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FUZZY CONTROL LAW OF HIGHLY MANEUVERABLE HIGH PERFORMANCE AIRCRAFT

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Abstract

A synthesis of fuzzy variable structure control is proposed to design a high-angle-of-attack flight system for a modification version of the F-18 aircraft. The knowledge of the proportional, integral, and derivative control is combined into the fuzzy control that addresses both the highly nonlinear aerodynamic characteristics of elevators and the control limit of thrust vectoring nozzles. A simple gain scheduling method with multi-layered fuzzy rules is adopted to obtain an appropriate blend of elevator and thrust vectoring commands in the wide operating range. Improving the computational efficiency, an accelerated kernel for on-line fuzzy reasoning is also proposed. The resulting control system achieves the good flying quantities during a high-angle-of- attack excursion. Thus the fuzzy logic can afford the control engineer a flexible means of deriving effective control laws in the nonlinear flight regime.

1. INTRODUCTION

High-angle-of-attack flight is now a relatively important issue in the design of flight control systems for maneuvering. Some tactical payoffs of the maneuverability can increase first-shot opportunities owing to the confusion of adversary pilots. Though maneuvers are performed at low speed without imposing undue load factors on the pilot, the rapid rates of motion can be beyond the pilot's control. Thus a closed loop control of high- angle-of-attack flight is required for both the pilot and the aircraft. Designing such a control system is further complicated by highly nonlinear aerodynamics during transient motion with large amplitude. Traditionally, flight control law for low to moderate-angle-of-attack flight regimes has been designed by using gain scheduled linear control methods on linearized models of the aircraft. This approach suffers for maneuvering flight because a lengthy procedure is required to elaborate gain schedule. Other modern robust multivariable control techniques provide an efficient means of developing linear controllers for aircraft when the nonlinearity is not too severe. Purely linear controllers are not able to control maneuverable aircraft effectively, since the rapid change of flight state precludes the use of locally linearized models.

A variable gain scheduling output feedback control has been developed to provide a class of controller that is maneuverable with high performance over a wide operating range. Ostroff's approach [1], using the concept of variable gain, was introduced and applied to the real system of F-18 aircraft. The objective of such an approach is to extend the operating range of the control law over the flight regime while continuing to use established linear control design and analysis techniques. The system equations were constructed as numerous linear models according to flight conditions. Whenever the flight conditions change, the variable gain output feedback is applied. In the other approach proposed by Buffington et al [2], the control law is based on a linear H_∞ design in conjunction with the trim state linearized dynamics and an appropriate nonlinear gain scheduled according to dynamic pressure variations. Two approaches probably represent the good controllers based primarily on linear design methodology in conjunction with somewhat ad-hoc nonlinear corrections. As other approach to improve performance of nonlinear aircraft systems, to reduce the response time of states in maneuvering at high angle of attack, nonlinear control techniques such as adaptive control has been introduced [4]. In this approach, reference trajectory is used as an intermediate step that allows the system to follow the command trajectory under a variety of design criteria. In order to prevent the destabilizing effects of control saturation, an approach to modify the thrust vectoring was introduced when saturation occurs in the elevators.

Recently, neural network as a method of intelligent control has been employed in high-angle-of-attack flight control because of its ability to accurately model nonlinear behavior [6]. The method has shortcoming that the amount of actual data, by onboard flight data recorders or wind-tunnel, are required to train the networks for real time modeling of nonlinear aerodynamic forces.

In such a situation, fuzzy control is a promising tool for high-angle-of- attack flight. In particular, fuzzy approach introduces an intelligent method of allocating thrust vectoring control when aerodynamic control effectors are saturated. Since Mamdani's research [7] was first performed by the motivation of Zadeh's linguistic approach based on fuzzy sets, control engineers have focused on the application of fuzzy logic for practically solving control problems. Basically, fuzzy control uses the linguistic expression of expert's *know-how* to capture the approximate nature of real systems. Therefore the heart of designing fuzzy control is how to achieve smart linguistic rules. However, it is not easy for the lack of systematic design procedures. Concerning fuzzy control, an appropriate reasoning method is necessary to deduce a possible conclusion from a collection of qualitative linguistic premises. The fuzzy variable structure control is proposed to design a closed-loop system of high-angle-of-attack flight and the simplified reasoning method with an accelerated kernel is utilized to accomplish all the computation of fuzzy reasoning. The subsequent sections present the procedure, from design to implementation, for a fuzzy control of high-angle-of-attack flight for a modified version of an F-18 aircraft and the advantages of employing the proposed methodology are discussed.

