Fuzzy PID Controller and its Application to the Field of Thermal Vacuum Tests of Aerospace Products

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Abstract: - The article first analyzes the characteristics of the control objects in thermal vacuum tests, points out the main problems and difficulties existence in the temperature control currently. Fuzzy PID controller is designed according to these characteristics. In order to verify this control method, three times of thermal vacuum tests are carried out. Results show that this Fuzzy PID control method has a small amount of overshoot, super adaptability without manual operation in the test. It provides a better solution to the problem in current control system short of intelligence and having a large quantity of overshoot, which greatly reduces the job intensity of test personnel on duty.

Key-Words: - Fuzzy Controller Thermal Vacuum Overshoot Temperature

1 Introduction

Spacecraft thermal vacuum test is carried at the vacuum and thermal cycling conditions to verify the spacecraft performance and function. It is one of several important environmental simulation tests in spacecraft developing process. In thermal vacuum test, vacuum circumstance and accurate degree of temperature control will directly affect the spacecraft thermal vacuum test results. An unqualified test will have an overmuch or less test of specimens. With the development of new spacecrafts, higher requirements of temperature control are put forward gradually. The current controller uses a smallest control period of one minute and control method is a manner of proportional control. This controller can't adjust the controller parameter values by itself in the tests. It is necessary for operators to adjust parameters manually based on their experience. This control method can't meet the tolerance requirements of 1℃ ~3℃ of specimens' temperature. Especially when the specimens' temperature is near to the target value, operators often need to suspend the procedure in order to change the parameters or restrict current value. It will cause a large overshoot when an inexperienced operator is on duty. Test result can't meet the test requirements in this situation. In addition, a test often lasts one week or even several weeks. This intensity is also a very big trial for operators. In order to improve temperature control accuracy and reduce the overshoot and test risk, a new control method is needed in addition to improving the system of hardware devices.

2 System Analysis and Control Mode Selection

Improving temperature control performance has been the aim for operators and technicians to resolve the problems mentioned above. This type of control objects with the characteristics of long process, big overshoot and uncertain disturbance. They also have many uncertain factors. It is difficult to establish a precise mathematical model. Adoption of a single control method in these control objects often causes a disappointed result. With more and more aircrafts produced, high control precision is requested. Based on control system of the characteristics, the author chooses Fuzzy PID controller, joined control experience of certain experts in the meantime. Thus, we can use traditional PID control method to resolve Fuzzy control's poor accuracy near the target value, using fuzzy control resolves the poor adaptability of PID control. Fuzzy control and PID control can work in different temperature range to exert each other's predominance. This complex controller is used in thermal vacuum tests. Results show that compared with former control, Fuzzy-PID control decreases the overshoot and enhances the capability of anti-disturbance.

3 Fuzzy PID Control Design

3.1 Analysis of the characteristics of Fuzzy control

Fortunately, fuzzy control is applicable for such control model in which the control object is complex and does not depend on perfect mathematical model[1]. There are excellent control characteristics for Fuzzy control such as quickly reducing the deviation when there is a large deviation, but regrettably it can not regulate the steady-state deviation of the system, that is, there will be a slight vibration at the vicinity of the equilibrium temperature. The integral role of 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 small deviation. Generally speaking, once the design of Fuzzy controller is completed, the language, rules and synthesis are fixed that there will be certain limitations for conventional Fuzzy controller. Therefore, a logic-judged function in special circumstances has been added to the software in order to prevent the poor control representation when there are large and uncertain factors occurred. Those increased functions of the system can adjust the parameters according to its own current running state so that they can modify the control rules indirectly. They make the system do automatic calibration on the controller in random environment and also make it remain a good performance even when the properties of charged object have some changes or disturbance. In other words, this method has considerable adaptive capacity.

