APPLICATION OF THE FUZZY LOGIC CONTROL THEORY TO THE DESIGN OF AIRCRAFT FLIGHT CONTROL SYSTEMS

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Abstract

In this paper, a fuzzy logic based flight control system for a hypersonic transporter is proposed, in order to provide the longitudinal stability in hypersonic region and to improve the responses of the vehicle as well as to make the responses exactly follow the commands. After brief introduction of the flight mechanical characteristics of the hypersonic transporter, the construction of the fuzzy logic controller for the hypersonic transporter is set up, in which angle of attack and pitch rate are chosen as input linguistic variables, and the deflection of elevator is the control variable. 14 fuzzy inference rules, which are designed to model a human operator's behaviours, are employed, and the fuzzy algorithm of *max-min composition* is used as inference mechanism. Performance evaluation of the fuzzy logic controller for the hypersonic transporter is carried out at four flight points, which are chosen from the whole flight envelope. The evaluation includes: 1) responses of the hypersonic transporter with the fuzzy logic controller to initial disturbance of angle of attack in hypersonic region, in which the vehicle without the controller is dynamic unstable, 2) comparison of the fuzzy logic controller with a conventional stability augmentation system and 3) robustness of the fuzzy logic controller to flight condition variation. The calculation results show that the fuzzy logic controller has a good ability to stabilize the vehicle in hypersonic region, and is fairly robust across the flight envelope. The superiority of the fuzzy logic controller to the conventional stability augmentation system is also demonstrated by the results.

Nomenclature

h_n = neutral point of aircraft
δ_e = elevator deflection angle, deg
δ_T = throttle setting
σ_T = thrust vector angle, deg
V = velocity of aircraft center of mass, m/s
α = angle of attack, deg
q = pitch rate, deg/s
θ = pitch angle, deg
μ = membership function
λ = rule modification parameter
Δ = incremental of a variable
Superscription
d = desired values

Introduction

Most research work of flight mechanics on the hypersonic vehicles for advanced space transportation systems focuses on the ascent performance and trajectory optimization[1,2]. However, the hypersonic transporter has some specific characteristics of flight control and stability. Compared with conventional aircraft, the "Sänger-type hypersonic transporter does not possess satisfactory flight mechanical properties in low subsonic region and is dynamic unstable in hypersonic region[3].

Furthermore, the separation flight maneuver takes place in hypersonic region[1], therefore the good characteristics of flight control and stability as well as satisfactory flying qualities will play a crucial role in the separation flight maneuver.

In this paper a fuzzy logic based flight control system for the hypersonic transporter is proposed to provide the longitudinal stability in hypersonic region and to improve the responses of the vehicle as well as to make the responses exactly follow the commands.

The fuzzy set is one of the fundamental concepts for

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fuzzy control and fuzzy system in fuzzy set theory[4,5]. Fuzzy sets are a generalization of the notions of ordinary (crisp) sets. In fuzzy sets qualitative and imprecise information can be allowed to be expressed in an exact way, and human decision making processes to be used to form an automatic control strategies. Thus, a fuzzy model strongly refers to human level of perception of reality, since we deal with the relationships of functions between linguistic labels rather than with numerical quantities. Experience shows that the FLC yields results superior to those obtained by conventional control algorithms. Recently, the value of applying fuzzy logic to the control of mathematically well characterized systems has also been recognized.

In recent years, FLC also begins to attract attention in aeronautical and astronautical fields and several research work has been done[6-10]. The first application of Fuzzy Logic Control Theory to aircraft flight control was made by L.I.Larkin. An autopilot controller based on fuzzy algorithms for the aircraft final approach and landing was developed[6]. A fuzzy logic F/A-18 automatic carrier landing system is developed and the results indicate that fuzzy logic could yield significant benefits for aircraft outer loop control[7]. In Ref. 8 fuzzy logic controllers as stability augmentation systems are investigated to counteract static and dynamic instabilities, while providing satisfactory handling qualities for a modern fighter aircraft. In other research, homing guidance schemes based on fuzzy logic jinking target maneuver and line-of-sight rate measurement corrupted with glint noise[9].

