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Abstract: The temperature control system is a highly nonlinear and uncertainty system, and using a conventional PID controller makes it difficult to achieve a good control effect. In this paper, a self-adaptive fuzzy PID controller is described. The model of controlled object is established by combining mechanism modeling with experiment. *Aiming at the problem that the parameter range of the self-adaptive fuzzy PID controller varies greatly and is difficult to adjust, a new method is proposed which can easily provide a more reasonable fuzzy controller output variable range.* The fuzzy rules based on experts' experience and knowledge are adopted. The simulation model is established using MATLAB/SIMULINK. The simulation results show that the self-adaptive fuzzy PID controller has better robust performance against system parameter changes and uncertainties.

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基于自适应模糊 PID 的飞机客舱温度控制

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摘要：飞机客舱温度控制系统具有高度非线性、不确定的特点，传统的 PID 控制很难取得良好的控制效果，因此设计了自适应模糊 PID 控制器。采用机理建模与实验相结合的方法，确定了系统的数学模型。*针对自适应模糊 PID 控制器参数范围变动较大，不易调节的问题，提出了一种能够很方便确定模糊 PID 控制器比例、积分以及微分三个参数合理范围的方法。*基于专家系统设计模糊规则。利用 MATLAB/SIMULINK 建立了仿真模型，仿真结果表明提出的自适应模糊 PID 控制器在抗系统参数摄动以及不确定方面具有更好的鲁棒性。

关键词：模糊 PID 控制器；飞机地面空调；飞机客舱；非线性；不确定参数

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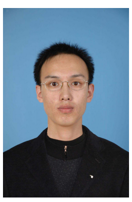
Introduction

The airplane ground air conditioner is applied to provide conditioned air to an airplane when the airplane is on the ground with its engines and auxiliary power unit shut down. It is intended to provide not only a comfortable temperature and humidity environment for crew and passengers alike, but also to reduce air pollution emissions. The airplane ground air conditioning system is generally



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composed of a wind system, a cooling system, a temperature control system, and an air conduit; among these components, the temperature control system is the most important part.

Nowadays, most of the controllers in the field of industrial production are conventional proportional-integral-derivative (PID) controllers because they offer several advantages: simple structure, mature theory, clear algorithm, and ease of setting parameters[1-3]. The proportional (P), proportional-integral (PI) and proportional-derivative (PD) controllers can be seen as different types of PID controllers. PID controllers are very effective for single-input, single-output linear time-invariant systems; however, they are not suitable for highly nonlinear and uncertain systems, where the parameters of a controlled object undergo relatively large changes, which leaves the PID controller at a disadvantage because the invariability of its adjustment coefficient cannot provide good control performance [4-5].

In 1965, Zadeh proposed the fuzzy sets theory, and since then the concept of fuzzy control has developed rapidly. In 1974, E.H. Mamdani designed a fuzzy controller and applied it to the operation control steam engine[6]. Nowadays, fuzzy control with the advantage of not requiring a controlled system with an accurate mathematic model is used widely in many fields; compared with conventional PID control which can easily achieve good performance for nonlinear, uncertainty and lag system, especially robustness is better. For example, for a single-input, single-output nonlinear uncertain system, adapted the fuzzy adaptive control method; the results showed that the proposed approach was effective. Although fuzzy control exhibits a robust performance for nonlinear and uncertainty systems, its static error is not delicate enough. Thus, in practice, fuzzy control is not used alone, and is instead often combined with a PID controller. In this setup, fuzzy control and PID controller are able to utilize their respective characteristics[7-8].

Due to the complex nature of the airplane ground air conditioning system and the influence of the environment, the temperature control of the aircraft cabin based on the airplane ground air conditioner is highly nonlinear and uncertain, which makes it difficult to establish a precise mathematic model; thus, it becomes challenging for a conventional PID control to achieve a good control effect. In this paper, a combined controller called self-adaptive fuzzy PID, which is a combination of fuzzy PID and conventional PID, is applied to the temperature control system; thus, there is no need for an accurate mathematical model[9-11]. The results of the simulation illustrate that the self-adaptive fuzzy PID has a good effect in terms of dynamic performance, static performance and robustness.

