Research on the Principle of Space High-precision Temperature Control System of Liquid Crystals Based Stokes Polarimeter

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Received 2020 4 7; accepted 2010 7 14

Abstract Magnetic field is one of the most important parameters of solar physics, and polarimeter is the key device to measure solar magnetic field. Liquid crystals based Stokes polarimeter is a novel technology, and will be used in the magnetic field measurement of the first space solar observation satellite, Advanced Space-based Solar Observatory, of China. However, the Liquid crystals based Stokes polarimeter in space is not mature in the world. Therefore, it is of great scientific significance to study the control method and characteristics of the device. The retardation of liquid crystal variable retarder is sensitive to the temperature, and the retardation changes 0.09° per 0.1°C. The error of polarization measurement caused by this change is 0.016, which affects the accuracy of magnetic field measurement. In order to ensure the stability of its performance, this paper proposes a high-precision temperature control system for liquid crystals based Stokes polarimeter in space. In order to optimize the structure design and temperature control system, the temperature field of liquid crystals based Stokes polarimeter is analyzed by finite element method, and the influence of light on the temperature field of liquid crystal variable retarder is analyzed theoretically. With analyzing principle of high-precision temperature measurement in space, a high-precision temperature measurement circuit based on integrated operational amplifier, programmable amplifier and 12-bit AD is designed, and a high-precision space temperature control system is developed by using integral separation PI temperature control algorithm and PWM driving heating films. The experimental results show that the effect of temperature control is accurate and stable, whenever the liquid crystals based Stokes polarimeter is either in the air or vacuum. The temperature stability is within ± 0.015°C, which is improving the stability of liquid crystals based Stokes polarimeter greatly.

Key words: liquid crystals based Stokes polarimeter, high-precision temperature measurement, space high-precision temperature control, temperature field analysis, PID control
1 INTRODUCTION

The evolution of solar magnetic field is the main reason for solar flares and coronal mass ejection (CME), which are the two most violent eruptions in the solar. In order to study the origin of and possible causal relations among solar flares, CME and solar magnetic field activities, Chinese scientists have proposed the Advanced Space-based Solar Observatory (ASO-S) satellite (Gan et al. 2019) expected to be launched in 2021. It is the second batch of scientific experimental satellites determined by the space strategic pilot science and technology program of the Chinese Academy of Sciences. The Full-disk MagnetoGraph (FMG), one of the three main loads of ASO-S satellite, will measure the full disk vector magnetic filed with high spatial-temporal resolution and high magnetic field sensitivity (Deng et al. 2019). Polarization modulation is the core technology to realize the measurement of solar magnetic field. At present, the measurement of solar magnetic field is mainly based on the changes of Stokes parameters of polarized light after Zeeman effect (Lin 2001), and then the information of solar magnetic field is retrieved by the radiative transfer models of the solar atmosphere.

Mechanical modulation and electro-optical modulation are the two common polarization modulation methods. The modulation velocity of mechanical is low and cannot meet the requirements of high-sensitivity magnetic field measurement of FMG. The electro-optical modulator crystal includes KD*P, ferroelectric liquid and Nematic liquid crystal. KD * P crystal is difficult to be used in space because of the complex structure of AC high-voltage modulation and silicone oil seal. The production process of ferroelectric liquid crystal is complicated, and there is no report about its application in space. Nematic liquid crystal is driven by low voltage with a relatively simple structure, and its polarization sensitivity and precision can meet the needs of measurement of solar magnetic field. It is the major direction for future development and expected to be adopted in the Solar Orbiter (Alvarezherrero et al. 2011) in 2020 (Lunched on Feb 10, 2020). Therefore, liquid crystals based Stokes polarimeter is the best choice for FMG to achieve high sensitivity polarization measurement. Thus, it is important to study its application, control and characteristic to realize scientific target of FMG.