Flight mechanical characteristics of the hypersonic transporter are first presented. The design procedure of the fuzzy logic controller for the hypersonic transporter is then described including determination of linguistic variables and formation of fuzzy inference rules. In the final section the calculation results of responses of the hypersonic transporter with the fuzzy logic controller are presented and discussed. The advantages of the fuzzy logic controller are evaluated through comparison with conventional stability augmentation systems.

Flight Mechanical Characteristics of the Hypersonic Transporter

The research presented in this paper is based on a realistic modelling of a two-stage hypersonic transportation system similar to the German "Sänger" concept. The winged carrier vehicle is equipped with a turbo-/ramjet engine combination, and the orbital stage, which also has a wing, is propelled by a rocket. It has a gross take-of weight of 332 Mg and a dry weight of 141 Mg. The vehicle is 81.34 m long with a span of 41.50 m and area of 1433 m^2. In Ref.1 the elevator deflection angle δ_e, throttle setting δ_T and thrust vector angle σ_T are employed as control variables of the four control systems. Here we use only elevator deflection angle δ_e as the control variable of the following control system. The control limit is

$$-26.2 \text{ deg} \le \delta_e \le 26.2 \text{ deg}$$

In order to investigate the flight mechanical characteristics of the hypersonic transporter, the longitudinal linearized equations of motion for perturbations from a horizontal reference flight condition are employed and may be expressed as

$$\dot{x} = Ax + Bu \tag{1}$$

where the state and control inputs are defined as

$$x = \begin{bmatrix} \Delta V / V_0 \\ \Delta\alpha \\ q \\ \Delta\theta \end{bmatrix} \qquad u = \Delta\delta_e \tag{2}$$

respectively. The Mach numbers and flight attitudes at four representative flight points, which are chosen from the flight profile of "Sänger"-type vehicle for calculations, are listed in Table 1. Flight point 1 represents low subsonic flight condition, and flight conditions from transonic to supersonic are represented by flight point 2. Flight point 3 corresponds to the hypersonic flight, and the separation flight maneuver will take place in the neighbourhood of flight point 4.

Table 1 Flight conditions for calculations

flight points	M (-)	H (km)
1	0.50	6.00
2	1.6	10
3	6.0	26.55
4	6.8	31.00

In Ref. 3, the longitudinal dynamic stabilities of "Sänger"-type hypersonic transporter are investigated in detail. The eigenvalues of the short-period mode at the trimmed points taken from Ref. 3 are listed in Table 2. Examining the distributions of the eigenvalues in Table 2, we note that at low subsonic flight region such as in trimmed point 1 the aircraft is dynamical stable, but the responses to a step-function input in elevator are not appropriate and slow because two eigenvalues of the short-period mode are negative real numbers. This features can be seen in Fig.1.

Table 2 Eigenvalues of the short-period mode

flight points	λ_1 (1/s)	λ_2 (1/s)
1	-1.78 + j0.0	-0.75 + j0.0
2	-2.71+ j2.69	-2.71 - j2.69
3	-1.41 + j0.0	+0.51 + j0.0
4	-1.18 + j0.0	+0.72 + j0.0

As the Mach number increases, at high subsonic up to supersonic region the eigenvalues turn into complex number with negative parts, and the aircraft is dynamical stable. The responses to elevator input shown in Fig. 1 are also good and quick similar to the typical normal aircraft.

At hypersonic region with the increase of the Mach number, the eigenvalues turn into real numbers, and one of the eigenvalues moves to positive axis. Then the aircraft is dynamical unstable. The responses to elevator input are divergent quickly, which is shown in Fig. 1.

The main reason for such dynamic behaviours of the aircraft is the change of the neutral point h_n with the Mach number. In the region of subsonic to transonic, with the increase of the Mach number, the neutral point moves backward. From Mach number 1.2 to 1.4 the neutral point stays unchanged. From Mach number 1.4, with the increase of Mach number, the neutral point moves continuously forward. When Mach number reaches 5.13, the neutral point falls on the center of gravity. The aircraft is neutral static stable. As the Mach number increases further, the aircraft becomes instable.

In order to stabilize the aircraft at the hypersonic region and improve the dynamic behaviours, four forms of stability augmentation systems (SAS) are selected, and syntheses of the control law and evaluation of the control systems are investigated at 13 flight points in the whole flight envelope in Ref. 3.

