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Piecewise adaptive PID controller and its application in thermal vacuum test of space products

Zhang Jun, Zhang Chunying, Zhu Xi, Ma Kun, Lu Tong
(Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China)

Abstract: On the basis of analysis on the characteristics of the control objects in the thermal vacuum tests and the current problems and difficulties in the temperature control, an adaptive PID controller is designed. In order to verify this control method, two thermal vacuum tests are carried out. The test results show that this adaptive PID control method enjoys many advantages, including small amount of overshoot and superior adaptability without the need of manual operation in the test. It provides a better solution to the problem in the current control system with the lack of automation and a large overshoot, and thus greatly reduces the labor intensity of manual adjusting.

Key words: thermal vacuum test; temperature control; overshoot; adaptive control; PID controller

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分段自适应 PID 控制器及其在航天产品真空热试验中的应用

张 军，张春莹，朱 熙，马 昆，路 彤
（北京卫星环境工程研究所，北京 100094）

摘要：文章在分析航天产品真空热试验时被控对象的特点及目前在温度控制方面存在的主要问题及难点的基础上，进行了极点配置自适应 PID 控制器的设计，并通过 2 次热真空试验验证了该控制方法的控制效果。结果表明，该 PID 控制方法具有超调量小、适应性强且在过程中无需手动调节等优点，较好地解决了目前热真空试验中控制系统智能性差和超调量大的突出矛盾，极大地减轻了试验人员的值班强度。

关键词：热真空试验；温度控制；超调；自适应控制；PID 控制器

0 Introduction

As one of important environmental simulation tests in the spacecraft development process, spacecraft thermal vacuum test is carried out in the vacuum environment and under thermal cycling conditions to verify the spacecraft's performance and functions. In this test, the vacuum degree and the accurate temperature control have direct bearing on the spacecraft thermal vacuum test results. With the development of new spacecrafts, the temperature control presents higher requirements. In the current controller, the smallest control period is one minute and the control method is in a manner of proportional control. The controller's parameters are adjusted not automatically in the tests, but manually based on the operator's experience. Thus the tolerance requirements of 1～4 ℃ of the specimen's temperature could not be met. Especially when the specimen's temperature is near the target value, the test has to be stopped in order to change the parameters or to restrict the current value. That means great intensity of labor and night, which may cause a large overshoot for an inexperienced operator on duty. In order to improve the temperature control accuracy and reduce the overshoot and the related test risk, a new control method is needed in addition to the improvement of the system of software devices[1].

1 System analysis and control mode selection

The improvement of the temperature control performance is important for operators and technicians to avoid the problems mentioned above which involves control objects with long processing time, big overshoot and uncertain disturbance[2]. It is difficult to establish a precise mathematical model. The adoption of a single control method for these control objects often comes up with a disappointing result[3]. With the development of spacecraft industry, a higher control precision is required. Based on the control system of the characteristics, the adaptive PID controller is adopted in this paper, which combines the control experience of experts in the meantime, thus reduces the overshoot and enhances the capability to combat the disturbance. Different PID controllers can work in different temperature ranges. This complex

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controller is used in thermal vacuum tests.

2 Adaptive PID controller design

2.1 Analysis of the characteristics of adaptive control

The adaptive control is applicable for control models in which the control object is complex and does not follow a perfect mathematical model[4]. Excellent control characteristics can be achieved by an incremental adaptive control such as to quickly reduce the deviation when there is a large one, but it cannot regulate the steady-state deviation of the system, that is, there will not be a vibration at the vicinity of the equilibrium temperature. The integral role of a PID controller can make up for these deficiencies, so higher accuracy, faster dynamic response and smaller overshoot would be obtained through relying mainly on the PID control while there is a small deviation. Generally speaking, for an adaptive controller, a logic-judged function in a special circumstances is added to the software to prevent the poor control representation for large and uncertain factors. The added functions of the system can adjust the parameters according to its own current running state so that they can modify the control rules indirectly[5]. The automatic calibration is done on the controller in a random environment and a good performance is maintained even when the properties of the charged object undergo some changes or disturbances. In other words, this method has a considerable adaptive capacity[6].