There are two liquid crystal variable retarders (LCVR) as core optical elements in the liquid crystal based Stokes polarimeter. The retardation of LCVR is sensitive to the temperature, and the retardation changes 0.9 per 1°C. The error of polarization measurement caused by this change is 0.016, which affects the accuracy of magnetic field measurement. Therefore, the temperature stability of LCVR in polarimeter is very important as it will directly affect the accuracy and validity of scientific data. FMG polarimeter will be used in vacuum under the condition of 22 ± 2°C, the working temperature is 35°C, and the temperature fluctuation is no more than 0.1°C (Deng et al. 2019). To achieve these targets, it is necessary to study the space high-precision temperature control system.

A lot of research has been done on the high-precision temperature control system. The temperature control system designed in the hydrogen atomic clock of the United States (Peng 2005) adopted the complex structure of three-stage temperature control, which can gradually improve the accuracy from the outside to the inside, and the temperature accuracy of the inner layer reached 10⁻⁴°C. The temperature control system of high-precision gravimeter designed by Wuhan Seismological Bureau (Wu et al. 2008) has a stable accuracy of 0.0001°C, yet the system should be placed in a room with accuracy of 0.1°C. The fuzzy PID
control method adopted by Song Minggang (Song & Fan 2001) made the accuracy of thermostatic bath with water or oil as the medium reach to 0.01°C. Zhu Junchao (Zhu et al. 2018) et al designed a high-precision temperature control system for optical crystals, whose accuracy was better than ± 0.002°C. The problem is the semiconductor cooler cannot be applied to the object with complex structure. The chip, structure and thermal insulation material of the temperature control system in space are limited due to the spatial environment. Yang Zhengqiu (Yang et al. 2014) designed a space temperature control system with accuracy ± 0.03°C based on DSP PID algorithm for the space liquid bridge. However, 24 bit AD, used in this study to achieve high-resolution temperature measurement, is difficult to obtain in space applications. The ASO-S satellite has an orbit of 720 km and its expected service life is no less than 4 years. It is necessary to use aerospace devices for polarimeter due to the severe space environment. In recent years, there has been a great improvement in the temperature control system in the control circuits and algorithms. The integration degree of the control circuit is higher and the power consumption is lower. Compound control algorithm and neural network algorithm are widely used to make the control scheme more intelligent to complete more complex control tasks. However, it is still a challenge for space temperature control system to reach high-precision.

In this paper, a high-precision temperature measurement circuit is designed by using low resolution AD, which can be widely used in aerospace applications. The temperature field of LCVR is more clearly understood as the thermal effect of light on LCVR is analyzed theoretically. The temperature control algorithm of integral separation PI is used in the system to meet high-precision control requirements, which can satisfy the needs of FMG polarimeter. The research results have been applied to the FMG development.

This article is introduced in the following four parts. The first part introduces the principle of space high-precision temperature control, including the principle of space high-precision temperature measurement and control algorithm; the second part introduces the system composition from three aspects: mechanical structure design, temperature control system hardware and software; the third part is about design of the temperature control experiment, recording and analyzing the experimental data; the last part summarizes the full text and proposes the improvement of the system.

2 PRINCIPLES OF HIGH-PRECISION TEMPERATURE CONTROL IN SPACE

The temperature control system of polarimeter requires a temperature control accuracy of 0.1°C. The key technology of high-precision temperature control system is high-precision temperature measurement and control algorithm. High precision temperature measurement is the premise of high precision temperature control, and temperature control algorithm is the kernel of high precision temperature control.

2.1 the Principle of High-precision Temperature Measurement in Space

High-precision temperature measurement is the premise of high-precision temperature control. Thermistor, used as temperature sensor, is connected to Wheatstone bridge in the system. For thermistor temperature sensor, high resolution temperature measurement is equivalent to high resolution resistance measurement. The MF61 sensor used in this paper is a negative temperature coefficient thermistor (NTCR). Its resistance
temperature curve (T-R curve) is shown in formula (1), where a, b, c and d are constants.

\[
t = \frac{2c}{-b + \sqrt{b^2 - 4c(a - l_{HR})}} - d
\]  

(1)

The sensor is connected to the Wheatstone bridge (R.Wu et al. 1990) circuit. If the bridge reference voltage is \( V_{ref} \), the bridge arm resistance is \( r \), and the bridge output voltage \( U \) is:

\[
u = V_{ref} \left| 0.5 - \frac{r}{R + r} \right|
\]  

