Development and Implementation of Information Processing System for Cesium Pumped Magnetometer

Zhenxin Yu[1]

Hangzhou Applied Acoustics Research Institute
kjxmabc@126.com, 18758184929

ABSTRACT

Weak magnetic field measurement technology is widely used in geomagnetic field inspection, geological survey, biomedical and military fields. Cesium-pumped magnetometer is a kind of weak magnetic field detection equipment with high precision and sensitivity, which is based on Zeeman effect of cesium atoms in magnetic field, optical pumping and magnetic resonance technology. In order to give full play to the role and value of cesium optically pumped magnetometer, many scholars began to develop the information processing system of cesium optically pumped magnetometer. Based on this, this paper introduces the basic principle of cesium optically pumped magnetometer, and introduces the development and implementation of cesium optically pumped magnetometer from two aspects of hardware facilities and software, in order to fully and effectively improve the information processing efficiency of cesium optically pumped magnetometer.

Keywords: *cesium optically pumped magnetometer; Information processing; System research and development*

1. INTRODUCTION

Nowadays, the application range of magnetic field measurement technology is more and more extensive, including bomb mining and military anti-submarine activities. Cesium-pumped magnetometer is a kind of magnetic measuring equipment with high precision, which is highly concerned by various countries [1]. Nowadays, many high-precision products have been developed abroad, but our country is still in the research and development stage, and there are relatively few mature products. Based on this, more and more scholars begin to discuss and study the information processing system of cesium optically pumped magnetometer, so as to promote the improvement of magnetic measurement efficiency in China. Therefore, how to develop and realize the information processing system of cesium optically pumped magnetometer has become the focus of many scholars.

2. RESEARCH STATUS

At present, the research of frequency detection technology has been paid attention by scholars. In actual production and research activities, the improvement of detection accuracy of many physical quantities mainly depends on the development of time-frequency measurement and control technology. Therefore, high-precision video signal detection technology is the focus of many developed countries [2]. With the development of precision positioning, communication, space detection and other technical fields, the accuracy requirements of video signal measurement technology are constantly improving. For example, the satellite-borne atomic clock on Beidou navigation satellite in China has a frequency stability of 10^{-12}, so the design process of real poison measurement equipment puts forward strict requirements. It can be divided into the following three types:

S. A. R. Khan et al. (Eds.): ICMSSE 2022, AHCS 12, pp. 665–670, 2023.
https://doi.org/10.2991/978-94-6463-056-5_97

Table 1 Comparison of Typical Frequency Measurement Schemes

Measurement method	Measuring principle	advantage	deficiency
Frequency measurement method	Set the gate time to 1s, and record the number of pulses passing through the signal to be tested within the gate time, which is the frequency of the signal to be tested.	Simple principle and implementation.	It can only detect the frequency simply, and the resolution is low. It is necessary to extend the gate time to improve the resolution.
Period measurement method	The gate signal is formed by the signal to be tested, and the pulse number of the standard frequency signal in the gate is recorded in detail to obtain the period of the signal to be tested, and then the frequency is obtained.	It can achieve the effect of equal progress measurement with high resolution.	To improve the resolution, it is necessary to increase the frequency of the standard frequency signal. The cost of ultra-high frequency standard frequency signal is high.
Cursor method	Through two standard frequency signals with similar frequencies, the coincidence detection and the timely departure counter record the number of two standard frequency signals, so as to obtain the period of the signal to be measured, and then calculate the reciprocal to obtain the frequency.	And high resolution can be obtained.	It is more difficult and demanding for the equipment core, and it is more difficult to realize the coincidence circuit because it is necessary to have a digital lock to generate two standard frequency signals with similar frequencies.