The structure of the work presented in this paper is organized as follows. The guiding principle of self-adaptive fuzzy PID controller is described in Section 1. The mathematical model of the temperature control system for an aircraft cabin is presented in Section 3. In Section 4, we discuss in detail the design of the fuzzy PID controller, and also describe fuzzification, establishment of the input and output variable domain, and establishment of fuzzy rules. The simulation results are presented in Section 5. Finally, the conclusions are given in Section 6.

1 Fuzzy PID Controller Principle

For the general structure of a fuzzy PID controller, there are two basic types. The first structure is illustrated in Fig. 1, and the second structure is

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illustrated in Fig 2. The general principle of a fuzzy PID controller illustrated in Fig. 1 is that the parameters of the PID controller are adjusted online through a fuzzy controller. The fuzzy controller with error e and error change de/dt as inputs, as well as K_p, K_i and K_d as outputs, consists of four sections: fuzzification, fuzzy control rule, fuzzy inference and defuzzification.

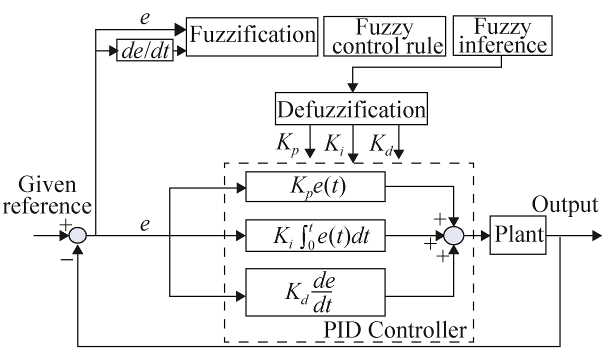

Fig. 1 One kind general structure of a fuzzy PID controller

Fig. 2 shows the structure of the second type of fuzzy PID controller, which is essentially a combination of fuzzy PID and conventional PID. Here, the conventional PID is used to determine the basic values of K_p, K_i and K_d, and the fuzzy controller is used to determine the values of ΔK_p, ΔK_i and ΔK_d. The ΔK_p, ΔK_i and ΔK_d as the outputs of the fuzzy controller are used to amend the basic values of K_p, K_i and K_d, in order to achieve a better control effect. In this paper, the second structure shown in Fig. 2 is adopted[12-13].

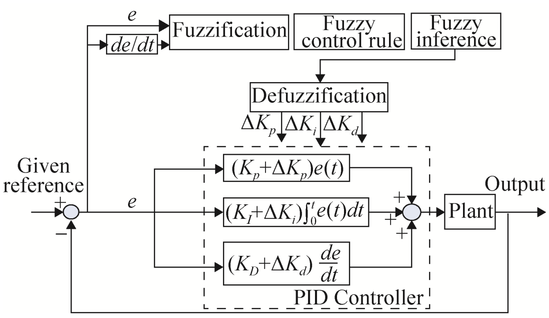

Fig. 2 Another type of general structure of a fuzzy PID controller

2 Mathematical Modeling Description

The general working view of an airplane ground air conditioner is illustrated in Fig. 3, which shows that the air conditioner is connected to the airplane through the air conduit.

