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A novel intelligent adaptive control of laser-based ground thermal test

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Abstract Laser heating technology is a type of potential and attractive space heat flux simulation technology, which is characterized by high heating rate, controlled spatial intensity distribution and rapid response. However, the controlled plant is nonlinear, time-varying and uncertainty when implementing the laser-based heat flux simulation. In this paper, a novel intelligent adaptive controller based on proportion–integration–differentiation (PID) type fuzzy logic is proposed to improve the performance of laser-based ground thermal test. The temperature range of thermal cycles is more than 200 K in many instances. In order to improve the adaptability of controller, output scaling factors are real time adjusted while the thermal test is underway. The initial values of scaling factors are optimized using a stochastic hybrid particle swarm optimization (H-PSO) algorithm. A validating system has been established in the laboratory. The performance of the proposed controller is evaluated through extensive experiments under different operating conditions (reference and load disturbance). The results show that the proposed adaptive controller performs remarkably better compared to the conventional PID (PID) controller and the conventional PID type fuzzy (F-PID) controller considering performance indicators of overshoot, settling time and steady state error for laser-based ground thermal test. It is a reliable tool for effective temperature control of laser-based ground thermal test.

1. Introduction

Thermal test processes are implemented during the qualification process of space device development. Environmental conditions in space contain the transient thermal load and vacuum are simulated to guarantee that a given space device will operate efficiently when subjected to real environments much different from those on earth.[1] It has been proved that the

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ground based testing method plays a highly important role in the development of the space device.[2–4] The external thermal flux simulation system is essential for the effective working of the thermal tests. At present, the conventional external thermal flux simulation system includes solar simulator, infrared heater and contact electric heater.[5,6] It has been reported that there were plenty of successful thermal tests using these external thermal flux simulation systems.[7–10] However, as the requirements appear for complex structure, accurate temperature control and rapid heating-up in some applications of thermal tests such as parabolic antennas, solar panels and precision optical systems,[11] there is an urgent need for better external thermal flux simulation techniques capable of handling better steerability of space and time than the conventional thermal flux simulation techniques.

Laser-based external thermal flux simulation technique is a promising candidate for ground thermal test for two major reasons. Firstly, laser beam has remarkable steerability of space. The spatial intensity distribution of laser beam can be shaped into the non-symmetry and non-uniform pattern by geometrical transform method[12–19] to meet the pressing needs of thermal tests of complex structures. Instead of the complicated design process of the conventional thermal flux simulation system by combining the infrared heaters and contact electric heaters, the intensity distribution of laser beam can be directly and specially designed based on the orbital temperature field of space devices to have better alignment between the real space environment and ground test environment. Secondly, the time response of laser heat flux simulation system is much faster than the conventional external thermal flux simulation systems. It might be difficult to precede high-accuracy transient thermal test by combining the infrared heater and contact electric heater due to the limit of the time response of heat flux simulation system.[11] However, the time response of laser heat flux simulation system is less than 100 ms. Using the laser heat flux simulation system can improve greatly the accuracy of transient thermal test and simulate the change of the real on-orbit temperature of space devices. Therefore, this paper presents a well-designed laser heat flux simulation system to improve the suitability and stability of the ground thermal test.

Effective thermal controller for heat flux simulation system is crucial for reliable working of the ground thermal test. Some befitting approaches of temperature control for ground thermal tests have been reported. The conventional PID controllers were improved based on arranging the transient process for the ground thermal test.[20] A real-time process simulator used by PLC programming for the ground thermal test was reported.[21] In many instances of ground thermal test, such as solar panels, the temperature range of thermal cycles is more than 200 K.[11] In order to develop the adaptability of controller, in recent years, several self-tuning controllers that continuously update the parameters of controller were proposed. The advantage of these controllers is that the parameters can be adjusted on-line to improve their adaptability. A fuzzy-PID controller was put forward for the thermal tests of space devices.[22] A fuzzy reference gain-scheduling control approach (FRGS) was investigated to control thermal vacuum chambers automatically and satisfy testing requirements.[23,24] A approach based on particle swarm optimization (PSO) and Takagi–Sugeno (TS) fuzzy model for describing dynamical behavior was proposed for thermal vacuum test systems.[25,26] The main limitation of the most reported works is that these controllers are used to the first-order or second-order linear system with dead time while it is difficult to apply these controllers to the processes of higher order nonlinear systems.

However, introducing the laser heat flux simulation system makes the controlled plant extremely nonlinear, time-varying and uncertainty. The performance of the above controllers for laser-based ground thermal test might be unsatisfactory in terms of large overshoot and excessive oscillation. Therefore, the aim of this paper is to develop a new intelligent adaptive controller based on the fuzzy logic to improve the performance of the laser-based ground thermal test. An adaptive PID type fuzzy logic controller is proposed by continuously adjusting the scaling factors of controller using an updating factor. A stochastic hybrid particle swarm optimization (H-PSO) algorithm is introduced to tune the initial values of scaling factors. To verify the performance of the proposed controller, a validating thermal test system has been established in the laboratory and the performance of the proposed controller is compared with the conventional PID (PID) controller and the conventional PID type fuzzy (F-PID) controller considering performance indicators of overshoot and settling time.

2. System description and dynamical modeling

2.1. Apparatus of laser-based thermal tests

The proposed laser-based thermal vacuum test system consists of a chamber, laser thermal flux simulation system, temperature measure system, intelligent adaptive thermal control system, center control, laser beam shaping system[18] and cryogenic vacuum pump system (Fig. 1). An Nd: YAG high-power continuous solid laser HLD1001.5 was used as the heat source of the laser-based ground thermal test. For simulating the orbit environmental conditions, firstly, vacuum was reached by using cryogenic vacuum pump system, and then the space device was heated for simulating orbit thermal cycles. For precisely emulating the temperature distribution of the space device in space, laser beam was shaped in a non-uniform spatial intensity distribution by the laser beam shaping system. In order to implement the transition thermal test, the surface temperatures of key points were measured by two infrared thermometers. The thermometers which were produced by Raytek Company were collected with the sampling interval 100 ms. The measurements of the thermometers were taken as the input of the intelligent adaptive controller. The output of the controller was the change of power of the laser beam. The main parameters of the laser-based thermal test are provided in Table 1.

2.2. Dynamical modeling of laser-based thermal test

As described in previous section, since the heating rate of laser is much faster than the rate of heat conduction inside the space device, temperature gradient of the space device should not be neglected. Thus heat conduction and radiation are the major heat sources of heat transfer for the space device.[27] The differential Eq. (1) of the laser-based thermal test process depends nonlinearly on local temperature T, as follows: