Pole assignment PID controller based on parameter identification and its application

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Abstract. In order to ensure spacecraft qualification before the delivery, thermal tests should be performed with regard to its performance specification. The aim of thermal tests is to examine the function and performance under extreme thermal and vacuum conditions, and also to detect possible manufacturing defects or check the rationality of theoretical thermal models. Temperature control of spacecraft products is one of the critical tasks in the thermal test, which has the characteristics of large thermal inertia and time-delay. Ordinary single control method often leads to poor performance or even out of control. In this paper, the model of control object is identified by the least squares recursive algorithm (LSRA). According to the identified parameters and the expected pole position, three parameters of the PID controller are obtained. In order to test the control effect of this control method, representative test data is selected for simulation analysis, and the simulation effect is satisfactory. Then this control method is applied to temperature control of satellite solar array of Chang’E-1. The results show that pole assignment and the self-tuning PID controller based on parameter identification has the advantages of strong adaptability and high control precision.

1. Introduction

The purpose of thermal test is to simulate the cold black and vacuum environment experienced by the on-board products in the space. Temperature control is the critical work in thermal test. With different thermal characteristics of various control objects, this work has the characteristics of long process time, big overshoot and uncertain disturbance. Because of different objects and multiple test cases in each test, it is difficult to establish a precise mathematical model. With the development of deep space exploration, a wide variety of new space products appear, which requests higher control precision. However, the traditional PID controller cannot adjust its parameter value according to the changing of the control object. In this paper, the least squares recursive algorithm (LSRA) is used to identify the model of the system. Control results show that this method has good control effect.

2. Determining control model structure

2.1. Heat balance equation of a control mode

The heat flux absorbed from solar radiation, earth’s radiation and reflection by the spacecraft product are simulated by absorbed flux method using infrared heating devices or film heater. Test operators adjust the product surface temperature according to the target temperature obtained by the calculation result. In this equivalent heat flux analysis, the steady-state equilibrium of a control node can be expressed in the equation:

\[ Q_{S+\lambda} + Q_I + Q_R + \sum_{n=1}^{k} A_{i-n} \sigma T_n^4 = A_i \sigma e_i T_i^4 \]  

(1)
Where, $Q_{s+a}$ is the solar radiation and the earth reflection, $Q_{ir}$ is infrared radiation absorbed from the earth, $Q_i$ is the heat consumption of the node. $A_{i-n}$ is radiant heat transfer resistance, $\sigma$ is Boltzmann constant, $\varepsilon_i$ is the thermal radiation absorbing coefficient, $T_n$ is the temperature of the node, $A_i$ is the area of the node, $T_i$ is the surface temperature of node $i$. When heat sink temperature is used to simulate the external heat flux, heat flux radiated by the node $i$ to the heat sink can be expressed as follows:

$$Q_i = \varepsilon A_i (\sigma T_i^4 - \sigma T_n^4) = \varepsilon A_i \sigma T_i^4 - \varepsilon A_i \sigma T_n^4$$

(2)

From expression (1) and expression (2), we can derive the following expression:

$$A_i \sigma \varepsilon T_i^4 - Q_{s+a} - Q_{ir} - \sum_{n=1}^{k} A_{i-n} \sigma T_n^4 = \varepsilon A_i \sigma T_i^4 - \varepsilon A_i \sigma T_s^4$$

(3)

When temperature of infrared heater $T_s$ is used to express heat flux relationship of node $i$, the following equation can be derived[3]:

$$\varepsilon A_i \sigma T_s^4 = Q_{s+a} + Q_{ir} + \sum_{n=1}^{k} A_{i-n} \sigma T_n^4$$

(4)

$$T_s = \sqrt[4]{\frac{Q_{s+a} + Q_{ir} + \sum_{n=1}^{k} A_{i-n} \sigma T_n^4}{\varepsilon A_i \sigma}}$$

(5)

In the thermal test, spatial heat flux is simulated accurately by controlling product temperature $T_i$. $T_i$ is used to calculate the reaching heat flux of node $i$, and $T_i$ is measured by temperature sensor.

