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Digital Design of High-Precision Magnetic Field for Hydrogen Maser †

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Abstract: Hydrogen maser is the time and frequency reference source of metrology, punctuality and scientific research in China, and it is the core equipment of national important projects such as deep space exploration, navigation and positioning. In this paper, a scheme to realize the digitization of magnetic field of hydrogen atomic clock is presented. We first design a simple programmable precise current source. And then we use a microprocessor-based intelligent control algorithm to automatically find the maximum power point corresponding to the output voltage of the single-chip microcomputer. Finally, the constant output voltage. In the actual test process, we designed the constant current source circuit output current step quantity can achieve 5 μA high precision, spectrum analyzer sampling efficiency and the control system work accuracy is very high.

Keywords: magnetic field; constant current source circuit; digitization; spectrum analysis; maximum operating power point

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1. Introduction

Hydrogen maser has the advantages of high frequency stability and low frequency drift. It has been widely used in the deep space exploration, navigation systems and frequency calibration. The quantum transition of hydrogen atoms and its signal detection are realized in the cavity-blub assemble of the hydrogen maser. Atomic transition signal amplitude of hydrogen maser directly determines the system signal to noise ratio, and thus affects system performance, which makes cavity-bulb assemble one of the most important parts of hydrogen maser. Straight solenoid is widely used in cavity-bulb assemble of hydrogen maser to generate the constant magnetic field for atomic transition 1**.**

The current of the straight solenoid is completed by applying voltage and matching digital dials with different resistance values. At present, We use the manual method to dial the digital dial, and there are big human factors that the signal we dialed is strong or weak is based on experience. The power point we actually used before may only be a relatively large value. Moreover, in view of the artificial dialing, the number of digits of the dial is limited, and the stepping amount of the digital dial is rather large. It will inevitably introduce a variety of transition frequency signal noise, affect the signal to noise ratio of the output frequency signal of the hydrogen maser, and ultimately has an impact on the hydrogen maser frequency stability. Here we show a digital design of the magnetic field of the hydrogen maser.

2. Methods/Results

Prior to this, we could only manually adjust the current by changing the magnetic field coil with a very large step on the voltage dial, usually more than 10 times, then take the maximum magnetic field power as the output voltage, in order to obtain a relatively large output power.

The hydrogen clock has three identical dials: one for the main field coil (main magnetic field), one for the upper field coil (compensating magnetic field), and one for the lower field coil (compensating magnetic field).

The shape of the dial is shown in Figure 1:

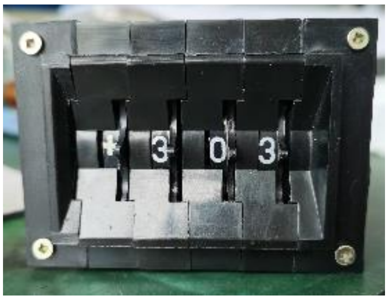

Figure 1. the shape of the dial.

The first digit from left to right is the positive and negative sign, which represents the direction of the current and is used to set the magnetic field in different directions. The last three digits represent the relative strength of the output voltage of the magnetic field.

Take the main magnetic field of the hydrogen atomic clock. The magnetic field coil is made of copper (indicated by dielectric constant and conductivity). The total resistance of the magnetic field coil is 80 ohms and the turns are 136 turns. The resistance of the main magnetic field coil of the hydrogen atomic clock is about 80 Ω. When the value of the main magnetic field dial is 010, the corresponding voltage output is 3.4 mV, the resistance value is 80 ohms and the corresponding current value is 42.5 μA. So the magnetic induction is 72.59 μG.

As can be seen from Tables 1 and 2, no matter how the dial is turned, the minimum step is only 0.3 mv, which makes it difficult to accurately dial to the point of maximum magnetic field power, it also takes a lot of manpower and time to move the dial several times to reach a relatively large power point.

Table 1. Small step voltage.

Results of The Main Magnetic Field Test			
Dial character	*Voltage/(mV)*	*Dial character*	*Voltage/(mV)*
001	0.3	010	3.4
002	0.7	020	6.8
003	1.1	030	10.3
004	1.5	040	13.7
005	1.8	050	17.2
006	2.2	060	20.6
007	2.6	070	24.1
008	3.0	080	27.5
009	3.4	090	31.0

Table 2. Big step voltage.

