Aircraft Dutch Roll Control by Fuzzy Logic Controller

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Abstract- The main aim of this paper is designing fuzzy control law for stabilizing aircraft dutch roll motion characteristics and its control performance was evaluated. The control law was designed for a large transport aircraft at low altitudes and low speed flight conditions. The control law was then applied to high altitudes and high speed flight conditions. The control performance for these conditions was evaluated. The evaluation showed good control performance to stabilize the dutch roll motion characteristics under all flight conditions for large transport aircraft. This means that the fuzzy control proved to provide effective flexible application to aircraft stability augmentation

Keywords – Fuzzy control, Aircraft Stability Augmentation, Dutch roll

I. INTRODUCTION

An example of the practical application of fuzzy control to the control system for aircraft in use seems to be unavailable. The control law for a stability augmentation system for an aircraft was designed by fuzzy control, and the resulting control performance was examined. Because fuzzy control laws do not presuppose the strict mathematical model of the control object, it is expected to be able to flexibly handle the change of the characteristics of the control object. First, the control law to improve the dutch roll characteristics of a large transport aircraft at low altitude and low speed flight conditions was designed. This same control law, without modifications, was later applied to high speed and high altitudes flight conditions. The resulting control performance was evaluated. Moreover, turbulence to the aircraft needs to be considered, and it has characteristics that fluctuate; they can be big and small and can vary. The control law should be effective for these conditions. Therefore, measures for that were planned and the effectiveness was studied.

Symbol
β: Sideslip angle (deg)
φ: Bank angle (deg)
p: Roll rate (deg/sec)
r: Yaw rate (deg/sec)
δa: Aileron deflection angle (deg)
δr: Rudder deflection angle (deg)

II. AIRCRAFT USED AS TEST MODEL

The model of a large transport aircraft were chosen as the control objects. The large transport aircraft model is a model (hereafter called DC-8) prepared based on the data of the DC-8 model which is described in Ref. 1. Concerning dimension, mass data, and aerodynamic data at subsonic speed and transonic speed, the values described in Ref. 1 were used. Concerning the equation of motion for the aircraft, which is the control object, lateral and directional 3 degrees of freedom equation of motion in body axis was made in the form of the state equation shown below.

$$x = Ax + Bu$$
$$y = Cx$$
$$\mathbf{x} = [\beta\ \varphi\ p\ r]^{T} \quad \boldsymbol{u} = [\delta a\ \delta r]^{T} \quad \boldsymbol{y} = [\beta\ p\ r]^{T}$$

Here,

x: State variable vector
u: Input vector
y: Output vector
A: Matrix of 4 column 4 row
B: Matrix of 4 column 2 row
C: Matrix of 3 column 4 row