Fuzzy Logic Controller of the Hypersonic Transporter

The input and output variables of a fuzzy system are called linguistic variables, as they take linguistic values (e.g., large, small and zero, etc.). The first step in developing the fuzzy logic controller of the hypersonic transporter is to determine which variables will be important in choosing an effective control action. The target of the FLC is to provide the longitudinal stability for the hypersonic transporter, which is unstable in hypersonic region, and to improve the responses of the vehicle as well as to make the response exactly follow the command. For these purposes, angle of attack α and pitch rate q are chosen as the input linguistic variables and the control variable is deflection of elevator δ_e. Once the input and control variables have been chosen, the linguistic values (fuzzy sets) that will be used to describe these variables must be defined. Each of the above mentioned three linguistic variables is assumed to take seven linguistic values defined as *Negative Big* (NB), *Negative Medium* (NM), *Negative Small* (NS), *Around Zero* (AZ), *Positive Small* (PS), *Positive Medium* (PM) or *Positive Big* (PB). The membership functions of the seven fuzzy values are explained by their possibility distributions on the universe of discourse from $-h$ to h as shown in Fig. 2. Here h takes value of 20.

The functional block diagram of FLC is illustrated in Fig. 3. FLC is intended to improve dynamic longitudinal stability around the set point or reach the desired angle of attack α^d through the deflection of elevator.

The fuzzy controller is designed to model a human operator's behaviour: No matter how large the pitch rate is, as long as the angle of attack is not close to its set point, relatively large incremental changes in deflection of elevator should be used to quickly drive the angle of attack to its set point. Once the angle of attack comes close to its set point rapidly, the pitch rate will be considered to impose damping and keep the angle of attack α as close to α^d as possible with little or no oscillation. As a result, the FLC is highly nonlinear and time varying.

All of these strategies are combined to form the following control rules which consist of coarse and fine rules. The coarse rules will reduce the angle of attack error with relative large incremental controls. Fine rules are employed to reduce or eliminate oscillations only in regions around the set point. Thus, incremental controls for the fine rules are weighted with suitable weight parameter λ. From a dynamic point of view, the fine rules can be thought of as a fuzzy angle of attack damper.

Coarse rules

If $\bar{\alpha}$ is PB and $\bar{q}$ is arbitrary, **then** $\Delta\bar{\delta}_e$ is PB
If $\bar{\alpha}$ is PM and $\bar{q}$ is arbitrary, **then** $\Delta\bar{\delta}_e$ is PM
If $\bar{\alpha}$ is PS and $\bar{q}$ is arbitrary, **then** $\Delta\bar{\delta}_e$ is PS
If $\bar{\alpha}$ is AZ and $\bar{q}$ is arbitrary, **then** $\Delta\bar{\delta}_e$ is AZ

Fine rules (with suitable weight λ)

If $\bar{\alpha}$ is AZ and $\bar{q}$ is PB, **then** $\Delta\bar{\delta}_e$ is PB
If $\bar{\alpha}$ is AZ and $\bar{q}$ is PM, **then** $\Delta\bar{\delta}_e$ is PM
If $\bar{\alpha}$ is AZ and $\bar{q}$ is PS, **then** $\Delta\bar{\delta}_e$ is PS
If $\bar{\alpha}$ is AZ and $\bar{q}$ is AZ, **then** $\Delta\bar{\delta}_e$ is AZ

where $\bar{\alpha}$, $\bar{q}$ and $\Delta\bar{\delta}_e$ are linguistic variables on the universe discourses and defined as

$$\bar{\alpha} = \frac{\alpha - \alpha^d}{G_\alpha}$$

$$\bar{q} = \frac{q - q^d}{G_q} \qquad (3)$$

$$\Delta\bar{\delta}_e = \frac{\Delta\delta_e}{G_{\delta_e}}$$

The counterparts of the above rules with the negative sign are symmetrical and are not listed. Here G_α, G_q and $G_{\delta e}$ are the scaled factors of the linguistic variables and defined as follows

$$G_\alpha = \begin{cases} \dfrac{\alpha_{max} - \alpha^d}{h} & \alpha \geq \alpha^d \\ -\dfrac{\alpha_{min} - \alpha^d}{h} & \alpha < \alpha^d \end{cases}$$

$$G_q = \begin{cases} \dfrac{q_{max} - q^d}{h} & q \geq q^d \\ -\dfrac{q_{min} - q^d}{h} & q < q^d \end{cases} \qquad (4)$$

$$G_{\delta_e} = \begin{cases} \dfrac{\delta_{e_{max}}}{h} & \delta_e \geq 0 \\ -\dfrac{\delta_{e_{min}}}{h} & \delta_e < 0 \end{cases}$$

The fuzzy inference algorithm can be written as

$$CN_i = \max_{k=1}^{m} \{\lambda_k \cdot \min[\mu_{VA_k}(\bar{\alpha}), \mu_{VQ_k}(\bar{q}), \mu_{VU_k}(i)]\} \qquad (5)$$

$$i = -h, -h+\Delta h, \cdots, -\Delta h, 0, \Delta h, \cdots, h-\Delta h, h$$

where VA(α), VQ(q) and VU(i) are the linguistic values of linguistic variables $\bar{\alpha}$, $\bar{q}$ and $\Delta\bar{\delta}_e$. λ_k is a suitable weight parameter for each rule. [-h, h] represents the universe of discourse for $\Delta\delta_e$. Δh is integral step.The defuzzification strategy can be written as

$$\Delta\delta_e = G_{\delta_e} \frac{\sum_{i=-n}^{n} i \cdot \Delta h \cdot CN_i}{\sum_{i=-n}^{n} CN_i} \qquad (6)$$

where $n = h / \Delta h$

Calculation Results and Discussion

Performance evaluation of the FLC for the hypersonic transporter is carried out using longitudinal models derived from "Sänger"-type hypersonic transporter, which are presented in Appendix. The parameters in (4) are chosen as follows:

α_{max}= 15 deg , α_{min}= -7 deg ,
q_{max}= 40 deg /s , q_{min}= -30 deg /s
$\delta_{e\,max}$= 26 deg , $\delta_{e\,min}$= -20 deg , h = 20

The membership function of the linguistic values for α, q and $\Delta\delta_e$ are shown in Fig.2. The output $\Delta\delta_e$ of the FLC is limited. If the output is smaller than -20 deg, the δ_e will take -20 deg. Similarly if the output is great than 26 deg, the δ_e will take 26 deg. A proportional gain K and a integral gain K_i are introduced in Fig.3. The gain constant K is used to change the amplitude of the FLC output, and the gain constant K_i is employed to eliminate the errors produced during the command follow-up actions.

If the initial values of the state variables ΔV, Δα, and Δθ are set in zeros, and the commands α^d and q^d are given, the command follow-up actions can be simulated. If α^d and q^d take zeros and some initial values of the state variables are not equal to zeros, the responses of the vehicle to initial disturbance can be simulated.

Stability Function of the FLC

Fig.4 shows the responses of the hypersonic transporter with the FLC to initial disturbance of angle of attack at flight point 4, at which the vehicle is dynamic unstable without the FLC. The initial values of state variables and the parameters in the FLC are as follows:

$\Delta\alpha(0) = 4$ deg $\Delta V(0) = q(0) = \Delta\theta(0) = 0$
$\alpha^d = q^d = 0$
$K = 12$ $K_i = 0.002$ $\lambda = 1.5$

The disturbance of angle of attack converges quickly shown in Fig.4 and after about 3 seconds the vehicle goes into a new steady state with greater velocity and smaller pitch angle. The good ability to stabilize the vehicle at hypersonic region is demonstrated by the figure.

Comparison of the FLC with Conventional SAS

In Fig.5 the responses of the vehicle with the FLC at flight point 3 are compared with those of conventional SAS, which is proposed and fully investigated in Ref.3, in order to reveal the advantage of the FLC.

The conventional SAS is a linear proportional feedback control system, in which the feedback variables are angle of attack and pitch rate with gain constant K_α and K_q, the control variable is deflection of elevator.

The commands α^d and q^d as well as the parameters in the FLC and the conventional SAS in Fig.5 are given as follows:

$\alpha^d = 3$ deg $\quad q^d = 0$ deg /s

$K = 12 \quad K_i = 0.002 \quad \lambda = 1.5$

$K_\alpha = -2 \quad K_q = -0.5$ s

Fig.5 shows that the angle of attack α with the FLC reaches the command's value rapidly after 1.2 seconds without oscillation but the conventional SAS takes 4.7 seconds to be settled at the desired state. The excellent performance of the FLC has been displayed by the figure. In the steady state the angle of attack with the FLC drifts off the desired value very slowly, because the desired pitch rate q^d is given as zero.

The changes of the deflection of elevator with angle of attack and pitch rate are displayed in Fig.6, in which K is equal to 1 and λ is 1.5. In this figure we can see that the variation of δ_e with α and q is highly nonlinear. This indicates that the FLC employs a highly nonlinear control strategy. Fig.6 shows that at negative and positive large angle of attack the pitch rate has not effect on the deflection of the elevator, that reflects the features of the fuzzy inference rules. When angle of attack is small, the pitch rate takes action and the variation is nonlinear.

Robustness of the FLC to Flight Condition Variation

Here, we investigate the robustness of the FLC. Specifically, we are concerned with how well the FLC for a given flight condition performs across the flight envelope. For this demonstration, we choose the FLC from flight point 3 and evaluated it at three other flight points 1, 2 and 4. The resulting performance is shown in Fig.7, in which commands α^d is 3 deg and q^d is 0 deg/s at flight points 3 and 4, and q^d is 0.7 and 2.0 deg/s at flight point 1 and 2, respectively. The parameters in the FLC are given as follows:

$K = 12 \quad K_i = 0.002 \quad \lambda = 1.5$

At flight points 1 and 2, the responses of α are slightly different from that at flight point 3. The responses of angle of attack at flight point 4 have a overshoot and oscillations, but the responses are acceptable.

The performance of the FLC at different flight points can be improved through adjustment of the parameter K and K_i. Fig.8 shows the responses of α for the FLC at the four flight points with the adjusted parameters, which are chosen as follows:

$K_i = 0.009$ for point 1 ; 0.02 for point 2 ;
0.002 for point 3 ; 0.0 for point 4

$K = 12$ for points 1, 2, 3 ; 16 for point 4

$\lambda = 1.5 \quad \alpha^d = 3$ deg

$q^d = 0.9$ deg/s for point 1; 1.9 deg/s for point 2;
0.0 deg/s for point 3; -0.1deg/s for point 4

The performance of the FLC at all the four flight points are substantially improved and the responses are identical.

Conclusion

A fuzzy logic based flight control system for a hypersonic transporter is proposed in this paper, in order to provide the longitudinal stability in hypersonic region and to improve the responses of the vehicle as well as to make the responses exactly follow the commands. In the construction of the fuzzy logic controller, angle of attack and pitch rate are chosen as input linguistic variables and the deflection of elevator is the control variable. As the key part of the fuzzy logic controller, the fuzzy inference rules are formed by 14 inference rules, which are designed to model a human operator's behaviours, and then the fuzzy algorithm of *max-min composition* is used as inference mechanism.

Performance evaluation of the fuzzy logic controller for the hypersonic transporter is carried out at four flight points, which are chosen from the whole flight envelope. The results show that the fuzzy logic controller can excellently stabilize the vehicle in hypersonic region. Through the comparison of the fuzzy logic controller with conventional stability augmentation system, the advantage of the fuzzy logic controller is demonstrated. The robustness of the fuzzy logic controller to operate at different flight conditions is investigated, and the results are acceptable. Finally, the better performances and identical responses have been achieved through adjustment of the parameters in the fuzzy logic controller.

