Boundary Controller Based on Fuzzy Logic Control for Certain Aircraft

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***Abstract*—A novel design method of boundary controller for certain aircraft based on fuzzy logic control is proposed in this paper. The method integrates optimization of fuzzy control function and on-line self-tuning of domain in fuzzy control system, which can largely improve qualities and adaptabilities of control system. A least squares algorithm of proportional gain α can optimize fuzzy logic rules. Self-tuning of domain on line can eliminates information loss caused by fuzziation. Integral control strategies can enhance stabilization and accuracy, improve system adaptability and limit deviation. Digital simulation within the full flight envelope demonstrated this new fuzzy controller brought about good control results.**

***Keywords*—fuzzy logic control; boundary condition; boundary value; adaptability; a least squares algorithm**

I. INTRODUCTION

In modern aerial warfare of aircrafts, it is necessary in the case of large maneuver flight within the full flight envelope. The pilot's misplay can make aircraft exceed tolerant boundary values of attack angle α or vertical overload n_y and run into dangerous navigation[1], for example, pushing or pulling control stick fiercely and so on. Because there is strong nonlinear in the dynamic model of an aircraft under different flight states, the traditional boundary controller not only was complicated in design. But also was bad in response speed, so it is hard to meet control demands and increase the probability of flight danger.

Over the past a couple of decades, many methods have been developed for self-tuning of controller parameters, and nowadays many control vendors offer such solutions. With high development of computer technology, the applications of fuzzy control get more and more in the field of flight control[2]. Because fuzzy control imitates human's actions according to operation experience and knowledge of human, it is suitable for obtaining the control rules and solving these problems such as imprecise model in nonlinear control system. It also shows high adaptability to diverse inner parameters of system. As a result, fuzzy control system, which was introduced in the design of boundary controller for a certain aircrafts, showed high efficiency.

A new kind of design of boundary controller based on fuzzy logic control is presented in this paper. As an aircraft is six-freedom, the new controller was applied to boundary control of attack angle α, vertical overload n_y and elevator angle Ψ in the case of large maneuver flight within the full flight envelope[3]. Digital simulation demonstrated this new fuzzy logic controller brings about good control results.

Ⅱ. CONTROLLER ALGORITHM AND CONFIGURATION

A. Control Rules

Control rules are the core of fuzzy logic controller. It determines efficiency and practicality of proposed controller. By all appearances, the applicability of unchangeable ones is bad. For fuzzy logic rule expressed as analytical expression is easy to regulate and achieve with computer, a new kind of fuzzy control algorithm with modified function is presented in this paper[4],[5],[6].

On the assumption that domain of error E, change-in-error E_c and control function U are defined as: {-N,…,-1,0,1,…,N}, so fuzzy logic rules with modified function can be expressed as:

$$U = \alpha E + (1-\alpha)E_c \qquad (1)$$

$$\alpha = \alpha_0 + \alpha_\tau \frac{|E|}{N} \qquad 0 \leqslant \alpha_0 \leqslant \alpha_\tau \leqslant 1 \qquad (2)$$

Where α is proportional gain of error E, its value directly reflects the weights of error E and change-in-error E_c. Theoretically, its value can on-line regulate according to the size of error E.

Apparently, self-tuning of proportional gain α can change fuzzy logic rule. We use performance standard of ITAE(integral of time multiplied by the absolute value of error) as guide lines of self-tuning, i.e.

