TEMPERATURE CONTROL FOR HYDROGEN MASER FREQUENCY STANDARDS

Yigen Fu, Zhongshi Zhou, and Xiaofan Liu
Beijing Institute of Radio Metrology and Measurement
P.O. Box 3930 Beijing, 100854 Peoples Republic of China

Abstract

Hydrogen masers with excellent long-term frequency stability are now used for frequency standards. In recent years, a lot of research and development of compact H-masers has been done at the Beijing Institute of Radio Metrology and Measurement. The long-term frequency stability and temperature coefficient of frequency are greatly affected by the temperature stability of the interior cavity. Therefore, one must pay attention to the interior cavity temperature control system in the development of compact H-masers. In this paper we will discuss and stress the following points:

(1) There are two representative methods in cavity frequency control. The first method is a combination of cavity temperature control and cavity frequency servo. The second method is the above, combined with total temperature compensation.

(2) The partial temperature compensation is used with cavity temperature control and cavity frequency servo in this method. The method of partial temperature compensation has a short time delay, and can reduce the effect of the temperature gradient. By using high-stability temperature sensors and multilayer, multipoint temperature controls, the temperature control accuracy can increase. In our H-masers, accurate decimal frequency synthesizers, high-velocity and high-isolation switches, low-noise up-frequency converters, and high-stability automatic frequency control systems have been developed. Hence, the achieved accuracy of the cavity frequency servo is better than 1 Hz.

(3) Since the above method was adopted, the performance of the compact H-masers has greatly improved in the laboratory.

1 INTRODUCTION

Hydrogen maser, with its excellent medium-term and long-term frequency stability, is now used as frequency standard. The hydrogen atomic frequency standard has now found a wide application in the fields of atomic time keeping, radio astronomy, aerospace, satellite navigation, etc., which has aroused great concern and brought about a lot of researches all over the world. In recent years, Beijing Institute of Radio Metrology and Measurement has made a lot of fruitful researches in the development of compact hydrogen maser. According to documents and our experience, the control on cavity resonant frequency is one of the key issues in the development of hydrogen maser.

The long-term frequency stability is mainly decided by the frequency tuning of resonant cavity and the cavity servo control system. Of these two factors, the former is related to temperature coefficient of the cavity, material property of the resonant cavity, aging change in storage bulb coating property, effect of magnetic field, etc., which sets a higher demand on the temperature control system of the frequency standard. This paper will discuss two representative schemes in the cavity frequency control, and an analysis and a comparison will be made on them. The paper will also present our scheme, i.e. to combine partial temperature compensation and cavity temperature control with cavity frequency servo. By adopting partial temperature compensation method, high-stability temperature sensor and multilayer and multipoint temperature control in our hydrogen maser, the interior cavity is possessed of a satisfactory temperature stability. And precision decimal frequency synthesizer, high-speed/high-isolation switch, low-noise up frequency converter and high-stability automatic frequency control system have been developed, which leads to an accuracy of cavity frequency servo better than 1Hz. Thanks to the above schemes, the performance of the compact hydrogen maser is greatly improved.

2 COMPARISON OF THE SCHEMES IN THE CAVITY FREQUENCY CONTROL

Two schemes in the cavity frequency control are involved at present.

The first one is to combine cavity temperature control with cavity frequency servo, which is a common scheme. The dimensions of the resonant cavity and storage bulb will influence the cavity frequency as the temperature varies, so the temperature stability is very important and it is necessary to keep temperature constant via a temperature control circuit. In order to reduce tractive effect, the automatic servo system of cavity frequency is employed besides precision constant temperature. The common electronic circuit tuning is easy, reliable and fast, which can improve the performance by several orders of magnitude. Therefore, the cavity temperature control and the cavity servo are two main necessary links for cavity frequency control.

The second one is to combine total temperature compensation and cavity temperature control with cavity frequency servo. The total temperature compensation method is stated below: Measure the frequency by cavity frequency sensor first, then feed the error signal of this frequency value into the control loop to drive the compensating heater which serves to regulate the cavity temperature control system, thus cavity frequency control can be realized. The relation between the master heater and the compensating heater can be adjusted by step-by-step method. When the ambient temperature changes slowly, the frequency-temperature coefficient can be adjusted to a very small value by compensation; when it changes dynamically, outer-layer temperature control and heat compensation can prevent and delay the dynamic interaction, however, the temperature compensation and the adjustment of time constant are comparatively troublesome.