Acknowledgments

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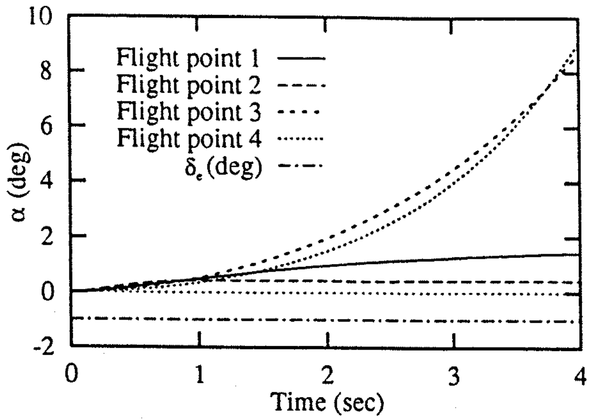

Fig.1 Responses to elevator input without control system

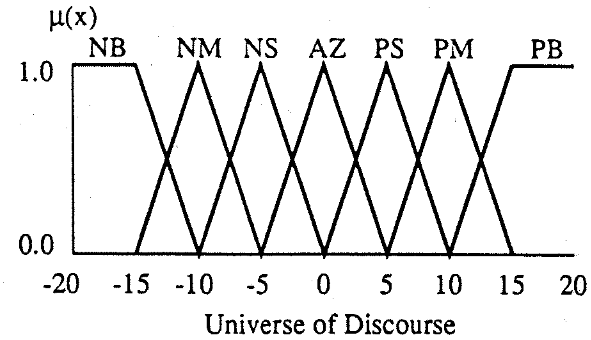

Fig. 2 Membership function of linguistic values for α,q and δ_e

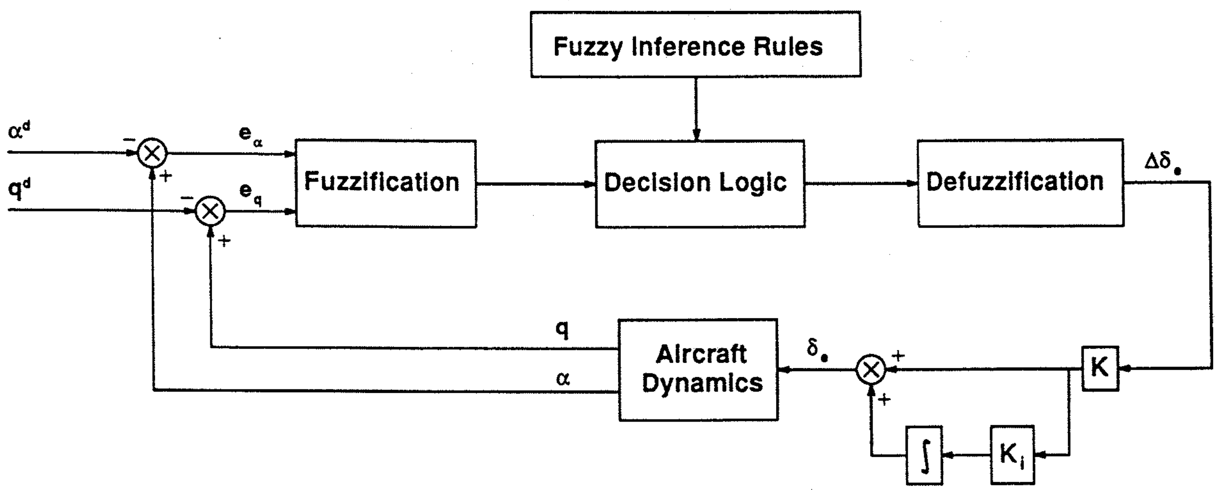

Fig. 3 Functional block diagram of FLC

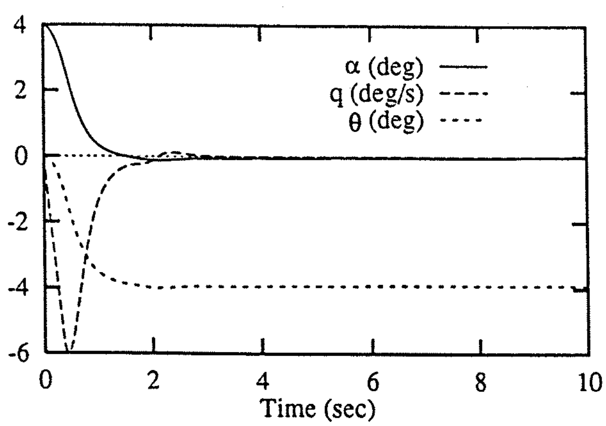