3. DETECTION PRINCIPLE OF CESIUM OPTICALLY PUMPED MAGNETOMETER

The detection principle of optical pumping magnetometer is that the energy levels of cesium atoms in the cesium absorption chamber are split due to Zeeman effect in the external magnetic field environment, and the ions at each Zeeman level are irradiated by the pump light to cause the optical pumping effect, which eventually leads to the polarization distribution of each ion Zeeman level [3]. In addition, if the change frequency of the added RF magnetic field is consistent with the transition frequency of the adjacent Zeeman energy level interval, each self-care distribution will gradually realize depolarization, and the optical magnetic resonance effect will be produced in the state of dynamic balance [4]. At this moment, the change frequency of light intensity in the absorption chamber is proportional to the intensity of external magnetic field, and the basic intensity of external magnetic field can be obtained by measuring this frequency.

Cesium optically pumped magnetometer is mainly composed of magnetic sensing probe and signal detection system, in which the magnetic sensing probe can be used to realize the optical pumping effect and magnetic resonance effect of working atoms in the external magnetic field to be measured, and the detection of the energy level interval transition frequency of Zeeman is converted into the detection of the transmitted light signal, which significantly increases the signal-to-noise ratio [5]. The value of the signal detection system is to detect the replication, phase and frequency related data of the optical signal, and then use the feedback loop to control the changing frequency of the RF magnetic field to make it stable at the resonant position. Finally, the detected frequency is used to calculate to confirm the strength of the external magnetic field to be detected.

4. HARDWARE DESIGN OF INFORMATION PROCESSING SYSTEM OF CESIUM OPTICALLY PUMPED MAGNETOMETER

4.1 The overall design of the system

The main function of high-precision information processing technology is to accurately detect the output signal frequency of the physical system, that is, the larmor frequency, and after obtaining its frequency, confirm the value of the external magnetic field by combining the relationship between the larmor frequency and the external magnetic field. In addition, it is necessary to obtain the geographic location of the positioning signal to confirm the measured position and then apply the algorithm to obtain the magnetic distribution map. In addition, the R&D personnel should confirm the influence of the physical system attitude on the normal operation of the equipment, and at the same time, the attitude sensing equipment should be used to confirm the current working state of the cesium optical pump magnetometer, so that the user can adjust the direction in time, and it is convenient to intelligently adjust the physical system according to relevant algorithms.

Combined with the above actual requirements, the system hardware includes the following parts: core board circuit, mixer board circuit and direct frequency doubling circuit. As shown in the following figure:

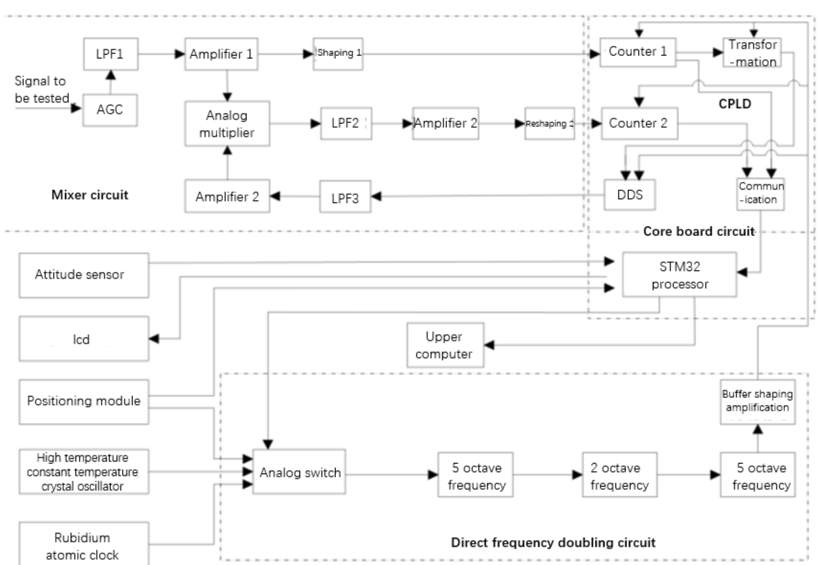

Figure 1: Structure diagram of information processing system of high-precision cesium optically pumped magnetometer

