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Measurement of Thermal Deformation Coefficient of Copper based on PID Control

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Abstract

In order to explore the thermal deformation of metal and measure the thermal deformation coefficient of copper rod, this study modified the Michelson interferometer appropriately, and replaced the traditional manpower with the thermal deformation of copper rod, which made the mirror base of the Michelson interferometer move. By counting the light and dark changes in the center of the interference image, the deformation of copper thermal deformation was finally calculated. In this study, the PID control temperature algorithm is adopted, and the STM32F407 processor is used as the main control chip to design the PID algorithm, and the control quantity of the PID algorithm is converted into the PWM wave with an adjustable duty ratio to control the heating execution unit. The research results show that the modified device can measure the deformation of metal thermal deformation, which is convenient and accurate, with high precision and low cost. The final measurement results are basically consistent with the standard thermal expansion coefficient of metal.

Keywords

PID; Temperature Control; Thermal Deformation of Metal.

1. Introduction

Thermal deformation is a kind of metal deformation, which refers to the plastic deformation of the metal above the recrystallization temperature. The temperature difference caused by different heating and cooling rates is the cause of thermal deformation. Usually, the change in unit length is used to characterize the thermal deformation. In practice, the metal deformation is very small, which can't be observed by human eyes, and can only be detected with the help of experimental instruments. Generally, this slight change can be ignored in actual production, but it is a factor that has to be considered in large-scale equipment or precision instruments.

The metal to be measured in this paper is a copper rod, and copper is an important part of the relay, which is used to protect the motor from overload and phase loss. By exploring the relationship between thermal relay disconnection temperature and deformation, the overload temperature of the motor can be determined more appropriately, and then the motor can be better protected. Measuring the thermal deformation coefficient of copper is of great significance in industrial production. Therefore, measuring the thermal deformation coefficient of copper is an important job.

Some traditional measurement methods use a single chip microcomputer, AD sensor, and high-precision laser sensor to measure the tiny thermal deformation of metal, and some use digital speckle interferometry to measure the thermal deformation of the metal[1]. However, the overall cost of the experimental device is expensive, and the experimental principle is complicated.

In this paper, the Michelson interferometer, a commonly used device for physical experiments in colleges and universities, is used for proper modification. The PID algorithm is used in the single chip program to realize the precise control of temperature. At the same time, the photoresistor is used to convert the change of the fringe in the interference into an electrical signal, which is shaped by a Schmitt trigger, amplified by the amplifier, and sent to the single-chip microcomputer for counting and display, so as to measure the tiny length of the copper rod, thereby calculating the thermal deformation of copper coefficient.

2. Working Principle of the System

The following diagram is a schematic diagram for measuring the thermal deformation coefficient of copper. Wrap the ceramic tube with heating tape, and then fix it with a wooden frame. One end of the copper rod is pressed against the mirror base of the reflector to make it fixed. In the experiment, the heating belt is used as the heat source, and the heating belt heats the air in the ceramic tube after power-on, so that the copper rod can be uniformly heated and deformed. In order to get clear and stable interference fringes on the receiving screen, the PID algorithm is used to control the temperature to rise slowly to the target temperature. Due to the gentle and controllable temperature rise, the length of the metal rod slowly changes slightly, and the slight length change D will drive the mirror base to move inward, which will make the M_2 mirror of the self-assembled Michelson interferometer move, thus making the interference fringes change easily to be recorded. Finally, at the receiving screen end, the variation of the number of turns between interference fringes is measured by the photoresistor to determine the length variation of the metal bar, so as to determine the thermal deformation coefficient of the copper bar.