(2)

When the resistance of the sensor changes \( \Delta r \) due to a small amount of temperature change \( \Delta T \), the output voltage of the bridge changes as:

\[
\Delta u = V_{ref} \frac{\Delta r R}{(R + r)(R + r + \Delta r)} \approx V_{ref} \frac{\Delta r}{(R + r)^2}
\]  

(3)

After it is amplified A times by the amplifying circuit, the voltage variation at the AD input is \( A\Delta u \), and the AD range is \( U_R \). In order to meet the temperature measurement with sufficient accuracy, the inequality of A should meet is:

\[
AV_{ref} \frac{|\Delta r| R}{(R + r)^2} \geq \frac{U_R}{2^{16}}
\]  

(4)

At the same time, in order to meet the temperature measurement of a certain range, the following inequality should be satisfied:

\[
Au \leq U_R
\]  

(5)

According to formula (4) and (5), A satisfies:

\[
\frac{U_R (R + r)^2}{2^{16} V_{ref} |\Delta r| R} \leq A \leq \frac{U_R}{V_{ref} 0.5 - \frac{r}{R + r}}
\]  

(6)

Therefore, when the magnification A is increased, the temperature measurement accuracy is improved and the temperature measurement range is narrowed. When the magnification A is decreased, the opposite is the case. With the PGA selected, A changes dynamically according to output voltage U. At the same time, the temperature measurement with high-precision and wide range is realized.

### 2.2 Temperature Control Algorithm and Control Mode

In view of the characteristics of polarimeter temperature control system, which requires high steady-state and low dynamic, the integral separation PI algorithm (Heredero et al. 2007) is selected as the main control mode. In this paper, as shown in formula (7), when the set temperature is far higher than the actual temperature, that is, when the temperature difference \( \delta \) is larger than a certain value \( c \), the system uses a certain constant maximum power \( P \) for heating; when the actual temperature exceeds a certain value \( b \), the heating power is 0; when the temperature difference is small, PI control is used.

\[
U(t) = \begin{cases} 
  P & \delta > c > 0 \\
  PI & c \geq \delta \geq -b \\
  0 & \delta < -b < 0 
\end{cases}
\]  

(7)

The temperature control algorithm outputs a floating-point number between 0 and 1, that is PWM (R.Wu et al. 1990) duty cycle. PWM is widely used in temperature control system to drive heating wire or TEC.
By increasing the minimum pulse frequency of PWM, the task of high-precision temperature control can be achieved. In this paper, polyimide heating films are used as the temperature control actuator. In order to achieve the best temperature control effect, the overall dimension of polyimide heating film, used as the temperature control actuator, is the largest area. The design drawing is as follows.

Fig. 1: the Dimensional drawing of heating film

2.3 Thermal Analysis in Space

Ideally, when the polarimeter is at a constant temperature, the heat loss of the system is equal to the heat gain. In addition to the steady heat flow generated by the heating films, the heat gain also includes the heat effect generated by the sunlight on the LCVR and the heat radiation from the environment. In vacuum, the heat loss is conducted in the form of heat conduction and radiation. Therefore, on the premise of satisfying the strength design of space structure, reducing the contact surface between the structure and the box, and setting up heat insulation plate reduce the heat conduction effect. At the same time, the thermal radiation can be reduced by whitening the surface or applying anti-radiation materials. The thermal analysis of the polarimeter is done by ANSYS, Fig.2 shows the temperature field distribution of the polarimeter in 22°C vacuum. As is shown in the figure the top temperature of the polarimeter is higher and the bottom is lower, and the temperature distribution range is 22.0 to 35.004°C.

Fig. 2: Temperature distribution of liquid crystals
From the picture on the right side of Figure 3, it can be seen that the lowest temperature of LCVR appears at the bottom of the inner side (inward side) of the wave plate, where the heat dissipation is high due to the wire outlet. As shown in the figure, the white circle is the optical aperture of the LCVR. The temperature change of this part is the key point, which ranges from 34.206 to 34.817 °C. According to the results of thermal analysis, there is a temperature gradient perpendicular to the bottom of LCVR, as shown by the arrow. The basic reason is that the upper and lower structure of the polarimeter is asymmetric, which results in the different heat dissipation rate between the two surfaces. Therefore, in order to reduce the temperature gradient in this direction, the symmetrical polarimeter structure is redesigned or the heating film is added to the bottom of LCVR.