Among the above hardware, the application of mixer circuit is relatively complicated, including AGC, mixer circuit of analog multiplication equipment, developed circuit and filter circuit [6]. The core board mainly contains STM32 processing equipment, CPLD and its subsidiary circuits. In addition to the above modules, other module circuits such as liquid crystal display and high-temperature constant-temperature crystal oscillator are added to the periphery. The frequency measurement function includes mixing board and digital logic realization in CPLD. The role of the attitude sensor is to detect the attitude data of the physical system, and the positioning module is responsible for obtaining the positioning data. STM32 processor is responsible for collecting the data of different modules, and managing the liquid crystal display and the communication of upper devices. The frequency doubling circuit is mainly responsible for doubling the high-stability standard source signal to the target frequency of 200MHz as the standard frequency signal.

4.2 Design scheme of direct frequency doubling

The frequency doubling coefficient is 20, so in the process of designing the direct frequency doubling circuit, you can first use the method of 5 frequency doubling, then apply the method of 2 frequency doubling twice, and finally realize the output of the frequency doubling signal of 200MHz. The structure block diagram is shown in the following figure:

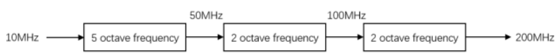

Figure 2: Overall block diagram design mode of 20 frequency doubling circuit

The basic structures of all levels of frequency doubling circuits are similar, and the front end is equipped with a Class C FET amplifier circuit and the first level resonant amplifier circuit with LC frequency selection network, which forms a 5-frequency doubling unit circuit [7]. The former takes the role of stroke pulse wave to supply rich harmonic components, and then uses LC resonance to realize preliminary frequency selection, while the latter uses high Q frequency selection network to continuously optimize signal quality. The second-stage frequency doubling is designed by resonant amplification equipment.

4.3 The overall scheme design of the mixer board

This part of the circuit mainly works with the digital logic of the programmable roadbed device to realize high-precision frequency detection of the signals transmitted by the physical system. The connection relationship of each link is shown in the following figure:

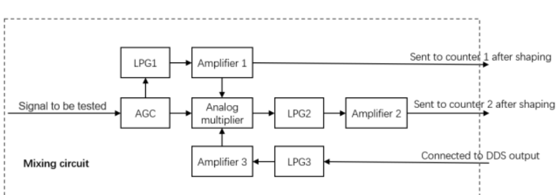

Figure 3: The relationship between the main modules of imposition

The module is mainly subdivided into three signal channels, in which the channel A is used to adjust the amplitude of the signal to be measured, including AGC, LPF1 and amplifier 1; Channel B is responsible for the filtering and amplification of DDS output signal, specifically including LPF3 and amplifier 3; Channel C is used for low-pass filtering and amplifying the difference frequency signal after mixing, specifically including LPF2 and amplifier 2. These three components cooperate with each other to realize analog signal processing.

4.4 Circuit design of attitude sensing equipment

When the angle between the optical axis of the optical pumping magnetometer and the geomagnetic field is equal to 6°, it will enter the dead zone and cannot be used normally [8]. After entering this area, Zeeman splitting fails, which weakens the signal-to-noise ratio of the signal system and makes it impossible to form an effective signal. In order to adjust the physical system to the best working state, it is suggested that the attitude sensing device should be used to detect the attitude information data of the physical system, so that users can collect the data for adjustment, and the remote attitude adjustment can be realized by using the three-dimensional drawing of upper-level equipment and mechanical equipment.