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$$J=\int_{0}^{\infty} t\,|e(t)|\,dt=\min \tag{3}$$

For time control of computer is discrete, eq.(3) can be rewritten as follows

$$J(k)=\sum_{i=1}^{k}|e(iT)|\,iT^{2}=\min \tag{4}$$

where

J(k) objective function at time instant k

e(iT) system error at time instant i

T sampling time interval

Eq.(4) gives a method of on-line self-tuning optimization in discrete-time control system. In order to resolve proposed problem, statistical forecast technology can be used to estimate the connection between the proportional gain α_1(α_1=α)of error E and the differential gain α_2(α_2=1-α) of change-in-error E_c, then directly estimate the system output errors and simply calculate linear objectives. On the assumption that system error e(k+1), α_1(k+1) and α_2 (k+1) at the *(k+1)th* time can be described as follows.

$$e(k+1)=b_0+b_1\alpha_1(k+1)+b_2\alpha_2(k+1) \tag{5}$$

According to present and preceding recording data e(i), a_1(i) and a_2(i)(i=1,2,…,k), we can make use of a least squares algorithm to obtain parameters b_0～b_2. Their estimation values B_0，B_1 and B_2 are the solution of following equations.

$$\begin{cases} P_{11}B_1+P_{12}B_2=Q_1 \\ P_{21}B_1+P_{22}B_2=Q_2 \\ B_0+B_1A_1+B_2A_2=\bar{E} \end{cases} \tag{6}$$

where $$\bar{E}=\frac{1}{k}\sum_{i=1}^{k}e(i)$$

$$A_1=\frac{1}{k}\sum_{i=1}^{k}\alpha_1(i)$$

$$A_2=\frac{1}{k}\sum_{i=1}^{k}\alpha_2(i)$$

$$P_{11}=\sum_{i=1}^{k}[\alpha_1(i)-A_1]^2$$

$$P_{22}=\sum_{i=1}^{k}[\alpha_2(i)-A_2]^2$$

$$P_{12}=P_{21}=\sum_{i=1}^{k}[\alpha_1(i)-A_1][\alpha_2(i)-A_2]$$

$$Q_1=\sum_{i=1}^{k}[\alpha_1(i)-A_1][e(i)-\bar{E}]$$

$$Q_2=\sum_{i=1}^{k}[\alpha_2(i)-A_2][e(i)-\bar{E}]$$

So the estimation value of e(k+1) can be written as

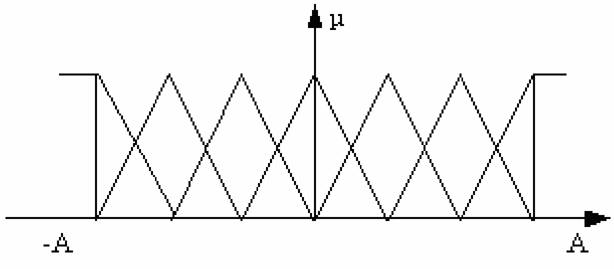
$$\tilde{e}(k+1)=B_0+B_1\alpha_1(k+1)+B_2\alpha_2(k+1) \tag{7}$$

Combined above expressions with eq.(1) and eq.(2) to optimize system parameter α_1 and α_2, the optimal control function can be obtained.

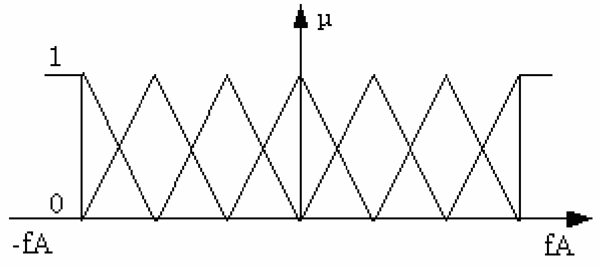
B. *self-tuning of domain*

Measuring grade and proportional gain are two important parameters to influence system performance. They were determined by input fuzzy variables and their corresponding control functions. Their principles are similar to change amplification coefficients of control system. But it is difficult to influence control quality by only on-line self-tuning two parameters. Research indicates that diverse states need different control functions U from instability to stability in fuzzy control system, and control function U is decided by membership functions. Regulating their corresponding membership functions according to the sizes of input fuzzy variables, we can change their ranges of domain. As a result, an optimized control function, which makes system keeping optimized control quality, can be selected on the basis of diverse states. In order to on-line self-regulate domain of input variables in fuzzy control system, a nonlinear function is expressed as follows:

$$f(E,E_c)=1-\exp(-\lambda\sqrt{(\alpha E)^2+[(1-\alpha)E_c]^2} \tag{8}$$



a. domain of e and $\dot{e}$



b. domain self-turing of e and $\dot{e}$

Figure 1. Domain of membership function

Where λ is design constant. Assume that initial domain of error E and change-in-error E_c are in [-A，A]. When E and E_c change during control, its domain can be self-regulated in [-fA，fA] as shown in Figure 1.b.