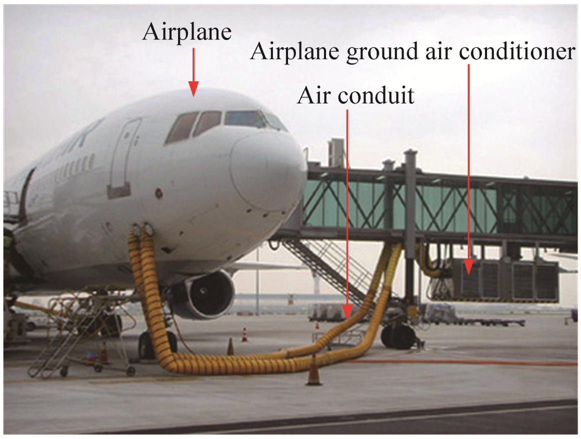

Fig. 3 General working view of airplane ground air conditioner

Due to the combined impact of the environment, air conduit, and aircraft cabin internal environment, the aircraft cabin temperature control system based on the airplane ground air conditioner is a complex and nonlinear system. In this case, it is difficult to establish a highly precise mathematic model. Ignoring some minor factors, the aircraft cabin can be treated as a single object; according to the law of conservation of energy, the equation can be written as[14]:

$$C_1 \frac{dt_n}{d\tau} = (L\rho c t_s + q_n) - L\rho c t_n + \frac{t_n - t_0}{r} \quad (1)$$

Where: C_1: capacity coefficient of aircraft cabin, (kJ/℃); L: air supply volume, (m^3/h); ρ: air density, (kg/m^3); c: specific heat at constant pressure of the air; q_n: heat dissipating capacity of aircraft cabin, (kJ/h); t_0: outside air temperature of aircraft cabin, (℃); t_n: inside temperature of aircraft cabin, (℃); t_s: interface temperature of air conduit and cabin, (℃); r: cabin thermal resistance of inside and outside skin,

(h℃/kJ).

$$rC_1\frac{dt_n}{d\tau}+rL\rho ct_n-t_n=rL\rho ct_s+(rq_n-t_0) \quad (2)$$

Considering the influence of the ground air conditioning and air supply pipe, (rq_n–t_0) is regarded as a system disturbance; thus, the transfer function of the generalized controlled object can be written as:

$$G(s)=\frac{K}{Ts+1}e^{-\tau s} \quad (3)$$

In equation 3, K can be converted into the magnification coefficient of control channel; here K=1. T is the system time constant. Using mathematical analysis of the ground air conditioning system and the actual test, it can be obtained that T=150 s, and the domain of τ is {10~14}. The system mathematical model can therefore be written as:

$$G(s)=\frac{1}{150s+1}e^{-\tau s}, \tau\in[10,14] \quad (4)$$

3 Design of Fuzzy PID Controller

3.1 Fuzzy Control

Fig. 4 shows the inputs and outputs of a fuzzy controller. Error e and error change de/dt are inputs, and ΔK_p, ΔK_i and ΔK_d are outputs. The range of error e is {-1 ~ 1}, and the range of error change de/dt is {-1 ~ 1}. Fig. 5 shows the membership function of the output variable ΔK_p, the scaling factor of which is {0~4}. Fig. 6 shows the membership function of the output variable ΔK_i, the scaling factor of which is {0~0.05}. Fig. 7 shows the membership function of the output variable ΔK_d, the scaling factor of which is {0~0.6}.

The range of the output variable is very important, as it influences the control effectiveness of the fuzzy controller. However, the establishment of the output variable's suitable range is difficult; generally, the scaling factor is based on experience and knowledge. In this paper, a new method is proposed, which can obtain a reasonable range of output variable. Thus, the system mathematical model can be written as formula (4).

