FUZZY CONTROL FOR ROLL AGILITY

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Abstract

To improve the roll agility of aircraft, whose lateral responses usually become sluggish under high AOAs and low dynamic pressures, or even a sharp lateral command motion of which may diverge partly due to degradation of the linear lateral flight controller, a fuzzy logic controller (FLC) was tried out in this paper. In the FLC the control rules are analytically expressed, and the optimization technique is then applied for the rule parameters and scaling factors. By comparisons of numerically simulated reponses between with the linear and fuzzy controller to 90 degree bank angle capture and 70 degree bank to bank command maneuvers under various flight conditions, it appears that fuzzy control can arouse the agile potentiality of aircraft within wider flight ranges and is more robust. In addition, the control law around zero error should be carefully designed, especially when precise control needed.

I. Introduction

These years a lot of efforts have been dedicated to the evaluation and enhancement of the within-visual-range air combat ability of fighters. For roll agility the most widely used metric is the minimum time to capture a 90 degree bank angle change (T_{RC90}) while holding a prescribed angle of attack[2]. Calculation results show, however, that T_{RC90} is usually much longer when performing a loaded roll at higher AOAs and lower dynamic pressures (see Fig.1)[3]. Even worse, it was reported that during rapid bank to bank command maneuvers the lateral motion itself might diverge[6].

On the other hand, simulation graphs demonstrate that the sluggishness or divergence in roll are partly due to degradation of the lateral flight controller, which works according to traditional linear control laws (see the dashed lines in Fig.4 of this paper and Fig.7.19 of Ref.6). In other words, it is possible to strengthen lateral agility by improving the controller. An natural approach is to scheme the control gains according to flight conditions. Nevertheless, an important consideration will lead to other ideas. That is, the limitations of linear design of control laws stick out with the enlargement of the flight envelope of aircraft, and investigation on nonlinear methods are getting even more necessary.

Since the publishing of L.A.Zadeh's papers on fuzzy sets theory and E.H. Mamdani's pioneering research on fuzzy control, the fuzzy logic controller (FLC) has been widely used in many industial fields[4,5]. Thus, a roll FLC was tried out in this paper to improve the agility of aircraft.

II. Design of Roll FLC

The controller is constructed as in Fig.2, including roll rate error and error variation as inputs, and incremental

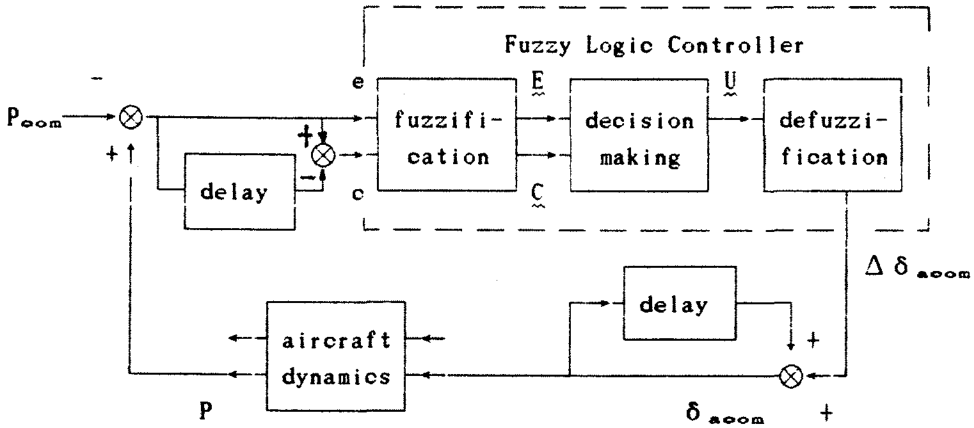

Fig.2 Roll FLC Constructure

command of the aileron deflection as its output. It is virtually a fuzzy PI controller, in which the error signal plays a role of integration, trying to drive the system to accurately follow a roll command, and the error variation a role of roll damper.

To exert appropriate aileron deflections, three stages will be passed through: fuzzification, decision making and defuzzification.

Fuzzification

Fuzzification is to map a definite input into a suitable fuzzy set within the universe of discourse, usually into a fuzzy singleton. Here the universe is quantized to 41 levels from -20 to 20. The fuzzification stage can be expressed as:

$$\begin{aligned} SUPP_{E(nT)} &= INT\,[e(nT)/G_P] \\ SUPP_{C(nT)} &= INT\,[c(nT)/G_{\Delta P}] \qquad (1) \\ e(nT) &= P(nT)-P_{com}(nT) \\ c(nT) &= e(nT)-e(nT-T) \end{aligned}$$

where, SUPP means the support (crisp) of a fuzzy set, and INT means quantization of a real number to the nearest integer.

Decision Making

This stage is executed based on approximate reasoning of linguistic variables. For the inputs $\underset{\sim}{E}$, $\underset{\sim}{C}$ and output $\underset{\sim}{U}$, seven linguistic values are defined, termed NB (Negative Big)$\triangleq$-3, NM(Negative Medium)$\triangleq$-2, NS (Negative Small)$\triangleq$-1, AZ (Around Zero)$\triangleq$0, PS (Positive Small)$\triangleq$1, PM (Positive Medium)$\triangleq$2, and PB (Positive Big)$\triangleq$3. See Fig.3 for their membership functions.

It is a common way to express control rules in the following form:

IF...AND..., THEN ..., ELSE
⋮
IF...AND..., THEN...

To automatically produce suitable rules, they are analytically expressed here. When $\underset{\sim}{E}$ is $\pm i$, $i=0,\dots,3$,

$$\underset{\sim}{U} = INT\,[\,a_i\underset{\sim}{E}+(1-a_i)\underset{\sim}{C}\,],\quad a_i \in [0,1] \qquad (2)$$

Because the inputs are fuzzified into singletons, the approximate reasoning process can be simpified as max-min composition algorithm. Suppose the inputs are fuzzified to the ith and jth level singletons $\underset{\sim}{E}^*$ and $\underset{\sim}{C}^*$, the output fuzzy value $\underset{\sim}{U}^*$ can be inferred from the control rules to be

$$\mu_{\underset{\sim}{U}^*}(k) = \max_{m,n=-3}^{3} \min \cdot \{ \mu_{\underset{\sim}{E}_m}(i),\ \mu_{\underset{\sim}{C}_n}(j),\ \mu_{\underset{\sim}{U}_w}(k) \} \quad (3)$$

where, $k=-20,-19,\ldots,20$, and w is determined from the rule "IF $\underset{\sim}{E}$ is $\underset{\sim}{E}_m$ ($\triangleq m$) AND $\underset{\sim}{C}$ is $\underset{\sim}{C}_n$ ($\triangleq n$), THEN $\underset{\sim}{U}$ IS $\underset{\sim}{U}_w$ ($\triangleq w$)" .

Defuzzification

In this stage the fuzzy output $\underset{\sim}{U}^*$ is mapped into a deterministic incremental control command $\Delta\delta_{acom}$ by the center-of-gravity algorithm.

$$\Delta\delta_{acom} = G_{\delta a} \frac{\sum_{k=-20}^{20} \mu_{\underset{\sim}{U}^*}(k)\cdot k}{\sum_{k=-20}^{20} \mu_{\underset{\sim}{U}^*}(k)} \quad (4)$$

Parameters Choosing

Once the controller constructure , universes of discourse, linguistic values and their membership functions are settled as above, the rest problem is how to choose appropriate a_0, a_1, a_2,a_3 in Eq.(2) for control rules and the scaling factors G_P, $G_{\Delta P}$ and $G_{\delta a}$. Optimization techniques are useful for it.

The objective function is given as:

$$J = \sum_{n=0}^{n_{max}} \left| e(nT) \right| \cdot T \quad (5)$$

and the so-called "Flexible Tolerance Polyhedron" method[8] is then employed.

Theoretically, all the above parameters can be taken as optimized variables. If so, it will be pretty time comsuming and seems to be unnecessary.