Their corresponding membership functions also self-regulate owing to self-tuning of domain. It achieves how to regulate control function U adaptively according to different size or direction of E and E_c. Consequently, this control not only eliminates information loss caused by measuring error, but also regulates gain adaptively in whole fuzzy control system.

So this control strategy makes control system keeping high adaptability and accuracy.

C. *Integral Control Strategies*

In order to improve stabilization accuracy, enhance system adaptability and restrict deviation, integral control strategies were defined as follows.

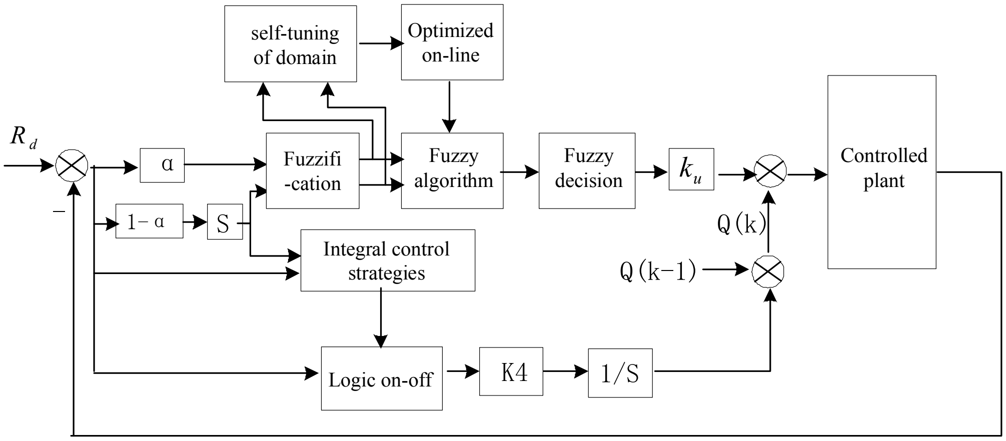


Figure 2. The configuration of fuzzy logic controller

IF $|E|<M_e$ and $|E_c|<M_c$ and $E\times E_c\leqslant 0$
THEN $Q(k)=Q(k-1)+K_1\times e(k)$
ELSE $Q(k)=Q(k-1)$

Where M_e and M_c are designed threshold, K_1 is gain value associated with corresponding error e(k). Finally, output gain value K_u can be expressed as follows:

$$k_u = k_u^{'} k_{u0} \qquad (9)$$

Where k_{uo} is proportional gain required out-line tuning according to demands of system performance, $k_u^{'}$ can be obtained from acquiring table as shown in Table.1.

TABLE I. ACQUIRING TABLE OF $K_U^{'}$

error	change-in-error						
	NB	NM	NS	ZO	PS	PM	PB
NB	5	5	4	3	2	2	1
NM	4	3	3	2	1	1	1
NS	4	3	2	1	1	1	2
ZO	3	2	1	1	1	2	3
PS	2	1	1	1	2	3	4
PM	1	1	1	2	3	3	4
PB	1	2	2	3	4	5	5

The model of fuzzy logic controller based on self-tuning of fuzzy logic rules is shown in Figure 2. With its robustness, stability, simple algorithm and high real-time response ability, and it doesn't need a precise mathematical model, so this fuzzy logic controller is proposed in the paper. Because our controlled plant is flight control system in certain aircraft, it is impractical to establish a precise mathematical model for quite a flew complex controlled plant. But it is apparent an aircraft requires high controlled performance and good anti-jamming capability. The configuration shown in Figure 2 is suitable for use alone as a controller because of above features.