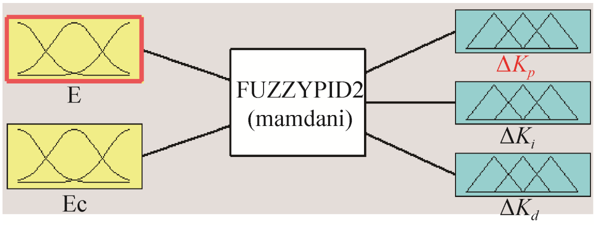

Fig. 4 Mamdani type fuzzy controller

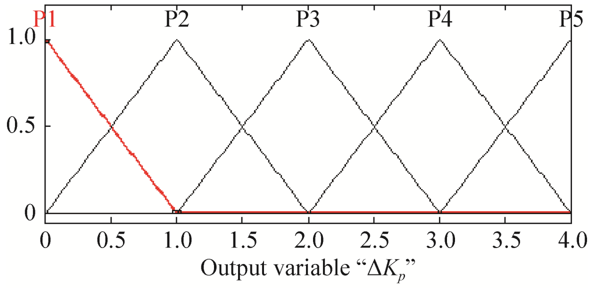

Fig. 5 Membership function of output variable ΔK_p

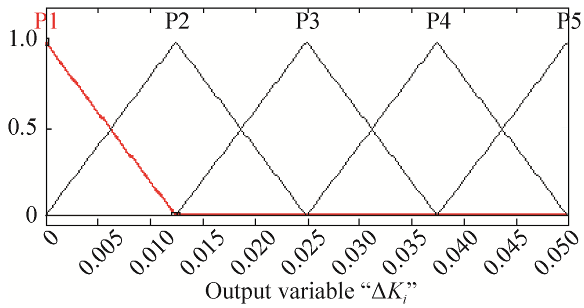

Fig. 6 Membership function of output variable ΔK_i

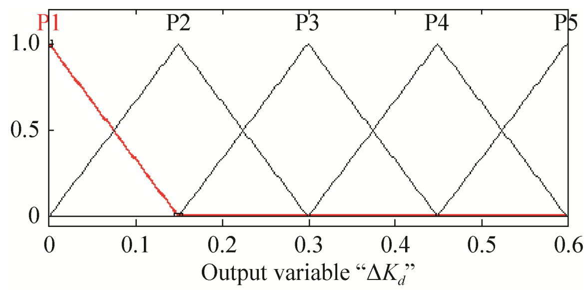

Fig. 7 Membership function of output variable ΔK_d

Three typical values of τ are chosen in this paper: τ=10 s, τ=12 s, and τ=14 s.

According to the three transfer functions discussed above, a conventional PID controller is

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adopted. The PID parameters are shown in Tab. 1. The simulation results are shown in Fig. 8. From Fig. 8, it can be seen that different mathematical models need different PID parameters; thus, a conventional PID controller is not suitable for the airplane ground air conditioning system.

According to the PID parameters in Tab. 1, fuzzy PID controller parameters are given in Tab. 2.

Tab. 1 PID Controller Parameters

PID	τ=10	τ=12	τ=14
K_p	4	7	8
K_i	0.05	0.08	0.1
K_d	0.1	0.3	0.7

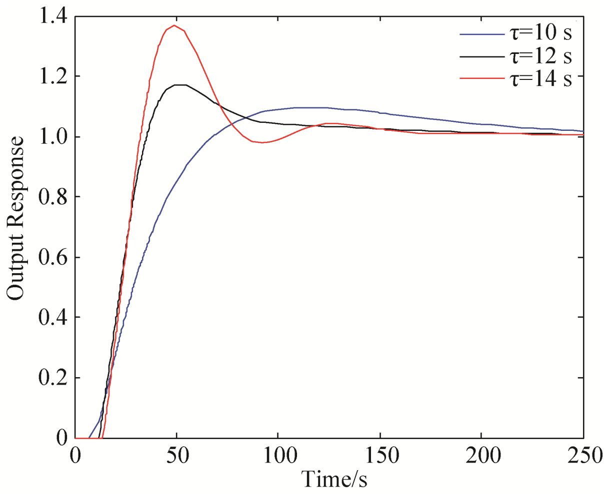

Fig. 8 Simulation results

Tab. 2 Fuzzy PID Controller Parameter

Fuzzy PID Controller Parameter	Base Value	Fuzzy PID Controller Parameter	Fuzzy Out Variable Range
K_p	8	ΔK_p	[0, 4]
K_i	0.1	ΔK_i	[0, 0.05]
K_d	0.7	ΔK_d	[0, 0.6]

3.2 Establishment of Fuzzy Rules

The fuzzy rules have a very significant impact on fuzzy controllers. The method based on experts experience and knowledge is adopted. Fig. 9 shows the typical step response curve. In Fig. 9, it can be seen that a typical dynamic response curve includes the following parts: AB segment, BC segment, CD segment, DE segment, EF segment, FG segment, GH segment, HI segment.