After separate optimizations, trade-off among under various conditions, and overall adjustments, they are chosen as:

$$a_0 = .5,\ a_1 = .5,\ a_2 = .7,\ a_3 = .8,$$

$$G_P = \frac{160}{20}\text{deg/sec},\ G_{\Delta P} = \frac{4}{20}\text{deg/sec},$$

$$G_{\delta a} = \frac{160T}{20}\text{ deg},$$

where, the sampling interval T = .02 sec. The control rules can be listed as in Table I.

$\underset{\sim}{E}$ \ $\underset{\sim}{C}$ ($\underset{\sim}{U}$)	-3	-2	-1	0	1	2	3
-3	-3	-3	-3	-3	-2	-2	-2
-2	-3	-2	-2	-2	-1	-1	-1
-1	-2	-2	-1	-1	0	1	1
0	-2	-1	-1	0	1	1	2
1	-1	-1	0	1	1	2	2
2	1	1	1	2	2	2	3
3	2	2	2	3	3	3	3

Table I. Control Rules in the Roll FLC

Ⅲ. Simulation Verification

Two maneuvers , 90 degree bank angle capture and 70 degree bank to bank, were simulated with the original linear PI roll controller and the fuzzy PI roll controller under different flight conditions (Fig.4,5). It can be seen from the 90 degree bank capture that the linear controller is not inferior to the fuzzy one under higher dynamic pressures and less normal load factors (or lower AOAs) (Fig.4 a,b), but when rolling at lower pressures or loaded (Fig.4 c,d), the FLC appears to be much more agile, T_{RC90} being about 1 second less. It is further proved in the bank to bank of Fig.5. Notice that in such a frequently commanded maneuver and under large dynamic pressures, the FLC seems to be undesirably sensitive. Anyway, the FLC appears to be suitable for a wider flight range. From another point of view, it will also be more robust from discrepances between design and real flight data, or measure errors.

IV. Conclusions

From the preliminary roll FLC in this paper, some characteristics of fuzzy control can be summed up as follows.

1. The FLC appears to be adaptable to a relatively wide flight range, and may tolerate discrepances between design and real flight data within a great extent.

2. Although there are no conventional guidelines for designing a FLC, once the control rules are analytically expressed, optimization techniques can be employed to guide suitable rules and scaling factors, and a trade-off procedure and repeated adjustments are also necessary.

3. Fuzzy control is discontinuous and essentially nonlinear, so that aircraft pilots may be unaccustomed. In addition, the control law around zero error should be designed more carefully for fear of small oscillations around the final state, especially when precise control needed.

After all, fuzzy control is relatively a newcomer, and worth investigating for current and future aircraft. Its potential use may extend to stall and post stall ranges, and it can be combined with other relative methods such as artificial neural networks to achieve preferable effect.

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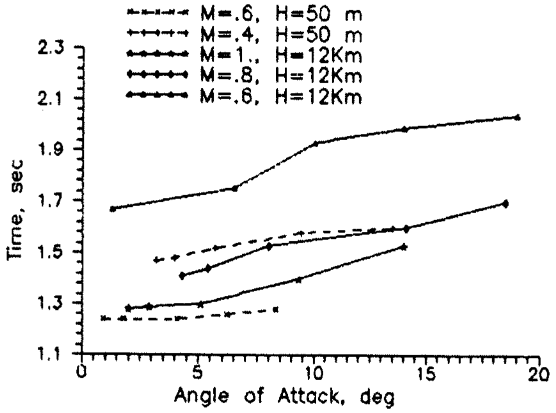
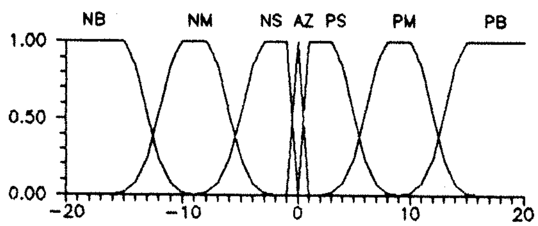
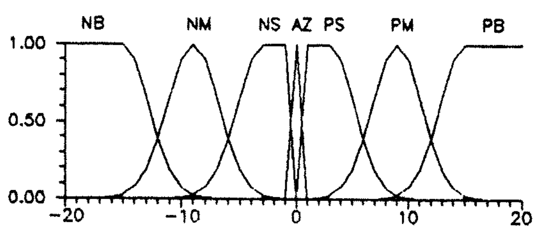


