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

Gan Zhengtao, Yu Gang *, **Li Shaoxia, He Xiuli, Chen Ru, Zheng Caiyun, Ning Weijian**

Key Laboratory of Mechanics in Advanced Manufacturing, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

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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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* Corresponding author. Tel.: +86 10 82544250.
E-mail address: gyu@imech.ac.cn (G. Yu).

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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:

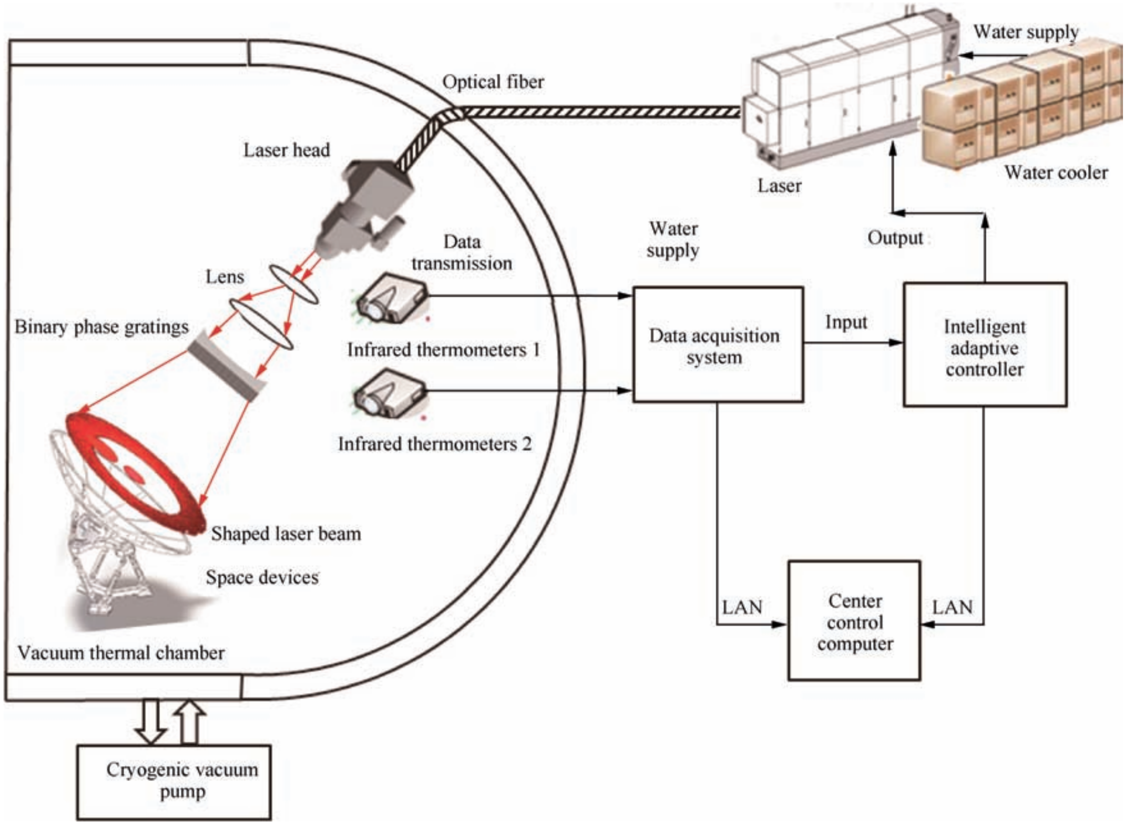


Fig. 1 Schematic of laser-based thermal vacuum test system.

Table 1 Parameters of laser-based thermal test.

Parameter	Value
Laser power (W)	1000
Defocusing distance (mm)	20
Focal distance (mm)	300
Laser response time (ms)	50
Laser beam pattern	Flat-top
Measuring diameter of infrared thermometer 1 (mm)	2
Measuring diameter of infrared thermometer 2 (mm)	4
Temperature measuring range (°C)	−40–600
Sampling interval (ms)	100
Spectral response (μm)	8–14
Measure angle (°)	30
Reference temperature (°C)	50, 100, 150, 200
Disturbance temperature (°C)	30
Thermal control method	PID, fuzzy-PID, intelligent adaptive control

