Digital Temperature Control Design for Hydrogen Atomic Clock (Postprint)

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Abstract

The objective of this design is to implement digital temperature control for a hydrogen atomic clock. Based on the fundamental principles of temperature detection and control, a constant temperature control system with two-stage temperature control (including the inner and outer ovens of the hydrogen clock) is designed. The temperature control system is mainly composed of a bridge circuit, an analog-to-digital conversion circuit, temperature calculation and Proportional-Integral-Derivative (PID) control system, Pulse Width Modulation (PWM) output circuit, and heating wires. At ambient temperatures ranging from 21°C to 25°C, a temperature stability of 0.002°C for the digital temperature control system is achieved, demonstrating the feasibility of digital circuits for hydrogen clock temperature control.

Full Text

Digital Temperature Control Design of Hydrogen Maser

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Abstract

This design implements digital temperature control for the hydrogen maser. Based on fundamental principles of temperature detection and control, a two-stage temperature control system was designed comprising the hydrogen maser's inner and outer furnaces. The temperature control system consists primarily of a bridge circuit, analog-to-digital conversion circuit, temperature calculation and PID (proportional-integral-derivative) control system, PWM (pulse width modulation) output circuit, and heating wire. When ambient temperature fluctuates between 21℃ and 25℃, the digital temperature control system achieves a temperature stability of 0.002℃, demonstrating the feasibility of using a digital board to control the hydrogen maser' s temperature.

Keywords: digital temperature control; hydrogen maser; PID control; two-stage temperature control

Preamble

To ensure thermistor consistency for the temperature control system, approximately 20 thermistors were placed in a constant temperature bath set between 40℃ and 50℃. Each thermistor was connected via wires to the outside of the bath. After the bath reached thermal equilibrium, the resistance of each thermistor was measured, and those with consistency better than 15Ω were selected. Following factory pre-selection and laboratory fine-selection, the thermistor consistency was considered to have met or exceeded the standards of the Smithsonian Astrophysical Observatory [4].

1.3 Specific Scheme

To achieve temperature control of the resonant cavity using this digital temperature control design, thermistors are connected to a temperature acquisition bridge circuit. The bridge circuit voltage undergoes analog-to-digital conversion, followed by temperature calculation and PID control of PWM output, thereby controlling the heating power. The overall scheme is illustrated in Figure 1 [Figure 1: see original paper].

1.4 Bridge Circuit

Thermistors are attached to the walls of different temperature control zones, and their resistance varies with changes in the inner and outer furnace temperatures. The temperature measurement circuit must convert these resistance variations into voltage signals. Two common circuit implementations exist for this purpose: (1) a bridge temperature measurement circuit requiring constant voltage, and (2) a constant-current source temperature measurement circuit. This design adopts the bridge temperature measurement circuit, which obtains the voltage across the thermistor through voltage division, determines the thermistor resistance, and then converts this to temperature through a series of formulas [5-6].

The bridge temperature measurement circuit is shown in Figure 2 [Figure 2: see original paper]. Resistors R1, R2, and R3 are high-precision resistors with $±0.1_{25}$ = 5.0339 kΩ and B = 3945.10. When temperature changes, Rt' s resistance varies while R1, R2, and R3 remain constant, keeping the voltage at U2 unchanged while the voltage at U1 changes. The voltage difference between the two bridge arms is:

$$\Delta U = U_1 - U_2 = \left(\frac{R_2}{R_1 + R_2} - \frac{R_t}{R_3 + R_t} \right) \cdot V$$

Since the hydrogen maser has multiple temperature control zones, the designed balanced bridge circuit is shown in Figure 3 [Figure 3: see original paper]. The differential output from the bridge arms is fed into the ADC input of the main control chip, which calculates Rt from ΔU and then determines the current temperature using the fitted temperature-resistance relationship for this thermistor.

The thermistor resistance is given by:

$$R = R_{25} \cdot \exp\left[B \cdot \left(\frac{1}{T} - \frac{1}{T_{25}} \right) \right] \quad (2)$$

where R_{25} is the zero-power resistance temperature coefficient at 25℃, T is the temperature, and T_{25} is 25℃. The current temperature is therefore:

$$T = \frac{1}{\frac{1}{B} \ln\left(\frac{R}{R_{25}} \right) + \frac{1}{T_{25}}} \quad (3)$$

1.5 ADC Circuit Design

To meet resolution requirements and obtain high-precision voltage values, we selected the 24-bit analog-to-digital converter ADS1256. This chip provides up to 23-bit noise-free resolution and a 30 kSPS data output rate. Its internal digital filter enables preliminary filtering of measured data, further improving the accuracy of the readout. The ADC circuit design for the hydrogen maser’ s digital temperature control system is shown in Figure 4 [Figure 4: see original paper].

1.6 Sliding Window Filtering

In high-precision temperature measurement and control systems, denoising is a critical data processing step that directly affects the stability and reliability of subsequent results. A hybrid filtering algorithm with a sliding window is employed to remove noise and interference from the voltage signal. The algorithm proceeds as follows: First, N×M voltage values are sequentially acquired and divided into N groups of M values each. Using median filtering, the M values in each group are sorted and the median is selected as the effective value for that group. This yields N values from the original N×M measurements, which are then ordered chronologically as U_1, U_2, U_3, ···, U . These undergo sliding window filtering, where the most recent sample and the previous N−1 samples are averaged. With each new data acquisition, the oldest data point is replaced, maintaining an updated set of N data points in the buffer.

