FUZZY LOGIC CONTROL OF A HIGH BYPASS TURBOFAN ENGINE

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استخدام منطق التحكم اللفظي للتحكم في المحرك النفاث المروحي

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الملخص

في هذا البحث تم تطبيق المنطق اللفظي للتحكم في المحرك النفاث المروحي التفاضلي و المتحكم التناسبي التكاملي في هذا الصدد. حيث تم ضبط معاملات كل من المتحكمين للحصول على أداء مناسب أثناء المرحلتين الانتقالية و الثابتة (المستقرة) بحيث لا تتعدى قيود المحرك. و قد استخدم النموذج الخطى لتطبيق التحكم اللفظي على حالتين من حالات التشغيل , أحدهما هي حالة الطيران المستقر , و الأخرى حالة الجسوء على سطح الأرض. و قد تم محاكاة المتحكم مع النموذج الخطى للمحرك أثناء حالتى الطيران السابقتين و تبين أن المتحكم التناسبي التكاملي يعطى نتائج أفضل.

ABSTRACT

Fuzzy logic control is applied to a high bypass turbofan engine (CF6). Both PI and PD controllers are applied. Each controller is adjusted to obtain suitable steady state and transient performance without exceeding the engine physical limitations. The controllers are designed based on the engine linear models. The controller derived for either model was checked for the other model, in order to verify that the controller for different operating conditions. Simulation results for a combined ramp and step inputs are presented. It was found that the PI fuzzy controller is more suitable for the engine.

1. INTRODUCTION

The first jet-propelled aircraft provide thrust modulation using rudimentary governor regulation. As engine/airframe system requirements broadened, aircraft turbine engines have increased in complexity and the engine cycles are even more complex. The trend

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toward more complex engines incorporating many variable geometry components (variable fan and compressor stator vanes, variable turbine nozzle area, and variable jet nozzle area) introduces an additional degree of freedom to meet the aircraft requirements with minimum cost and maximum safety. Mission, airframe, and engine requirements are combined to generate prioritized control criteria which may differ in details according to the propulsion system application. These criteria can be outlined as (1) engine protection (temperatures, pressures, and speed limits), (2) engine stability (engine fluctuations and surge margins), (3) steady state performance and accuracy, and (4) transient requirements. Simply, the controller function is to provide the correct steady state and transient performance without exceeding design limits (excessive heating, compressor surge, and flame shutoff). Therefore, engine must be controlled over its entire operating range. Early classical control techniques in which each control loop is evaluated individually were suited for old and simple engines. However, such techniques are cumbersome and time consuming when applied to variable cycle type of engines[1]. The variable geometry engines are modeled as multi input multi output (MIMO) systems. Linear control theory (pole placement, linear quadratic control, ...) was used to control the engine around certain steady-state operating point (rim control) [2-3]. The controller feedback gains produced from some important points on the flight envelope are then scheduled to control the engine over of its whole operating range. For nonlinear engine models, with gain scheduling linear control, the operation of the engine may be not safe, because of exceeding the operating limits. Thus, the acceleration and deceleration schedules are used together with feedback gain schedule[4]. In this paper, fuzzy logic control is applied to some operating conditions of the engine.

Fuzzy control is a very active area of fuzzy logic application. Mamdani and his students [8] applied fuzzy control to a steam engine. Many researches and applications were carried out on different processes like vehicles, aircrafts, spacecrafts, robots ...etc. It was found that fuzzy control can work well for ill defined systems in which a mathematical model can not be obtained. It also give good performance and it is more robust.

The paper is organized as follows. In section 2, engine description and its linear dynamic model is presented. Fuzzy control is discussed in section 3 showing the operations carried on it and how it can manipulate the linguistic variables. Also, the analogy between famous classical controllers (PI and PD) and the corresponding fuzzy ones is declared. In section 4, simulations are carried out for different engine models. Final conclusions are found in section 5.