2. AIRCRAFT MODEL

The aircraft model described in this paper is based on a modified version of the F-18 aircraft. A nonlinear, longitudinal dynamic model of a modified F-18 aircraft with elevators and thrust vectoring nozzles is used for developing a fuzzy control system for high-angle-of-attack flight. The elevators are useful at normal flight conditions, while the thrust vectoring control is useful at high-angle-of-attack flight, low-dynamic-pressure-operating conditions, where the conventional aerodynamic control effectiveness is inadequate. The nonlinearities of both the aerodynamics and the thrust vectoring are preserved in the model. The model was described by four state variables, angle-of-attack alpha (α), total speed (V), pitch rate (q), pitch angle (θ).

The aerodynamic coefficients C_{D_o}, C_{L_o}, C_{m_o} depend on α, V, altitude, and the elevator angle (δ_e). The damping coefficients C_{L_q}, $C_{L_{\dot{\alpha}}}$, C_{m_q}, $C_{m_{\dot{\alpha}}}$ are dependent on α, V, altitude, but not function of δ_e. The mathematical structures of the stability derivative coefficients are based on wind tunnel data. The components of the engine thrust force T are expressed by the thrust vectoring nozzle deflection in the pitch axis δ_v:

$$T_x = T\cos(\delta_v) \tag{1}$$

$$T_z = T\sin(\delta_v) \tag{2}$$

The primary control surface of aircraft is the elevators for longitudinal modes. The model includes actuators of elevators that have position limit, from -24 to 10.5 degreasers. The actuator dynamics is modeled as a first-order lag with time constant 1/30 s. It is the same for the case of vane deflection of the thrust vectoring. But the absolute amplitude of nozzle deflection is limited to 20 degreasers, and its rate is limited at 80 degreasers/s. This saturation results in hard nonlinear models of both δ_e and δ_v.

3. ON-LINE FUZZY REASONING

For the fusion of fuzzy logic and high-angle-of-attack flight technology, on-line reasoning process should be implemented for the fuzzy controller based on non-fuzzy processors of the flight controller unit. Since the control action in a real-time system is determined within a given sampling time, the computation of the reasoning is a considerable task. Therefore, a method of calculus for fuzzy reasoning is proposed to implement fuzzy control for real-time control based on non-fuzzy processors.

3.1 Simplified Fuzzy Reasoning

To explore the fuzzy reasoning, the following fuzzy production rules are typically used:

$$\underset{l=1}{\overset{n\,x\,m}{ALSO}}\left(IF(e(k)\ is\ A_l\ AND\ ec(k))\ is\ B_l, THEN\ \left(u(k) is\ C_l\right)\right) \tag{3}$$

Where $u(k)$ is the control at *k*th discrete time. Error $e(k)$ is the difference between the command value and the output of angle-of-attack, and the rate of change of error at *k*th time is $ec(k)$. The adjectives, A_l, B_l, and C_l are the linguistic attributes of fuzzy set for $e(k)$, $ec(k)$, and $u(k)$, respectively. If the subdivision of phase plane Ω into non-overlapping cells is simply accomplished by choosing a number of n x m of rule points, then each point is labeled by a double suffix (*i, j*) where *i*=1,... n, and *j*=1, ... , m.

At each sampling time, a rule base is directly scanned by the addressing scheme to search a rule that is fired. Then the sets of triples [A_l, B_l, C_l] are selected, which are the nearest points to an arbitrary given state. The form of Cartesian product as defines the space of active cell:

$$\Omega_e = [A_{i-1}, A_i] \times [B_{i-1}, B_i] \times [C_l]$$

Denumerating the given state by the scaling factor, an active index is chosen as an integer number to search the active cell. By scaling factors a_i, the universe of discourse for the error $e(k)$ is scaled into the integer indices $E_i(k)$, where *i*= 1,..., n, as follows:

$$\left(E_1(k), E_2(k),..., E_n(k)\right) = \left(a_1e_1(k), a_2e_2(k),..., a_ne_n(k)\right) \tag{5}$$