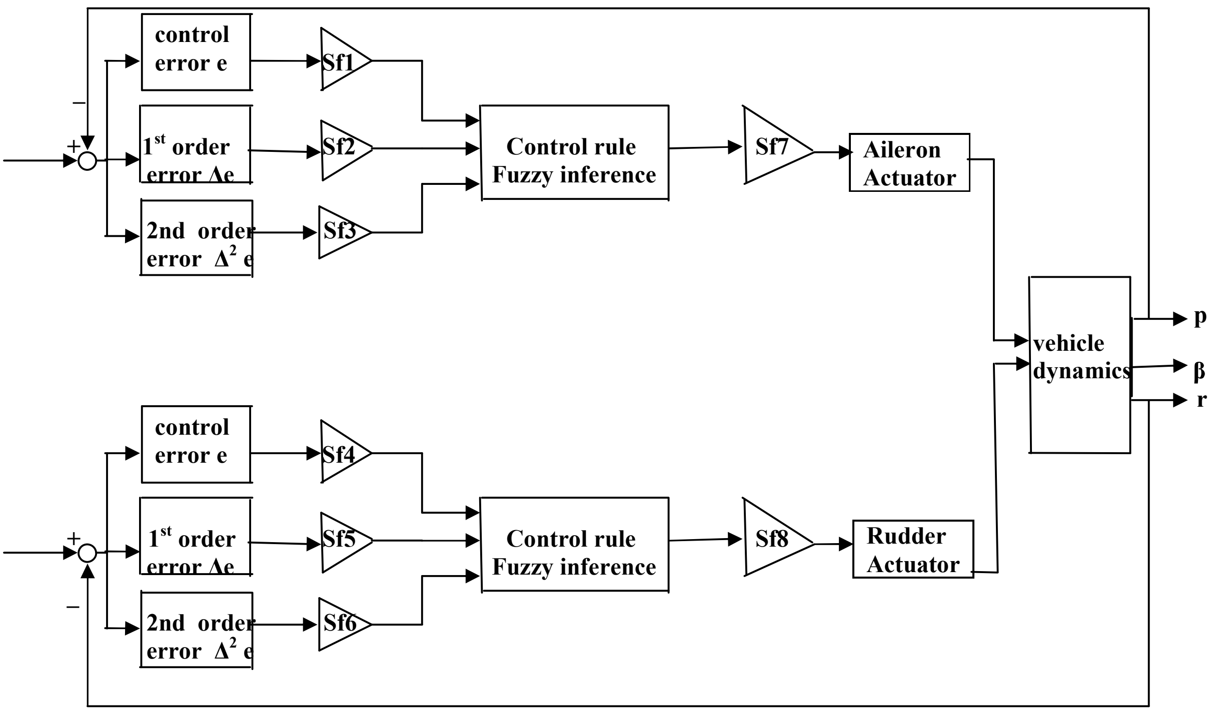

Fig. 1. Block diagram of Fuzzy control law for stability augmentation system

III. FLIGHT CONDITIONS

The flight conditions to examine the dutch roll characteristics are shown in the 5 cases in Table 1 for the DC-8 large transport aircraft. For the DC-8 aircraft, flight condition 1 is at minimum speed at sea level, flight condition 2 is at low speed at 6100 feet altitude, flight condition 5 is at transonic speed at 35,000 feet altitude. These flight conditions cover from low altitude to high altitude and from low speed to high speed. As for the transport aircraft, because the cruising is the main flight condition, flight conditions of cruising at 20,000 feet and 40,000 feet altitudes were chosen. Dutch roll characteristics for flight condition for DC-8 models are described in Tables 1.

Flight condition	**1**	**2**	**3**	**4**	**5**
Altitude (ft)	sea level	6100	6100	12200	35000
Mach number	0.198	0.5	0.5	0.8	2.00
Angle of attack (deg)	8.5	6.8	0	4.6	-0.9
Period of dutch roll (sec)	3.06	2.51	2.10	2.07	1.02
Damping factor of dutch roll	0.196	0.038	0.160	0.096	0.087

Table 1. Flight conditions of DC-8 large transport aircraft.

IV. DESIGN OF THE CONTROL LAW FOR THE STABILITY AUGMENTATION SYSTEM

4.1. Input and output

When the fuzzy control is applied to the control law for the stability augmentation system, it is necessary to decide the input to the fuzzy inference part. Because its purpose is to improve the dutch roll characteristics during this time, the roll rate p and yaw rate r are used for the inputs. Based on a 1/60 second sampling time, control error 'e', first order difference 'Δe' and second order difference '$\Delta^2 e$' for one sampling time interval are chosen as the input elements. Figure 1 shows a block diagram of control law for stability augmentation system. To quickly attenuate the oscillation caused by the dutch roll, roll rate p is fed back and is input to the fuzzy inference part; the output of the fuzzy inference part is used as a deflection command to control aileron; the yaw rate r is fed back and is input to the fuzzy inference part; the output of the fuzzy inference part is used as a deflection command to control the rudder. Two fuzzy inference parts in Fig. 1 are the same ones, and the content of this is described in 4.2–4.4. SF1–SF8 in Fig. 1 are scaling factors. The purpose of which is to set the balance and ranges of three inputs and to convert the inference result into an appropriately scaled control deflection command.