2.2 Establish the benchmark parameters of PID controller

The incremental PID controller refers to the output of a digital PID controller, which is the incremental control volume $\Delta u(k)$. With the form of a recurrence formula, we can obtain expressions as follows[7]:

$$\begin{aligned}&\Delta u(k)=K_{\mathrm{p}}\Delta e(k)+K_{i}e(k)+K_{\mathrm{d}}[\Delta e(k)-\Delta e(k-1)]\\&\Delta e(k)=e(k)-e(k-1)\end{aligned}, \tag{1}$$

where $u(k)=u(k-1)+\Delta u(k)$.

A lot of preliminary work for the PID controller is required in order to obtain the initial parameters. One way is to use the summarized experience of predecessors for reference, the other one is to do a theoretical derivation and a test validation. The theoretical derivation is based on the pole placement self-tuning method, which assumes that the temperature objects can be described as a second-order system (theoretical analysis and experimental results show that most temperature objects can be described as systems of second order), so the system's mathematical model can be written as

$$G(z)=\frac{z^{-d}(b_0+b_1z^{-1})}{1+a_1z^{-1}+a_2z^{-2}}, \tag{2}$$

where a_1, a_2, b_0 and b_1 are time-varying unknown parameters[8], and have to be identified on-line; d is known as the system delay factor, which is set as 1. We use the pole placement self-tuning method to get the initial parameters of the PID controller next. The closed-loop structure of the pole placement self-tuning PID control system is shown in figure 1[9].

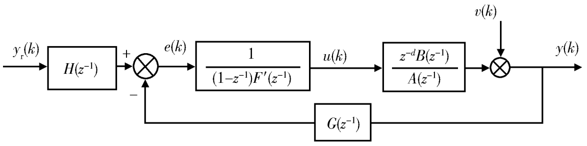

Fig. 1 Pole placement self-tuning PID control structure

The mathematical model is shown as

$$A(z^{-1})y(k)=z^{-d}B(z^{-1})u(k)+y_{\mathrm{d}}, \tag{3}$$

Where: y_{d} is the offset of system; $A(z^{-1})=1+\sum_{i=1}^{n}a_iz^{-i}$; $B(z^{-1})=\sum_{i=0}^{n-1}b_iz^{-i},(b_0\neq 0)$.

The PID control by the type is shown as

$$F(z^{-1})u(k)=H(z^{-1})y_{\mathrm{r}}(k)-G(z^{-1})y(k),$$

$$F(z^{-1})=(1-z^{-1})F'(z^{-1}). \tag{4}$$

In order to eliminate the offset items, we choose the parameters as follows:

$$\begin{cases}F'(z^{-1})=1+f_2z^{-1},(-1<f_2<0)\\G(z^{-1})=g_0+g_1z^{-1}+g_2z^{-2}\\H=G(1)=g_0+g_1+g_2\end{cases}. \tag{5}$$

Then the corresponding PID control strategy can be expressed as

$$u(k)=[-k_{\mathrm{p}}-\frac{k_{\mathrm{d}}(1-z^{-1})}{1+f_2z^{-1}}]y(k)+\frac{k_i}{(1-z^{-1})(1+f_2z^{-1})}\cdot$$

$$[y_r(k)-y(k)]. \tag{6}$$

The relationship between the various parameters is as follows:

$$\begin{cases}g_0=k_{\mathrm{p}}+k_{\mathrm{i}}+k_{\mathrm{d}}\\g_1=k_{\mathrm{p}}(f_2-1)-2k_{\mathrm{d}}\\g_2=k_{\mathrm{d}}-f_2k_{\mathrm{p}}\end{cases}. \tag{7}$$