$$\rho c_{\mathrm{p}}\frac{\partial T}{\partial t}=\left(\frac{\partial}{\partial x}k\frac{\partial T}{\partial x}+\frac{\partial}{\partial y}k\frac{\partial T}{\partial y}+\frac{\partial}{\partial z}k\frac{\partial T}{\partial z}\right)-(\sigma\varepsilon A)\cdot\left(T^{4}-T_{ab}^{4}\right) \tag{1}$$

where $\partial T/\partial t$ denotes the transition rate, T denotes the mean temperature on the measure point, T_{ab} is the ambient temperature, $\partial T/\partial x$, $\partial T/\partial y$ and $\partial T/\partial z$ denote the temperature gradient in the coordinate direction, k denotes the thermal conductivity, c_{p} denotes the heat capacity, ρ denotes the density of the space device, σ denotes the Stefan–Boltzmann constant, ε denotes the emission capacity, and A denotes the equivalent radiated area of measure point.

From Eq. (1), the controlled plant is nonlinear. Because the thermophysical property of space device depends on temperature, the controlled plant is time-varying. The controlled plant is also time-delaying because of the optical properties of the space devices under test as well as its physical properties such as specific heat capacity and equivalent thermal conductivity. Furthermore, it is extremely difficult to obtain all the thermophysical property depending on temperature as well as the optical parameters such as absorptivity and reflectivity of laser, so the controlled plant is uncertainty. Based on the above points, the conventional control method might be inappropriate for the laser-based ground thermal test. This paper advocates the use of an adaptive PID type fuzzy logic control approach for thermal control. Fuzzy logic control, as an intelligent control approach, can count human experience into control system.[28] Because the fuzzy logic control systems have ability to handle uncertain nonlinear system, this method is a beneficial choice for controlling laser-based thermal test.

3. Intelligent adaptive control strategy

An intelligent adaptive PID fuzzy logic control strategy is proposed and explained. The proposed control system is shown in Fig. 2. It includes a PI and a PD fuzzy logic control.

The control system shown in Fig. 2 consists of process and controller and there is a load disturbance affecting the control process. Due to the load disturbance, controlled plant tends to

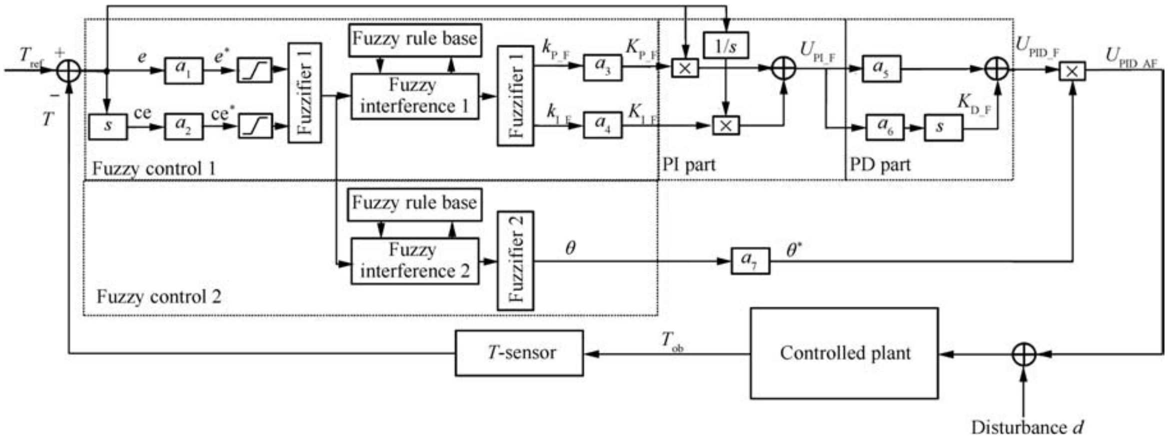


Fig. 2 Intelligent adaptive control system structure diagram.

drive away from its desired temperature. The process variable T_{ob} is the real temperature of measure point which is controlled. In this study, only one measure point is chosen. This measure point is located in the center of the laser irradiation where the local temperature is the highest than that in other locations. Using the measure point layout, the maximum temperature in the specimen can be controlled during the thermal test process. The controlled plant is affected by the control variable $U_{\mathrm{PID\_AF}}$. In this paper, the output signals of controller can be equivalent to the laser output power, since the used laser machine HLD1001.5 is controlled by the digital control (i.e., PROFIBUS). The controller has two inputs and one output. The inputs are the measured temperature T and the reference temperature T_{ref} and the output is the control signal (i.e., laser power) $U_{\mathrm{PID\_AF}}$. θ and θ^* are adaptive factors of the controller.