4.2. Setting of antecedent and consequent parts

First, the part that corresponds to the antecedent part of the "if-then" form, which is the feature of the fuzzy control, that is, the part that corresponds to "if" is set up as follows. control error 'e 'is if input is positive (P: Positive), if input is zero (Z: Zero), if input is negative (N: Negative), The above 3 kinds of variables (fuzzy label) are set up as antecedent part variables. A similar subdivision is done to first order difference 'Δe' and second order difference '$\Delta^2 e$'. Membership functions of these three variables are as shown in Fig. 2(a). The horizontal axis of this figure is the input to the fuzzy infeence part shown as a value of control error 'e', first order difference 'Δe', or second order difference '$\Delta^2 e$' multiplied by scaling factor (SF). Next, the consequent part, that is, the part of "then", is defined. This is an output variable that is output based on the antecedent part. The output of the fuzzy inference part is obtained by using this output variable. This output multiplied by the scaling factor gives aileron and rudder deflection command. Output variables that are result of inference are subdivided to seven items as shown below and set as fuzzy labels in the consequent part. Positive Big (hereafter PB) (output variable = 1) Positive Medium (hereafter PM) (output variable = 2⁄3) Positive Small (hereafter PS) (output variable = 1⁄3) Zero (hereafter ZE) (output variable = 0) Negative Small (hereafter NS) (output variable= −1⁄3) Negative Medium (hereafter NM) (output variable =−2⁄3) Negative Big (hereafter NB) (output variable= −1).