Substituting expression (5) into (4), we get the following closed-loop system equation,

$$(AF+z^{-1}BG)y(k)=Hz^{-1}By_{\mathrm{r}}(k)+Fy_{\mathrm{d}}\cdot \tag{8}$$

This is a simple 4-order closed-loop system. When A and B are known, we can get F and G by calculation and make the closed-loop characteristic polynomial equal to the expected polynomial $A_{\mathrm{m}}(z^{-1})$,

$$A_{\mathrm{m}}(z^{-1})=AF+z^{-1}BG. \tag{9}$$

When the parameter values of A and B are identified, F and G can be uniquely identified, and then the PID control parameters can be obtained. The parameter values of the controller can be calculated as follows:

$$\begin{cases} f_2 = \dfrac{(q_2 + a_1 - a_2) b_0 b_1^2 - b_0^2 b_1 a_2 - b_1^3 (q_1 - a_1 + 1)}{b_0 b_1^2 (a_1 + 1) - b_0^2 b_1 (a_1 + a_2) + b_0^3 a_2 - b_1^3} \\ g_0 = \dfrac{q_1 - a_1 + 1 - f_2}{b_0} \\ g_1 = \dfrac{a_2}{b_1} - \left(\dfrac{a_2}{b_1} + \dfrac{a_1}{b_1} - \dfrac{b_0 a_2}{b_1^2}\right) f_2 \\ g_2 = \dfrac{-a_2 f_2}{b_1} \end{cases} . \tag{10}$$

The PID parameters are obtained before the tests by repeated analyses and calculations of the object and the usual control experience. The appropriate PID parameters for the solar panels and the antenna are established. The selection of data is done automatically in accordance with the infrared heating device selection and different objects defined by program at the preliminary test. It is worth emphasizing that the parameters are just like the initial parameters, which can be adjusted according to their own conditions in the process of the temperature control.

2.3 Impact on system performance and the adjustment principles of PID controller parameters

Usually, with different $|e|$ and different $|ec|$, the self-tuning request of process parameters k_p, k_i and k_d can be simply summed up.

Considering the current structure of the software system, the differential module component is not adopted in the algorithm. It will be considered in the follow-up work. At the conclusion of the summing up, with the PID parameter adjustment principles, the adaptive Fuzzy PID controller can be designed[10].

The temperature control process can be divided into three parts as shown in figure 2. We can implement different intelligent control strategies for different parts. The satisfactory temperature control can be obtained.

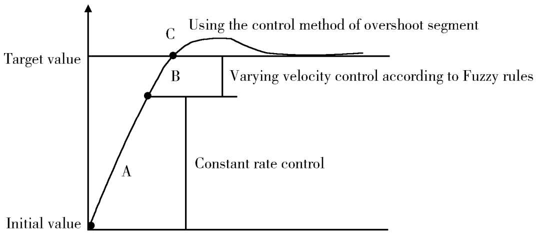

Fig. 2　Temperature control methods for each parts

At the segment A, the constant rate control can be adopted in accordance with the requirements given in reference documents. The current velocity can be set at the range of 1～2 ℃/min before the test at present. Once set, the velocity does not need to be changed in the course of the experiment. This current velocity range is usually required in large antenna thermal vacuum tests.

At the segment B, within 15 ℃ to the target temperature value, fuzzy control rules should be adopted in order to control the declining of the rate. From the correspondence between the temperature and the heating, the cooling rate is presented in Table 1.

Table 1　Relationship between temperatures and heating rates

e/℃	15	11	7	4.5	3	2	1
v/(℃·min^{-1})	1	0.8	0.6	0.4	0.3	0.1	0.2

Rules of current adjusting are as follows:

The scope of the current increment is (-0.2 ℃/min, +0.2 ℃/min). Therefore it is proposed to set the value of the current fuzzy language as (Negative Large, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle, Positive Large), recorded as (NB, NM, NS, ZE, PS, PM, PB). The scope of e is [-15 ℃, +15 ℃], the definition of E is recorded as (NB, NM, NS, ZE, PS, PM, PB)[11].

Set the range of ec as: (-3 ℃/min, +3 ℃/min), therefore it is proposed to set the value of the fuzzy language of ec as (Negative Large, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle, Positive Large), recorded as (NB, NM, NS, ZE, PS, PM, PB). The fuzzy control rules are set in the following mode:

R_i: if $E(k)=E_i(k)$ and $Ec(k)=Ec_i(k)$, then $\Delta u(k)=\Delta u_i(k)$. (11)

The division of the output directly affects the system dynamic process. With a finer division, higher control accuracy can be obtained, but at the same time a greater workload is required, so it can be selected in accordance with the actual system. According to the experience in the past, at different stages of the temperature, the amount of the current increment is different. When an overshoot occurs, a special control strategy is used to decrease the overshoot rapidly without using the complex control algorithms in the ascending or descending phase of the temperature.