2.2. Composition of thermal test system

The external heat flux in space is generally simulated by infrared array or infrared cage. The product temperature is controlled by adjusting the current working in the infrared devices. A closed loop control system consists thermal vacuum chamber, infrared devices, test product or sample, power system and data acquisition system, which can be seen in Figure 1.

![Figure 1. Infrared cage and sample in the thermal vacuum chamber.](image)

During the test, the controller gives signal to drive DC powers outputting current to the infrared heater. The controller compares the product temperature data with the target value and then makes modifications until reaching the required temperature. According to the analysis of control system composition, we can get the transfer function block diagram of the control system as shown in Figure 2[4].
2.3. Structure of control model

When the composition of the control system is determined, the task of identification is to recognize the characteristics of the control system. Theoretical analysis and experimental results show that most control objects in thermal test can be described as second-order systems[5], so the system mathematical model can be described as below:

\[ G(z) = \frac{z^{-d}(b_2 + b_1 z^{-1})}{1 + a_1 z^{-1} + a_2 z^{-2}} \]  

(6)

The time-varying unknown parameter \( a_1, a_2, b_1, b_2 \) should be identified online, \( d \) is the system delay, which can be set as 1. This formula can be expressed in a difference equation form:

\[ A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k) \]  

(7)

Where: \( y \) is the output, \( u \) is the input, \( k \) is discrete time series;

\[ A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} \]

\[ B(z^{-1}) = b_1 + b_2 z^{-1}, (b_1 \neq 0) \]  

(8)

\( a_1, a_2, b_1, b_2 \) are time-varying unknown coefficients and needed to be identified online.

3. System Identification

3.1. Least squares recursive algorithm (LSRA)

In a dynamic system, the output of the system is determined by its previous value, the target value and the previous input of the system. In this paper, LSRA is used to identify control system parameters. Let \( u(k) \) and \( y(k) \) indicate the input and output of the system. \( u(k) \) and \( y(k) \) have the following relational expression:

\[ y(k) + \sum_{i=1}^{n} a_i y(k-i) = \sum_{i=1}^{n} b_i u(k-i) + e(k) \]  

(9)

Where, \( u \) is the input, \( e(k) \) is the error caused by modeling. \( a_i \) and \( b_i \) are parameters to be identified.

Set the target function as below[6]:

\[ min \{ J(\theta) \} = \frac{1}{N} \sum_{k=n+1}^{n+N} e^2(k) = \frac{1}{N} \sum_{k=n+1}^{n+N} [y(k) + \sum_{i=1}^{n} a_i \cdot y(k-i) - \sum_{i=1}^{n} b_i \cdot u(k-i)]^2 \]  

(10)

Let

\[ \phi_k^T = [-y(k-1), \ldots, -y(k-n), u(k-1), \ldots, u(k-n)] \]

\[ \theta^T = [a_1, a_2, \ldots, a_n, b_1, b_2, \ldots, b_n] \]

\[ \Phi_N = [\phi_1^T, \phi_2^T, \ldots, \phi_N^T]^T \]

\[ y_N = [y(1), y(2), \ldots, y(N)]^T \]

Where, \( \phi \) is temporary variable, is the input, \( e(k) \) is the error. Then, formula (9) can be expressed as follows:

\[ y(k) = \phi_k^T \cdot \theta + e(k) \]  

(12)
Minimize the objective function $f(\theta)$, then

$$\theta_{LS}^A = (\Phi_N^T \Phi_N)^{-1} \cdot \Phi_N^T \cdot y_N$$

(13)

Express $\theta_{LS}^A$ as a form of difference equation:

$$\theta_{N+1}^A = (\Phi_{N+1}^T \Phi_{N+1})^{-1} \cdot \Phi_{N+1}^T \cdot y_{N+1}$$

(14)

Where, $\Phi_{N+1} = [\Phi_N, \phi_{N+1}^T]^T$, $y_{N+1} = [y_N, y(N + 1)]^T$.