3.2 Incremental PID control algorithm

PID control has a variety of forms. With the development of computer technology, digital PID controllers will gradually replace traditional analog PID controllers. Digital PID control algorithms are usually divided into two types: location-type PID control algorithm and incremental PID control algorithm. Incremental PID control algorithm is used in this article because of that it can reduce the effect or impact when there is some mishandling and switch between manual and automatic control. It is easy to achieve non-disturbance switch. The control increment just relies on the dates of the three up to date periods. Therefore, it is easy to achieve a better control performance just by using this method.

Incremental PID controller refers to the output of digital PID controller is the incremental control volume $\Delta u(k)$ .In accordance with recurrence formula, we can obtain expressions of $\Delta u(k)$.

3.3 Establish the benchmark parameters of PID controller

The author has done a lot of pre-work for PID controller in order to obtain the initial parameters. One way is using the summarized experience of predecessors for reference, the other one is theory consequence and test validation. Theoretical derivation is based on pole placement self-tuning method, this method assumes that the temperature objects can be described as second-order system (Theoretical analysis and experimental results show that most temperature objects can be described as systems of second-order plus time delay), so the system mathematical model can be written as the following form,

$$G(z) = \frac{z^{-d}(b_0 + b_1 z^{-1})}{1 + a_1 z^{-1} + a_2 z^{-2}} \quad (1)$$

In the expression, a_1, a_2, b_0, b_1 are time-varying unknown parameters[2], have to be identified on-line; d is known as the system delay. We use pole placement self-tuning method to get the initial parameters of PID controller next. Closed-loop structure of pole placement self-tuning PID control system is shown in Figure 1[3].

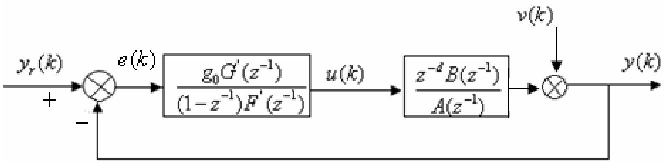

Fig.1 Pole Placement Self-tuning PID Control Structure

The mathematical model is shown as follows:

$$A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k) + y_d \quad (2)$$

Where: y_d is the offset of system,

$$A(z^{-1}) = 1 + \sum_{i=1}^{n} a_i z^{-i},\ B(z^{-1}) = \sum_{i=0}^{n-1} b_i z^{-i}, (b_0 \neq 0).$$

Impose PID control by the type is shown below:

$$F(z^{-1})u(k) = H(z^{-1})y_r(k) - G(z^{-1})y(k) \quad (3)$$

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

$$\begin{cases} F(z^{-1}) = 1 + (f_2 - 1)z^{-1} + f_2 z^{-2}, -1 < f_2 < 0 \\ G(z^{-1}) = g_0 + g_1 z^{-1} + g_2 z^{-2} \\ H = G(1) = g_0 + g_1 + g_2 \end{cases} \quad (4)$$

Then the corresponding PID control strategy can be expressed as:

$$u(k) = [-k_p - \frac{k_d(1-z^{-1})}{1+f_2 z^{-1}}]y(k) + \frac{k_i}{(1-z^{-1})(1+f_2 z^{-1})}[y_r(k) - y(k)] \quad (5)$$

The relationship between the various parameters is as follows:

$$\begin{cases} g_0 = k_p + k_i + k_d; \\ g_1 = k_p(f_2 - 1) - 2k_d; \\ g_2 = k_d - f_2 k_p; \end{cases} \quad \square 6$$

□

Take expression (4) into (3) expression, we can get the following closed-loop system equation:

$$(AF + z^{-1}BG)y(k) = Hz^{-1}By_r(k) + Fy_d \quad (7)$$

This is a simple 4-order closed-loop system, while A and B having been known we can get F and G by calculating and make the closed-loop characteristic polynomial equal to hope polynomial $A_m(z^{-1})$, using the formula is expressed as below:

$$AF + z^{-1}BG = A_m(z^{-1}) \quad (8)$$

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

$$\begin{cases} f_2 = \dfrac{(q_2 + a_1 - a_2)b_0 b_1^2 - b_0^2 b_1 a_2 - b_1^3(q_1 - a_1 + 1)}{b_0 b_1^2(a_1 + 1) - b_0^2 b_1(a_1 + a_2) + b_0^3 a_2 - b_1^3}; \\ g_0 = \dfrac{q_1 - a_1 + 1 - f_2}{b_0}; \\ g_1 = \dfrac{a_2}{b_1} - \left(\dfrac{a_2}{b_1} + \dfrac{a_1}{b_1} - \dfrac{b_0 a_2}{b_1^2}\right) f_2; \\ g_2 = \dfrac{-a_2 f_2}{b_1}; \end{cases} \quad (9)$$