For this reason, we adopt the scheme of combining partial temperature compensation and cavity temperature control with cavity frequency servo. In fact, the partial temperature compensation method is to adopt an additional sensitive element to measure the temperature change at a correlation point; through compensation by electronic circuit, a high-performance constant temperature can be obtained. As temperature measurement, balance and compensation are conducted in two different positions, the influence of the temperature gradient can be reduced; moreover, the partial temperature compensation method has the advantages of short time delay, convenient circuit regulation, etc.

3 CAVITY FREQUENCY SERVO CONTROL SYSTEM

The cavity servo control system is composed of two decimal frequency synthesizers, two IF up frequency conversion circuits, high-speed synchronous switch, microwave up frequency converter, error signal control loop, varactor diode fitted in the physical cavity, etc. Through these unit circuits, the feed-cavity signals f_1 and f_2 alternatively changing controlled by 10Hz symmetrical square wave. The frequency cavity functions as a high-Q frequency discriminator. f_1 and f_2 reference sources are very stable, $f_1=f_0+\Delta f$, $f_2=f_0-\Delta f$ (taking Δf as 15kHz) and $(f_1+f_2)/2=f_0$ (hydrogen atom transition frequency). If the resonant frequency of the physical cavity is equal to the hydrogen atom transition frequency, the error signal equals zero; if the cavity frequency is higher, an error signal is generated through frequency discrimination, and a voltage with negative polarity is delivered from the control loop and applied on the varactor diode, then the reverse bias of the diode drops, the junction capacitance increases and the raised cavity frequency is pulled back to f_0; otherwise, if the cavity frequency is lower, the dropped cavity frequency is pulled back to f_0.

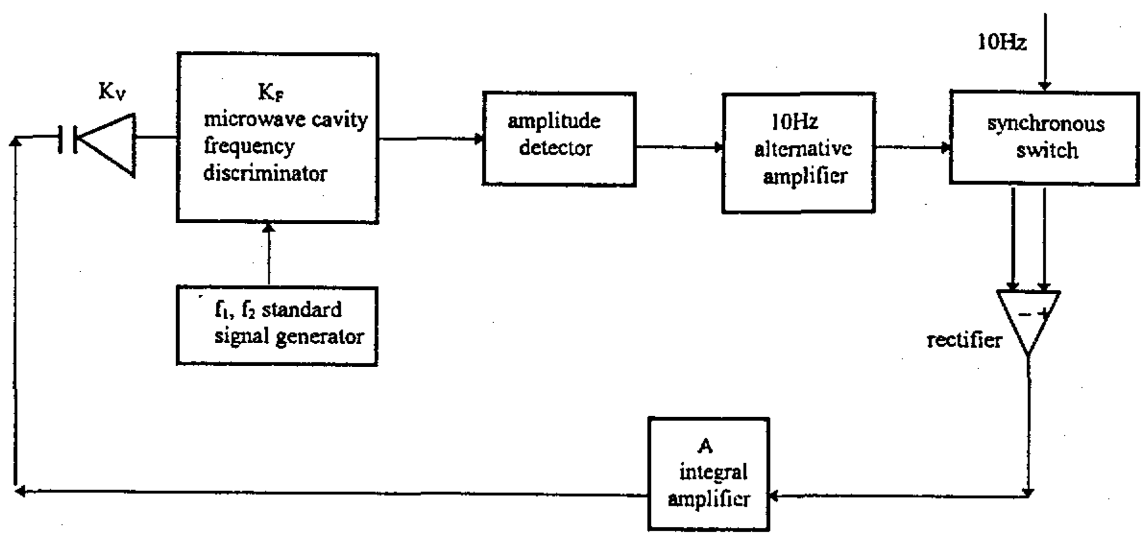

Fig.1 Block diagram of cavity frequency servo control system

Fig.1 is block diagram of cavity frequency servo control system, whose control equation can be written as:

$$\Delta f_N/\Delta f_0=1/1+K_F \cdot |K_V| \cdot A$$

where,

Δf_0: frequency drift caused by various factors of the physical cavity

Δf_N: remainder frequency deviation caused by automatic servo of the cavity frequency

K_F: sensitivity of the frequency discriminator

K_V: voltage-control sensitivity of the varactor diode

A: total gain of the alternative amplifier, integral amplifier, etc.