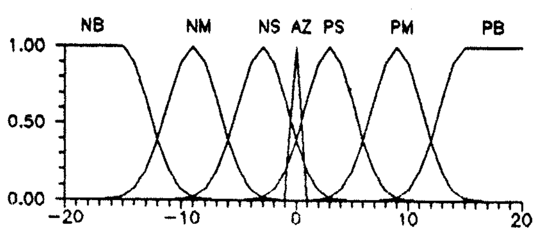
Fig.1 Time to Capture 90deg Bank Angle



(a) for error linguistic values

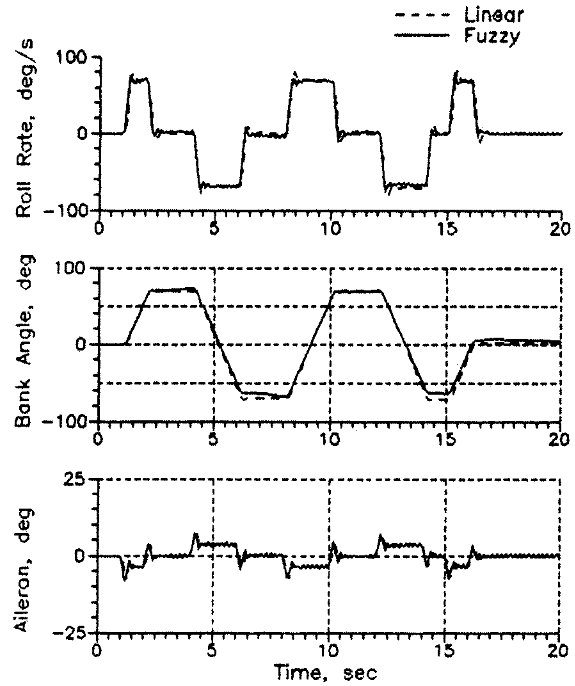


(b) for error rate linguistic values

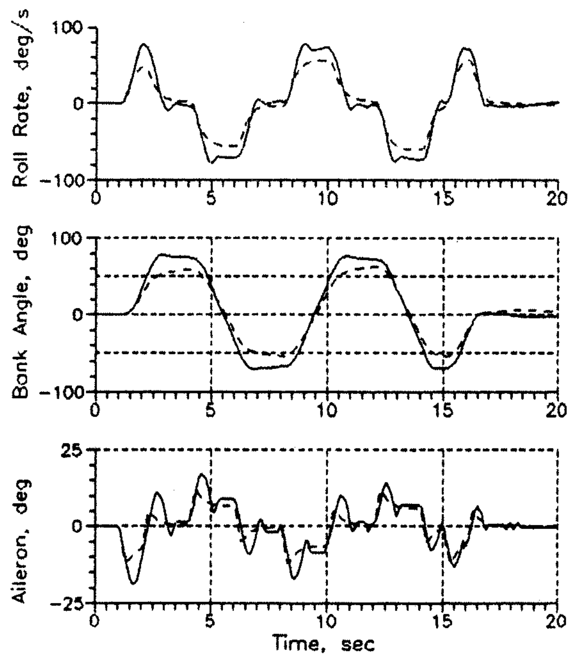


(c) for output linguistic values

Fig.3 Membership Functions in Roll FLC