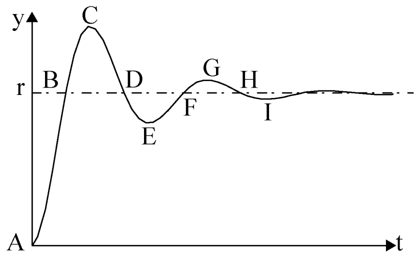

Fig. 9 Typical Dynamic Step Response Curve

AB segment: error e>0, and error gradually decreased as time goes on. de/dt>0, and de/dt gradually decreased. When the error is larger, K_p should also be larger, K_i=0 and K_d=0. With error e gradually decreasing, K_i and K_d should gradually increase, and K_p should become smaller.

BC segment: error e<0, and $|e|$ gradually increased. de/dt >0, and de/dt gradually decreased. Nearby, B, in order to reduce the overshoot, should choose the larger K_p and smaller K_i. With $|e|$ gradually increasing, K_p should decrease, and K_i, K_d should increase.

CD segment: error e<0, and $|e|$ gradually decreased. Error change de/dt<0, and de/dt gradually decreased. K_p should gradually increase, and K_i and K_d should decrease.

DE segment: error e>0, and e gradually increased. Error change de/dt<0, and de/dt gradually decreased. K_p should suitably gradually decrease, and K_i and K_d should increase.

EF segment: error e>0, and error gradually decreased as time goes on. de/dt>0, and de/dt gradually decreased. The regulating law of K_p, K_i, K_d is similar to the AB segment, but K_p, K_i and K_d should decrease accordingly.

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FG segment: error e<0, and $|e|$ gradually increased. de/dt>0, and de/dt gradually decreased. The regulating law of K_p, K_i, K_d is similar to the BC segment, but relatively K_p, K_i and K_d should decrease accordingly.

GH segment: error e<0, and $|e|$ gradually decreased. Error change de/dt<0, and de/dt gradually decreased. The regulating law of K_p, K_i, K_d is similar to the BC segment, but relatively K_p, K_i and K_d should decrease accordingly.

According to the regulating rules described above, the fuzzy control table can be summed up in Tab. 3~5[15].

Tab. 3　Fuzzy rule of ΔK_p

ΔK_p		E				
		NB	NS	ZO	PS	PB
Ec	NB	P5	P5	P4	P4	P1
	NS	P5	P4	P4	P3	P3
	ZO	P4	P3	P2	P5	P4
	PS	P3	P2	P2	P4	P5
	PB	P3	P1	P1	P4	P5

Tab. 4　Fuzzy rule of ΔK_i

ΔK_i		E				
		NB	NS	ZO	PS	PB
Ec	NB	P2	P1	P3	P4	P5
	NS	P1	P2	P2	P3	P4
	ZO	P3	P1	P4	P2	P3
	PS	P1	P1	P2	P2	P2
	PB	P2	P2	P3	P1	P1

Tab. 5　Fuzzy rule of ΔK_d

ΔK_d		E				
		NB	NS	ZO	PS	PB
Ec	NB	P4	P3	P2	P3	P2
	NS	P2	P2	P1	P2	P1
	ZO	P1	P1	P1	P2	P1
	PS	P4	P2	P4	P2	P2
	PB	P5	P3	P5	P3	P1

4　Simulation Results and Discussion

4.1 Establishing simulation model

According to the general principle of fuzzy PID controller illustrated in Fig. 2, the simulation model is established using MATLAB/SIMULINK, as shown in Fig. 10~11 shows the internal structure of the PID controller subsystem shown in Fig. 10. The parameters of the simulation model are displayed in Tab. 2.