Results of The Main Magnetic Field Test			
Dial character	*Voltage/(mV)*	*Dial character*	*Voltage/(mV)*
100	34	111	38
200	68	222	76
300	103	333	114
400	137	444	152
500	171	555	190
600	206	666	229
700	240	777	267
800	274	888	305
900	309	999	343

So we design a scheme to digitize the magnetic field of hydrogen atomic clock by scanning the power value of the magnetic field coil with a small step voltage, and then find the corresponding voltage of the maximum power point and keep the output constant.

First, the microprocessor outputs a PWM square wave whose duty cycle gradually increases from 0 to 1 in steps of 1/65,535 to the high-precision current source circuit. Then the precision current source passes through a second-order low-pass filter, multiplexer, and operational amplifier. The magnetic field coil of the hydrogen maser generates a constant weak magnetic field by applying a micro current. The magnetic field provides the quantization direction for the transition of the hyperfine structure energy level, so that the transition $[F=1, m_F=0] \leftrightarrow [F=0, m_F=0]$ (σ transition) is achieved. The output frequency signal of the hydrogen maser is sampled by the host computer design system and processed by real-time images, and then handed over to the microprocessor to control and compare the power of the output frequency signal. Finally, based on the intelligent control algorithm, real-time search and comparison of the maximum power point together with its corresponding output voltage, determine the maximum output signal power point, effectively improve the signal to noise ratio. Consequently it can improve the frequency stability of the hydrogen maser (Figure 2).

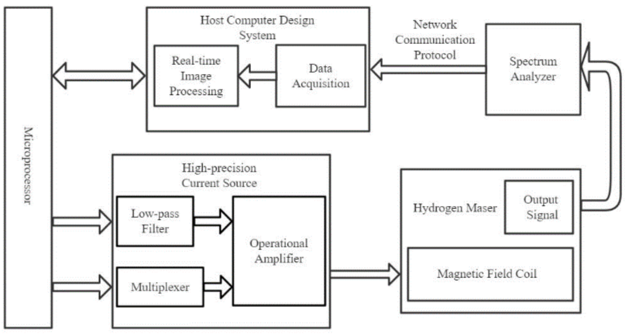

Figure 2. system structure diagram.

2.1. The Precision Current Source

Because the current required by the magnetic field coil of hydrogen atomic clock is relatively small, when the current is added to the magnetic field coil, it is necessary to add small step by step to get the working power under different current, and the required output current is very stable 2. The current can only be superimposed by a large step, which does not meet the requirement of hydrogen atomic clock for magnetic field coil current, and its stability is not up to the requirement. Therefore, we have innovated and invented a precise constant current source circuit controlled by voltage, which can not only output the current at a step rate of less than 5 microamperes, according to the magnetic field conditions can choose different gear output in line with the magnetic field state of large current, small current or smaller current (ten times a gear) 3.

In order to be able to accurately control the voltage and stable output micro-ampere level constant current, the circuit is designed as shown in Figure 3:

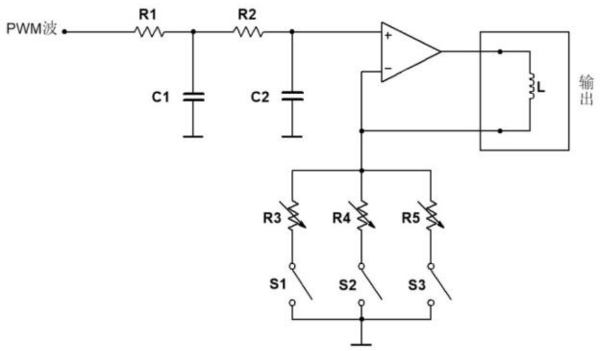

Figure 3. the precision current source.

PWM wave is a square wave with adjustable duty ratio, and the maximum voltage is 3.3 V. There is a common scheme for using a control system to output a controllable voltage: using a dedicated DAC chip. Although the DAC chip response speed is faster, but the common 8-bit or 10-bit DAC chip resolution is low, and DAC chip often has some nonlinear characteristics. Therefore, this paper uses PWM wave with adjustable duty ratio to carry out Fourier expansion for square wave with high level A, low level 0, duty ratio P (0 < p < = 1) and angular frequency ω through the low-pass filter:

$$f(t) = p \cdot A + \sum_{n=1} \left[A(\sin n\pi p - \sin n\pi (2-p)) \cos n\omega t \right] \quad (1) \tag{1}$$

The resistors R1 and C1 form a low-pass filter, and similarly the resistors R2 and C2 form a low-pass filter, and the two filters are connected in series to form a second order low-pass filter to filter out the AC component, the DC component is guaranteed to enter the operational amplifier, thus achieving a stable and controllable DC voltage output. When designing the filter circuit, one hand should reduce the ripple as far as possible, on the other hand should take into account the response speed of the circuit 4.

