Development of an Intelligent Control System for Spacecraft Vacuum Thermal Test

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Abstract. This article develops a spacecraft component-level vacuum thermal test intelligent control system, which can control the thermal vacuum chamber to automatically complete the entire test process including establishing a vacuum environment, setting temperature control parameters, switching test conditions, and executing shutdown procedures. It is the first to complete the one-key boot function in similar domestic laboratories. This system combines thermostat, parameter identification and self-tuning control technology to complete the temperature control of the test piece. It solves the technical problems of complex thermal characteristics of test piece, large time delay, and overshoot in temperature control. The system also has the function of automatic conversion of test condition and provides a guarantee for the smooth development of the vacuum thermal test of the spacecraft and its components.

1. Background
Vacuum thermal test is a necessary test item for spacecraft products. For a long time, due to the low automation level of the test equipment, low test efficiency, poor control accuracy and easy overshoot during the control process, temperature control and test condition conversion need to be completed manually. With the rapid increase in test products, previous experience control mode cannot meet the current requirements. In this paper, through software design, an intelligent control system is developed. First, it can complete the automatic control of the whole process of the vacuum chamber from startup to shutdown, complete the monitoring and alarm of the key parameters of the equipment too. Second, it completes high-precision intelligent temperature control of sample, and proposes a programmable test condition conversion method.

2. Automatic control of thermal vacuum chamber

2.1. Composition of thermal vacuum chamber
The thermal vacuum chamber is used to simulate the vacuum, cold-dark environment and temperature alternation experienced by the spacecraft once in orbit[1]. It mainly includes a vacuum system, a cryogenic system (providing a cold background), and a temperature control (heat flow simulation) system. System structure diagram is shown below in figure 1.
2.2. **System hardware configuration**

This system uses two-level distributed control architecture with Siemens S7-300 series PLC as the core. Through the data exchange between the local control cabinet and the remote computer, the overall monitoring of the chamber operating is realized. As the core controller, PLC is used for the actual execution unit of all control functions. It adopts a modular configuration structure on the hardware, which has flexible adaptability and expandability[2]. It can configure corresponding modules for different types of equipment to realize the effectiveness of the entire equipment. For a thermal vacuum chamber, the main monitoring objects and network structure are shown in figure 2.

2.3. **Software development**

System software includes two parts: PLC lower-level software and upper-level system software. The lower-level controller (PLC) software adopts STEP V5.X supporting Siemens S7 series for programming, including control of various objects, control logic and connection the communication between each port device. It realizes the control of all devices in the field control cabinet[3]. The control system needs to control vacuum pumps, valves, refrigerators, sample temperatures and the function of test condition switching, shutdown procedures, etc. The interface is shown in figure 3.
3. High precision intelligent control technology of temperature

Combining depth development of thermostat, the system uses the parameter identification and self-tuning PID technology to achieve the precise temperature control. Figure 4 below is the principle diagram of the temperature control system.

![Principle diagram of temperature system](image)

This method uses the control algorithm to calculate the PID value of the current temperature range, and then transmits the control signal and the current PID value adjustment to thermostat. In a thermal test, the input of the identification object is the loading current of the infrared heater, and the output is the temperature. The mathematical model of the system can be written as follows[4].

\[
G(z) = \frac{z^{-d}(b_0 + b_1 z^{-1})}{1 + a_2 z^{-1} + a_3 z^{-2}}
\]

Where, \(a_1, a_2, b_0, b_1\) are time-varying unknown parameters, which must be identified online.

Among them: \(d\) is the number of delay steps, \(d=0\)[5]. The following figure shows the model coefficients and identification errors identified by the temperature and current data of an infrared cage during a satellite thermal test:
According to the identified coefficients, the system temperature value is estimated. The comparison between the estimated value and the real value and the error are shown in the figures below.

As can be seen from the above figures, during the temperature transition phase, the system parameters change rapidly. A single PID parameters often cause overshoot or even lose control[6]. This technology extracts system information according to the sampled data and applied current at each inflection point of temperature control. It uses parameter identification methods to obtain system parameters, and then obtains a suitable PID parameter adjustment for the thermostat. Control result shows that this method achieves small overshoot and high-precision. The following figures show a comparison chart of the control effect of the traditional control method and the new method.
4. Automatic circulation of test condition
In order to ensure that thermal vacuum chamber automatically conducts tests in accordance with the test process and preset test conditions. It is necessary to control the vacuum subsystem, heat sink subsystem and temperature control subsystem according to the chamber status and test parameters to perform corresponding work. In general, each cycle is divided into two states, high temperature and low temperature, which are kept for a certain period of time, then a number of repeated cycles are performed to complete the entire test process. Typical temperature cycle conditions are shown below.

The achievement of test condition conversion and temperature balance determination functions mainly depends on sending corresponding instructions to thermostat or temperature control module. According to the definition of each parameter in the description of the test conditions, the requirements of the conditions such as the temperature of each step and the holding time must be decomposed before the test. After completing the development of all hardware interfaces, the system realizes a one-key boot function. Click "Start" to complete entire test process.

5. Conclusion
This paper develops a spacecraft component-level vacuum thermal test intelligent control system through software and hardware design. The system can automatically control the chamber according to the test conditions, including establishing a vacuum environment, setting temperature control parameters, switching test conditions, and executing shutdown procedures. Combined with thermostat, parameter identification and self-tuning control technologies, an intelligent control method is developed to
complete the temperature control of the test piece. It solves the problem of complex thermal characteristics, large hysteresis, and easy overshoot. It can meet various control methods such as target temperature control, square wave automatic tracking control, and rate control. This system has been operating stably for more than 2 years, providing a guarantee for the smooth development of the vacuum thermal test of the spacecraft and its components.

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