Let $P_N = (\Phi_N^T \Phi_N)^{-1}$, we can get the following formula:

$$P_{N+1} = (\Phi_{N+1}^T \Phi_{N+1})^{-1} = (P_N - \frac{P_N \Phi_{N+1}\phi_{N+1}^T \Phi_{N+1} P_N}{1 + \phi_{N+1}^T P_N \Phi_{N+1}})$$

(15)

The following formula can be obtained by substituting expression (15) into the formula (14),

$$\theta_{N+1}^A = \theta_N^A + \frac{P_N \Phi_{N+1}}{1 + \phi_{N+1}^T P_N \Phi_{N+1}} \cdot [y(N + 1) - \phi_{N+1}^T \cdot \theta_N^A]$$

(16)

3.2. Identification of an unknown model

In order to verify the identification effect on an unknown control model, temperature and current data of a satellite product in a thermal test is used. The initial parameters are set as: $P = 100* I_4$, which is a fourth-order unit matrix. $\theta = [0; 0; 0; 0]$ is the initial value of control model. The figure below shows the identified model coefficients and error.

Identification result shows that parameters of the control method changing quickly according to the temperature changing when the historical data is identified using LSRA. The compared result and error verify that LSRA has high identification accuracy. Parameters identified can be seen in Figure 3 and the error can be seen in Figure 4.

**Figure 3. Identification result of control model.**
4. Pole assignment PID controller

According to the above description, the model structure of the temperature object can be regarded as known. Only the parameters of the model are unknown. Theoretical analysis and experimental results show that most temperature objects can be described as a system of second-order plus time delay[9].

The equation to describe closed-loop system is:

\[ A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k) + y_d \]  \hspace{1cm} (18)

Where: \( y_d \) is offset, \( n=2 \).

The Figure 5 below shows the closed-loop structure of the pole assignment self-tuning PID control system.

\[ G'(z^{-1}) = 1 + \frac{g_1}{g_0}z^{-1} + \frac{g_2}{g_0}z^{-2} \]
\[ F'(z^{-1}) = 1 + f_1z^{-1}, \quad F' \text{ is added for filtering}[10]. \]

In order to simplify the calculation during the thermal test, the initial value of PID parameters are gotten before the tests by repetitious analysis, calculation and previous experiences[11].
5. Simulation and application

5.1. Simulation
In order to verify the effect of this control method, data of thermal test is selected. This test basically represents the most common temperature requirements in the thermal tests. The left graph of Figure 6 shows the target temperature control effect with pole assignment self-tuning PID control method. Fixed PID parameters are used in the same test with same target temperature. Result in the right of Figure 6 shows not good enough control effect because the overshoot is big.

Figure 6. The control effect using auto-adjusting PID control.

5.2. Application
Thermal vacuum tests are chosen to fully check the control method’s performance. These tests consist of two different objects and different test cases of each object. All tests contain high and low temperature cases as sample experiences in orbit.

5.2.1. Target temperature control. A high precise of waveguide temperature control is needed in a thermal test. By applying a step response to the control system, the ideal pole position is obtained, and the controller is designed according to the pole position. Ideal step response curve of the control system is shown in Figure 7 (left). Results of simulation analysis show that this control method has achieved good results. The real control effect is shown in Figure 7 (right).

Figure 7. Waveguide temperature control effect of a communication satellite.
5.2.2. Temperature control with multi-zone coupled. In order to fully verify the control effect for spacecraft products with multi-loop and mutual coupling effect between multiple control areas, this control method was applied to four solar array panels of Chang'E-1 satellite in thermal test. The target temperatures are set to -95 °C, -25 °C, -75 °C and 20 °C respectively to verify the control effect during the entire temperature range. The actual control effect is shown in Figure 8.

![Figure 8. Target temperature control curve of Chang'E-1 satellite solar panels using new control method.](image)

5.3. Result analysis
When the temperature is close to a very high value, maximum overshoot is 0.6 °C which is much better than the +3 °C required in test outline. When the temperature goes very low, maximum overshoot is about 1.6 °C, and it drops to ±0.8 °C after one oscillation cycle, which is better than ±1 °C required in test outline.

6. Conclusions
In summary, pole assignment PID control method is based on the parameter identification. PID configuration of the pole configuration estimate the model of the system with LSRA. Pole assignment PID control method can adjust the controller parameters and control temperature more precisely. It has a better dynamic performance and needs less manual operator. This method is more efficient, stable, reliable and robust, which makes the temperature simulation more precise in the thermal test.

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