The output voltage of the filter is controlled by the duty cycle of the PWM wave. When the duty cycle of the PWM wave changes, the change of its DC component is equivalent to a step signal superimposed on the original DC component. The Fourier transform of step signal is composed of an impulse function which reflects the DC component and an inverse proportional function which reflects the change of the signal. The better the performance of the filter, the stronger the inverse proportion function is suppressed, which means that the response of the output voltage is slower when the duty cycle of the input square wave is changed.

Therefore, it is contradictory to reduce the ripple and speed up the response. The filtering performance should not be too good while ensuring that the uncertainty brought by the ripple is not higher than that of the rest of the system. On the other hand, the higher the frequency of PWM wave, the smaller the ripple after filtering, of course, too high frequency of PWM wave may also bring uncertainty. Therefore, the ripple should be reduced by increasing the PWM frequency appropriately 5.

The invention enables the filtered DC voltage to be used to control a voltage control current source constructed by an in-phase operational amplifier as shown in Figure 5, and then the constant current source circuit outputs the required current value.

Because the hydrogen atomic clock is installed for the first time, it is necessary to observe the output frequency signal, it is necessary to pass a strong current through the

Zeeman magnetic field coil to see the frequency signal generated by the transition of the hydrogen atomic clock. After the verification of the parameters, the hydrogen clock works normally, and further demagnetizing operation is needed. After that, only a few micro-amperes of weak current are needed in the Zeeman magnetic field coil. Therefore, the current source needs to provide at least two current stalls. The current source requires low energy conversion efficiency but high control accuracy. R3, R4, and R5, and their respective branch switches S1, S2, and S3 make up a three-stage adjustable calibration loop that adapts to the current level required in different situations.

As shown in Figure 3. The switches S1, S2, and S3 in figure are controlled by relays in the control system. R3 is the lower resistance, R4 is the higher resistance, and R5 is the higher resistance. When a larger current is required, the control close S1 is connected to R3, and when a smaller current is required, the control close switches S2 or S3 are connected to R4 or R5. L for the control of the hydrogen atomic clock Zeeman magnetic field coil, easy to understand to show the voltage control of the precise current source output to load the part.

According to the circuit shown in Figure 3, set the output voltage of PWM wave to U, and load the constant small current I on the magnetic field coil L. When the switch is closed, I = U/R3; when the switch is closed, I = U/R4; when the switch is closed, I = U/R5. At the same time, the three-stage micro-adjustment potentiometer also has the calibration function.

Compared with the traditional technology, the circuit has the advantages of stable output constant current, micro-ampere level of current step, and satisfying the current requirement of the hydrogen atomic clock Zeeman magnetic field; According to the different state of the magnetic field can be multiplexed to choose different levels of current load on the magnetic field coil.

2.2. Spectrum Analyzer to Sample Power Points

The clock output frequency signal power value of the data acquisition system through the Control System connected to the LXI interface to the spectrum analyzer data sampling. First, the spectrum analyzer coordinates and the vertical coordinates of the corresponding points in an array sample out, and then put into a file one by one save, and then use Python's drawing function to sample these arrays in real time and draw in the image, the next step of the data processing is to find the maximum power point, which will be handled by the spectrum analyzer system 6.

The data acquisition method of the invention has the advantages of strong real-time, less than 0.05 s time difference between the real image and the spectrum analyzer image after testing, and high accuracy, the error rate can be controlled within 0.05%, and the working state of the spectrum analyzer can be monitored remotely by the host computer.

2.3. The Control Algorithm

A micro control system is used to control the spectrum analyzer and current source circuits. The maximum voltage of the micro-control system is 3.3 V. This voltage best matches the maximum allowable voltage of the magnetic field of the hydrogen atomic clock and is the maximum output voltage of the microprocessor system.

