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RESEARCH ON IMPROVED DUAL-CHANNEL FUZZY LOGIC CONTROLLER FOR AIRCRAFT

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Abstract. *The conventional single-channel Fuzzy Logic Controller (FLC) used for aircraft attitude control cannot eliminate steady-state error. Aiming at this problem, this paper designs an improved dual-channel fuzzy control rule base. This paper elaborates the control structure of the FLCs for aircraft attitude control, and then introduces the improved dual-channel aircraft FLC rule base adopted in this paper, compared with the published results, the fuzzy controller designed in this paper is simpler, in line with the aircraft control law, and the coupling degree is low. MATLAB/Simulink is used for aircraft 6-DOF simulation with FLC designed in this paper. The simulation results show that the control effect of the improved dual-channel FLC is better than that of the traditional PID controller, which can effectively eliminate the steady-state error, and improve the control effect with great robustness.*

Keywords: Control law, Fuzzy control, Dual-channel, Nonlinear control

1. **Introduction.** The concept of fuzzy set was proposed by Professor Zadeh in 1965 [1]; he then introduced the concept of type 2 fuzzy sets in 1975 [2]. After decades of development, fuzzy control has been widely used in practical applications. Most fuzzy controllers are nonlinear controllers, which have great effects in approximation accuracy and efficiency, and convergence speed of learning algorithms.

Many researches regard fuzzy controller directly as aircraft attitude controller, and great progresses have been made in this field. Fuzzy control can be directly used for the attitude control of the aircraft [3-5], and the advantage is that the control rules of the aircraft attitude control can be intuitively explained. At the same time, the robustness of the fuzzy controller is better for unsteady aerodynamic forces.

FLC can also form a cascade controller, such as Fuzzy-PID controller and Fuzzy-PD controller with other controllers [6,7], which is another solution to the nonlinear aerodynamic problems of aircraft. For example, the High-Altitude Long Endurance (HALE) aircraft can fly continuously for up to three months. Its characteristic is that the display ratio is very large, and the influence of aeroelasticity cannot be ignored. The gain scheduling by fuzzy controller can realize the smooth change of controller gain and improve the control quality [8].

Fuzzy controller has some other applications in aircraft control. For example, fuzzy controller can be combined with PDC method, which can provide intuitive proof for controller design and stability analysis [9,10].

Fuzzy controller can also be combined with intelligent algorithm. For example, it can be combined with neural network to form Adaptive Neuro-Fuzzy Inference System (ANFIS)

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controller, and even ANFIS controller and PID controller can be combined. The nonlinear controller formed by these methods has strong robustness, especially in the case of external disturbance or wing damage, it can still maintain qualified control quality [11,12].

In addition to aircraft control, fuzzy control theory can also be applied to other aspects of aerospace field.

The commonly used aircraft aerodynamic modeling method is least square. Fuzzy logic theory can also be used for aerodynamic modeling. For example, the Mamdani Fuzzy Inference Network (MFIN) can be used for aerodynamic modeling with great robustness to noise. It also has the nonlinear approximation ability of neural network [13]. The method based on T-S fuzzy logic combined with Gustafson and Kessel (G-K) clustering algorithm can also achieve great dynamic modeling accuracy [14].

The design of multi-UAV formation flight control system includes top-level and bottom-level design, which requires formation keeping on the basis of bottom-level attitude stability control. Fuzzy controller can be competent for top-level and bottom-level control tasks and improve the durability under model uncertainty [15-17].

In addition to aircraft control, fuzzy control theory has practical applications in many other fields. In the medical field, fuzzy control is applicable to situations that need to be judged, such as the diagnosis of heart disease and diabetes [18-21]. In view of the good nonlinear characteristics of fuzzy control, FLC has applications in many fields, such as power transmission [22,23], agriculture [24], and automobile [25].

As a nonlinear control method, FLC has been greatly developed in the application of aircraft control. In [4], the authors proposed a dual-channel FLC, but the rule base of incremental channel fuzzy control proposed in this literature was relatively complex. In the large maneuverable stage, the incremental channel will also play an important role, which will affect the control effect of the original single-channel FLC. Aiming at this problem, this paper tries to propose a new incremental channel rule base which is easier to explain and adjust gains.