PID parameters are gotten before the tests by repetitious analysis and calculation of object and the usual control experience. The appropriate PID parameters for the solar panels and antenna have been established. The selection of data would be decided automatically in accordance with the infrared heating devices selection and different objects by program at pre-test. It is worth emphasized that the parameters are just as the initial parameters, they would be adjusted according to their own conditions in the process of temperature control.

3.4 Impact on system performance and their 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 software system, the differential module component is not adopted in the algorithm. It will be considered in follow-up work. At the conclusion of summing up the PID parameters adjustment principles, fuzzy PID controller can be designed.

Temperature control process can be divided into three parts as Figure 2 showing, we can implement different intelligent control strategy as long as different parts. It will be able to achieve satisfactory temperature control exhibition.

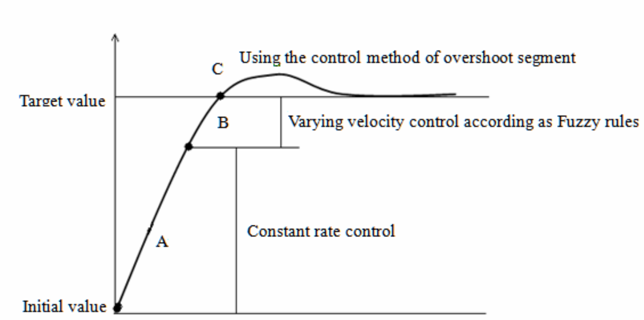

Fig.2 Temperature control methods for each parts

At paragraph A, you can implement constant rate control in accordance with the requirements of consult documents. Current velocity can be set at the range of 1□/min-2□/min before test at present. Once set, the velocity does not need to be changed in the course of the experiment. This current velocity range is usual required at large antenna thermal vacuum tests.

At paragraph B , within 15□ to the target temperature value, fuzzy control rules should be adopted in order to control the decline of rate. The correspondence between temperature and heating, cooling rate are presented as follow form shown:

Table 1 Corresponding Relation between Temperatures and Heating Rates is shown as follows:

e□□□	15	10	7	5	3	2	1
v□□/min□	1	0.8	0.6	0.4	0.3	0.1	0.2

Rules of current adjusting are as follows:

The scope of current increment is (-0.2□/min ,+0.2□/min). Therefore it is proposed to set the value of 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)[4].

Set the range of ec as: (-3□/min, +3□/min); therefore it is proposed to set value of 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). Fuzzy control rules set in the mode of:

R_i □ if $E(k) = E_i(k)$ and $Ec(k) = Ec_i(k)$ then $\Delta u(k) = \Delta u_i(k)$ □

The division of output directly affects the system dynamic process. Divided in more detail, you can get

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higher control accuracy, but at the same time you should pay out greater workload, so you can select it in accordance with the actual system. With the experience gotten in the past, at different stages of temperature, the amount of current increment is different. When overshoot occurs, a special control strategy is used to decrease overshoot rapidly without using the complex control algorithms in the ascending or descending phase of temperature.