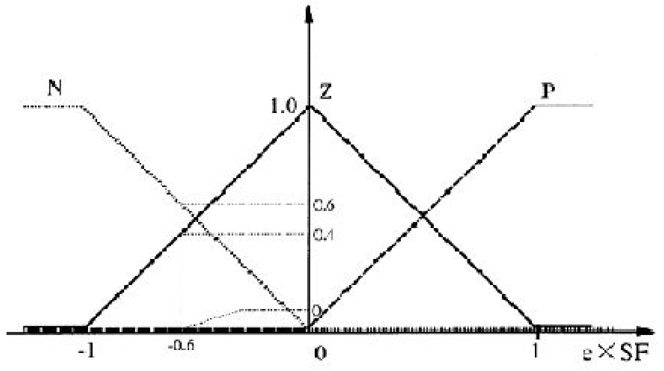

Figure 2(a) control error membership function

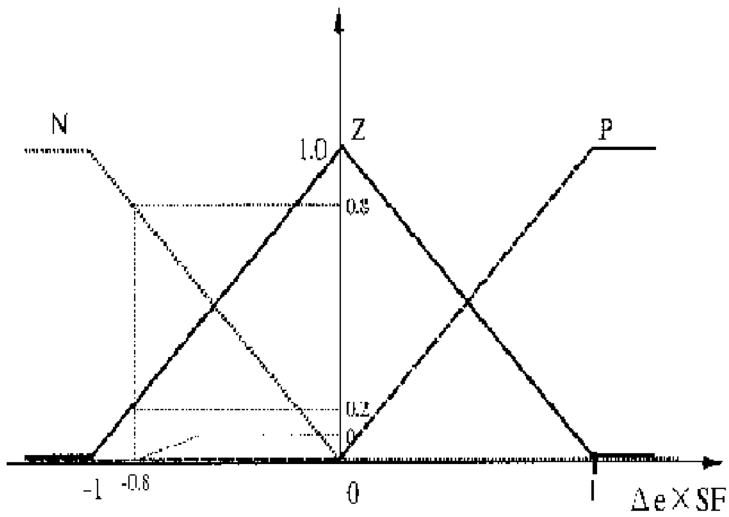

Figure 2(b) first order error membership function

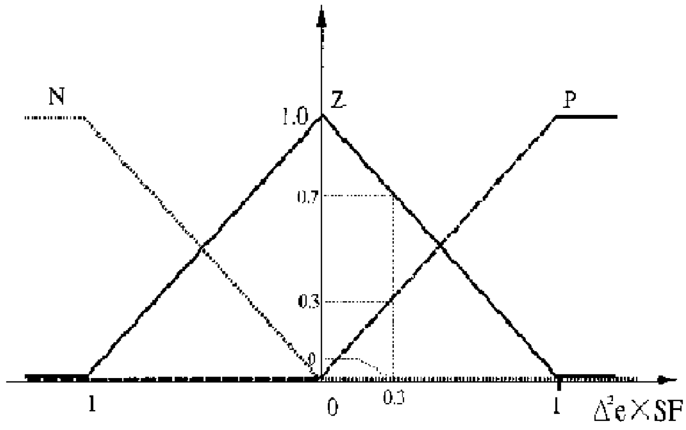

Figure 2(c) second order error membership function

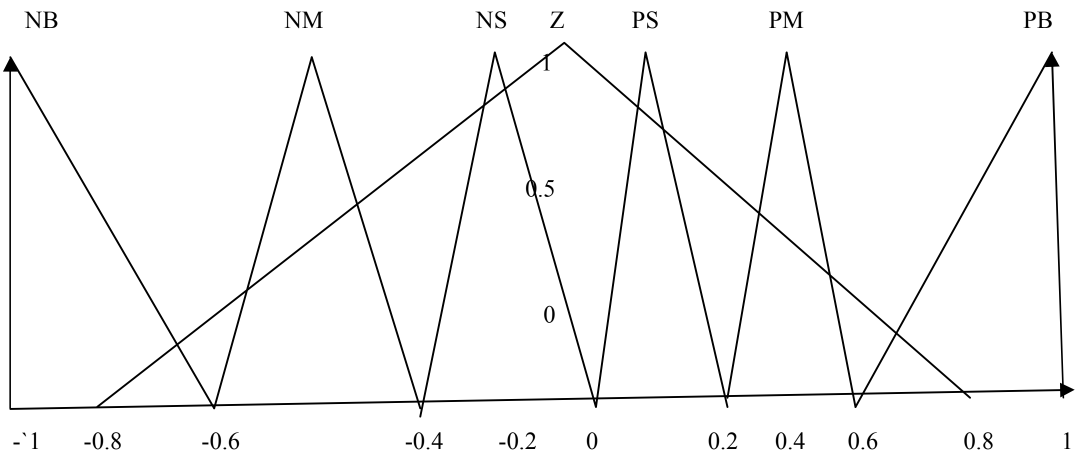

Figure 2(d) output membership function

e is N	$\Delta^2 e$			
		N	Z	P
Δe	N	NB	NB	NM
	Z	NB	NM	NS
	P	NM	NS	ZE

e is Z	$\Delta^2 e$			
		N	Z	P
Δe	N	NM	NS	ZE
	Z	NS	ZE	PS
	P	ZE	PS	PM

e is P	$\Delta^2 e$			
		N	Z	P
Δe	N	ZE	PS	PM
	Z	PS	PM	PB
	P	PM	PB	PB

Fig. 3. Organized fuzzy control rule.

4.3. Fuzzy inference part control rule

Correspondence of fuzzy label (P, Z, N) of the antecedent part variable control error '*e*', first order difference 'Δe', second order difference '$\Delta^2 e$' , and seven fuzzy labels of the output variable, which is a consequent part variable, were composed as the fuzzy control rule as shown in Fig. 3.