3 Test

3.1 Test program & results

To fully verify the method by test, two thermal vacuum tests are designed, which consist of two different objects and different test cases for each object. Different temperature ranges are set as the target temperature, of which 0 ℃, -50 ℃, 40 ℃, 90 ℃ is for the first test, and -100 ℃, -30 ℃, -80 ℃, 10 ℃ is for the second test. Results are shown in figure 3 and figure 4 separately.

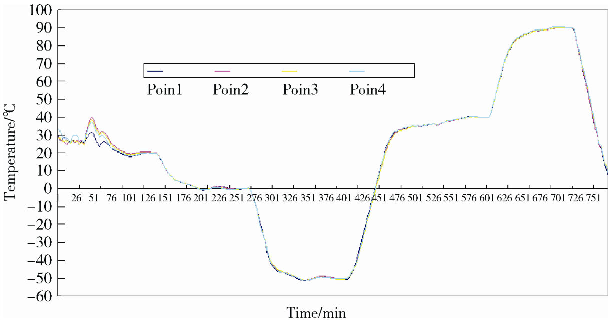

Fig. 3　Sample temperature curve for the first test

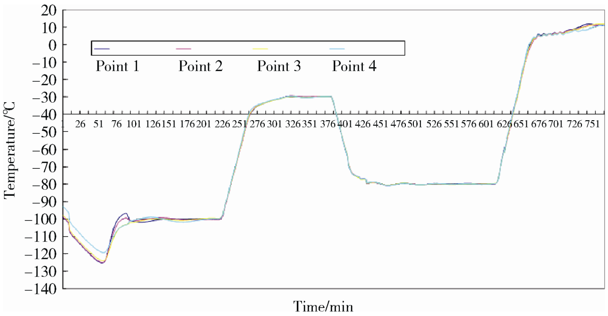

Fig. 4 Sample temperature curve for the second test

Tests reveal that this control method reduces the overshoot(<3℃) and enhances the capability of anti-disturbance, which also alleviates the operators' labor intensity to a great extent, and lowers the test risk.

Using the traditional PID control for the same objects, the results are shown in figure 5.

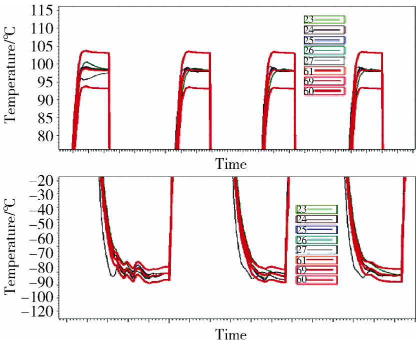

Fig. 5 Temperature curve for the same object using the traditional PID

3.2 Results analyses

3.2.1 Overshoot

1) Using the adaptive PID control

when the temperature goes very high, the maximum overshoot is 0.6 ℃, far less than +3 ℃ as required in the test outline. When the temperature goes very low, the maximum overshoot is about 1.6 ℃, and drops to ±0.8 ℃ after one oscillation cycle, better than ±1 ℃ as required in the test outline.

2) Using the traditional PID control

When the temperature goes very high, the maximum overshoot is 3.6 ℃, near +4 ℃ as required in the test outline. When the temperature goes very low, the maximum overshoot is about -6.24 ℃, with several oscillation cycles, higher than -4 ℃ as required in the test outline.

3.2.2 Anti-disturbance

At the end of the second test, the background temperature keeps changing in the course of the heat sink returning to the normal. The control system still maintains the temperature around the target value of 10 ℃, while the maximum overshoot is 1.3 ℃.

4 Conclusions and Prospective

This paper makes an attempt to use the adaptive PID control in spacecraft thermal vacuum tests. The results reveal that the expectation is realized with this method, and the method can be applied in some more tests. The control algorithm tends to be mature after many tests and summarizations. In conclusion, the adaptive PID controller is shown feasible through tests.

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（编辑：许京媛）

作者简介：张 军（1980—），男，硕士学位，主要从事热真空试验技术研究。E-mail: junbit21995@sohu.com。