Design of digital detection circuit for signal of helium optical pump magnetometer

Summary

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Abstract. Magnetic field measurement technology is an important method to study physical phenomena related to magnetic field. Magnetic field measurement, especially weak magnetic field measurement, often plays a vital role and has important theoretical significance and engineering value for the research of high-performance magnetic field measurement instruments. The helium optical pump magnetometer is a high-precision magnetic measuring device that uses optical pumping and magnetic resonance to realize magnetic field measurement based on the principle of optical magnetic resonance. It has the advantages of low noise, wide measurement range, and low temperature working environment. It has significant advantages in the field of weak magnetic field measurement and can be widely used in scientific research, national defense construction, industrial production, daily life and other fields. The traditional detection circuit is based on a voltage-controlled oscillator as the core and an analog circuit-based detection system. The modulation signal is used for magnetic field detection. The detection speed is slow, and the modulated signal will superimpose an interfering magnetic field on the probe, affecting the measurement result. This paper designs a digital detection system with DDS technology as the core, which greatly improves the speed of detecting the magnetic field. A new swing swing frequency method is used to avoid the interference of the modulation coil, and a breakthrough in detection speed is achieved, reaching a sampling frequency of 20Hz. To meet the requirements of a system that requires continuous measurement at a faster rate.

1. Introduction

Helium optical pump magnetometer is a high-sensitivity magnetometer based on optical pump technology. It is based on the energy level of elemental atoms in the magnetic field to generate the Zeeman effect. Sensitivity magnetic measurement equipment [1-4]. It can be used not only to measure the total strength of the magnetic field, but also to measure the gradient of the magnetic field; it can be used to measure both the slow change of the magnetic field and the high-speed transient magnetic field [5]. In fields such as life, magnetic field measurement, especially weak magnetic field measurement, often plays a vital role [6-9].

The digital detection system of the helium optical pump magnetometer is to detect the change of light intensity in the optical system and generate a rapidly changing frequency signal to the RF coil to continuously adjust the RF field. At the same time, the swing frequency technology is used to quickly change the frequency of the RF field to find the magnetic resonance point. The characteristic of the resonance point has the largest amplitude of the double frequency and the smallest fundamental frequency. The double frequency is used to track to the vicinity of the resonance area. Finally, the fundamental frequency is judged to accurately track the resonance point, so that the light intensity passing through the absorption chamber is always kept weakest. That is to achieve the locking and...
tracking of the measured magnetic field by the RF field frequency.

2. Bandpass filter processing circuit
The band-pass filter can filter out part of the interference and noise of the signal. In this design, the state variable filter UAF42A is used for design. Figure 1 shows the internal structure diagram.

The transfer function of the band-pass filter is shown in equation (1):

\[
\frac{V_{bp}(s)}{V_i(s)} = \frac{A_{bp}(\omega_n / Q)}{s^2 + s(\omega_n / Q) + \omega_n^2}
\]

In the design of the band-pass filter, the calculation formula of each parameter is as formula (2):

\[
\omega_n^2 = \frac{R_2}{R_1R_FR_2C_1C_2}
\]

Figure 1 UAF42 internal structure diagram

\[
Q = \frac{R_4(R_G + R_Q)}{1 + \frac{R_G}{R_1} + \frac{R_G}{R_2}} \left(\frac{R_2R_F}{R_1R_FC_1C_2}\right)^{1/2}
\]

\[
A_{bp} = \frac{R_4}{R_G}
\]

Among them \( R_1 = R_2 = R_4 = 50K\Omega \), \( C_1 = C_2 = 1000pF \) has been determined by the chip internally. For the convenience of calculation, the substitution \( R_{F1} = R_{F2} \) is obtained as follows:

\[
\omega_n = \frac{10^9}{R_{F1}}
\]

\[
Q = 0.5\left(1 + \frac{50000(R_G + R_Q)}{R_G R_Q}\right)
\]

Suppose the gain of the band-pass filter \( A_{bp} \) is 1, the center frequency (the frequency of the modulation signal) \( f_0 = 1000Hz \), the width of the pass band \( \Delta f = 75Hz \), then
\[ \omega_n = 2\pi f_0 = 6280 \text{ rad/s} , \quad Q = f_0 / \Delta f = 13.3 , \quad \text{then:} \]

\[ R_{F1} = 10^9 / \omega_n = 159.236 k\Omega \]

(8)

\[ R_G = 50 k\Omega \]

(9)

\[ R_Q = 2.032 k\Omega \]

(10)

These three parameters are the parameters of the baseband pass filter, which can achieve the purpose of band pass filtering. The schematic diagram is shown in FIG. 2. After the design of this parameter, the purpose of band-pass filtering is achieved. The schematic diagram is shown in Figure 2. Since the fourth operational amplifier is also integrated in UAF42A, the amplifier can be used to amplify the filtered signal after bandpass filtering. The magnification is 50 times, so in Figure 2 \( R26 = 500 K\Omega \), \( R27 = 10 K\Omega \).