The proposed controller can be divided into three parts: a PI type fuzzy logic controller (PI-FLC), a conventional PD controller and an adaptive fuzzy controller. The combination of the PI-FLC and PD controller can provide a concise and worthy control configuration. By tuning the parameters (scaling factors) of PI-FLC and PD controller, relative great control performance can be obtained for laser-based ground thermal test. However, the main limitation of the PI-FLC and PD controller is that the performance of the controller directly depends on the scaling factors which are fixed during the process. So an extra adaptive fuzzy part is introduced into the proposed controller to on-line adjust the scaling factors of PI-FLC and PD controller. The proposed controller contains seven tuning parameters (α_1–α_7) to adjust the control response. As shown in Fig. 2, α_1 and α_2 are the scaling factors of input, α_3 and α_4 are defined as the scaling factors of PI-FLC controller, and α_5 and α_6 represent the scaling factors of PD controller. A novel on-line approach is proposed to adaptively adjust the output scaling factors via the parameter of α_7. Therefore, the benefits of the proposed intelligent adaptive control over the conventional PID control (PID) or conventional PID type fuzzy logic control (F-PID) for laser-based thermal test system are as follows:

(1) The output laser power ($U_{\mathrm{PID\_AF}}$) is approximately proportional to the temperature error (input). The proposed controller has reason to be a great substitution of the PID control.
(2) Each section of the proposed controller can be improved independently for the outstanding performance of controller.
(3) The controller contains seven necessary parameters (α_1–α_7), and thus it has capacity to be optimized to have better performance.
(4) Because the scaling factors are real time adjusted during the ground thermal test, the control performance like overshoot and settling time can be minimized.

3.1. Membership functions

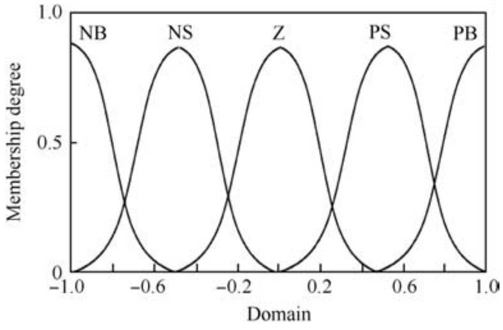
The membership functions of fuzzy control 1 and fuzzy control 2 for the inputs on the normalized interval $[-1, 1]$ (e^* and ce*) and the outputs on the normalized interval $[0, 1]$ ($k_{\mathrm{P\_F}}$ and $k_{\mathrm{I\_F}}$) are shown in Fig. 3. The Gauss membership function is used. The inputs and outputs related to rule bases are presented in Table 2. The membership functions of the fuzzy control 2 for output on the normalized interval $[0, 1]$ (θ) are presented in Fig. 4. The fuzzy sets and linguistic values are shown in Table 3.

3.2. Stability analysis

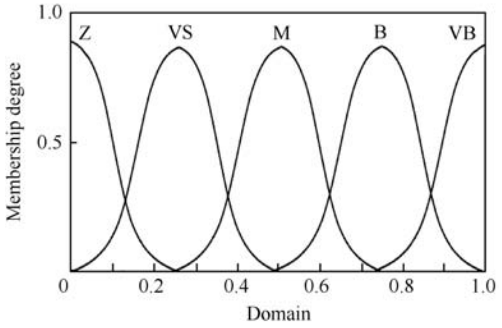
In order to obtain the stability condition of controlled system, firstly, by analyzing the structure of proposed controller (Fig. 2), the fuzzy gains (K'_{P_F}, $K'_{\mathrm{I\_F}}$, $K'_{\mathrm{D\_F}}$, $T_{\mathrm{I\_F}}$ and $T_{\mathrm{D\_F}}$) and transfer function can be obtained. In this section, the adaptive factor θ^* is neglected to simplify the analysis. Then, the bounded-input/bounded-output (BIBO) stability of the proposed controlled system can be analyzed by using the "small-gain theorem".[29]