A scan algorithm for active indices computes the addresses of the active cell that lies on the given state. First, the anchor point is initialized at the (1,1) location in the rule base. And then, through the comparison of the representative value $e_i(k)$ with an integer index $E_i(k)$ and the given error $e(k)$, the active rule searching is repeated in a column-wise. If the value of $e_i(k)$ which is larger than $e(k)$ has been found, the integer number $E_i(k)$ is set to an active index. The same searching procedure is also used for the rate of change of error $ec(k)$. Thus, a given input pair $[e(k),\ ec(k)]$ is assigned to the corresponding 4 triples as follows:

$$A_{i-1}(k) < e(k) < A_i(k), and\ B_{j-1}(k) < ec(k) < B_j(k) \tag{6}$$

If membership functions in a fuzzy cell were chosen, at the stage of design, to be disjointed at a non-active cell, the fuzzy reasoning can be performed by the dominant local rules on a master cell instead of using the full set of rules. Since the bulk of operation for fuzzification is combined to defuzzification for an executable crisp output, the algebraic product of fulfillment is used for conditional connective *AND*. The parallel firing appears to be well suited for the rule sentence connective *ALSO*. Utilizing the center of gravity method for defuzzification, the resultant form of the fuzzy reasoning is constructed as:

$$u(k) = \sum_{i=1}^{4} C_{id} \cdot \varphi_i(k) \tag{7}$$

Where C_{id} is the defuzzificated value of the membership function C_i that can best represent the linguistic description [11], and the fuzzy shape function $\varphi_i(k)$ is defined as follows.

$$\varphi_i(k) = \frac{w_i(k)}{\sum_{i=1}^{4} w_i(k)} \tag{8}$$

The weighting factor of firing strength in the *ith* production rule, $w_i(k)$, is computed by the product of the membership values in the *ith* rule's premise as:

$$w_i(k) = A_i^m(e(k)) \,.\, B_i^m(ec(k)) \tag{9}$$

All the procedure of a simplified reasoning with fuzzy accelerated kernel is well illuminated in Fig. 4.

4. FUZZY VARIABLE STRUCTURE CONTROL

In this section, a fuzzy variable structure control is proposed to design a high performance controller for a high-angle-of-attack flight system. In an effort to make the design of the fuzzy rule base easier, the fuzzy variable structure control is modularized into three fuzzy counterparts, which are duplicated from the knowledge of PID control, sliding control, and gain scheduling, respectively.

4.1. Fuzzy Counterpart of PID Control

In design of a fuzzy controller, two major drawbacks come up lengthy tuning effort of fuzzy rule-base and the lack of objectivity. In order to alleviate the drawbacks, the know-how of mathematical control technology is connected to the systematic design method of fuzzy control. Despite the advent of many sophisticated control techniques, the simple PID control algorithm can handle the majority of feedback loops in practical systems very well.

$$u_{pid}(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt} \tag{10}$$

Where $u_{pid}(t)$ is the control variable, and e is the control error which is the difference between reference input command α_c and measured output value α. The control variable is a sum of three terms, which has the proportional gain K_p to the error, the integral gain K_i to the integral of error, and the derivative gain K_d to the derivative of error, respectively. A simple tuning method based on step response data can be applied for the three PID gains. Of course, the PID control is often insufficient to obtain the desirable transient response, because the tuning method is based on the information of only a point in Nyquist curve. However, the tuning by Ziegler-Nichols method is widely used to get implicit crude estimate of plant dynamics experimentally. It is, thus, a natural consequence that a combination of a fuzzy logic and a popular PID control has been introduced to bypass explicit mathematical modeling. From a control designer's view, it would be helpful to have an implicit model in which the rule base can be tuned simply by using the knowledge of the PID control. The developed idea behind these types of controllers is to combine the ability of fuzzy PID control. A fuzzy counterpart of the PID controller is constructed by the parallel connection of velocity form in (11) and position form in (12) as follows:

$$\Delta u_{FPI}(k) = FLC_{PI}[e(k),\ ec(k)] \tag{11}$$

$$\Delta u_{FPD}(k) = FLC_{PD}[e(k),\ ec(k)] \tag{12}$$

Where FLC denotes the fuzzy control with the rule base and membership functions. The rate of change of e is denoted by ec, and the control of the velocity form is denoted by $\Delta u_{FPI}(k)$. If the PID control form is discretized by both backward difference method for differentiation and Euler method for integration, scaling factors of the fuzzy PID controller shown in Fig. 2 can be directly determined. Thus the summation of $u_{FPD}(k)$ and the integration of $\Delta u_{FPI}(k)$ obtain the control of the fuzzy PID controller:

$$u_{FPD}(z) = \left(C_{pd} + T\frac{C_{pi}}{z-1} \right) \text{x} \left(\frac{1-z^{-1}}{T\,ecf} + \frac{1}{ef} \right) e(z) \tag{13}$$