Figure 2 The principle diagram of baseband pass filtering

Similarly, suppose the gain of the band-pass filter \( A_{BP} \) is 1, the center frequency (frequency of the modulation signal) \( f_0 = 2000 Hz \), the width of the pass band \( \Delta f = 150 Hz \), then \( \omega_n = 2\pi f_0 = 12560 \text{ rad/s} , \quad Q = f_0 / \Delta f = 13.3 \), then:

\[ R_{F1} = 10^9 / \omega_n = 79.618 k\Omega \]

(11)

\[ R_G = 50 k\Omega \]

(12)

\[ R_Q = 2.032 k\Omega \]

(13)

These three parameters are the parameters of the baseband pass filter, which can achieve the purpose of band pass filtering. The schematic diagram is shown in FIG. 3. Due to the existence of the fourth operational amplifier of UAF42A, the amplifier can be used to amplify the double frequency signal after band-pass filtering. Select the magnification as above.



Figure 3 Schematic diagram of double frequency band pass filtering
3. Fundamental frequency signal processing circuit

The fundamental frequency signal extracted by the band-pass filter is processed by the lock-in amplifier, and the phase sensitive detector is the core link. Because the phase-sensitive detector is very sensitive to both amplitude and phase, the signal should be compensated for the phase before entering the phase-sensitive detection. The purpose is to better cooperate with the reference signal to obtain the optimal amplitude response characteristics, which can also improve the sensitivity of the circuit system. The schematic diagram of the phase shift circuit is shown in Figure 4 (a).

The principle diagram of the phase sensitive detector is shown in Figure 4 (b).

If R4, R5, 56 are equal, the amplification factor is 1, so the output signal of the operational amplifier can be expressed as $V_o = V_i$ (when the switch is open), $V_o = -V_i$ (when the switch is closed), because the input signal is less than the resonant frequency when the RF frequency is less than the reference signal is inverted, and the amplitude is from small to large to small, so the output of the phase sensitive detector appears as the negative part of the magnetic resonance curve model. When the RF frequency is greater than the resonance frequency, the input signal is in phase with the reference signal, and the amplitude is from small to large to small, so the output of the phase-sensitive detector appears as the positive part of the magnetic resonance curve model.

4. Processing circuit of double frequency signal

The modulation of the double frequency is different from the fundamental frequency. Since the double frequency signal is an auxiliary signal, the final guarantee of accuracy is the signal locked and amplified by the fundamental frequency, so the requirement for the double frequency signal is not high. The traditional method uses a lock-in amplifier to improve the signal-to-noise ratio of the double frequency, but sacrifices the dynamic response of the circuit system, so that the tracking lock speed is limited. Perform conditioning and use a low-pass filter with a cutoff frequency of 100 Hz to process the rectified signal to ensure the dynamic response of the circuit system, improve the tracking lock speed, and achieve a breakthrough in sampling rate. The schematic diagram is shown in Figure 5. In order to make the signal output voltage level adjustable, a two-stage inverting operational amplifier is used for amplification. One stage is used to amplify 4 times, and the other stage is used to ensure that the phase of the signal remains unchanged.
5. Application of DDS technology
In the entire detection system, the generation of radio frequency is crucial. To ensure high frequency accuracy and fast switching speed, the frequency can be freely changed and the phase is continuous. Direct digital frequency synthesis (DDS) meets this requirement.

In this project, the AD9851 special circuit is used for RF signal generation. The schematic diagram is shown in Figure 6.

![Figure 6 AD9851 schematic](Image)

The RF signal generated by the AD9851 cannot directly drive the RF coil, and a corresponding drive circuit is required. This design uses the CD4069 inverting amplifier for RF drive, which can isolate the AD9851 from being directly connected to the external sensor and generate sufficient driving capacity, even if the sensor is unexpected, it will not cause loss to the AD9851. The schematic diagram of the drive circuit is shown in Figure 7.

![Figure 7 RF drive circuit](Image)

The square wave generated by the AD9851 is a unipolar signal, which needs to be converted into a bipolar signal. After the coupling capacitor is added, it can be converted into a bipolar signal. It can also isolate the mutual interference between the front and back stages, but the inverter circuit is still unipolar. After the power supply is driven, the signal becomes a unipolar signal again. Therefore, a coupling capacitor needs to be added after the output of the second stage inverter, and then the voltage is divided and output to the RF coil.