Here is a brief introduction to the overall structure of the article. In the introduction, we investigate the development and application history of FLCs, including aircraft control and other applications. Subsequently, the six-degree-of-freedom dynamic modeling of the aircraft is carried out, which is the basis of subsequent analysis and simulation. The third section of the article explains the structure of FLCs and the rule base. The fourth section introduces the simulation content. Firstly, the target aircraft, simulation condition design and simulation results are introduced, and the corresponding analysis is given for the simulation results. Finally, the article summary is given in the conclusion.

2. **Dynamic Modeling of 6-DOF Aircraft.** For the motion of an aircraft in 6-DOF, the velocity vector is shown as below. Velocity is expressed in vector form and contains three components in the body coordinate system.

$$\boldsymbol{V} = [u \quad v \quad w]^T \tag{1}$$

The angular velocity vector is shown as below. It contains three components around the center of mass of the plane,

$$\boldsymbol{\Omega} = [p \quad q \quad r]^T \tag{2}$$

By analyzing the force acting on the aircraft and decomposing it into vectors in the corresponding coordinate axes, the expressions of acceleration and angular velocity of the aircraft can be obtained. Dynamic equations can be written as

$$\begin{cases} \dot{u} = rv - qw + \dfrac{F_x}{m} \\ \dot{v} = pw - ru + \dfrac{F_y}{m} \\ \dot{w} = qu - pv + \dfrac{F_z}{m} \\ \dot{\phi} = p - \tan\theta(q\cos\phi - r\sin\phi) \\ \dot{\theta} = q\sin\phi + r\cos\phi \\ \dot{\psi} = \dfrac{q\cos\phi - r\sin\phi}{\cos\theta} \end{cases} \tag{3}$$

F_x, F_y, F_z are the resultant forces of three axes, and θ is pitch angle, ψ is yaw angle, and ϕ is roll angle.

The centroid moment is the derivative of the angular velocity of the aircraft to time

$$\begin{bmatrix} J_{xx} & J_{xy} & J_{xz} \\ J_{yx} & J_{yy} & J_{yz} \\ J_{zx} & J_{zy} & J_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \boldsymbol{M} \tag{4}$$

where J_{xx}, J_{yy}, J_{zz} are the rotational inertia of the three axes of the aircraft, and J_{xy}, J_{xz}, J_{yx}, J_{yz}, J_{zx}, J_{zy} are the inertial product of the aircraft to each axis. For axisymmetric aircraft, the above equation can be simplified as

$$\begin{bmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & J_{yz} \\ 0 & J_{zy} & J_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \boldsymbol{M} \tag{5}$$

Similarly, by analyzing the moment the aircraft is subjected to, the expression of the angular acceleration of the aircraft can be obtained, as shown in Equations (6), (7), and (8)

$$\dot{p} = \frac{M_x}{J_{xx}} \tag{6}$$

$$\dot{q} = \frac{M_y J_{zz} - M_z J_{yz}}{J_{yy} J_{zz} - J_{yz}^2} \tag{7}$$

$$\dot{r} = \frac{M_z J_{yy} - M_y J_{yz}}{J_{yy} J_{zz} - J_{yz}^2} \tag{8}$$

By bringing the corresponding variables into the corresponding expression, the final dynamic equation form can be obtained. See the equation representation below.

$$\dot{u} = rv - qw + \frac{F_x}{m} \tag{9}$$

$$\dot{v} = pw - ru + \frac{F_y}{m} \tag{10}$$

$$\dot{w} = qu - pv + \frac{F_z}{m} \tag{11}$$

$$\begin{aligned} \dot{p} &= (L_R + (N_{ml} - N_{mr}) * y_1)/\, J_{xx} \\ \dot{q} &= ((Th_t + M_R) * J_{zz} - N_R * J_{yz})/\left(J_{yy} J_{zz} - J_{yz}^2\right) \\ \dot{r} &= (N_R * J_{yy} - (Th_t + M_R) * J_{yz})/\left(J_{yy} J_{zz} - J_{yz}^2\right) \end{aligned} \tag{12}$$

This paper makes the following assumptions while modeling.

1) Since the main research content of this paper is the controller structure, the fuselage deformation of concern for elastic mechanics is not taken into account. So the aircraft is rigid and does not consider the elastic effect of its deformation.

2) Preliminary verification of the effective performance of the controller needs to be carried out under common simulation conditions, and the simulation process in this paper is short, and factors such as earth curvature have little effect on the simulation. So, in this article, we ignore the influence of earth rotation, and the ground coordinate system is an inertial system.