It can be seen from above that K_F, K_V and A should be greater so as to decrease the remainder frequency deviation. However, the unstability of the system will be increased with the increase of the gain; therefore, a compromise scheme should be considered in design; and a varactor diode with small temperature coefficient, high-Q value and a certain linearity should be selected (Note: Its direction and height should be taken into consideration when it is fitted into the physical cavity.). In addition, it is also very important to reduce the phase noise at the sideband frequencies f_1 and f_2 of f_0 and the noise of all components in the control loop, to raise the spectral purity and the stability of the loop, to design an appropriate bandwidth, etc.

Through well-conceived design and delicate debugging, the technical problem has been solved and the control accuracy of the cavity frequency servo system is better than 1Hz.

4 PRECISION TEMPERATURE CONTROL CIRCUIT

The temperature stability of the temperature-control system is a function of the system structure and the circuit design.

4.1 Structure of the Temperature-Control System

As the key part of the hydrogen maser, the resonant cavity is required of a highest temperature stability; besides, the cover, neck and some microwave elements also need a constant temperature. In view of this, we have designed a constant-temperature system with a fair temperature-keeping effect and double-layer and multipoint control function.

4.2 Outer-Layer Temperature Control Circuit

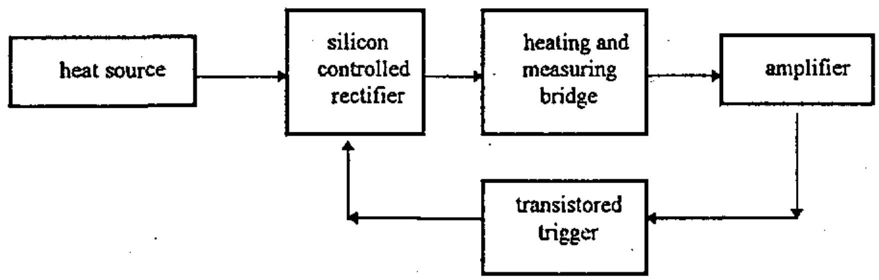

Fig.2 Block diagram of outer-layer temperature control circuit

As shown in Fig.2, heating and measuring are conducted in the same bridge which adopts double-wire non-inductive resistor and whose four arms are made of two materials, i.e. manganin wire and copper wire, actually acting as a temperature sensitive element. In the positive half-wave state of the circuit, the difference signal from the bridge, having been amplified and phase discriminated, forms a trigger pulse to trigger the controlled silicon element, then the heating voltage enters the heating bridge via the controlled silicon element. At first, the system stays in a cooling state and the difference signal is comparatively large, so the controlled silicon, with a great angle of flow, is in a fast heating state. When the constant-temperature zone approaches the set temperature, both the difference angle and the angle of flow of the controlled silicon become smaller. At last, the system stays in a balanced state when heat dissipation equals heating. It has been proven from our over-two-year tests that this circuit is characterized by stable and reliable operation, simple structure, easy adjustment and comparatively high temperature stability.