6. Detection system based on swing frequency
The traditional method of modulating the coil will generate a disturbing magnetic field and affect the measurement accuracy. In order to further speed up the detection speed and stability, the swing frequency method is used to remove the modulation coil, and its structural block diagram is shown in Figure 8:
Different from the traditional frequency modulation method, the new swing frequency method is adopted. At the same time of sweeping the frequency, the current sweep frequency is swung, so that the role of the previous modulation coil can be achieved, and the interference of the modulation coil is eliminated. When away from the area near the resonance frequency, conduct a frequency search in large steps, then enter the vicinity of the resonance frequency area, use the double frequency signal as the auxiliary judgment condition, use the fundamental frequency signal as the precise tracking resonance frequency, and constantly fine-tune the resonance frequency to adapt to small changes in the external magnetic field.

ADS1256 also uses the finished module for easy application, and its schematic diagram is shown in Figure 9:

![Figure 9 ADS1256 schematic](image)

## 7. Experimental results

### 7.1. DDS technical test

The radio frequency signal of this design uses a square wave output. Figure 10 shows the different output frequency waveforms during the frequency sweep process. It can be seen that the frequency output during the frequency sweep process is very stable.

![Figure 10 DDS technical test](image)
The measurement range of the digital detection system designed in this paper is 32000nT to 64000nT, and the frequency range of the corresponding RF signal is 900KHz to 1.8MHz. The fundamental frequency and the double frequency signal have been led out from the test point, and the signal characteristics of the two channels of the oscilloscope are simultaneously observed. The frequency range set in the program is from 1MHz to 2MHz, and the step frequency is 1Hz, 10Hz, 100Hz, and 200Hz, respectively, and the waveform shown in Figure 11 is obtained.

In Figure 11, the abscissa is the scan time, and the ordinate is the amplitude. The amplitude characteristics of the fundamental frequency and the double frequency can be clearly observed, which is consistent with the theoretical model. Outside the resonance zone, the amplitudes of the fundamental frequency and the double frequency are very small. When entering the resonance zone, two peak points appear in the envelope of the fundamental frequency signal, while at the magnetic resonance point, the fundamental frequency signal is zero, and the double frequency signal amplitude is the largest. When the step frequency is set to 180 Hz, the tracking frequency of 20 Hz can be achieved with equal step sweep.

The precise tracking of the resonance point is achieved by the signal characteristics of the fundamental frequency. Outside the resonance zone, the amplitude of the fundamental frequency signal is very small. When entering the resonance zone, the fundamental frequency signal has two peak points, which are The fundamental frequency signal crosses the zero point and changes monotonously, and the zero point is the magnetic resonance point to be tracked by the detection system. After judging into the resonance area by the amplitude of the double frequency signal, the detection system starts to collect the voltage of the fundamental frequency signal, and the position of the resonance point is judged by the monotonic comparison, while continuously detecting whether the amplitude of the double frequency
signal is in the resonance area or exceeds the resonance area. Perform a system reset and rescan the frequency.

7.2. Field test
In order to better test and analyze the helium optical pump magnetic measurement system developed in the paper, the detection system was tested in the field in the suburbs. There are few peripheral electrical equipment and passing vehicles, and the magnetic field interference generated by the outside world is weak. The test site is shown in Figure 12.

In the experiment, the continuous measurement of the fixed-point space magnetic field is carried out, and the magnetic measurement system is placed on the ground still for 30 minutes. The change of the magnetic field value is shown in Figure 13. It can be seen from the measurement data in the figure that the field magnetic field has high stability, the data fluctuation range is small, and the average difference of multiple measurements is only 40nT, indicating that the stability of the magnetic field detection system designed in this paper has reached a high level.

After the static continuous test, the magnetic field detection distance comparison test was carried out. First place the magnet 20cm away from the magnetic probe, start moving the magnet from near and far, stay for 5 seconds for every 1 meter of movement, and then return to the starting position from far and near. The test results are shown in Figure 14. As can be seen from Figure 14 (a) and (b), the test results reflect the data mirroring process well, especially at a distance of about 2 meters from the probe, magnetic field fluctuations (dotted lines in the figure) can be inferred. Out, there are metal objects near the place that have an effect on the average magnetic field.

![Field test field diagram](image1)

![Data graph of continuous measurement of external magnetic field](image2)
8. Conclusion

The digital detection system of the helium optical pump magnetometer designed in this paper, by studying the characteristics of the fundamental frequency and double frequency in the magnetic resonance region, uses the lock-in amplifier’s high signal-to-noise ratio but narrow output signal bandwidth and slow response speed. The characteristics of the large (fast response) double-frequency full-wave rectification and filtering output are tracked to the vicinity of the resonance area through the double-frequency signal, and the resonance point is accurately tracked through the fundamental frequency, so that the accuracy and speed of the measurement of the detection system are guaranteed. The adopted DDS technology outputs a wide range of RF frequencies, which can meet the measurement requirements of the entire geomagnetic field.

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