3. **Main Research Contents.**

3.1. **FLCs for aircraft attitude control.** The general FLC includes four main components, including rule base, inference system, fuzzifier and defuzzifier. Figure 1 shows the general structure of the fuzzy controller.

1) Rule base: Rule base is the core part of an FLC; it is defined according to the prior knowledge of the controller designer for the controlled model.

2) Inference system: Inference system determines which rules are triggered and how much they are triggered by using the rule base and the mathematical method used to assign weights. A well-designed inference system needs to have the following characteristics: 1) It can make a choice intuitively; 2) A clear and easy-to-calculate formula with high efficiency.

3) Fuzzifier: The function of the fuzzifier is to map crisp input to the antecedent fuzzy set. The fuzzifier has the following design criteria. 1) The fuzzifier should follow the principles of fuzzification, that is, for a crisp input x, the fuzzy set near x should have a larger membership value. 2) The fuzzifier should have a certain function of overcoming the input noise. 3) The fuzzifier should help simplify the computation of inference system.

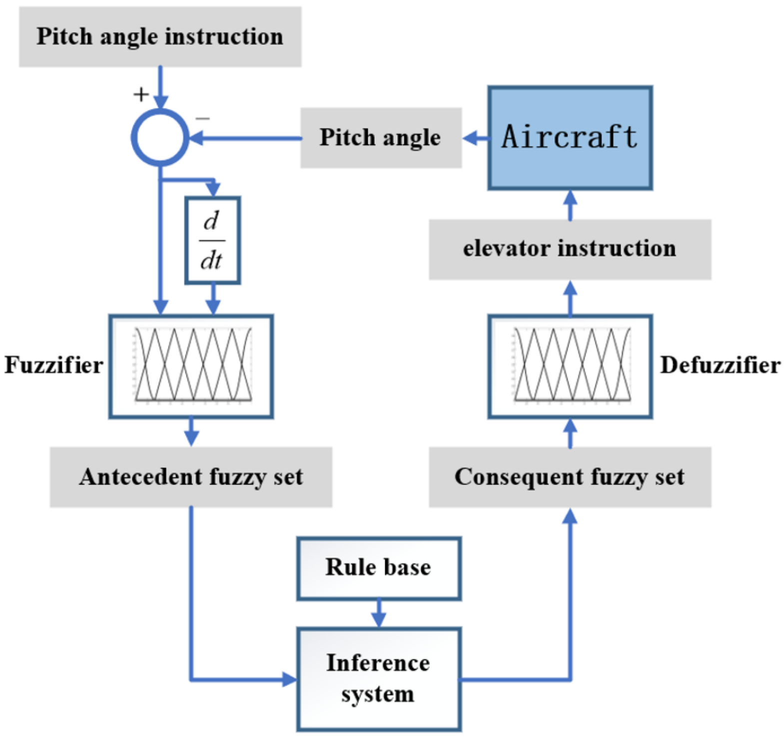

FIGURE 1. General structure of the fuzzy controller for aircraft attitude control

4) Defuzzifier: The function of the defuzzifier is to map the consequent fuzzy set $\boldsymbol{B}$ to the crisp output y, which can be understood as the reverse process of the fuzzifier. The defuzzifier has the following design criteria: 1) y may be located near the center of $\boldsymbol{B}$ or have a large membership value in $\boldsymbol{B}$; 2) it is easy to calculate; 3) small changes in $\boldsymbol{B}$ will not cause the substantial changes of y.

Taking longitudinal control as an example, first, the flight control guide loop solves the pitch angle command, and the pitch angle error is obtained by making the difference between pitch angle command and the real pitch angle detected by the sensor, and at the same time, the error is derived from time to obtain the error change rate. The error and the error rate of change are input to the fuzzy controller, then the fuzzy controller solves the control command, and outputs the control command to the actuator to control the flight attitude of the aircraft.

The membership function includes input membership function and output membership function. The function of the input membership function is to map the crisp input of the system into antecedent fuzzy set, and the function of the output fuzzy set is to map the consequent fuzzy set which comes from inference system into crisp output.

The input of fuzzy controller is

$$\begin{cases} e = \theta_c - \theta \\ \Delta e = \dfrac{de}{dt} \end{cases} \tag{13}$$

where θ_c is pitch angle command.

The FLC can be expressed as

$$\delta_e = f(e, \Delta e) \tag{14}$$

where δ_e is elevator command.