4.3 Interior-Layer Temperature Control Circuit

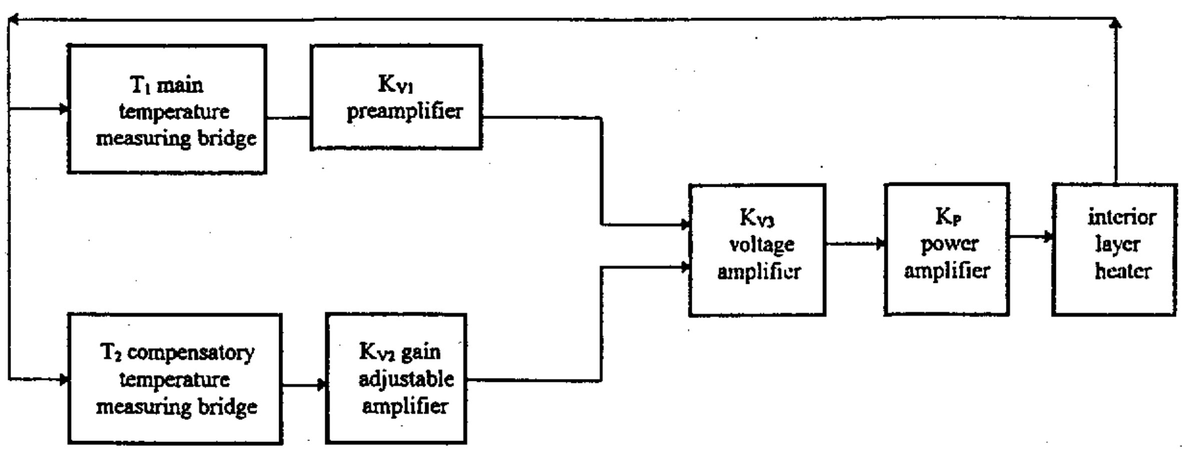

Fig.3 Block diagram of interior-layer temperature control circuit

The structure of the circuit is shown in Fig.3. The circuit features as follows. First, it adopts platinum-resistance thermometer with a fair long-term stability as its temperature-sensitive element so as to reduce its self-heating effect; secondly, by adopting partial compensation circuits T_2 and K_{V2}, selecting optimum correlation compensating point and adjusting gain G_{V2}, the temperature-control effect of improving the performance by 1~2 orders of magnitude can be got; thirdly, its preamplifier is characterized by a low noise, high sensitivity and reliable wiring. Moreover, the bridge and the preamplifier are in a temperature-control environment.

The delicate design and adjustment of double-layer and multipoint temperature control will lead to a satisfactory temperature stability of the interior cavity.

5 TEST AND TEST RESULTS

A series of tests are required in the development of hydrogen maser, such as tests of short-term, medium-term and long-term frequency stability and test of frequency accuracy; test of frequency-temperature coefficient having a closest relation with temperature, tests of interior-layer short-term and long-term temperature stability, test of interior-layer temperature sensitivity, etc.

The test method of the frequency-temperature coefficient is to place the hydrogen maser in a constant-temperature environment and to raise the ambient temperature by Δt. After the temperature gets stable, measure the variation of its output frequency; the test method of the interior-layer temperature sensitivity is to place thehydrogen maser in a constant-temperature environment and to raise the ambient temperature by Δt. After the temperature gets stable, measure the variation of its interior-layer temperature; the test method of the interior-layer short-term and long-term temperature stability is to adopt the standard platinum-resistance thermometer commonly used in the world, assisted by a stable and sensitive bridge or a high- performance digital ohmmeter.

All methods and devices involved have been certified by relevant metrical authority.

Up to now, repeated tests have been performed, and the test curves are respectively shown in Fig.4 and Fig.5.