Here, the triaxial acceleration sensor is mainly used to detect the inclination and elevation, and the magnetoresistive sensor is used to detect the included angle with the geomagnetic field. The way to measure the inclination angle and elevation angle is to determine the angle between all axes of the acceleration sensor and the reference position separately. Generally, the X axis and Y axis of the reference position picking device are in the horizontal direction, and the Z axis and the horizontal plane keep the vertical relationship. Read the three-axis gravity acceleration projection, x, y, z, and combine with geometric knowledge to get:

$$\theta = \tan^{-1}\left(\frac{x}{\sqrt{y^2+z^2}}\right) \tag{1}$$

$$\psi = \tan^{-1}\left(\frac{y}{\sqrt{x^2+z^2}}\right) \tag{2}$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{x^2+y^2}}{z}\right) \tag{3}$$

Among them, θ and ψ represent tilt angle and elevation angle, which should be paid special attention to. And the included angle formed by the optical axis and the geomagnetic field direction can be detected by a triaxial magneto-resistive sensor, which calculates the included angle formed between the geomagnetic field and the optical axis of the physical system by using the projection of the detected geomagnetic field on three different axes of the magneto-resistive sensor.

5. SOFTWARE DESIGN OF INFORMATION PROCESSING SYSTEM OF CESIUM OPTICALLY PUMPED MAGNETOMETER

5.1 Digital logic software design and improvement

According to different functions, the whole digital logic can be subdivided into counter 1 module from cnt_1, counter 2 module cnt_2, conversion module convert, digital frequency synthesis module dds and SPI communication module spi. See that QuartusII software can be used to design the internal top-level module diagram, and Verilog language can be used to design the internal module.

The overall workflow of the digital part is as follows: Firstly, after low-pass filtering and developed credit reporting, the signal to be tested is transmitted to cnt_1 module in one path, and the gate time of 0.1 is formed by dividing the standard signal. The cnt_1 measurement is controlled to obtain the frequency f_0, and the other path is mixed with dds output signal.

Secondly, the detection result f_0 is transmitted to the convert module. With the improvement of calculation flow and special processing of convert module, the floating-point operation is completed, and finally the frequency control word N is calculated.

Thirdly, N is directly transmitted to the frequency synthesis module dds to output a signal with a frequency difference of 500Hz with the signal to be measured. After the signal is adjusted, it is mixed with the signal to be tested, then the difference frequency signal is refined by low-pass filtering, and a difference frequency signal f_1 which can be detected is obtained by amplification and shaping.

Fourthly, the difference frequency signal is accurately detected by cnt_2, and the detection result is transmitted to spi and f_0 to form a data packet which is transmitted to the embedded processor.

The key here is to ensure that the frequency error of the difference frequency signal after mixing should be reduced as much as possible, which depends on the frequency accuracy of DDS synthesized signal. Here, a high-precision clock source is used as a reference signal, such as a 10MHz rubidium atomic clock signal, with the highest frequency stability of 10^{-12}. This signal becomes a standard frequency signal after direct frequency doubling processing, which ensures the accuracy of the reference. In addition, the frequency error of DDS synthesized signal should be lower than 10^{-3}Hz required for measurement accuracy. The 48-position phase accumulation device is used here, and the DDS frequency resolution value is 10^{-7}Hz under the background that the standard signal is 200MHz. Therefore, the error caused by frequency mixing is lower than the accuracy requirement of frequency detection, which ensures the validity of the results.

Furthermore, since the following difference frequency signal changes in a small range around 500Hz, the frequency measurement accuracy of counter 1 only needs to meet the level of 10Hz, and the corresponding gate time is 0.1s. As for the 500Hz frequency difference design, the fixed frequency difference will lead to the narrow bandwidth of the output difference frequency signal, which provides convenience for the design of filtering equipment after mixing. At the same time, it is necessary to consider the sampling rate in the whole measurement process. Although the low frequency difference signal is detected by periodic method, the accuracy is improved, but it will cause the gate time to increase, which is not conducive to the growth of the whole sampling rate. However, if the difference signal frequency value is too high, the measurement accuracy will be weakened, so it is necessary to ensure the balance between sampling rate and accuracy.