Fig. 4 Responses to initial disturbance with the FLC

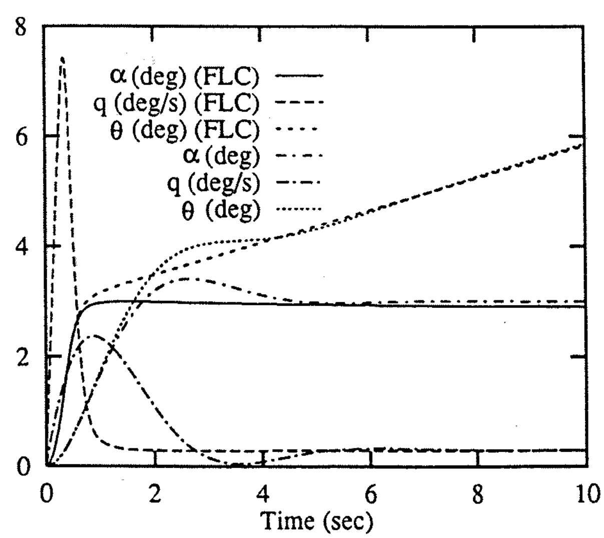

Fig. 5 Comparison of the FLC with the SAS

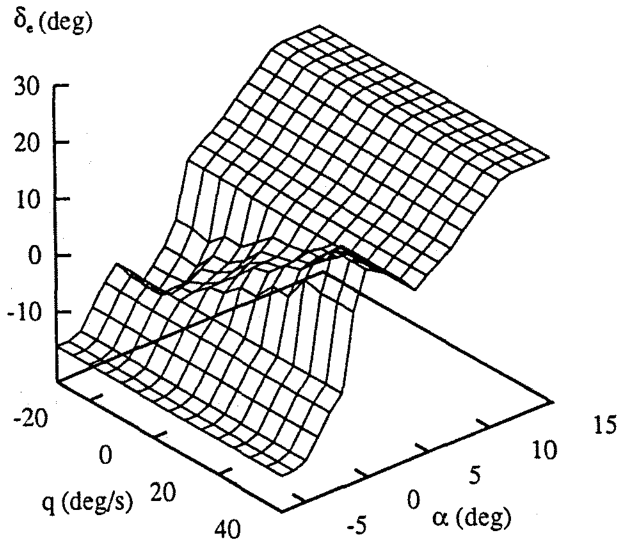

Fig. 6 Change of δ_e with α and q

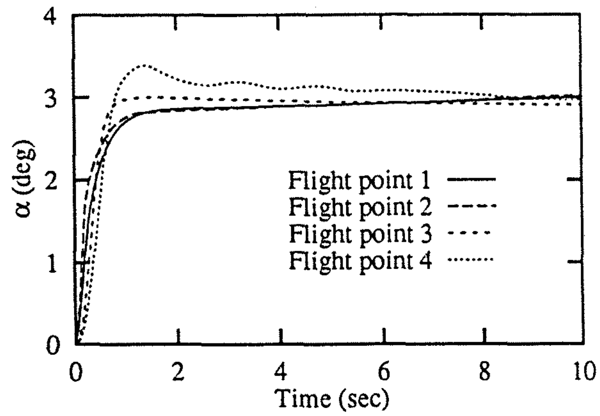

Fig.7 Robustness of the FLC to flight condition change

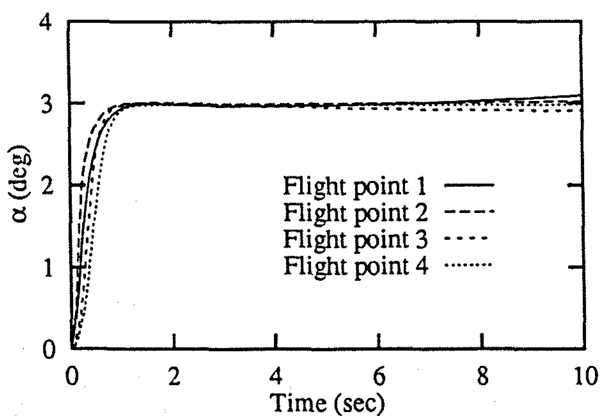

Fig.8 Vehicle responses with adjusted parameters