Comparing (10) and (13) in z-domain, coefficients are related as follows:

$$K_p + \frac{K_d}{T} = \frac{C_{pd}}{ef} + \frac{C_{pd}}{ecf} \tag{14}$$

$$K_p - K_i T + 2\frac{K_d}{T} = \frac{C_{pd}}{ef} + 2\frac{C_{pd}}{T\,ecf} - T\frac{C_{pi}}{ef} - \frac{C_{pi}}{ecf} \tag{15}$$

$$\frac{K_d}{T} = \frac{C_{pd}}{T\,ef} - \frac{C_{pi}}{ecf} \tag{16}$$

Where C_{pd} and C_{pi} denote output scaling factors of position form and velocity form, respectively. The terms ef and ecf denote input scaling factors of error and error rate, respectively, and T is sampling time interval. It is effective that these 4 coefficients are iteratively searched by considering the three equations above. Since the designed fuzzy controller is analogy of the conventional PID controller, it becomes quasi-linear controller that can adjust the gain in the desired subregion of phase plane. Therefore the knowledge of PID control can be a metarule that provides a systematic construction of a fuzzy rule base.

5. NONLINEAR SIMULATION

A nonlinear longitudinal modeling shown in section 2 is used to design a high-angle-of-attack flight controller. Under a nominal flight condition at an altitude of 4,500 m and a speed of around 0.3 Mach, the proposed controller was simulated and compared with the results of previous applied controllers such as an adaptive controller. Two control inputs with the scheduled thrust magnitude, elevator angle and thrust vectoring angle, are generated from the control calculation. The practical aspects considered in the design procedure are the transition between the flight modes, the incorporation of trim conditions in the nonlinear simulation, and a dead-band nonlinearly in the thrust vectoring angle. The effective thrust vectoring for dead band is estimated as a function of nozzle area, and added to thrust vectoring command. Longitudinal stick step inputs are used to demonstrate performance of the fuzzy variable structure controller during nonlinear simulations at low-angle-of-attack of 5 degrees, maximum lift of 35 degrees and high-angle-of-attack of 60 degrees conditions. Initial trims are chosen as angle-of-attack of 5 degrees, pitch rate of 0 degrees/s, pitch angle of 6.3 degrees, and total speed of 135 m/s. -0.8 degrees, 0 degrees, and 80KN give elevator angle, thrust vector angle, and magnitude of thrust, respectively.

In order to check for the tracking performance of a high-angle-of-attack flight, the proposed controller is simulated under the flight scenario illustrated in Fig. 3 that considers pitch-up, pitch-down command. Therefore, the scenario is devised for the nonlinear simulation of transitional modes with a rapidly changing flight command. The resulting angle-of-attack response shows that the proposed controller is to be comparable for the prescribed design goals. Fig. 4 and 5 illustrate that, at low dynamic pressure conditions, the thrust vectoring nozzles are more dominant control effectors than elevators. The characteristics of the response are similar to that of variable gain feedback control method reported by Ostroff [1]. The angle-of-attack of the variable gain approach reached 55 degrees in just under 3.5 seconds and settling time to 60 degrees took about 6 seconds In one-step ahead prediction controller, the angle-of attack reached 55 degrees in 2.1 second and settling time to 60 degrees took 3 seconds [4]. The time optimal control with a limitation of 40 degrees per second on the thrust vectoring reached 55 degrees in 1.8 seconds [12]. On the other hand, the angle of attack of the proposed controller starts at 5 degrees trim and reaches 55 degrees in less than 1.8 seconds, then slightly settles the initial command of 60 degrees in 2.0 seconds. Comparing to the previously applied control methods, a considerable reduction of reaching time is obtained by the proposed controller. From the results, it is presented clearly that the fuzzy variable structure control is suitable for the control of high angle of attack flight. It shows that the proposed method can provide the adaptability for abruptly changing flight condition, in the wide operating range, through the effective utilization of the redundant effectors.

6. CONCLUSIONS

A fuzzy variable structure control method with multi-layered fuzzy rules is proposed in this paper to design a high angle of attack flight controller for a maneuverable version of a F-18 aircraft. With a basic idea of incorporating fuzzy logic in PID control, the proposed design methodology can improve the performance. The fuzzy counterpart of PID control is effective to the design of initial rule base by tuning without linear mathematical models of system. Moreover, multi-layered fuzzy rules offer an adaptive scheme for addressing the redundant effectors in transitional flight modes. The simulation results show that this controller can be utilized effectively to control high performance aircraft such as a modified F-18 aircraft for rapid maneuvers with large changes in angle of attack.