4 Test

4.1 Test Program & Results

To fully test the method, we design three thermal vacuum tests. These three tests consist of two different objects and different test cases of each object. These three tests contain different temperature range. In the first test, the aim temperatures are set in different time as 30□, 15□, 35□, 20□. Result is shown in figure 3:

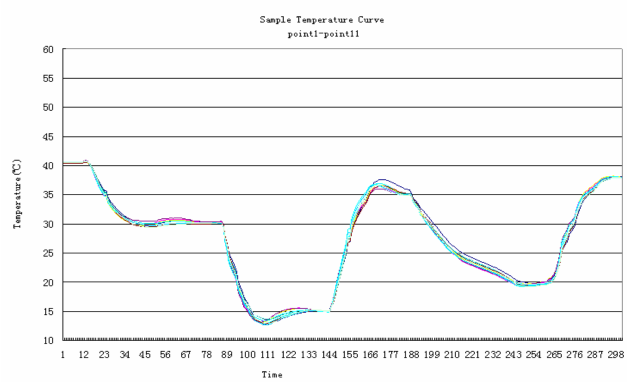

Fig.3 Temperature Curve of Solar panel

The target temperature values are set in different time as 0□, -50□, 40□, 90□ in the second test. Result is shown in figure 4:

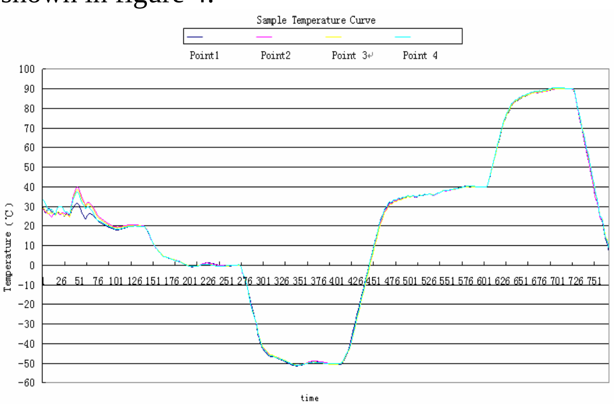

Fig.4 Sample Temperature Curve for the Second Time

The target temperature values are set in different time as -100□, -30□, -80□, 10□ in the third test. Result is shown in figure 5:

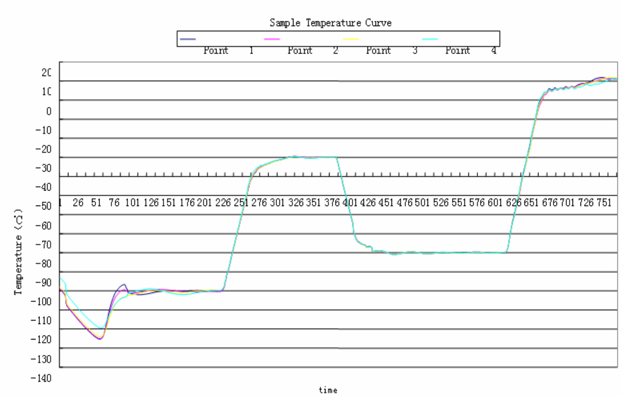

Fig.5 Sample Temperature Curve for the Third Time

Tests reveal that this control method decreases the overshoot and enhances the capability of anti-disturbance, and also alleviates operators' labor to a great extent, lowers test risk.

4.2 Result Analysis

4.2.1 Overshoot

When the temperature goes very high, maximum overshoot is 0.6□, far away from +3□ required in test outline. When the temperature goes very low, maximum overshoot is about 1.6□, and drops to ±0.8□ after one oscillation cycle, lower than ±1□ required in test outline.

4.2.2 Anti-disturbance

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

4.2.3 Anti-Coupling

In the last two tests, distance between two close samples is about 30cm-40cm while distance between two infrared lights is about 45cm-50cm. It is probable that one light heats two samples in the same time, in other words, it means coupling in the loop does exist and this is similar to the actual thermal vacuum tests.

5 Conclusions and Prospect

This paper makes an attempt to bring Fuzzy PID control into spacecraft thermal vacuum tests. Results reveal that this method meets the expectation and is capable to be applied in practice after some more tests. The control algorithm tends to be mature after times of tests and summarizations. In conclusion, Fuzzy PID controller is proved feasible through tests validating above. Given enough time, equipments and more tests, this method will work up to excellent results.

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