Finally, it should be ensured that the data obtained from the previous and subsequent monitoring are completely consistent, that is, the frequency of dds output signal will not change during the monitoring of difference frequency signal by counter 2, and the frequency of dds output signal can be changed at a uniform speed only after the monitoring of counter 2 is finished. Here, the signal synchronization mechanism is applied. Before the measurement of counter 2 is completed, the measurement result of counter 1 is locked and saved to ensure that the frequency of dds output signal does not change. After the measurement of counter 2 is completed, the measurement result of counter 1 can be updated and output for the next detection.

5.2 Embedded design

The embedded software focuses on the reception and calculation of digital logic measurement information data, micro positioning data and attitude measurement data. The first job is to initialize all modules and global variables, and then introduce them into the main program loop. First, the processing of larmor frequency data reading meter of programmable logic device is realized, then the reading and processing of Beidou /GPS positioning data and the reading and processing of attitude sensor data are completed, and finally the communication combination between embedded processing device and host device is completed, that is, the necessary data is packaged and uploaded to the host device in an appropriate way.

5.3 Software design of upper computer

The main function of the upper computer software is to further collect and process the measurement information data. Part of the subprogram is developed with QT library under QT-creatror. It can realize the following functions: First, complete serial communication with the lower device; Second, analyze the data and display it in space; Thirdly, according to OpenGL graphics library, combined with the information data obtained by attitude sensor equipment, the 3D image of physical system is drawn, which is convenient for remote control.

6. CONCLUSION

Cesium-pumped magnetometer is a very sensitive physical system, but it must be integrated with a high-precision information processing system to achieve ideal performance. Therefore, it is particularly important to develop the information processing system of cesium optically pumped magnetometer. R&D personnel should make clear the working principle of cesium optically pumped magnetometer, and design hardware and software facilities reasonably, so as to develop the information processing system of cesium optically pumped magnetometer to meet the actual needs, so as to give full play to the role of cesium optically pumped magnetometer and improve the processing quality and efficiency of relevant information data. In the future research, we will further try to explore low-power solutions to minimize the functional loss. For example, we will try to replace the original lead-acid battery with lithium battery, and actively explore how to realize the miniaturization of cesium optically pumped magnetometer to improve its portability.

REFERENCES:

[1] Dong Haifeng, Jun Guo, Zhang Haiyang, et al. Double AOM laser frequency stabilization system for cesium atomic magnetometer [J]. chinese journal of scientific instrument, 2020,41(10):129-135.

[2] Dou Ziyou, Cheng Defu, Zhou Zhijian. Frequency measurement method of optically pumped magnetic gradiometer based on FPGA [J]. Journal of Sensing Technology, 2018,31(2):170-174.

[3] Fu Jiqing, He Qing, Zhang Wei. Signal characteristics of laser-pumped cesium-helium magnetometer [J]. Journal of Metrology, 2020, 41(3): 354-358.

[4] Liu Leisong, Zhang Le, Lu Yuantian, et al. Study on noise characteristics of photoelectric detection circuit of cesium optically pumped magnetometer [J]. chinese journal of scientific instrument, 2018, 39(9):203-210.

[5] Wang Weidong, Yang Guoqing, Liang Shangqing, et al. Design and research on low power control system of atomic magnetometer [J]. Shanghai Aerospace, 2017,34(2):47-51

[6] Xu Qingfeng, Liu Li, Huang Shenshuo, et al. Research and experiment on compensation method of cesium optical pump aeromagnetic system of a domestic UAV helicopter [J]. Journal of Naval Aviation Engineering College, 2020,35(1):153-160.

[7] Xie Yin, Luo Fangxue, Zhang Fan, et al. Geomagnetic noise compensation technology based on cesium optically pumped magnetometer [J]. Measurement Technology, 2022,42(1):26-31.

[8] Zhang Jin, Huang Chenggong. Design of portable magnetometer data acquisition system based on Raspberry Pi computing module and FPGA [J]. Electronic Testing, 2021(24):17-19.