III. DESIGN AND SIMULATION OF SYSTEM

The principle block of boundary control system is shown in Figure 3. The theory of boundary controller based on fuzzy logic control is as follows: When present attack angleα, vertical overload n_y and elevator angle Ψ are all less than their tolerant boundary values, outputs of three fuzzy logic controllers are all plus. According to theory of minimum selected system, the minimum of three outputs will be selected as feedback signal. Because the proposed control system is minus feedback loops, servomechanism movement can follow stick displacement all along. There is a certain interval between servomechanism and stick fulcrum. As a result, control stick can move freely.

When one of three variables(α, n_y and Ψ) exceeds its tolerant boundary values, the output of its corresponding fuzzy logic controller is minus. According to theory of minimum-selected system, the minus output will be selected as feedback signal. Consequently, the whole control system turns into plus feedback loops, servomechanism movement can't follow stick displacement again. Because the open-loop gain of proposed control system is so big, Servomechanism will prevent stick displacement in short time. At the same time, stick dithering signal generator will produce 8Hz dithering signal to inform pilot that danger will come.

Sometimes,α, n_y and Ψ didn't exceed their tolerant boundary values but one of them changed intensely. The output of its corresponding fuzzy logic controller is also minus and cause shaking ahead. It avoids aircraft running into dangerous control states.

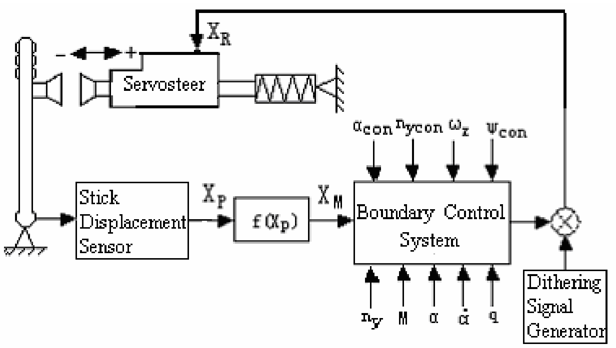


Figure 3. boundary control system principle block

The system configuration of boundary controller based on fuzzy logic control depicted above is shown in Figure 4. Where α_{con}, n_{ycon} and ψ_{con} are tolerant boundary values, which are determined by flight control computers according to present flight state of the aircraft.

Substantially, Figure 4 is a kind of nonlinear PID controller. As an aircraft is six-freedom, within height H=4～18km and mach number M=0.6～2.3 flight envelope, we added longitudinal model of an aircraft to the proposed control system and simulated. Large numbers of flight simulation results indicated this new fuzzy control method got good control results.

In the case of pilot pushing or pulling control stick, displacement response curves of servo- mechanism in relation to balance situation are shown in Figure 5 within p=198mmHg. Where curve.1 is ramp response when M=o.8 and curve.2 is when M=1.5.

As seen from Figure 5.A, servomechanism movement can follow stick displacement all the time and trend to stabilization in 3～5 seconds in the case of pushing or pulling stick reposefully at about 2°/s speed. No one in three variables(α, n_y and Ψ) exceeds its tolerant boundary values in 8 seconds.