Before the crisp input is mapped into antecedent fuzzy set, it needs to be scaled to the universe of discourse, the universe of discourse for aircraft attitude fuzzy controller is $[-1, 1]$, the lower limit and upper limit of the universe of discourse use the z membership function and the s membership function as the membership function, respectively, and the rest of membership functions are triangle membership functions. The design criterion of the membership function in this paper is to divide the scaled crisp input into seven grades according to the size which are named as NB, NM, NS, Z, PS, PM and PB. The output membership function is also divided by this criterion.

The definition of z membership function is

$$f(x) = \begin{cases} 1, & x < p \\ 1 - 2 \times \left(\dfrac{x-p}{q-p}\right)^2, & p < x < \dfrac{p+q}{2} \\ 2 \times \left(\dfrac{q-x}{q-p}\right)^2, & \dfrac{p+q}{2} < x < q \\ 0, & q < x \end{cases} \tag{15}$$

In polynomial (15), p is the left endpoint and q is the right point.

The definition of triangle membership function is

$$f(x) = \begin{cases} \dfrac{x-p}{q-p}, & x < q \\ 1, & x = q \\ \dfrac{r-x}{r-q}, & x > q \end{cases} \tag{16}$$

In polynomial (16), p is the left endpoint, r is the right point and q is center point.

The definition of s membership function is

$$f(x)=\begin{cases}0, & x<p\\ 2\times\left(\dfrac{p-x}{q-p}\right)^2, & p<x<\dfrac{p+q}{2}\\ 1-2\times\left(\dfrac{x-q}{q-p}\right)^2, & \dfrac{p+q}{2}<x<q\\ 0, & q<x\end{cases} \tag{17}$$

In polynomial (17), p is the left endpoint and q is the right point.

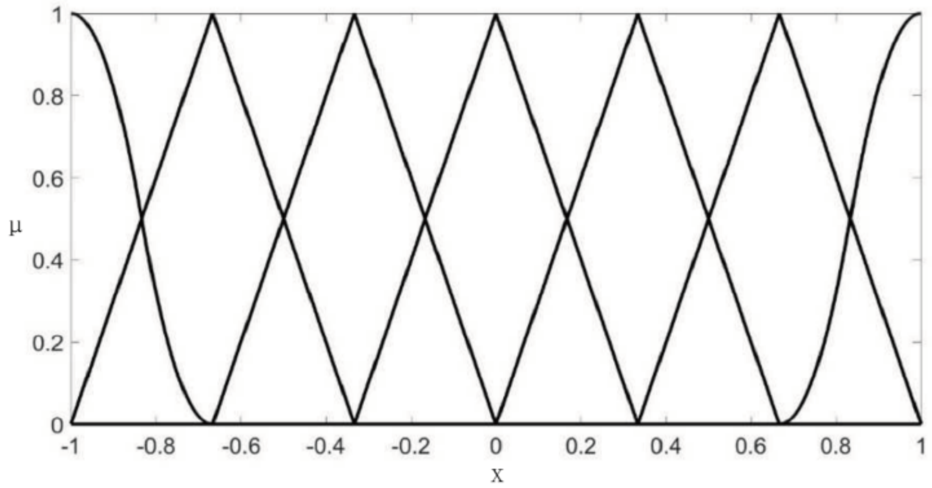

FIGURE 2. Membership function

The rule base for FLC is shown as below, Z means zero. For labels with two letters, the first letter is either N, means Negative, or P, means Positive, and the second letter can be S/M/B, which respectively mean small/medium/big. Each label corresponds to a degree with polarity, for example, "NB" means "Negative Big".

TABLE 1. Rule base for single-channel FLC

E \ ΔE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	PS	PM
NM	NB	NB	NM	NM	NS	PS	PM
NS	NB	NB	NM	NS	Z	PM	PB
Z	NB	NM	NS	Z	PS	PM	PB
PS	NB	NM	Z	PS	PM	PB	PB
PM	NM	NS	PS	PM	PM	PB	PB
PB	NM	NS	PS	PM	PB	PB	PB

3.2. **Dual-channel FLCs for aircraft attitude control.** The design concept of rule base for single-channel fuzzy controller is similar to the PD controller, and it will generate steady-state errors, an additional parallel channel can effectively eliminate steady-state errors. The dual-channel FLC includes two channels: absolute channel and incremental channel. A single-channel conventional FLC is a single absolute channel FLC.