2. ENGINE LINEAR DYNAMIC MODEL

The model used is a high bypass (design bypass ratio of about 5) separate flow turbofan engine (CF6). It consists of fan, low and high pressure compressors, combustor, low and high pressure turbines, and cold and hot nozzles. The air passes through the fan and then divides into two streams, a hot stream that passes through the engine core and finally expands through the hot nozzle, and a cold stream which is ducted (bypassed) around the compressor and turbine sections and then expands through the cold nozzle. Both the fan and low pressure compressor is driven by the low pressure turbine while the high pressure turbine drives the high pressure compressor, as shown in Fig. 1.

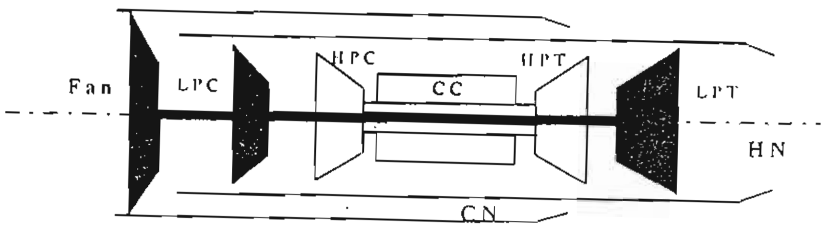

Fig. 1 Diagrammatic sketch of the CF6 turbofan engine

The engine nonlinear dynamic model comprises the component intervolumes where there are accumulations of mass and energy, and rotor inertia of the two spools. The engine components themselves are considered as static elements, consequently the engine components steady state characteristic maps are considered herein. Since the frequency of the intervolumes is high in nature, their response can be ignored. Hence the rotor inertia has the dominant effect on the engine dynamics. Based on the principle of conservation of angular momentum, the excess power between turbine and compressor can be expressed as

$$P_{ex} = I\omega(d\omega / dt) \tag{1}$$

Substituting $\omega = 2\pi N / 60$ in equation 1, yields

$$N^{\cdot} = P_{ex} / (JN) \tag{2}$$

where $J = (2\pi / 60)^2 I$.

Equation 2 can be linearized as

$$\Delta N^{\cdot} = \Delta P_{ex} / (JN) \tag{3}$$

The excess power P_{ex} is a function of the engine thermodynamic states which are in turn functions of the spool speeds. Equation 3 is applied to the engine two spools. In state space form, the model characteristics and output equations are :

$$\dot{X} = AX + BU \tag{4}$$

$$Y = CX + DU \tag{5}$$

where A,B,C, and D are obtained from the engine steady running point. The state vector $X = [\Delta N_h \quad \Delta N_l]^T$, the output vector $Y = [\Delta N_h \quad \Delta N_l \quad \Delta T_6 \quad \Delta P_6]^T$, and the control input U is the change in fuel flow rate. Numerical values of the matrices A, B, C, and D, are obtained at 100% corrected core engine speed and for two flight conditions. The first is the sea level static condition (take off) while the other is the cruise condition, altitude of 10670 m, and 0.85 flight Mach number.

At takeoff (sea level)

$$A = \begin{bmatrix} -3.015 & -0.747 \\ 0.58 & -15.05 \end{bmatrix},\ B = \begin{bmatrix} 5907 \\ 3608 \end{bmatrix},\ C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0.0308 & 0.1146 \\ 625.5 & 2252.8 \end{bmatrix},\ D = \begin{bmatrix} 0 \\ 0 \\ 191.8 \\ 0 \end{bmatrix}$$

At cruise condition, 10770 m altitude and 0.85 Mach number

$$A = \begin{bmatrix} -1.1864 & -0.3191 \\ 0.2325 & -6 \end{bmatrix},\ B = \begin{bmatrix} 6490 \\ 3953 \end{bmatrix},\ C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0.0289 & 0.1082 \\ 252 & 906 \end{bmatrix},\ D = \begin{bmatrix} 0 \\ 0 \\ 487.8 \\ 0 \end{bmatrix}$$

3. DESIGN OF THE FUZZY CONTROLLER

3.1 FLC Configuration

The basic FLC configuration, shown in Fig.2, comprises four main principal components Fuzzification, Knowledge Base, Decision Making Logic and Defuzzification.