An integer N is set in the algorithm, initially initializing N = 1 to change the duty cycle of the PWM wave: 65,535. Because the maximum memory address in a microprocessor is the 65,535, the duty cycle denominator can not be greater than the 65,535, and the output voltage is (3.3 * N)/65,535 when the duty cycle is N/65535. The output voltage of the micro-control system is changed when the duty cycle of PWM wave is changed.

In order to keep the output current of the constant current source at the micro-ampere level and the step size as small as possible, the minimum step size of PWM wave duty cycle provided by the control system is increased in turn, for every 1/65,535 increase in duty cycle, the frequency spectrum of the magnetic field coil signal in the output circuit is analyzed.

Spectrum analysis is the first signal into the spectrum analyzer, and then through the Upper Computer connected to the LXI port read real-time image, extract the image of each point in the horizontal and vertical coordinates saved in a file to get a power point P, a frequency point F, and a number N *, which is an integer that we set ourselves, a power point P, a frequency point F and a numerical value N * (corresponding to the power point N) are obtained. The three numerical values are arranged in an array and stored in a file, and then the corresponding power graph of the frequency point is drawn. Then the image pattern drawn is the signal analysis graph in the spectrum signal analyzer. Finally, the value of each point in the image is transmitted to the raspberry dispatch control system.

In the process of N increasing from 1 to 3.3 V (voltage slightly from 0 to 3.3 V) 7, the first power is first set to Max power, and then is discarded if the power is less than Max, on the other hand, if the power is greater than Max, the maximum power point Max is set.

Finally, we run the self created intelligent control algorithm shown in Figure 4 and get the duty cycle, 65,535, when the voltage applied to the magnetic field coil of the hydrogen clock maximizes the power of the hydrogen clock, the control system is then told to stabilize the output voltage (N * 3.3)/65,535 V, thus automatically finding the maximum power point and making the micro control system automatically fix the corresponding output voltage, the constant current source controlled by voltage can output the optimum current which makes the magnetic field coil of hydrogen atomic clock work at the maximum power point, the digital design of magnetic field dial is realized.

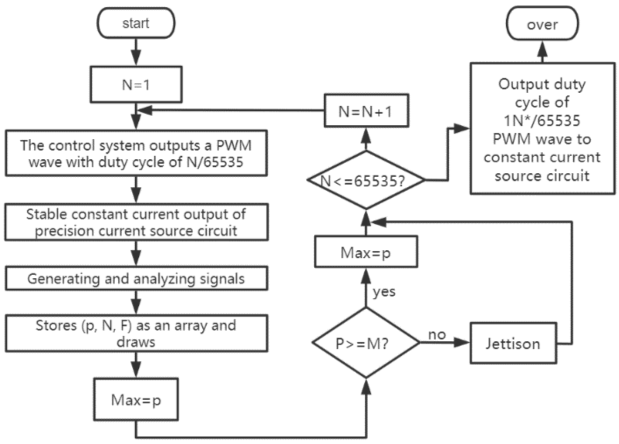

Figure 4. the samping method.

The advantages of the original intelligent control algorithm in this paper are: the algorithm is simple, the code has been greatly optimized; the running speed is fast; the time delay is extremely small, is about 0.01 s; it is suitable for the micro-control system-raspberry pie; the parameter setting is reasonable, smooth operation; ti has high accuracy, and the maximum power point found is the true maximum power point within the range of duty cycle stepping, rather than a relatively large power point as before the traditional dial.

In the actual experiments, the present output step of the constant current source circuit we designed can reach a high precision of 5 μA. Meanwhile, the digital sampling efficiency of the spectrum analyzer and the control system run quickly.

3. Discussion/Interpretation

Experiments show that the automatic design of the magnetic field digital dial about the hydrogen maser meets the requirements, and the performance is stable and dependable.

This research is of great significance, and it can facilitate our subsequent high-precision, homogenization design of the magnetic field and the overall digital design of the hydrogen maser. In other words, the digital design can make the control of the hydrogen maser more intelligent.

4. Conclusions

On the whole, the small resolution and high-precision magnetic field design has a wide range of applications. It can not only be used in hydrogen maser, but also universally applicable to the environments that require high-precision magnetic fields. It can also be combined with other new technical means to further optimize the design of the magnetic field. In the future, we will continue to improve its output current accuracy and reduce the system response time.

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