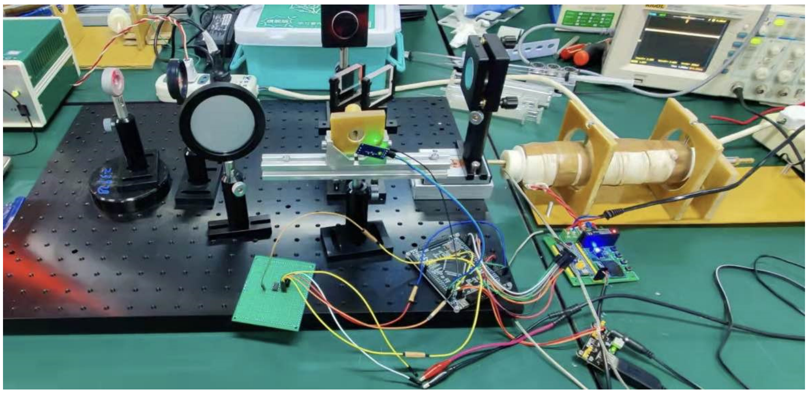

Figure 1. Physical map of the device

3. System Design

3.1. Modification of Michelson Interferometer

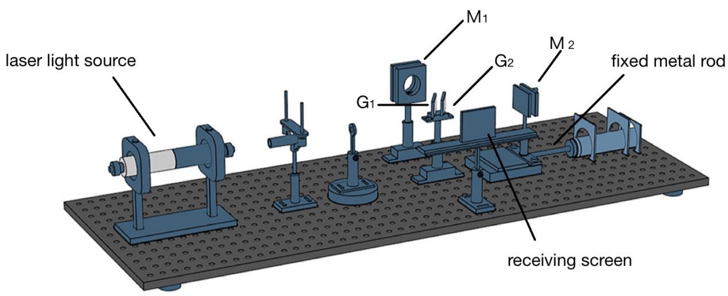

Figure 2. Device model drawing

As shown in the figure, the device used in this paper is modified on the basis of the original Michelson interferometer device. Another receiving end with a small hole is placed at the original receiving screen, and the photosensitive resistor of the counting module is fixed on the small hole to observe the light and dark changes of the fringes. At the same time, a heating device with a fixed copper rod is added at the right end of the mirror base of the reflector.

The manufacturing process of the heating device is complicated. First, the ceramic tube is wound with a heating belt, so that the cavity of the ceramic tube can be heated by energizing the heating belt. A copper rod (overall length 27cm, diameter 5.9mm) with its left end connected to the bottom of the left end of the ceramic tube contacts the bottom of the mirror base outwards and the other end is fixed with a ceramic rod. At the same time, the central axis of the ceramic tube and copper rod should be horizontal. Finally, a wooden frame is made of wood to fix the device.

A copper rod heating fixing device is shown in the figure.

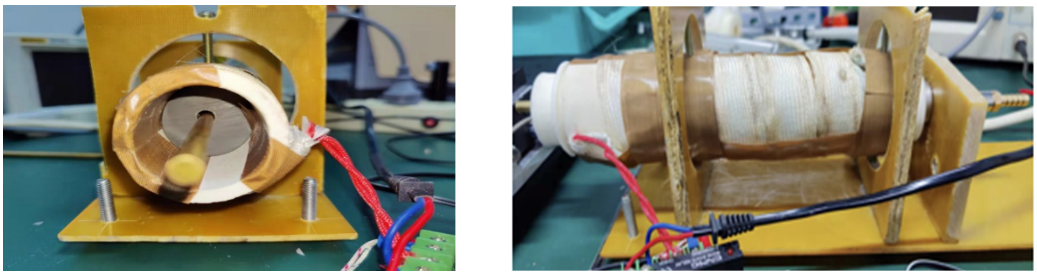

Figure 3. Cross-section and section of the device for fixing

3.2. PID Temperature Control Part Design

In order to observe the thermal deformation of copper and obtain reasonable data, it is necessary to control the heating rate when heating, so that the temperature of the copper rod can slowly rise to the target temperature, so that reasonable data can be collected. In this paper, the PID control algorithm is selected for temperature control. PID control method has been widely used because of its simple working principle and easy realization. Adjusting the differential, integral and proportional parameters can speed up the response speed of the system, eliminate the steady-state error of the system and improve the dynamic performance of the system[2].

The output of the PID controller can be regarded as a kind of (error) compensation. Depending on the difference from the set value, the deviation is added to the final result through a series of operations, so that the result meets or approaches the requirements. PID is composed of proportional unit (P), integral unit (I), and differential unit (D). The system deviation is corrected by adjusting the coefficients of these three devices. The proportional link is used to reduce deviation, the integral link is used to eliminate static error, and the differential link is used to speed up the response speed of the system and reduce the adjustment time[3].

In this paper, the STM32F407 based on the ARM Cortex-M4 architecture is used as the main controller of the PID control system, and the PT100 is used as the front-end temperature sensor. The temperature information is converted into a voltage signal by constant current source excitation and then converted into a digital signal by the MAX6675 digital-to-analog conversion module. Pass it to STM32F407, execute PID algorithm in STM32F407, adjust PWM (Pulse Width Modulation) duty cycle according to the error increment of PID output, cooperate with relay, PWM is used as the signal source of driving heating circuit to realize high-precision constant temperature control [4].