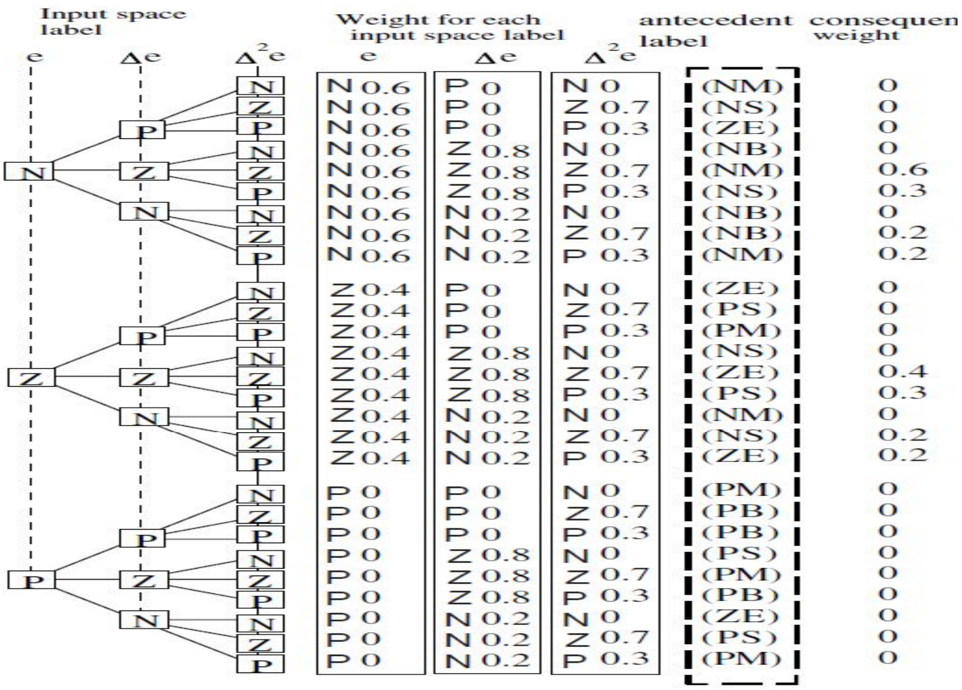

Fig. 4. Result of fuzzy inference

4.4. Process of fuzzy inference

According to the membership function in Fig. 2(a), the weight of P (Positive), Z (Zero), and N (Negative) is obtained from the value of control error '*e*', first order difference 'Δe', and _second order difference '$\Delta^2 e$', which are multiplied by a scaling factor (SF). Although the value of '*e*', 'Δe' and '$\Delta^2 e$' changes as a function of time, the procedure of the fuzzy inference is described in the following example by combining the value of *e*, 'Δe', and '$\Delta^2 e$'. For instance, if e×SF is −0.6, the weight of N is 0.6, the weight of Z is 0.4, and the weight of P is 0, as shown in Fig. 2(b). If Δe×SF is −0.8, the weight of N is 0.8, the weight of Z is 0.2, and the weight of P is 0, as shown in Fig. 2(c). If _2*e* × SF is 0.3, the weight of N is 0, the weight of Z is 0.7, and the weight of P is 0.3, as shown in Fig. 2(d).

A minimum value of the weight of N, Z, and P of each control error '*e*',first order difference'Δe', and _second order difference '$\Delta^2 e$' is set as consequent's weight, as shown in Fig. 4. After the weight of 27 kinds of control rules are obtained, they are added at each consequent label; then the entire center of gravity position is calculated as shown in Fig. 5. This center of gravity position is an output of the fuzzy inference part; it is multiplied by the scaling factor and the control deflection command is obtained. The aileron deflection command and the rudder deflection command are independently calculated as shown in Fig. 1.