In the dual-channel FLC, the roles of the two channels are different. The function of the absolute channel is to improve the response speed of the aircraft, and the incremental

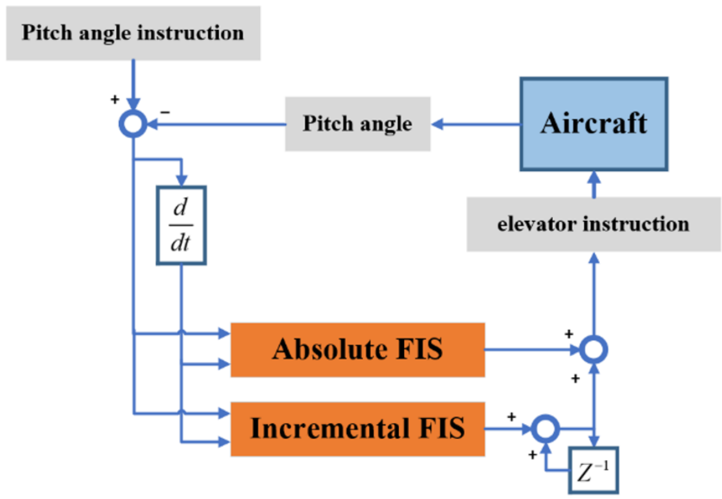

FIGURE 3. Dual-channel FLC

channel can reduce the steady-state error. The configuration of the dual-channel FLC is shown in Figure 3.

The rule base for incremental FLC is modified from [4]. The modified rule base is more suitable for the simulation model used in this paper. The modified incremental channel FLC pays more attention to the small steady-state error in the constant state. At the same time, in the original rule set for the large maneuver stage, the incremental FLC remains inactive during the grand maneuver phase to ensure the control effect of the absolute FLC, the physical meaning of the modified rule base is intuitive and the parameter adjustment is convenient.

TABLE 2. Rule base for incremental channel

E \ ΔE	NB	NM	NS	Z	PS	PM	PB
NB	Z	Z	PB	PM	PS	Z	Z
NM	Z	Z	PM	PS	NS	Z	Z
NS	Z	Z	PS	PS	Z	Z	Z
Z	Z	Z	Z	Z	PS	Z	Z
PS	Z	Z	Z	NS	NS	Z	Z
PM	Z	Z	NS	NS	NM	Z	Z
PB	Z	Z	NS	NM	NB	Z	Z

4. Simulation Verification.

4.1. **Simulation conditions.** In this paper, MATLAB/Simulink is used to build a 6-DOF model of the aircraft to verify the effect of the dual-channel FLC.

The aircraft model used in this paper is a light fixed-wing Aircraft. The relevant information of the aircraft is shown in Table 3.

In the simulation, the initial pitch angle is 0°, and then the step command of the step pitch angle changes with time as shown in Table 4. This kind of verification instruction setting is transformed many times, which can comprehensively extract the control effect of the controller. It is worth noting that because the verification aircraft in this paper is a small aircraft, the pitch angle does not need to take a large value, and 5 degrees is the normal maneuver amplitude.

TABLE 3. Aircraft information

Index	Value
Wingspan	3.5 m
Chord length	0.33 m
Wing area	1.2 m^2
Cruising speed	25 m/s
Take-off weight	20 Kg

TABLE 4. Instruction-Time

Time (s)	Instruction
0-60	Take off
60-80	$\theta_{cmd} = 0°$
80-100	$\theta_{cmd} = 5°$
100-120	$\theta_{cmd} = 0°$
120-140	$\theta_{cmd} = -5°$
140-160	$\theta_{cmd} = 0°$

Since the FLC needs to map the crisp input to the domain and the crisp output is also within the domain, it needs to reduce this value to the limit range of the real elevator deflection angle, so the gain of the fuzzy controller needs to be designed. In order to reduce the workload as much as possible, the controller gain of FLCs is determined by the input and output of the controller instead of manual adjustment. This method comes from [4].

TABLE 5. FLC gains

Channel	Gain	Value
Absolute	Input e	10
	Input Δe	1
	Output	40
Incermental	Input e	20
	Input Δe	10
	Output	20

The aircraft longitudinal controller is the single-channel FLC or dual-channel FLC introduced in this paper or PID controller, and the speed and heading controllers are both PID controllers.

4.2. **Single-channel FLC vs. dual-channel FLC.** In order to verify the performance of the dual-channel FLC in eliminating the steady-state error, this paper compares the control effects of the dual-channel FLC and the single-channel FLC through comparative simulation. Figure 4 and Figure 5 show the comparison chart of the tracking effect of the pitch angle command.