Therefore, the PID control expression is:

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$$Pwm+=K_p*[e(k)-e(k-1)]+K_i*e(k)+K_d[e(k)-2e(k-1)+e(k-2)] \quad (1)$$

Where e(k) is the current deviation, e(k-1) is the last deviation, e(k-2) is the last deviation, K_p is the proportional parameter, K_i is the integral parameter, and K_d is the differential parameter, and Pwm is the representative incremental output.

The heating system has great inertia and hysteresis. When the heater is turned off, the temperature will still rise for some time. If this problem is not handled properly, the output of the control system will fluctuate and overshoot. In order to solve this problem, after many experiments, it is found that properly increasing the sampling time temperature can reduce the shock and overshoot, and finally get better results[5].

3.3. Design of Counting Unit

Fix the photoresistor at the light inlet of the receiving end to make it in the center of the interference circle. After the copper rod is heated and expanded, the mirror base of the Michelson interferometer moves to the left, and the device begins to produce interference images. At the receiving end, the light and dark change in the center of the interference image makes the resistance of the photosensitive resistor constantly change, and the voltage of its circuit constantly changes. The changed voltage is amplified by the amplifier circuit, and a low-frequency signal similar to a sine wave can be obtained, which is shaped by a Schmitt trigger composed of NE555 and output as a square wave[6].

Connect the pins of the single-chip microcomputer to the output of the amplifying circuit, and each time a square wave is generated, the single-chip microcomputer enters an interrupt to count, and each count represents light and dark change once, that is, the deformation variable is half a wavelength, which is calculated based on this. At the same time, the single-chip microcomputer drives the four-pin OLED screen through IIC protocol, displays the number of received pulses on the screen, and displays the calculated total deformation after receiving.

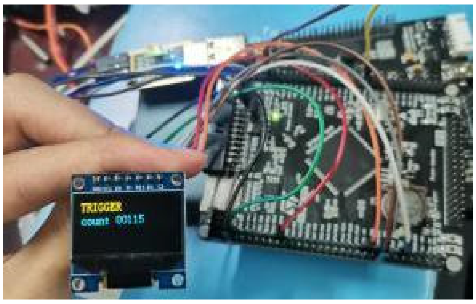

Figure 4. Counting unit

4. Experimental Process

1) Put the copper rod in close contact with the mirror M_2, and turn on the temperature control system of the single chip microcomputer to raise the temperature evenly, so as to heat the copper rod.
2) Fine-tune the device so that the ceramic rod can push the mirror M_2 to slide smoothly before testing.
3) Raise the temperature of the heating belt, and adjust the instrument until interference fringes appear on the observation screen.
4) Turn on the light control measurement module of the single chip microcomputer, scan the interference pattern of the Michelson interferometer, and record the change number of interference fringes at a certain temperature change value.

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5) Change the temperature value and record the interference fringes again.

5. Test Results and Analysis

After measurement, the strongest light intensity at the center of the interference image is about 15cd, so the threshold of the photoresistor is set to 15cd. If a light-dark change occurs, it will be processed by the photoresistor and the single-chip microcomputer, and then the counter will automatically increase by one.

As for the measurement of length change and thermal expansion coefficient, it is measured every 10°C, except for the initial temperature, five times in total.

The data are as follows:

Table 1. The first measurement data

Temperature (second time)	Number of change turns (n)	Sum of turns
30	0	0
40	119	119
50	63	182
60	218	400
70	147	547
80	114	661

Table 2. The second measurement data

Temperature (second time)	Number of change turns (n)	Sum of turns
30	0	0
40	99	99
50	131	230
60	150	380
70	158	538
80	221	759

Because of the data error, that is, the error caused by the measurement process (the temperature change in the ceramic cavity is not synchronized) and the error of the system itself (the copper rod is not in close contact with the slide rail, and some of the copper rods are exposed). Therefore, only data of 30-80 degrees are taken to remove the points with large errors.

Several sets of data have been measured before, and only two of them are shown here.