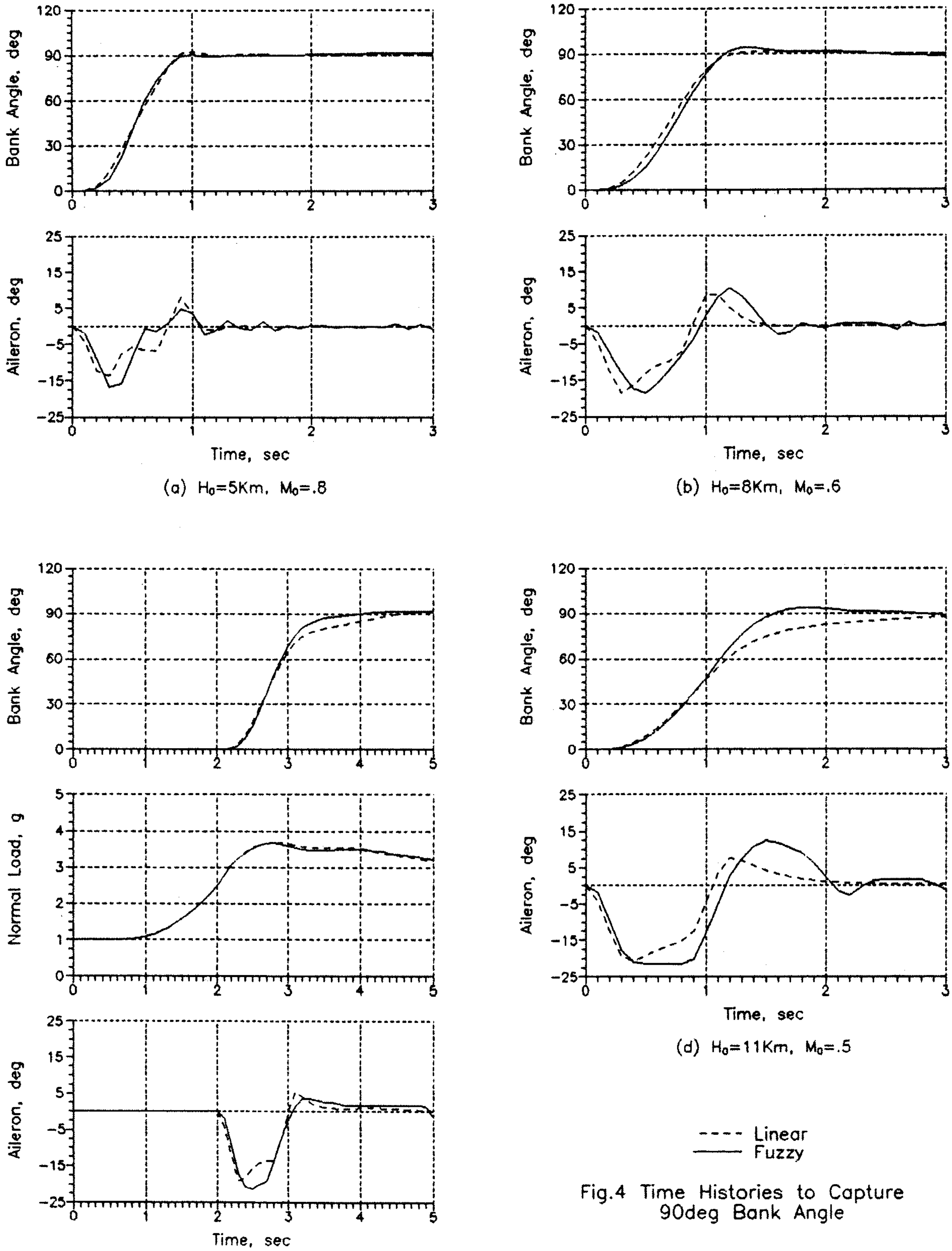


(a) H_0=5Km, M_0=.8



(b) H_0=11Km, M_0=.5

Fig.5 Responses to 70deg Bank to Bank Command



(a) H_0=5Km, M_0=.8

(b) H_0=8Km, M_0=.6

(c) H_0=8Km, M_0=.6, loaded

(d) H_0=11Km, M_0=.5

Fig.4 Time Histories to Capture 90deg Bank Angle