Proton magnetometer sensor design and its performance

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Abstract. The proton sensor is an important part of the proton magnetometer, which is mainly responsible for generating a polarizing magnetic field and receiving induced signals. This paper presents the design scheme of the proton sensor, including the selection of the internal coil structure of the sensor, the selection of the internal solution, and the design of the sensor shielding layer. Then introduces the proton sensor of the Canadian GSM-19T proton magnetometer, which is one of the world's leading proton magnetometers. And the performance of the two sensors is compared and analyzed by designing sensor performance test experiment. The experimental results show that the initial amplitude of the test signal of the proton sensor is 2.2V, and the signal decay time constant is 0.86s, the performance is similar to that of the Canadian proton sensor.

1. Introduction
The traditional proton magnetometer is a scalar quantum magnetometer made based on the Larmor precession effect of hydrogen protons in the geomagnetic field. Because of its advantages of high reliability, simple operation, convenient portability, low price, etc. It has been widely used in many fields such as geological survey [1-3], coal field exploration, oil and gas exploration, archaeology [4,5] and mineral exploration and prediction.

The JPM series proton magnetometer developed by this research group has realized functions such as time, multiple measurement modes, multiple sampling rates, automatic tuning, tracking tuning, data storage and transmission on the console, which can meet the needs of field testing. But there are still deficiencies in sensor research. The performance of the proton sensor will have a vital impact on the technical indicators of the proton magnetometer. In view of the current problem, this paper studies the sensor of the proton magnetometer from principle to realization, and introduces in detail the internal coil structure of the proton sensor, the type of internal solution, and the method of shielding interference. Finally, a comparative experiment of sensor performance test was carried out on the JPM proton sensor and the Canadian GSM-19T proton sensor, and the experimental results were analyzed and evaluated.

2. Introduction to proton magnetometer sensor
The proton sensor is mainly composed of an internal solution and an internal coil. The types of internal solutions mainly include deionized water, kerosene, methanol, alcohol, glycerin, etc. They provide a large amount of hydrogen protons. Different solutions have different initial amplitudes of test signals and signal decay time constants. According to the structure, the internal coils can be divided into solenoid coils, cylindrical coils, toroidal coils [6] and “8” type coils [7]. The coil model diagrams of different structures are shown in Figure 1.
Figure 1 Different coil structure, diagrams (a) is a solenoid coil, (b) is a cylindrical coil (c) is a toroidal coil, (d) is a “8” type coil

The advantage of the solenoid coil is that it is easy to wind, but the coil structure has omni-directivity. When the direction of the magnetic field generated by the sensor is parallel to the direction of the magnetic field to be measured, the Larmor precession signal will not be generated, so that the magnetic field cannot be measured. That is, there is a measurement dead zone. And it is very sensitive to the external AC magnetic field. If there is a relatively large magnetic field of several tens of Hz on the surface of the earth, an induced electric potential will be generated on the solenoid. This induced electric potential will even be greater than the voltage generated by Larmor precession, thus affecting measuring.

Cylindrical coils and toroidal coils, because the magnetic field they generate is distributed in a loop inside the coil, they are omnidiirectional, there is no measurement dead zone. But the disadvantage is that it is difficult to wind, and it takes a lot of manpower to wind a coil, so it cannot be mass-produced. It can only be used in very professional occasions that require high omnidirectional magnetometers.

The last “8” type coil structure is convenient for winding. It only needs to wind two identical square coils and connect them together. And this structure does not have a measurement dead zone, but the signal amplitude generated in the worst case can only reach half of the best case.