4.2 Simulation results

The simulation results are shown in Fig. 12. when τ=10 s, τ=12 s, τ=14 s and τ=15 s, the step response curve is given.

From the simulation results, it can be seen that not only does the fuzzy PID controller exhibit good robustness, but it also performs better than the conventional PID controller (Fig. 8). It is proved that the fuzzy PID controller has strong robustness to changes in τ. Moreover, percentage overshoot, settling time and dynamic adjustment process are better than those shown in Fig. 8. The performance indicators are given in Tab. 6.

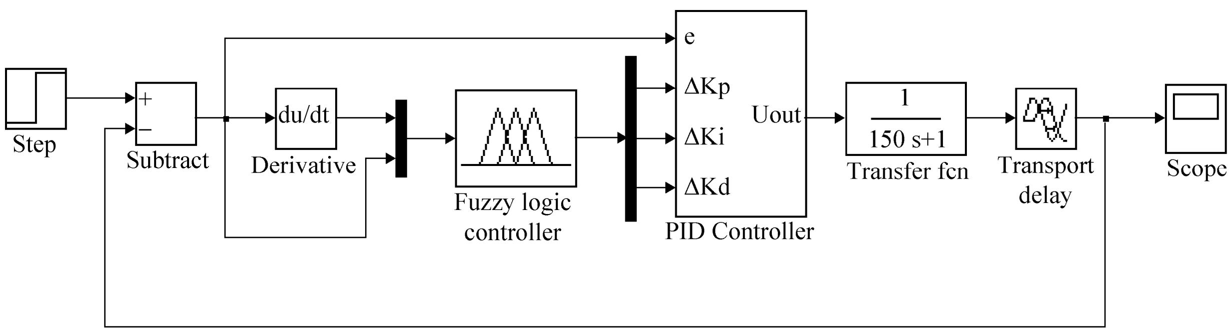

Fig. 10　Simulation model

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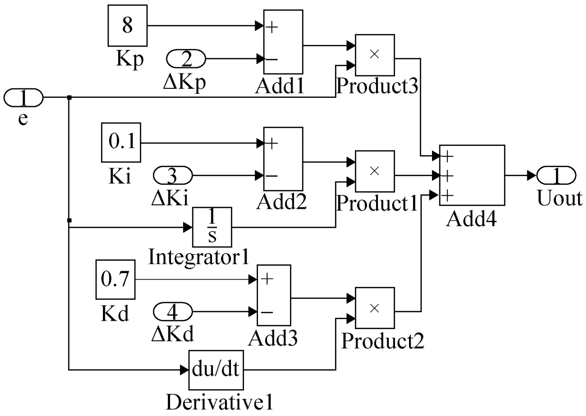