As shown in the figure 4 below, the vertical temperature gradient decreases obviously, with 35°C heating films added to the bottom of LCVR. The temperature range of LCVR aperture is 34.732 to 34.853°C, the inhomogeneity is 0.121°C, far less than the previous 0.611°C.

For a further comparative study, the temperature fields of LCVR at 20 °C and 24 °C are analyzed, and the results are shown in Table 1 below. It can be seen from the table that with the change of vacuum temperature, the temperature field of LCVR also changes, and when the external temperature is lower, the temperature heterogeneity of LCVR is greater; when the heating film is added at the bottom of LCVR, the temperature field is more uniform. In addition, when there is no heating film on the bottom and the vacuum temperature changes from 20 °C to 24 °C, the lowest temperature of LCVR drift reaches 34.330-34.084 =
Table 1: LCVR temperature distribution under different simulation settings

<table>
<thead>
<tr>
<th>Simulation type</th>
<th>Vacuum temperature °C</th>
<th>Min temperature °C</th>
<th>Max temperature °C</th>
<th>Inhomogeneity °C</th>
<th>Sensor position temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No heating film on the bottom</td>
<td>20</td>
<td>34.084</td>
<td>34.788</td>
<td>0.704</td>
<td>34.919</td>
</tr>
<tr>
<td>No heating films on the bottom</td>
<td>22</td>
<td>34.206</td>
<td>34.817</td>
<td>0.611</td>
<td>34.927</td>
</tr>
<tr>
<td>With heating films on the bottom</td>
<td>24</td>
<td>34.330</td>
<td>34.844</td>
<td>0.514</td>
<td>34.936</td>
</tr>
<tr>
<td>With heating films on the bottom</td>
<td>20</td>
<td>34.681</td>
<td>34.824</td>
<td>0.143</td>
<td>34.941</td>
</tr>
<tr>
<td>With heating films on the bottom</td>
<td>22</td>
<td>34.732</td>
<td>34.853</td>
<td>0.121</td>
<td>34.949</td>
</tr>
<tr>
<td>With heating films on the bottom</td>
<td>24</td>
<td>34.766</td>
<td>34.871</td>
<td>0.105</td>
<td>34.958</td>
</tr>
</tbody>
</table>

0.246°C, which exceeds the index of 0.1 °C fluctuation of the project. When the heating film is added at the bottom, this parameter changes to 34.766-34.681 = 0.085°C, which meets the requirements. Therefore, through the finite element analysis, we know that adding heating film at the bottom can not only make the LCVR temperature field more uniform, but also greatly reduce the LCVR temperature drift caused by the external temperature change. It can be predicted that when 35°C heating films are applied to the left and right sides of LCVR, the temperature field of LCVR will be more uniform and stable, while it also leads to more complex structures.

The meaning of the last column in Table 1 is the temperature of the position where the sensor is installed, which can represent the temperature of the sensor. Therefore, it can be seen that the temperature change of the sensor is weakly related to the installation position of the heating film and the vacuum temperature, and the maximum temperature change is less than 0.05 °C. In other words, if we test the performance of the temperature control system, whether there is heating film on the bottom of LCVR or not, the experimental results have the same physical significance. Therefore, in the later temperature control system test experiment, heating film is not installed at the bottom of LCVR.

Because of the complex unsymmetrical structure design, it is finite element, as the main method, that analyzes the effect of heat conduction and radiation. However, the approximate analytical solution of photothermal can be obtained under certain ideal assumption. When sunlight passes through LCVR, there will be a certain thermal effect inside, which will affect the temperature field of it. LCVR structure (Heredero, R. L 2007) is shown in the figure below. In the middle of the wave plate is liquid crystal materials. Polyimide layers, transparent indium tin oxide (ITO) electrodes, fused-silica substrates and the outermost anti-reflective (AR) coatings are symmetrically distributed from the innermost layer to both sides. Therefore, LCVR is a 9-layer composite structure composed of 5 materials. To simplify the heat transfer model, the model of LCVR is transformed into a single-layer structure by neglecting the thin AR coatings, the IOT electrodes, liquid crystal material and the polyimide layers.