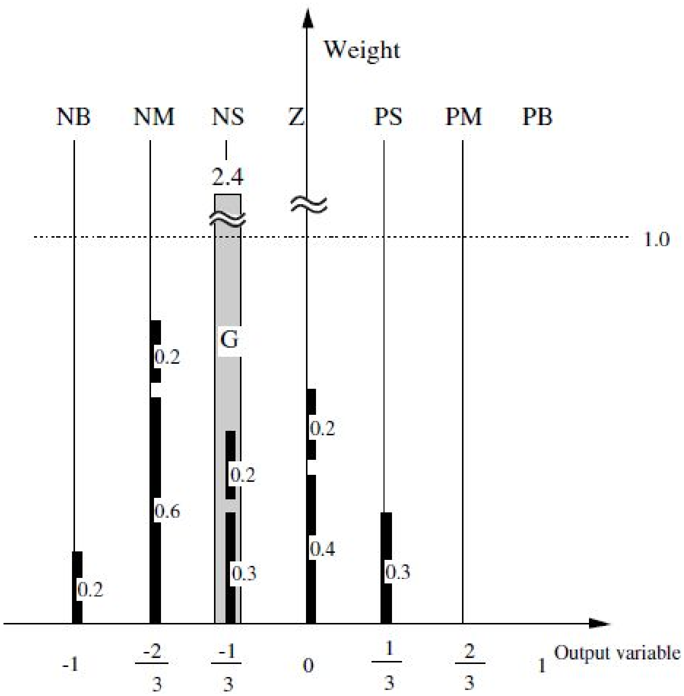

Fig. 5. Computation of center of gravity position.

4.5. Setting of scaling factor
To improve the dutch roll characteristics of the DC-8 high-speed aircraft of flight condition 2 in Table 1, the scaling factor has been adjusted. First of all, from SF1 to SF6 they have been adjusted so that each input to the inference part is settled within the range from −1 to 1 and does not become too small. Next, SF7 and SF8 have been adjusted to obtain excellent control performance. Later, to adjust the balance of three inputs to improve the control performance, SF1 to SF6 have been slightly adjusted

V. CONTROL PERFORMANCE

5.1. Control performance in different flight conditions
Because the fuzzy control law does not presuppose the strict mathematical model of the control object, it is expected to be able to flexibly manage the change in the characteristics of the control object. So the control performance was examined for the flight conditions set in chapter 3 for low altitude and high altitude and from low speed to high speed. The simulation with the same rudder doublet control deflection input was done to flight conditions 1, 3, 4, and 5 of Table 1. The same scaling factors, which are adjusted to improve the dutch roll characteristics of DC-8 high speed aircraft's flight condition 2, were applied. This means that the fuzzy logic controller proved to provide effective flexible application to aircraft stability augmentation.

5.2 Simulation Results
The simulation results show the stabilization of sideslip angle, roll rate and yaw rate which are characteristics of dutch roll which are shown in figure 6.

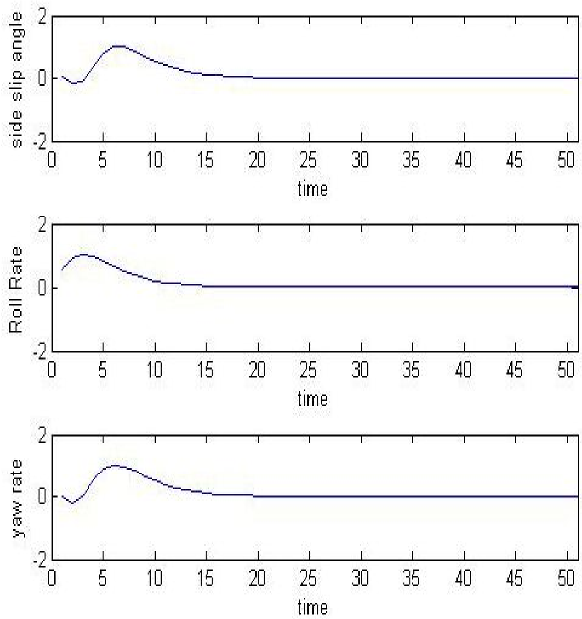

Figure 6. Simulation results

VI.CONCLUSION

The fuzzy logic controller was designed for a DC-8 jet transport aircraft at mach number 0.84 and altitude 12,200 feet and at mach number 2.00 and attitude 35000 feet flight conditions .The control performance for these flight conditions was evaluated. The evaluation showed good control performance to stabilize the dutch roll characteristics. It has been demonstrated that the fuzzy control exhibits flexibility which has sufficient capability when applied to the control law of the stability augmentation system of the DC 8 jet transport aircraft. Simulations show the controller adequately follows the desired output.

VII.FUTURE WORK

The dutch roll damping can be made by using fuzzy logic controller with extended the scale of degree. The fuzzy logic controller should be implemented to a hardware package incorporated onboard the aircraft.

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