Fig. 11 Subsystem of PID controller

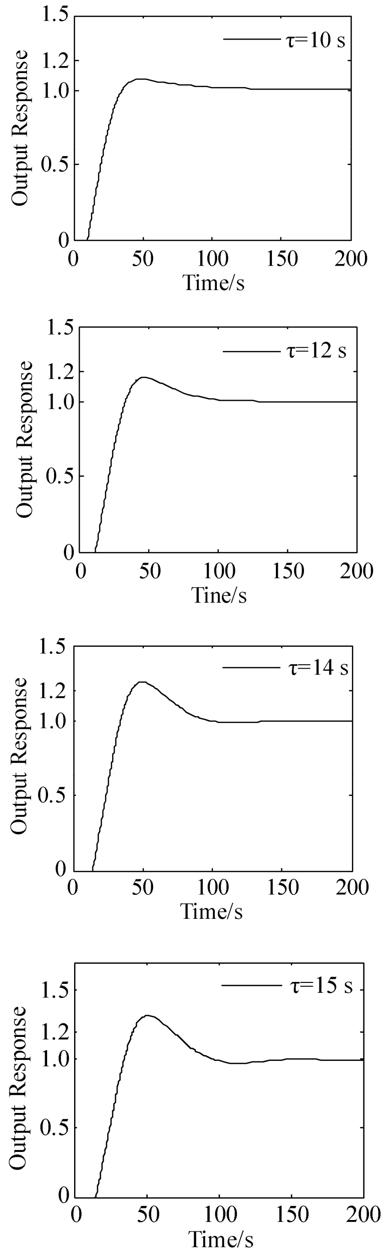

Fig. 12 Simulation Results

Tab. 6 Performance indicators of fuzzy PID controller

Performance indicators	τ=10	τ=12	τ=14
percentage overshoot	9%	18%	25%
settling time	160s	125s	100s

Fig. 13 presents the simulation result in case of the disturbance rejection problem. At t=150 s, the impulse interference is introduced to the control system, from the output response in Fig. 13, it is can be seen that the controller system could return to a stable state when the disturbance eliminate.

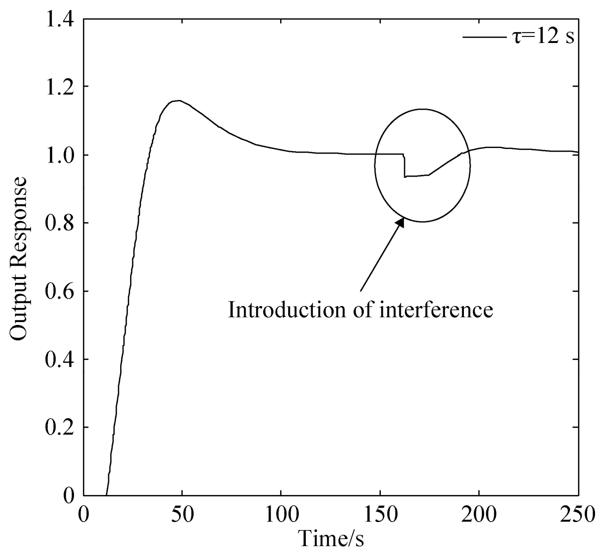

Fig. 13 Simulation results with introduce of interference

When designing the fuzzy PID controller, this paper only takes into account of the changes of delay time τ, not take into account of the possible changes of time constant T. The simulation results when change of T is illustrated in Fig. 14. Fig. 14 it is showed that the fuzzy controller has better robustness to changes of time constant T.

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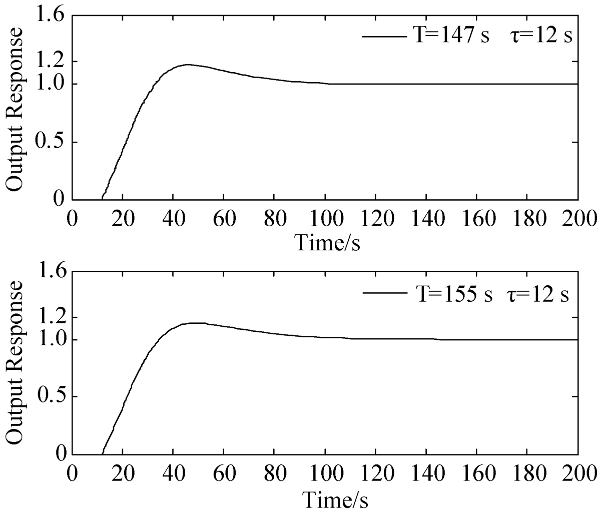

Fig. 14 Simulation results with disturbance of time constant *T*

5 Conclusions

In this paper, the self-adaptive fuzzy PID controller has been presented. The parameter of self-fuzzy PID controller in detail is given. Simulation result show that the self-fuzzy PID controller not only have better robustness to the parameter changes of controlled object, but also have relatively better performance in percentage overshoot, settling time and dynamic adjustment process.

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