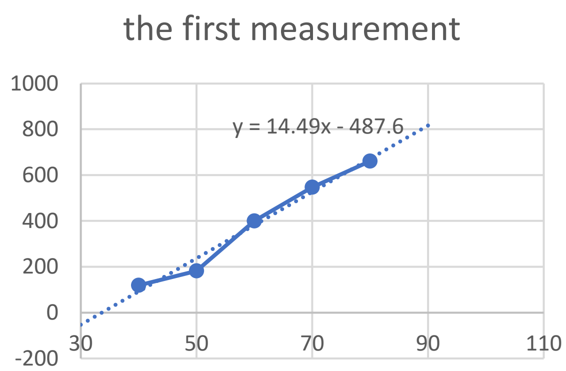

Figure 5. The first measurement

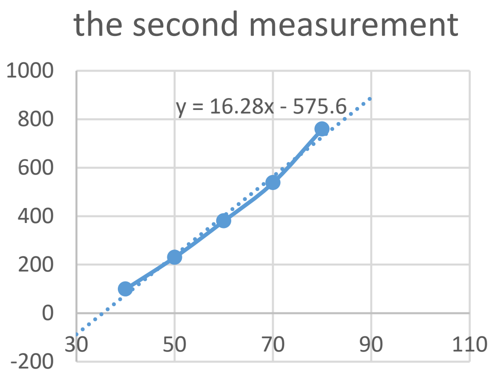

Figure 6. The second measurement

The slope k of the number of turns with temperature plotted from the above data is shown in the figure:

$$K=\frac{\Delta N}{t_1-t_2} \tag{2}$$

According to the measured data, when the temperature rises by 0.1 degrees and the length of the copper rod are 27cm, there will be a light-dark change at the center of the circle, that is, a halo will be swallowed, and then a light-dark change will represent a half wavelength change so that the conversion length of copper can be obtained. (wavelength λ=632.8nm, n is the number of changing turns, and l is the displacement difference)

The wavelength calculation formula is:

$$\lambda=\frac{2\Delta L}{N} \tag{3}$$

At room temperature, the transformation of solid linear expansion with temperature can be expressed by the empirical formula as follows:

$$L(t)=L_0(1+\alpha t) \tag{4}$$

In this formula, α is called the linear expansion coefficient of solid; L_0 is the length when t=0℃. The experiment shows that α is a constant when the temperature changes little. The length of the object at room temperature t_1℃ can be measured experimentally as L_1, and the length elongation when the temperature rises to t_2 is △L. According to the above formula, we can get:

$$L_1=L_0(1+\alpha t_1) \tag{5}$$

$$L_2=L_0+\triangle L=L_0(1+\alpha t_2) \tag{6}$$

Eliminate L_0 to get:

$$\alpha=\frac{\triangle L}{L_1(t_1-t_2)-\triangle L t_1} \tag{7}$$

When t_1 and t_2 are small, because △L is much smaller than L, the above formula can be written as:

$$\alpha=\frac{\triangle L}{L_1(t_1-t_2)} \tag{8}$$

The average linear expansion coefficient of α at temperature (t_1-t_2) is obtained from the equation. And △L can be obtained by the number of turns of interference fringes in the Michelson interferometer.

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$$\alpha=\frac{N\lambda}{2L_1(t_1-t_2)}=\frac{K\lambda}{2L_1} \tag{9}$$

That is, the result of the first measurement data is $\alpha=\frac{14.49*632.8*10^{-9}}{2*27*10^{-2}}$= 0.169 * 10^{-4}m/degree, the result of the second measurement data is $\alpha=\frac{16.28*632.8*10^{-9}}{2*27*10^{-2}}$= 0.191 * 10^{-4}m/degree, and the average value is 0.18 * 10^{-4}m/degree.

The standard thermal expansion coefficient of copper rod found on the Internet is 0.178 * 10^{-4}m/degree, and the error is less than 10^{-6}, so the experimental results are within the allowable error range.

6. Conclusion

The STM32 single-chip microcomputer temperature control device designed and manufactured in this paper, combined with the Michelson interferometer and single-chip microcomputer light control measuring device, can accurately measure small length changes such as thermal expansion and cold contraction. The device automatically records interference images, and automatically calculates and displays the results. Compared with the conventional measurement method, the device in this paper applies the automatic control theory to the physical experiment interdisciplinary, and the measurement is convenient and accurate, with high precision and low cost. In the aspect of the experimental application, the sample to be tested in this experiment is a copper rod, which is an important part of a relay and is used to protect the motor from overload and phase loss. By exploring the relationship between thermal relay disconnection temperature and deformation, the overload temperature of the motor can be determined more appropriately, and then the motor can be better protected. Measuring the thermal deformation coefficient of copper is of great significance in industrial production. Therefore, measuring the thermal deformation coefficient of copper is an important job.

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