From the block diagram (Fig. 2), the proposed controller is designed to have its own fuzzy proportional factor ($K'_{\mathrm{P\_F}}$), fuzzy integral factor ($K'_{\mathrm{I\_F}}$) and fuzzy derivation factor ($K'_{\mathrm{D\_F}}$), which can be formulized as follows ($F\{\alpha\}$ denotes the fuzzy transfer function):

$$U_{\mathrm{PI\_F}} = K_{\mathrm{P\_F}} e + K_{\mathrm{I\_F}} \int e\,\mathrm{d}t = \alpha_3 F\{\alpha_2\} e + \alpha_4 F\{\alpha_1\} \int e\,\mathrm{d}t \tag{2}$$



(a) e^* and ce*



(b) $k_{\mathrm{P\_F}}$ and $k_{\mathrm{I\_F}}$

Fig. 3 Membership functions.

Table 2 Rule base for $k_{\mathrm{P\_F}}$ and $k_{\mathrm{I\_F}}$.

ce*	e^*				
	NB	NS	Z	PS	PB
NB	VB	VB	VB	VVB	VVB
NS	M	VB	VB	VB	M
Z	S	M	VB	M	S
PS	VB	B	VB	B	M
PB	VB	VB	VB	VB	VB

$$\begin{aligned} U_{\mathrm{PID\_F}} &= \alpha_5 U_{\mathrm{PI\_F}} + \alpha_6 \frac{\mathrm{d}U_{\mathrm{PI\_F}}}{\mathrm{d}t} \\ &= (\alpha_3\alpha_5 F\{\alpha_2\} + \alpha_4\alpha_6 F\{\alpha_1\})e \\ &\quad + \alpha_4\alpha_5 F\{\alpha_1\}\int e\mathrm{d}t + \alpha_3\alpha_6 F\{\alpha_2\}\frac{\mathrm{d}e}{\mathrm{d}t} \end{aligned} \tag{3}$$

$$K'_{\mathrm{P\_F}} = \alpha_3\alpha_5 F\{\alpha_2\} + \alpha_4\alpha_6 F\{\alpha_1\} \tag{4}$$

$$K'_{\mathrm{I\_F}} = \alpha_4\alpha_5 F\{\alpha_1\} \tag{5}$$

$$K'_{\mathrm{D\_F}} = \alpha_3\alpha_6 F\{\alpha_2\} \tag{6}$$

$$T_{\mathrm{I\_F}} = \frac{K'_{\mathrm{P\_F}}}{K'_{\mathrm{I\_F}}} = \frac{\alpha_3 F\{\alpha_2\}}{\alpha_4 F\{\alpha_1\}} + \frac{\alpha_6}{\alpha_5} \tag{7}$$

$$T_{\mathrm{D\_F}} = \frac{K'_{\mathrm{D\_F}}}{K'_{\mathrm{P\_F}}} = \left(\frac{\alpha_4 F\{\alpha_1\}}{\alpha_3 F\{\alpha_2\}} + \frac{\alpha_5}{\alpha_6}\right)^{-1} \tag{8}$$

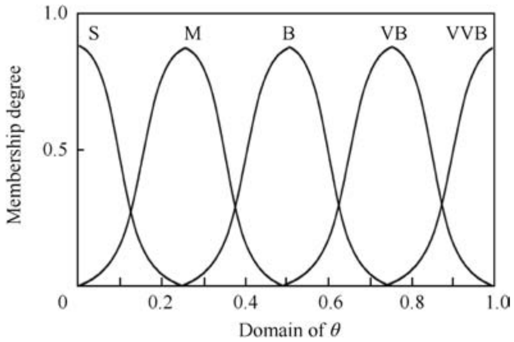


Fig. 4 Membership functions for θ.

Table 3 Fuzzy sets and linguistic values.