After processing by this hybrid filtering algorithm, the acquired voltage signals have noise and interference effectively removed, resulting in minimal jitter in the converted temperature signal and meeting the system' s sensor precision requirements [7].

1.7 Temperature Calculation

The inner and outer furnaces contain multiple temperature control zones. To minimize heat flow and temperature gradients, each zone is set to a slightly different temperature. The temperature calculation flowchart is shown in Figure 5 [Figure 5: see original paper]. The temperature calculation and PID control algorithm determine the current temperature from the bridge circuit' s voltage difference and compute the PID control output based on the difference between current and target temperatures [8].

1.8 Fuzzy PID Control Algorithm

A PID controller regulates the proportional, integral, and derivative components of an error signal. Its block diagram is shown in Figure 6 [Figure 6: see original paper], where $r(t)$ is the setpoint temperature, $c(t)$ is the actual system temperature output, $e(t)$ is the temperature error input to the controller, and $u(t)$ is the PID controller output and plant input. The core control formula is:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int e(t)\, dt + T_d \frac{de(t)}{dt} \right] \quad (4)$$

A fuzzy control system consists of three main components: fuzzification, fuzzy inference and defuzzification, and the rule base. Its fundamental structure is shown in Figure 7 [Figure 7: see original paper] [9]. Through months of experimentation and continuous PID algorithm improvement, analyzing temperature stability of the resonant cavity under different algorithms, the fuzzy PID algorithm was ultimately selected as optimal for the hydrogen maser' s constant temperature system.

1.9 Heating Module/Power Drive Module

The power provided by the PWM output from the counter chip is far below the heating module' s requirements. Therefore, a power drive circuit is added after the PWM output stage, as shown in Figure 8 [Figure 8: see original paper] [10-11].

2.1 Experimental Setup

The furnace assembly consists of the heating furnace, heating wire, control thermistors, and detection resistors. The heating module uses double-twisted heating wire, which avoids generating magnetic fields that could affect the maser oscillation signal's frequency and intensity, while maintaining insulation between the heating wire and furnace wall. Detection resistors are used for temperature monitoring and control precision verification.

The hydrogen maser has multiple temperature control zones, with thermistors and heating wires in each zone connected to the digital board. The digital board is housed in a custom shielded enclosure to minimize external interference. Simultaneously, digital multimeters monitor the detection resistors in the inner and outer furnace cavities to determine temperature stability.

2.3 Hydrogen Maser Inner/Outer Furnace Temperature Fluctuation

From October 29, 2022 at 16:05 to October 31, 2022 at 02:18, laboratory room temperature was monitored using a digital multimeter at one-minute intervals, yielding 2,053 data points. Temperature was calculated from thermistor resistance values, as shown in Figure 9 [Figure 9: see original paper]. The room temperature varied from 21℃ to 25℃.

In this 21-25℃ environment, the outer furnace temperature was set to 37℃ and the inner furnace to 45℃. A 6.5-digit digital multimeter continuously acquired resistance values from thermistors attached to the inner and outer furnace walls, with temperature values derived from the resistance-temperature relationship to enable real-time temperature monitoring. Sampling occurred at one-minute intervals for at least 24 hours.

Since the constant temperature system' s stability depends on external environmental temperature fluctuations, comparative experiments were conducted between the existing analog temperature control system and the digital temperature control system under identical room temperature conditions to directly demonstrate the different control effects. The outer furnace thermistor was monitored for at least 24 hours, with temperature fluctuations shown in Figure 10 [Figure 10: see original paper]. The outer furnace temperature fluctuated by approximately 0.2℃, reducing the laboratory' s 4℃ temperature variation to about 0.2℃.

Monitoring the original analog temperature control circuit for the hydrogen maser revealed inner furnace temperature fluctuations of approximately 0.05℃, as shown in Figure 11 [Figure 11: see original paper]. The digital circuit can adjust the PID algorithm to continuously improve temperature control performance. When connected to the hydrogen maser, the digital temperature control circuit monitored the inner furnace thermistor for at least 24 hours. The inner furnace temperature trend from power-on to stabilization is shown in Figure 12 [Figure 12: see original paper], with stabilized temperature fluctuations shown in Figure 13 [Figure 13: see original paper].

The digital control board can maintain inner furnace temperature fluctuations within approximately $±$0.004℃. The standard deviation, which measures sample fluctuation magnitude (larger values indicate greater fluctuation), is calculated as:

$$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (5)$$

where $\bar{x}$ is the mean, n is the sample size, and $x_1, x_2, \dots, x_n$ are sample values. Calculating the temperature data from the digital temperature control circuit yields a standard deviation of 0.002, corresponding to a temperature stability of 0.002℃.

Furthermore, the hydrogen maser inner furnace' s temperature stability is significantly affected by the environment, with different ambient temperature fluctuations producing different post-control stability levels. Limited by the available environmental temperature stability, comparative experiments between digital and analog boards were conducted under relatively large ambient temperature fluctuations (21-25℃). The results demonstrate the feasibility of digital board temperature control.

This paper employs digital temperature control through hardware circuit design and continuous PID algorithm improvement. In a 21-25℃ environment, the hydrogen maser' s two-stage inner/outer furnace temperature control system achieves a final temperature stability of 0.002℃.

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