The working principle of the proton sensor is the Larmor precession effect. According to atomic physics, protons will continuously spin around their centers. Since protons have positive charges and a closed loop is generated during the spin process, they will have magnetic moments. When the sensor is placed in a non-magnetic environment, the orientation of the magnetic moments of all protons in the solution is disorganized and does not show a uniform magnetic moment to the outside. When the sensor is placed in the geomagnetic field to be measured, because the geomagnetic field is stable, the total magnetic moment of the protons in the solution is oriented parallel to the direction of the geomagnetic field, and there is no Larmor precession effect. In order to generate the Larmor precession effect, in actual measurement, the console needs to generate a polarization current first. The generated polarization current will pass through the internal coil of the sensor to generate a polarization magnetic field in the direction perpendicular to the magnetic field to be measured. In the total magnetic field of the polarizing magnetic field and the geomagnetic field, the magnetic moments of the protons in the solution are oriented to align along the direction of the total magnetic field. The larger the polarizing magnetic field, the closer the angle between the geomagnetic field and the total magnetic field is to 90
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degrees. At this time, the console controls to suddenly turn off the polarization current, and the polarization magnetic field disappears, so the polarized proton magnetic moment will make Larmor precession along the direction of the geomagnetic field in the remaining geomagnetic field. The relationship between the magnetic field to be measured and the Larmor precession frequency is:

\[ B_e = 23.4874 f \]  

In the formula, \( B_e \) is the field strength of the magnetic field to be measured, the unit is nT, and \( f \) is the Larmor precession frequency, the unit is Hz. The precession of protons will be affected by thermal collisions, causing the induced signal to decay exponentially. The attenuation constant of the signal attenuation is related to the internal solution of the sensor. Then the proton sensor transmits the received Larmor signal to the console, and the console computer obtains the magnetic field value of the magnetic field to be measured by calculation through formula (1).

3. Sensor design and performance

The factors that affect the performance of the proton sensor mainly include the initial amplitude and decay time constant of the Larmor signal generated by the proton magnetometer during the test. When the proton magnetometer is during the test, in a measurement cycle, it includes a polarization phase and a signal receiving phase. In the polarization phase, the console provides the sensor with a DC polarization current, which generates an external magnetic field perpendicular to the measured magnetic field required for Larmor precession through the internal coil of the sensor. In the signal receiving phase, the internal coil of the sensor is responsible for receiving the generated Larmor signal. Under the same decay time constant, the larger the initial amplitude of the signal, the larger the remaining signal amplitude after the same decay time. When the environmental noise is the same, the signal-to-noise ratio of the proton magnetometer is also higher. Under the condition of the same initial amplitude of the signal, the larger the time constant, the slower the decay of the Larmor signal. Since it is necessary to ensure that the Larmor signal is greater than the noise interference signal during the test, the larger the time constant, the longer the effective measurement time.

In order to explore the performance of the JPM proton sensor, it is necessary to design experiments to test these two factors. The sensor performance test experiment is designed to first use the scopemeter to measure the Larmor signal generated by the proton magnetometer during the measurement, and in order to reduce the experimental error caused by chance, the process was tested six times and the measured data was saved, and then use the MATLAB software to analyze the data saved in the scopemeter. When analyzing the initial amplitude of the signal, the 6 measurement results will be displayed. When analyzing the time constant, the fitting function polyfit will be used to fit the attenuation of the Larmor signal according to the principle of least squares curve fitting, and finally the results of each fitting are displayed in order, and the average value is taken as the measurement result of the time constant.

4. Performance test experiment

4.1. Canadian Proton Sensor

Canada GEM Company is a well-known company with a history of more than 30 years that specializes in the development and production of magnetometers. The magnetometers it produces are recognized as the standard series of magnetometers and are sold well all over the world. The GSM-19T standard proton precession magnetometer produced by it is currently the magnetometer with the largest sales volume and the most widely used. Its application fields include various sub-disciplines of earth sciences such as mineral exploration, petroleum and natural gas structure survey, geological mapping, archaeology, and earthquake prediction. The main technical indicators of GSM-19T are: sensitivity reaches 0.05nT, resolution reaches 0.01nT, accuracy is ±0.2nT, measurement range is 20000 to 120000nT, gradient tolerance is greater than 7000nT/m, sampling rate is from 3 seconds to 60 seconds. It is one of the world's leading proton magnetometers.
First, a sensor performance test experiment was carried out on GSM-19T. The experiment site was selected in a grove in Jilin University. The results of the experiment are as follows:

![Image](image1.png)

**Figure 2** Larmor signal of 6 sets of data tested by GSM-19T proton sensor

![Image](image2.png)

**Figure 3** Time constant of 6 sets of data tested by GSM-19T proton sensor

Analyzing the experimental data, we can get that the initial amplitude of the signal of the GSM-19T proton sensor is 2.1V and the signal decay time constant is 0.85s.