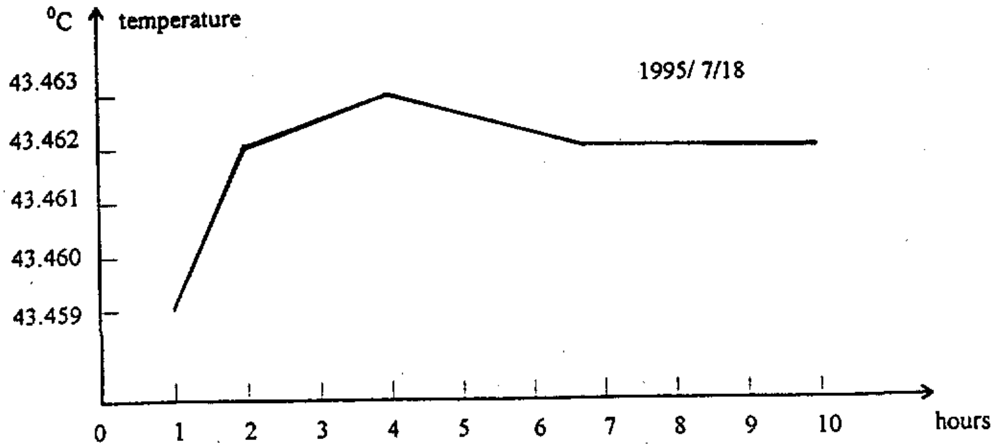

Fig.4

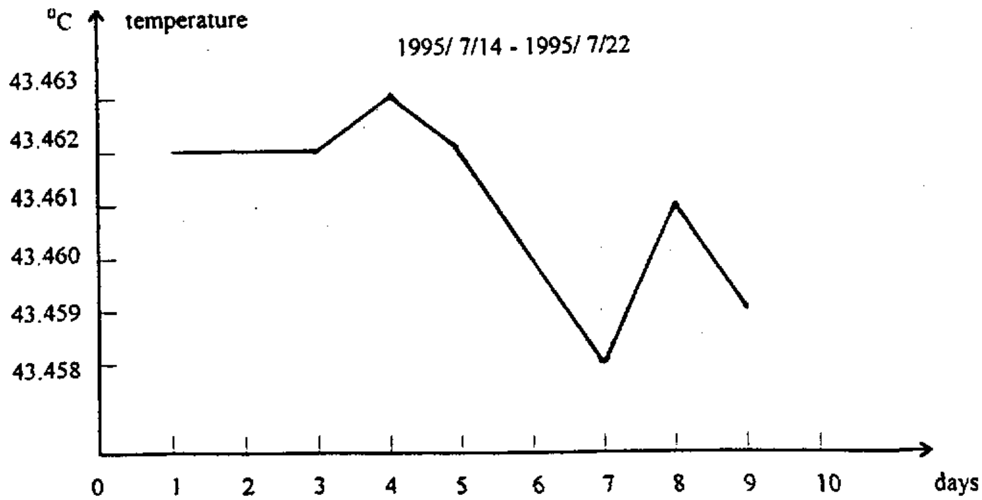

Fig.5

Interior layer <u>10 hours</u> temperature stability <u>±0.002</u> ℃

Interior layer <u>9 days</u> temperature stability <u>±0.003</u> ℃

When the ambient temperature changes by 1 ℃, the interior-layer temperature change is $\underline{10^{-3}}$℃.

6 CONCLUSIONS

The cavity frequency control scheme of combining partial temperature compensation and cavity temperature control with cavity frequency servo is adopted. According to the test result of the interior-layer temperature stability of 0.002 ℃ and the control accuracy of the cavity frequency servo system better than 1Hz, it can be ensured that both the frequency-temperature coefficient and the long-term frequency stability of the hydrogen maser are better than 1×10^{-14}.

We gratefully acknowledge Ms. Yanjun Zhang's energetic assistance in our undertakings in development and test.

7 REFERENCES

[1] Y. Fu, *"Temperature control system for compact hydrogen maser,"* Beijing Institute of Radio Metrology and Measurement (restricted).

[2] Z. Zhou, *"Electronic receiver system for hydrogen maser,"* Beijing Institute of Radio Metrology and Measurement (restricted).

[3] H.T.M. Wang 1982, *"Characteristics of oscillating compact hydrogen masers,"* Proceedings of the 36th Annual Symposium on Frequency Control, 2-4 June 1982, Philadelphia, Pennsylvania, USA (U.S. Army Electronics and Development Command), pp. 249-254.

[4] F.L. Walls 1987, *"Analysis of high performance compensated thermal enclosures,"* Proceedings of the 41st Annual Symposium on Frequency Control, 27-29 May 1987, Philadelphia, Pennsylvania, USA (IEEE), pp. 439-443.

[5] Y.G. Gouzhva, A.G. Gevorkyan, A.L. Myasnikov, G.M. Kruyukov, V.Z. Gankin, O.N. Kornishov, and S.D. Teplova 1995, *"Activities of the Russian Institute of Radio Navigation and Time in development of GLONASS on-board Q-enhanced oscillating compact H-maser,"* Proceedings of the 1995 IEEE International Frequency Control Symposium, 31 May-2 June 1995, San Francisco, California, USA, pp. 140-148.

[6] N.A. Demidov, E.M. Zhov, B.A. Sakharov, and A.A. Vljanov, *"The investigation of performances of compact active and passive H-masers,"* Institute of Electronic Measurements KVARZ, N. Novgorod, Russia Gagar in Prospect 176 Russia 603009 Nizhuij Novgorod.