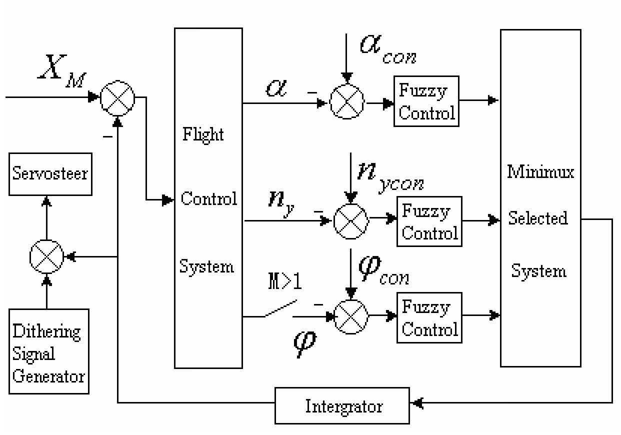
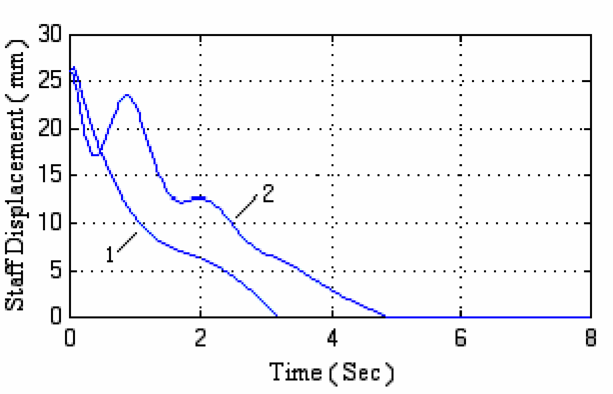
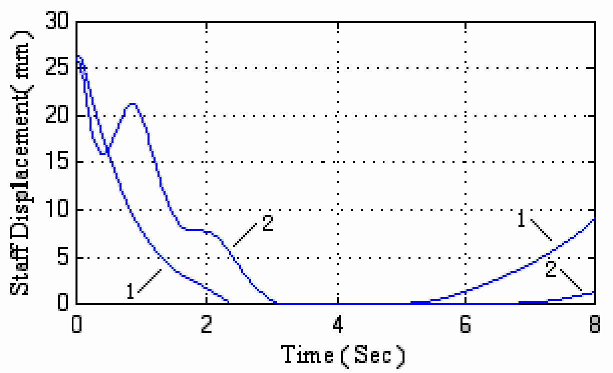


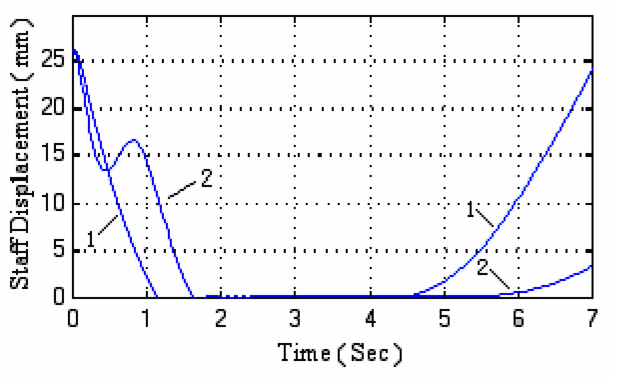
Figure 4. The proposed control system configuration



A. Push or pull stick at the speed of 2°/s



B. Push or pull stick at the speed of 4°/s



C. Push or pull stick at the speed of 6°/s

Figure 5. Servomechanism displacement response curves

In the case of pushing or pulling stick fleetly at about 4°/s speed as shown in Figure 5.B, servomechanism movement can follow stick displacement in initial 2～3 seconds. But the whole control system turns into plus feedback loops at 6th～7th second and soon the aircraft runs into dangerous control state.

In the case of push or pull stick fiercely at about 6°/s speed as shown in Figure 5.C, curve.1 and curve.2 go into unstable state rapidly at 5th second. As known from real-time monitoring, α, n_y and Ψ didn't exceed their tolerant boundary values. Dithering signal generator ran ahead because of intense changes of control variables.

As seen from above analysis, the proposed control system can meet demands of control and have high accuracy.

Simulation results tallied with actual flight. Simulating in other diverse heights and mach numbers, we also got same conclusions.

Ⅳ. CONCLUSION

It is a new research direction how to design boundary controller based on fuzzy logic control within the full flight envelope. Because there is strong nonlinear in dynamic model of an aircraft, it is difficult to use traditional methods to design optimized controller. The simulation and experimental results showed that the proposed controller has obviously simple scheme and high control accuracy. It can be concluded from the study that the proposed controller can also be used as a reference in the development of fuzzy logic controller for other similar control systems.

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