### 4.2. JPM proton sensor

The physical picture of the internal coil of the JPM proton sensor is shown in the figure below:

![Image](image3.png)

**Figure 4** The physical picture of the internal coil of the JPM proton sensor
The internal coil of the JPM proton sensor uses a “8” type structure, which is composed of two square coils with exactly the same number of winding layers in reverse series. The same winding method is to ensure that the electrical parameters of two separate square coils are the same. For example, they have the same resistance and inductance. This ensures that the “8” type coil can have a certain degree of anti-interference ability during the actual measurement of the proton magnetometer. Because the external magnetic field interference will produce equal currents in two identical coils, and the two coils are connected in reverse series, interference current will cancel each other out due to the opposite directions.

The internal solution of the JPM proton sensor uses aviation kerosene. The main considerations for selecting the internal solution of the sensor are the signal attenuation time constant and the operating temperature. JPM series proton magnetometers usually have a sampling rate of 3.0s during testing. In this measurement mode, the polarization time of the sensor is 1.6s, the signal receiving time is 1.4s. Kerosene has a suitable decay time constant, so that when kerosene is used as an internal solution, it can ensure that the proton magnetic moment is completely oriented in the same direction as the total magnetic field of the geomagnetic field and the polarizing magnetic field during the polarization phase. and it can also ensure that there is sufficient effective measurement time in the signal receiving phase. And the boiling point of kerosene is generally higher than 150 degrees under standard atmospheric pressure, and the freezing point is generally lower than -30 degrees. This allows the proton magnetometer to perform experiments under extreme temperature conditions.

The method of applying shielding to the JPM sensor is to add a shielding layer on the outside of the sensor. Its working principle is that when the electromagnetic field passes through a medium, part of the energy at the surface of the medium will be reflected, and some of the energy will be contotaled inside the medium, so the electromagnetic energy actually transmitted will be attenuated to a considerable extent, therefore, the medium layer forms a shield against electromagnetic fields. The shielding effect can be measured by the shielding effectiveness SE. The shielding effectiveness expression in engineering is:

\[ SE = A + R + B(dB) \]  

In the formula, A is the absorption loss of electromagnetic wave transmission in the medium, R is the reflection loss of electromagnetic wave on the surface of the medium, and B is the loss of multiple reflections of electromagnetic wave inside the medium. Among them, the absorption loss A is proportional to the thickness of the shielding material. The higher the magnetic permeability and electrical conductivity of the material, the greater the absorption loss. The reflection loss R increases with the increase of conductivity, so gold, silver, copper and other good conductor metals have good reflection characteristics. And when the frequency is low, the shielding effectiveness is dominated by R, and when the frequency is high, A will play a leading role. Therefore, the JPM proton sensor chooses lithium copper conductive paint with good shielding effect as the material of the shielding layer.

The sensor performance test results of the JPM proton sensor are as follows:
Analyzing the experimental data, it is obtained that the initial amplitude of the signal of the JPM proton sensor is 2.2V, and the time constant is 0.86s, which is similar to the performance of the Canadian GSM-19T.

5. Conclusion
Experimental results and data analysis show that the initial amplitude of the test signal of the proton sensor of the Canadian proton magnetometer GSM-19T is 2.1V, and the signal decay time constant is 0.85s. The JPM proton sensor uses an internal coil with a “8” type structure, aviation kerosene as the internal solution, and lithium copper conductive paint coating as the shield. The initial amplitude of the test signal is 2.2V, and the signal attenuation time constant is 0.86s. It has reached performance similar to that of GSM-19T.

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