The simulation results show that when using single-channel FLC to control the aircraft to track the pitch angle step command, there is always a command tracking steady-state error, while the dual-channel FLC can eliminate the steady-state error.

In order to quantitatively evaluate the performance of the two controllers in eliminating the steady-state error, the average value of the steady-state error value of 85 s – 95 s is selected as the index to evaluate the ability of the two controllers to eliminate the steady-state error.

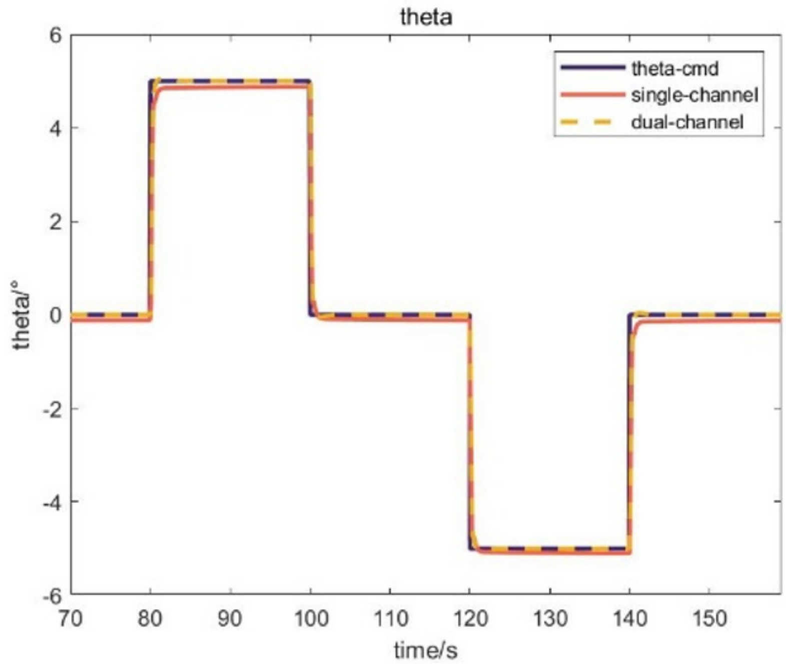

Figure 4. Single-channel vs. dual-channel FLC pitch angle command tracking

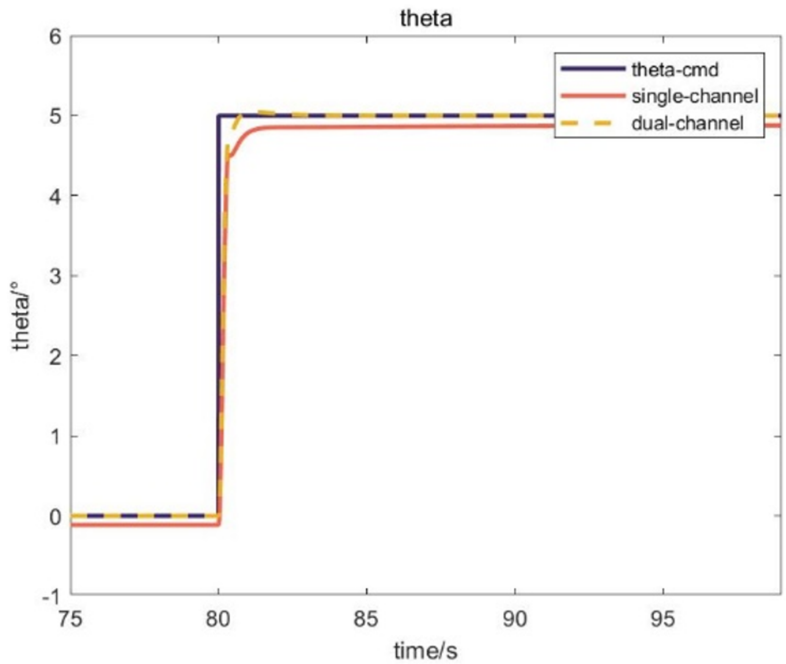

Figure 5. Partial enlarged view of Figure 4

Table 6. Steady-state error of single/dual-channel FLC

Indicator	Single-channel	Dual-channel
Steady-state error (°)	0.13	0

The comparison shows that the single-channel FLC causes a relatively large steady-state error, while the dual-channel FLC effectively eliminates the steady-state error.