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Table 1 Scaling Factor of Fuzzy Set

Adjective	NB	NM	NS	ZE NBs ZEs PBs	PS	PM	PB
A	-60	-35	-10	0	10	35	60
B	-60	-25	-5	0	5	25	60
C	-1	-0.66	-0.33	0 -1.5 0 1.5	0.33	0.66	1

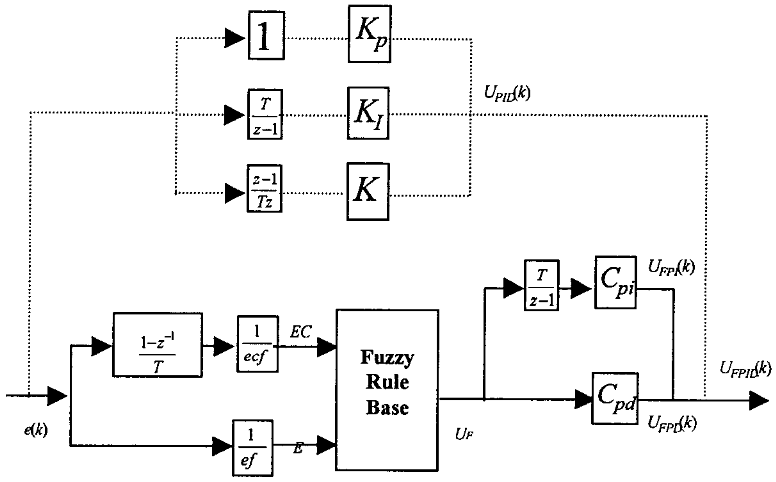

Fig 2 Analogy of Fuzzy PID Control

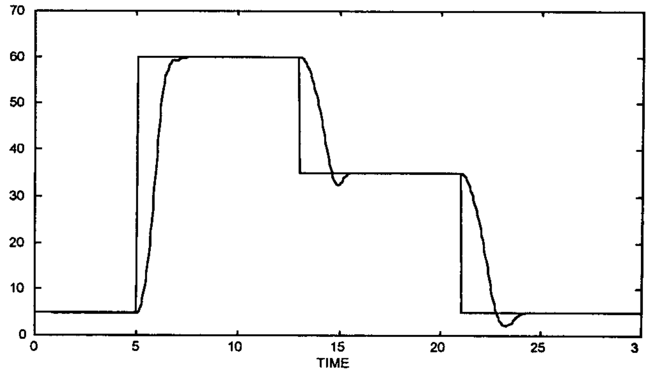

Fig 3 Angle of Attack

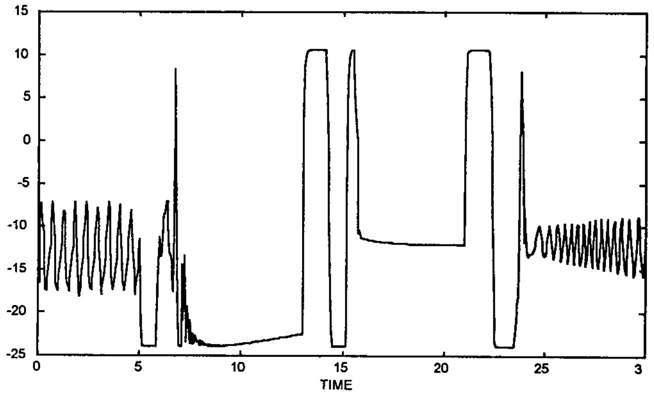

Fig. 4 Elevator Angle

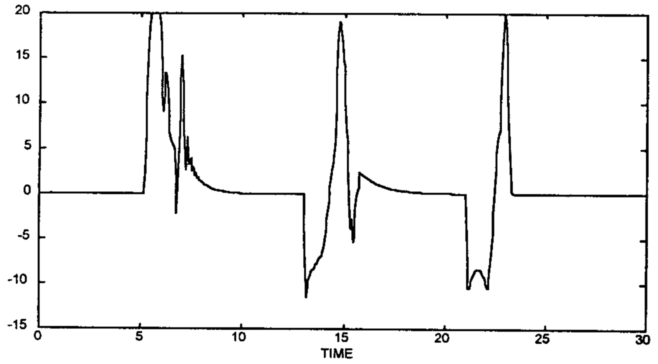

Fig. 5 Thrust Vector Angle