Fuzzy set	Linguistic value
NB	Negative big
NS	Negative small
Z	Zero
PS	Positive small
PB	Positive big
S	Small
VS	Very small
M	Medium
B	Big
VB	Very big
VVB	Very very big

Theorem. *A sufficient condition for the nonlinear fuzzy PID control system to be BIBO stable is that the given nonlinear process has a bounded norm (gain) as* $\|\Phi\| < \infty$ *and the parameters of the fuzzy PID controller,* w_e, $w_{\Delta e}$, w_u, $w_{\Delta u}$, *(or* $K'_{\mathrm{P\_F}}$, $T_{\mathrm{I\_F}}$ *and* $T_{\mathrm{D\_F}}$ *in* Eqs. (3)–(8)), *satisfy*

$$K'_{\mathrm{P\_F}}\left(1 + \frac{T_{\mathrm{D\_F}}}{T_{\mathrm{I\_F}}} + \frac{\Delta t}{T_{\mathrm{I\_F}}} + \frac{T_{\mathrm{D\_F}}}{\Delta t}\right) \cdot \|\Phi\| < 1 \tag{9}$$

where $\|\Phi\|$ is the operator norm of the given $\Phi(\bullet)$, or the gain of the given nonlinear system, usually defined as[30]

$$\|\Phi\| = \sup_{v_1 \neq v_2, k \geqslant 0} \frac{|\Phi(v_1(k)) - \Phi(v_2(k))|}{|v_1(k) - v_2(k)|} \tag{10}$$

If a nonlinear control system can be given, the stability condition of controlled system can be obtained by substituting Eq. (3)–(8) into the Eq. (9).

3.3. Output scaling factors

To adjust the output scaling factors on-line, an adaptive method using fuzzy rule base is presented to tune θ. The dynamic relationships between the parameters of the proposed controller and the scaling factors are listed below:

$$U_{\mathrm{PID\_AF}} = \theta^*\left(K_{\mathrm{P\_F}}e + K_{\mathrm{I\_F}}\int e\mathrm{d}t + K_{\mathrm{D\_F}}\frac{\mathrm{d}e}{\mathrm{d}t}\right) \tag{11}$$

$$K_{\mathrm{P\_AF}} = \theta^* K_{\mathrm{P\_F}} \tag{12}$$

$$K_{\mathrm{I\_AF}} = \theta^* K_{\mathrm{I\_F}} \tag{13}$$

$$K_{\mathrm{D\_AF}} = \theta^* K_{\mathrm{D\_F}} \tag{14}$$

3.4. Rule bases of fuzzy control 2

For improving the adaptation of the proposed controller, the rule bases of fuzzy control 2 are presented to adjust θ (Table 4). The following fuzzy rule clauses have been taken into account:

(1) For achieving the better performance in terms of overshoot and settling time, when e^* is big, while e^* and ce* are opposite signs, the gain θ is modified larger. This can be written in IF-THEN clauses: if e* is PB and ce* is NB, then θ is VB.

(2) For decreasing the impacts caused by delays, a small value of θ is modified to ensure the controller work within the excepted range. When e^* is positive and big, but e^* and ce* have the same sign, the gain θ should be adjusted small to prevent performance of controller deterioration. This can be written in IF-THEN clauses: if e^* is PB and ce* is PB, then θ is Z.

(3) Based on the demand of thermal test, there should be a sharp variation of the gain θ around the reference temperature to avoid overlarge overshoots. For example, if e^* is Z and ce* is NB, then θ is VS. This clause denotes that the controlled process is just near the reference temperature and rapidly away from it. In this case, a relative small θ should be modified to prevent the upward more excessively resulting in a relatively acceptable overshoot.

3.5. Design method of scaling factors

The proposed intelligent adaptive controller is engaged with both the PI-FLC and PD effects and the influence of adaptive factor θ makes the gain design more complicated and time-consuming. Thus, in this study, a H-PSO algorithm is applied to tune scaling factors ($\alpha_1 - \alpha_7$). It has been proved that the H-PSO algorithm can combine the benefits of the PSO and BFO algorithm as well as avoid their defects.[31] It is reported that the performance of PSO and BFO is limited because of premature convergence. The particles are easy to converge in the local optimal point; however, the global optimal point has been passed.[32] The H-PSO algorithm breaks through this shortcoming by using the method of elimination dispersal of bacteria, and hence the ability of converging to the global optimal point is improved. The details of H-PSO algorithm are presented in the literature.[31,33,34]

Table 4 The proposed rule bases for θ.