4.3. **Dual-channel FLC vs. PID controller.** In order to compare the control effect of the dual-channel FLC introduced in this paper and PID controller, the attitude angle command tracking simulation is designed under the same conditions as the above section. The simulation results are shown as follows.

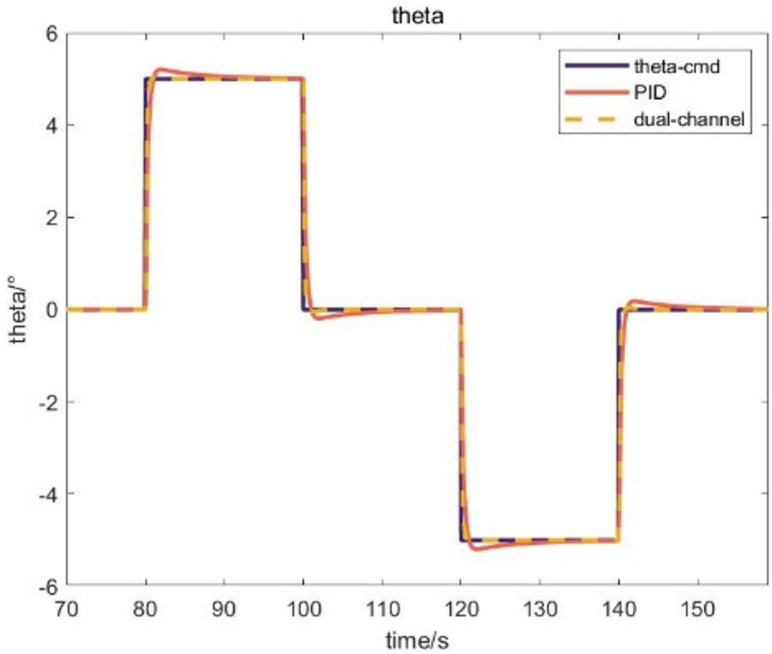

Figure 6. Dual-channel FLC vs. PID controller pitch angle command tracking

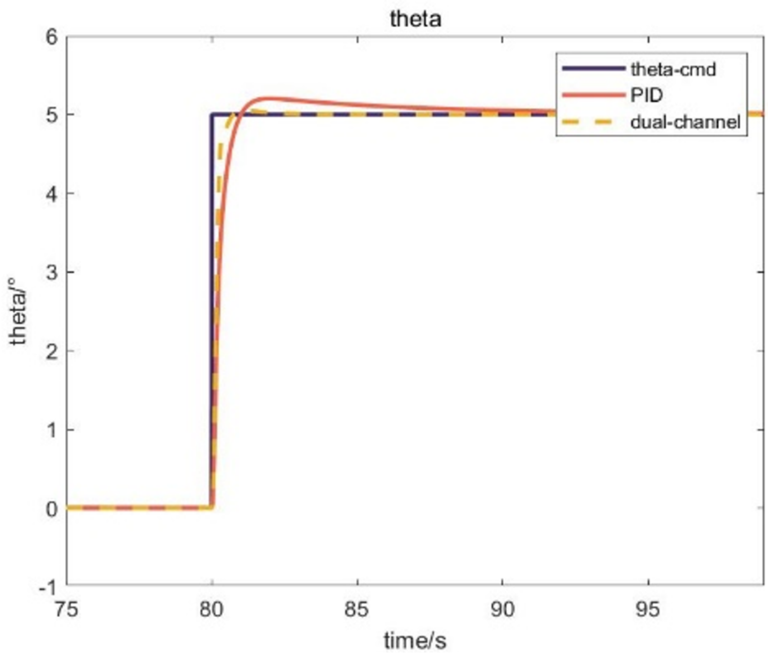

Figure 7. Partial enlarged view of Figure 6

Take overshoot, rise time, settling time and peak time as evaluation indicator to evaluate the control performance of the two controllers. The values are as follows.

TABLE 7. Index comparison

Indicator	PID controller	FLC
Overshot (%)	4.1	0.9
Rise time (s)	0.280	0.145
Settling time (s)	7.420	0.600
Peak time (s)	2.495	1.640

The simulation results show that compared with the traditional PID controller, the overshoot of the improved dual-channel FLC is only 22% of that of the latter, and the peak time, settling time and rise time are 52%, 8% and 66% of that of the latter. Through these indicators, it can be seen that FLCs have a good performance in control accuracy, response speed and stability. Compared with PID controller, the control effect of FLCs has been greatly improved.

