrument, expressed as:

$$\delta = \sqrt{\sum_{i=1}^{N}(\Delta X_i - \Delta\overline{X})/(2N)} \qquad (4)$$

Where ΔX_i is the difference between the ith measurements of the two sensors and ΔX is the difference between the mean values of the N measurements of the two sensors.

In this measurement, the cycle time is set to 3s for 30 minutes, and the middle 200 groups of data are taken for sensitivity calculation. Take the direction 1 in the horizontal plane as an example, the measurement results when sensor is placed in direction 1 are shown in figure 5. According to Eq. (4), the sensitivity reaches 0.07nT. When the sensor is placed in other directions, the sensitivity is still calculated by this method.



(a) (b)

Figure 5: (a) Magnetic field intensity, (b) Differences of two sensors.

3.3.2 Analysis of system sensitivity

The signal amplitude and system sensitivity measured when sensor in 9 directions in the horizontal plane are listed in Table 1.1 and Table 1.2:

Table 1.1: Experimental data when sensor in position 1~5.

Direction	1	2	3	4	5
Amplitude/V	2.50	2.40	2.27	2.13	2.03
Sensitivity/nT	0.07	0.08	0.08	0.08	0.09

Table 1.2: Experimental data when sensor in position 5~9.

Direction	5	6	7	8	9
Amplitude/V	2.03	2.09	2.18	2.43	2.50
Sensitivity/nT	0.09	0.08	0.08	0.08	0.08

The signal amplitude and system sensitivity measured when sensor in 4 directions in the vertical plane are listed in Table 2:

Table 2: Experimental data when sensor in vertical plane.

Direction	1	2	3	4
Angle/ °	0	30	75	60
Amplitude/V	0.57	0.80	2.38	2.05
Sensitivity/nT	0.18	0.16	0.08	0.10

According to Table 1.1, Table 1.2 and Table 2, system sensitivity and signal amplitude are affected by the angle between the major axis of the sensor and the geomagnetic field. The larger the angle, the higher the sensitivity is.

When the major axis of the sensor is perpendicular to geomagnetic field, the amplitude of Larmor signal and the sensitivity can reach 2.50V and 0.07nT, respectively.

4 DISCUSSION

As shown in Figure 6, the sensor of Overhauser magnetometer is composed of low frequency coil and radio-frequency cavity. Low frequency coil is made of a pair of reverse winding coaxial solenoids. The radio-frequency cavity filled with free radical solution is inside the low frequency coil.

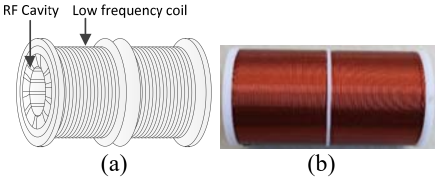


Figure 6: (a) Sensor structure, (b) Low frequency coil.

DC magnetic field inside the sensor is simulated by Ansoft Maxwell software as shown in Fig.7.

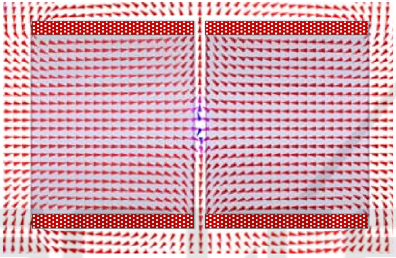


Figure 7: Axial magnetic field distruibution.

It can be seen from Fig.7 that the DC polarization field generated by the low frequency coil is mainly parallel to the major axis of the coil. According to the measurement, the sensor can produce the Larmor signal with maximum amplitude when the DC polarization field is perpendicular to the geomagnetic field. Otherwise, the amplitude of the Larmor signal will be reduced. At the edge of the coil, the DC polarization field is perpendicular to the major axis of the coil. When the sensor is parallel to the geomagnetic field, the low frequency coil can still induce the Larmor signal. However the signal is weak and the system sensitivity is poor. The distribution of the polarization field described above is the key factor for the directivity of the sensor.

5 CONCLUSIONS

Factors affected directivity of sensor are discussed in this paper. Considering the direction of Changchun geomagnetic field is vertical to the south 30 degrees pointing to the ground. The experiments are carried out in both horizontal and vertical planes.

The experimental results indicate that when the sensor is perpendicular to the geomagnetic field, the signal amplitude and the sensitivity are both the highest. When the sensor is parallel to the geomagnetic field, the signal amplitude is the smallest and the sensitivity is the lowest. According to the simulation of low frequency coil, DC polarization field inside the sensor is mainly parallel to the major axis of the coil. But at the edge of the coil, DC polarization field is perpendicular to the major axis of the coil. All of these results reveal that the direction of DC polarization field can effectively influence the sensor's directivity. The sensor discussed in this paper have no dead zones, but poor omnidirection. An optimized low frequency coil design with equal perpendicular and parallel polarization magnetic fields will be investigated in further study.

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