![Fig. 5: Structure Diagram of LCVR](image-url)
The attenuation rate of the light in the medium is directly proportional to the intensity of the light, when the light passes through the semitransparent homogeneous medium. \( \alpha \) is the absorption coefficient of light; \( I_0 \) is the initial light intensity; \( I \) is the light intensity through the optical path of \( x \). If the light beam only transmits in the crystal, it can be reflected as:

\[
\frac{dI}{dx} = -\alpha I
\]

Integrated:

\[
I = I_0 e^{-\alpha x}
\]

Equation (10) expresses the light intensity at the \( x \) position in the translucent medium. Then, the intensity loss of the light at \( x \) position is:

\[
dI = -\alpha I_0 e^{-\alpha x} dx
\]

Assuming that the light loss intensity is dissipated in the form of heat, in the section with an area of \( S \) and a time of \( T \), the thermal energy \( Q \) generated by the light is:

\[
dQ = -dI * st = st\alpha I_0 e^{-\alpha x} dx
\]

That is to say, the intensity of the internal heat formed by the light is \( \Phi_x \):

\[
\Phi_x = \frac{dQ}{dv} = \frac{dQ}{stdx} = \alpha I_0 e^{-\alpha x}
\]

In the steady-state, the differential equation of heat conduction of infinite medium with a heat conduction coefficient \( \lambda \) satisfies the following requirements:

\[
\frac{d^2t}{dx^2} + \frac{\Phi_x}{\lambda} = 0
\]

Then get:

\[
t = \frac{I_0}{\alpha \lambda} e^{-\alpha x} + c_1 x + c_2
\]

Therefore, the influence of the light on the temperature field of homogeneous medium in steady-state is shown in equation (14). Ideally, the temperature distribution is only related to the thickness of LCVR. In this case, the temperature distribution in LCVR is from high to low from the incident surface to the exit surface, and the distribution of temperature field, ideally, ranges basing on the negative exponential equation of natural constant. Based on the above inference, the temperature field of LCVR, with vertical light, can be described by equation (14) under the condition that the light intensity, initial temperature and physical properties of each material in LCVR are known. It can also be seen from this formula that the main means to maintain the longitudinal uniformity of the temperature field of the LCVR and reduce the photothermal effect of LCVR are: adding insulating glass in front of the polarimeter, and reducing the thickness of LCVR. The three different aspects above, high-precision temperature measurement, control algorithm, and thermal analysis are analyzed theoretically, then the hardware circuit, temperature control algorithm and heating scheme are determined. Thus, the key problem of high precision temperature control system is solved and the specific implementation will continue.
3 INTRODUCTIONS OF SYSTEM

In space, weight and heat insulation are strictly limited, so the main frame of polarimeter is designed by titanium alloy one-time forming technology. In order to reduce the heat conduction rate, a heat insulation pad is added between the main body and the base, and a convex structure is designed on the contact face of base to reduce the contact area. To weaken the influence of thermal radiation, the outer surface of the structure is covered by 10 units of black carburizing films. The structure of polarimeter is shown in the figure 6.

![Fig. 6: Liquid crystals based Stokes polarimeter](image)

The resolution of AD commonly used in space projects is low because of the limitation of electronic components on satellites, which cannot meet the design of high-precision temperature measurement circuit. In order to obtain high-precision temperature (0.01°C resolution), the temperature acquisition circuit is mainly composed of sensors, Wheatstone bridges, amplification circuits, PGAs, low-pass filter circuits and 12-bit AD. The control flow is realized by MCU, and MCU communicates with host computer at the same time to transmit data and set parameters. PWMs are output and heating films are driven by heating circuits (maximum power 6W) to realize high-precision temperature control. The system hardware block diagram is shown in Figure 7.