ce*	e^*				
	NB	NS	Z	PS	PB
NB	Z	Z	VS	M	VB
NS	VB	VS	VS	B	B
Z	VB	M	VB	M	B
PS	B	B	Z	VS	Z
PB	VB	M	VS	Z	Z

The performance of the proposed stochastic algorithm extremely depends on the objective function and incorporated performance indicators. Because the conventional indicators of integral absolute error (IAE) and integral-of-time-multiplied absolute error (ITAE) hardly accurately represent the performance of the controller,[35] this paper contains the objective function listed below:

$$\begin{cases} \int_0^\infty (\beta_1|e| + \beta_2 U_{\mathrm{PID\_AF}}^2)\mathrm{d}t + \beta_3 t_{\mathrm{r}} & \text{If } \Delta T \geqslant 0 \\ \int_0^\infty (\beta_1|e| + \beta_2 U_{\mathrm{PID\_AF}}^2 + \beta_4|\Delta T|)\mathrm{d}t + \beta_3 t_{\mathrm{r}} & \text{If } \Delta T < 0 \end{cases} \tag{15}$$

where e is the error of controlled system, $U_{\mathrm{PID\_F}}$ is the controller output at the time t, $\beta_1 - \beta_4$ are the weight factors, t_{r} is the rising time of controlled plant and $\triangle T = T(t) - T(t-1)$.

4. Experimental results

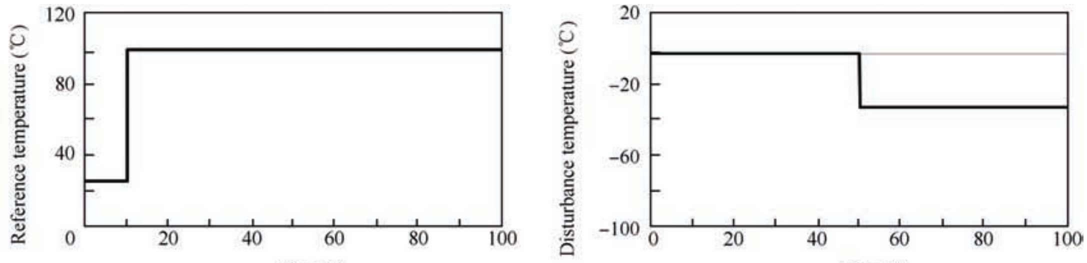
To validate the effectiveness of the proposed intelligent adaptive controller, three different controllers including PID control, PID type fuzzy control and proposed intelligent adaptive control were considered in a verifying laser-based ground thermal test system, which is shown in Section 2.1. The Ziegler–Nichols method was used to design the PID and the stochastic genetic algorithm (GA) method[34] was used to tune the scaling factors of F-PID while the proposed H-PSO algorithm was used for the intelligent adaptive control. The tuned gains for each method are shown in Table 5.

Figs. 5(a) and (b) show the reference temperature and load disturbance for the verifying laser-based thermal test. The variation of the output fuzzy part 2 gains (θ) is shown in Fig. 5(c). Fig. 5(d) indicates the responses with the reference and load disturbance changes. The details of Fig. 5(d) are shown in Figs. 5(e) and (f). The performance indicators of settling time and overshoot are shown in Table 6. The error band of τ^* is 0.05 K for temperatures and 2% final value for others, and units for σ^* are "K" for temperatures and% for others in Table 6.

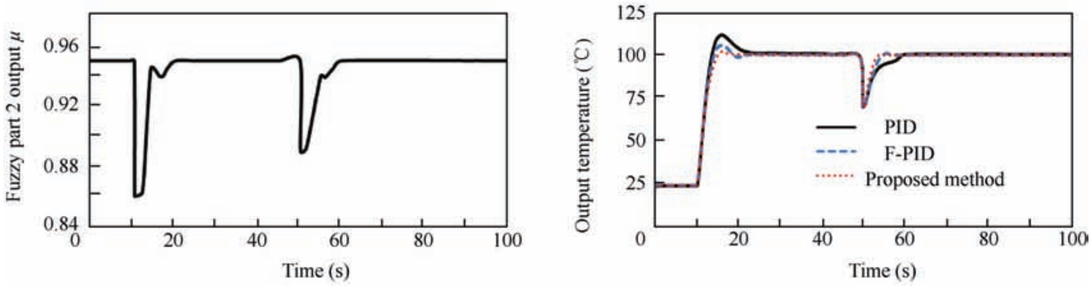
As it can be seen in Fig. 5 and Table 6, the proposed intelligent adaptive control remarkably improves the performance of the F-PID and PID controller. The F-PID decreases the settling time and overshoot partly compared with the PID controller; however it causes the fluctuation of controlled temperature. This shortcoming has been tackled by combining the self-adjusted scaling factors and θ (Fig. 5(c)). The stability of the thermal test is improved. The overshoot of the proposed controller is smaller compared with the values in PID and F-PID controller, which are 0.9%, 7.7% and 15.9% respectively. The settling time is also smaller than the values of PID and F-PID controller, which are 5.5 s, 9.1 s and 11.6 s

Table 5 Design methods and tuned gains for each method.