4.4. **Robustness verification of dual-channel FLC.** In order to verify the robustness of the dual-channel FLC while facing aerodynamic uncertainty, this paper sets the pitch moment coefficient and elevator effect with errors of ±20% respectively to observe the pitch angle tracking effect.

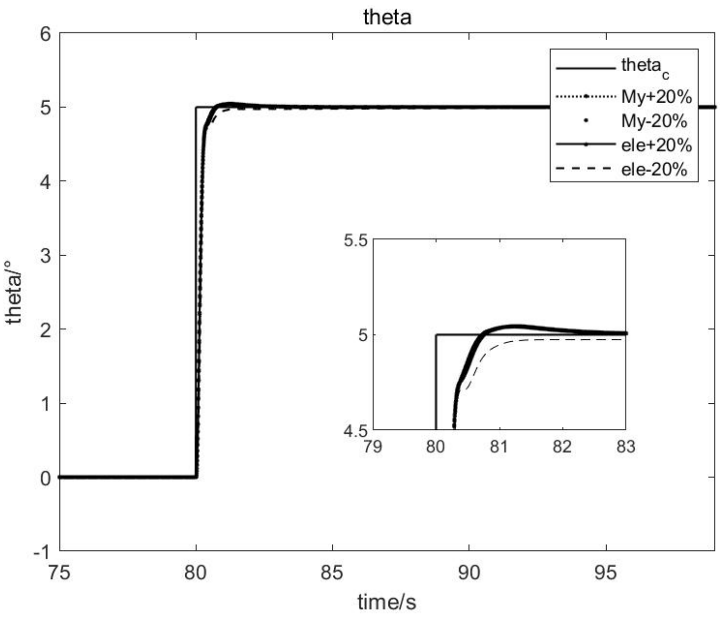

FIGURE 8. Robustness verification simulation result

The simulation results show that the dual-channel FLC still has great control quality when the pitch torque and elevator effect have errors within ±20%. It is proved that it has great robustness. In this section, My +20% means pitch moment is 120% of true value, My −20% means pitch moment is 80% of true value, ele +20% means elevator control efficiency is 120% of true value, and ele −20% means elevator control efficiency is 80% of true value.

As a comparison, simulation of the pitch angle command tracking of the PID controller under the same aerodynamic error conditions is set up for the robustness comparison with the FLC. The simulation results are shown in the figure below.

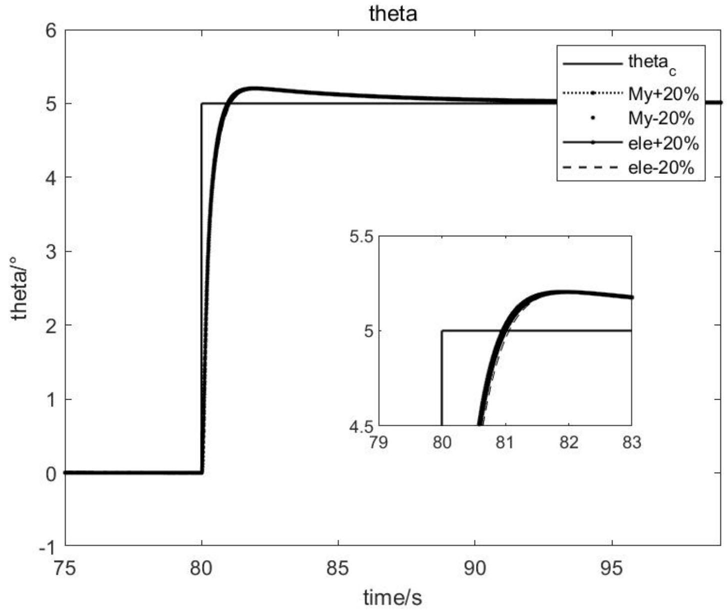

FIGURE 9. Robustness verification simulation result (PID)

It can be seen from the simulation results that both PID controller and FLC have good robustness in the face of aerodynamic uncertainty. In addition, FLC maintains fast and stable response to step commands.

5. **Conclusions.** In this paper, an improved dual-channel FLC rule base is designed to solve the problem of steady-state error of attitude tracking in the single-channel conventional FLC. Compared with the type I FLC, the improved controller can eliminate the steady-state error with strong robustness. At the same time, the simulation results show that compared with the PID controller, the dual-channel FLC has smaller overshoot, shorter rise time, settling time and peak time, and better tracking effect.

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