![Fig. 7: Hardware block diagram of temperature control system](image)
The flow chart of temperature control system is shown in Figure 8. When the system starts to work, and the control parameters are initialized, the system firstly obtains the original data of channel 0 from AD, and carries out digital filtering after a group of filtering data is collected. The resistance and temperature of thermistor are calculated by AD data. Then the temperature control algorithm, using the temperature value, calculates the PWM duty cycle. Finally, the system outputs PWM and a control flow is completed. For the next cycle, it switches AD channel, with temperature data of second channel got, to start the other control flow.

![Temperature control system flow chart](image)

**Fig. 8: Temperature control system flow chart**

4 TEMPERATURE CONTROL EXPERIMENT AND RESULTS

The circuit board was designed and debugged, and the experiment for temperature control system was done in the air and vacuum. As shown in Figure 9, the control box and vacuum test box were used in the experiment. In the room (22±1°C) and in the vacuum (22±1°C, 100 Pa), the temperature was set at 35°C, and the stability of the system was tested by three temperature control experiments. The curves of temperature control are shown in Figure 10, and the statistical table of control characteristics is shown in Table 2. It can be seen from the table that the temperature control system operated stably and had high repeatability in the air. The first time to rise from 30°C to 35°C took about 51s. After three fluctuations of 51∼54s, the maximum deviation is 0.0152°C. In vacuum, the three values are 50∼52s, 62∼65s, and 0.0250°C. The results are much better than the project fluctuation index of 0.1°C. It can be inferred that when the ambient temperature becomes 20 ± 2°C, even if the temperature fluctuation is estimated by a larger value, that is 2 * 0.0152 = 0.0304°C and 2 * 0.0250 = 0.0500°C, which also meets the requirements of the project.

Therefore, either in the air or vacuum, the temperature control system has satisfied the requirements of high-precision. However, due to the change of environment, the rising time and the steady-state time of
Table 2: Statistical data of temperature control experiment

<table>
<thead>
<tr>
<th>Experimental type</th>
<th>No</th>
<th>Rise-time/s (30~35 °C)</th>
<th>Stationary time/s</th>
<th>Average temperature/°C</th>
<th>Max deviation/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the air</td>
<td>1</td>
<td>51</td>
<td>51</td>
<td>35.0452</td>
<td>0.0141</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>51</td>
<td>54</td>
<td>35.0345</td>
<td>0.0152</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>51</td>
<td>52</td>
<td>35.0464</td>
<td>0.0152</td>
</tr>
<tr>
<td>In the vacuum</td>
<td>1</td>
<td>54</td>
<td>65</td>
<td>35.0473</td>
<td>0.0236</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>55</td>
<td>62</td>
<td>35.0482</td>
<td>0.0217</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>54</td>
<td>63</td>
<td>35.0478</td>
<td>0.0250</td>
</tr>
</tbody>
</table>

Polarimeter temperature in vacuum are longer, and the temperature stability is slightly lower than that in the air.

5 CONCLUSIONS

In this paper, the high-precision temperature measurement circuit is formed by studying the principle of high-precision temperature measurement; the temperature control algorithm of integral separation PI is
determined by analyzing the heat transfer characteristics of polarimeter; and the optimal temperature heat scheme is proposed by finite element thermal analysis method. At last, a high-precision space temperature control system based on integral separation PI is designed. A comparative test in vacuum and air was carried out. The experiment results show that the system can achieve high-precision temperature control in both air and vacuum. In the air, the thermostatic stability of temperature control is better than $\pm 0.010^\circ C$, and in the vacuum, it is better than $\pm 0.015^\circ C$. The principle and scheme of high-precision and wide range temperature measurement circuit designed in this study can be widely used in other space projects of high-precision temperature measurement requirements.

Acknowledgements The authors would like to thank the supporting of these Grants: The National Natural Science Foundation of China (11427803, 11427901, 11773040), The Strategic Pioneer Program on Space Science, Chinese Academy of Sciences (CAS) (XDA04061002 and XDA15010800), The Public Technology Service Center, National Astronomical Observatories of CAS (829011V01).

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