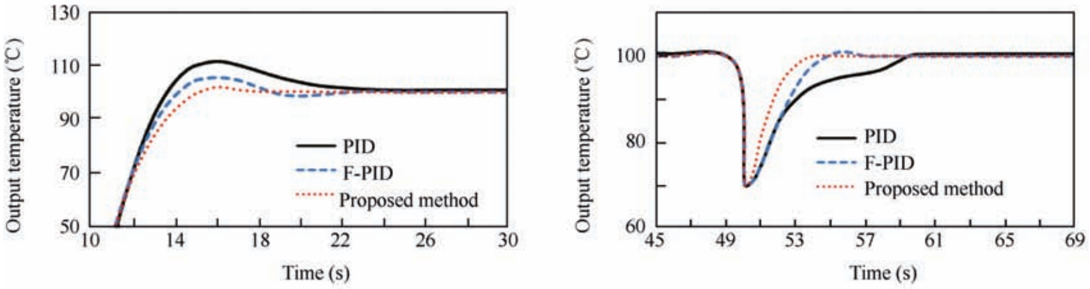
Controller	Design method	Tuned parameter
PID	Ziegler–Nichols	$K_{\mathrm{p}} = 1.85$, $K_{\mathrm{i}} = 0.65$, $K_{\mathrm{d}} = 0.22$
F-PID	GA[34]	$K_{\mathrm{e}} = 0.44$, $K_{\mathrm{d}} = 0.8$, $\alpha = 1.77$, $\beta = 0.54$
Proposed	H-PSO	$\alpha_1 = 0.1$, $\alpha_2 = 1$, $\alpha_3 = 1.43$, $\alpha_4 = 0.55$, $\alpha_5 = 0.78$, $\alpha_6 = 1.05$, $\alpha_7 = 1.18$



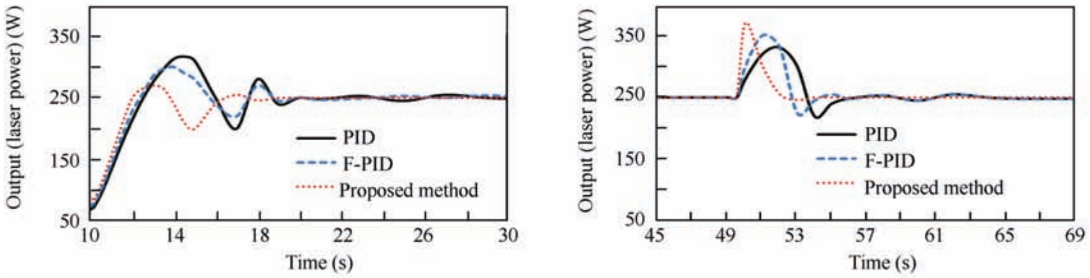
(a) Reference temperature (b) Disturbance temperature



(c) Output of the fuzzy part 2 (d) Changes in refernce and disturbance signals



(e) Details of Fig.5 (d) from 10 s to 30 s (f) Details of Fig.5 (d) from 45 s to 70 s



(g) Details of output from 10 s to 30 s (f) Details of output from 45 s to 70 s

Fig. 5 Transient responses with PID, F-PID and proposed method.

Table 6 Settling time τ and overshoot σ of PID, F-PID and proposed method.

Parameter	PID		F-PID		Proposed method	
	τ^*	σ^*	τ/τ^*	σ/σ^*	τ/τ^*	σ/σ^*
Key point temperature T	11.6	15.7	0.78	0.49	0.47	0.06

respectively. Furthermore, the recovery time of the proposed controller is smaller than PID and F-PID controller under the given load disturbance. These facts illustrate that the proposed intelligent adaptive controller performs more excellent and stable compared with the PID and F-PID controllers.

To verify the adaptability of the temperature control system, the different reference temperature was set. The reference temperature was set as 50 °C, 100 °C, 150 °C and 200 °C, respectively. The results are shown in Fig. 6. The overshoot, settling time and steady state error using the PID, F-PID and proposed adaptive controller are shown in Table 7. The error band of τ^* is 0.05 K for temperatures and 2% final value for others, units for σ^* and $\mathcal{E}^*$ are "K" for temperatures, and τ^* is "s" for steady state time and% for others in Table 7. As can be seen, when reference temperature changed, PID had relatively large fluctuation for settling time and overshoot

Table 7 Settling time τ, overshoot σ and steady state error $\mathcal{E}$ of PID, F-PID and proposed controller under different reference temperatures.

Reference temperature (°C)	PID			F-PID			Proposed control		
	τ^*	σ^*	$\mathcal{E}^*$	τ/τ^*	σ/σ^*	$\mathcal{E}/\mathcal{E}^*$	τ/τ^*	σ/σ^*	$\mathcal{E}/\mathcal{E}^*$
50	9.9	12.7	0.45	0.70	0.77	0.63	0.39	0.23	0.23
100	11.6	15.7	1.15	0.78	0.49	0.31	0.64	0.06	0.04
150	15.0	6.2	1.18	0.71	0.52	0.75	0.59	0.15	0.36
200	12.2	15.4	2.39	0.94	0.48	0.33	0.81	0.06	0.09

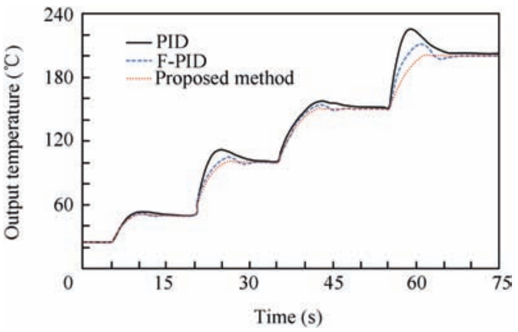


Fig. 6 Transient responses with PID, F-PID and proposed control under reference temperatures of 50 °C, 100 °C, 150 °C and 200 °C.

(from 6.2% to 15.4%). However, for the proposed adaptive controller, the overshoot was more stable and much lower (less than 3%), and besides, settling time was shorter (less than 10 s). This demonstrates that the adaptability of the proposed adaptive controller improves greatly compared with the PID and F-PID controller.

5. Conclusions

In this paper, a novel intelligent adaptive controller based on PID type fuzzy logic is proposed to improve the performance of laser-based ground thermal test. The output scaling factors of proposed controller are real time adjusted by introducing a fuzzy coefficient θ. The stochastic method based on an advanced H-PSO algorithm is improved to calculate the initial scaling factors of the proposed controller. The transient performance of the proposed intelligent controller is compared with the PID and F-PID designed by the Ziegler–Nichols and GA methods. The performance indicators considered contain the overshoot, settling time and steady state error. Some important conclusions are listed as follows:

(1) The overshoot of the proposed controller is smaller compared with the values in PID and F-PID controller, which are 0.9%, 7.7% and 15.9% respectively. The settling time is also smaller than the values of PID and F-PID controller, which are 5.5 s, 9.1 s and 11.6 s respectively. Furthermore, the recovery time of the proposed controller is smaller than PID and F-PID controller under the given load disturbance.

(2) The proposed controller can enhance capacity of laser heat flux simulation system, and it is a reliable tool for effective temperature control of laser-based ground thermal test. The proposed controller performs more excellent and stable compared to the above mentioned controllers for laser-based ground thermal test. The other advantage of the proposed controller is that the adaptability and robustness were improved greatly.

(3) Since the proposed control method only uses the commercial equipment, implementation of it in industrial applications is straightforward. Furthermore, it is a promising approach which can be applied to other industrial processes where the temperature needs to be controlled accurately.

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Gan Zhengtao is a Ph.D. candidate at Institute of Mechanics, Chinese Academy of Sciences. He received his B.S. degree from Chongqing University. His major research interest is mechanics in advanced manufacturing.

Yu Gang went to UK to study high-resolution molecular spectroscopy in 1987. In 1992, professor Yu received the Ph.D. degree in physics from University of Strathclyde. From 1992 to 1995, he went on with postdoctoral research at Heriot-Watt University. He returned to China at the end of 1995 and has become a researcher in Institute of Mechanics, Chinese Academy of Sciences since then.