3.2 Discretization / Normalization of Universe of Discourse

Usually the measured input data is transformed into a normalized universe of discourse (usually [-L , L]) using the mapping function :

$$x_i^n = F\,(G_{xi} * x_i) \tag{6}$$

where G_{xi} is the i-th input scaling factor. The mapping function F may be linear or nonlinear.

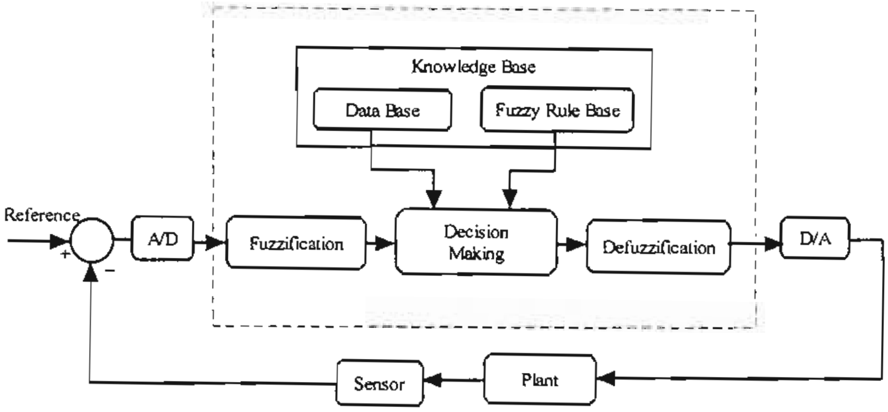

Fig. 2 Configuration of the FLC

3.3 Scaling Factors

If the range of discourse is normalized to the range of [-L, L] then the scaling factors are determined from

$$G_E = \frac{L}{E_{max}},\ G_{CE} = \frac{L}{CE_{max}} \text{ and } G_U = \frac{L}{U_{max}} \tag{7}$$

These factors requires the knowledge of maximum values of E and CE which are not available all the time. U_{max} is determined from the maximum allowable control action restricted by the available power. Performance is highly affected by these scaling factors.

3.4 Fuzzification

The crisp values are converted into fuzzy values. The shape and number of membership functions are considered part of this process. The membership functions was taken as triangular functions as shown in Fig.3.

3.5 Decision Making

This part perform two tasks, generating rules and inferring the output from this rules. Fuzzy control rules are usually in the form of conditional statements of the form :

If <(antecedent)> Then <(consequent)>

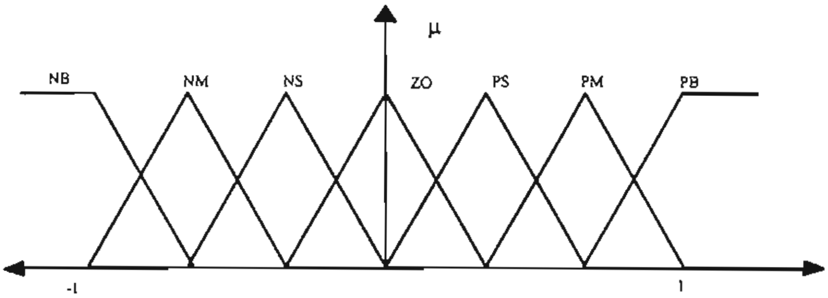

Fig. 3 Membership function for fuzzy variables (E, CE and U)

These rules are easy to implement by fuzzy conditional statements in fuzzy logic. The complete rule matrix can be generated as shown in Table 1

Table 1 Classical PD Fuzzy controller Rule Matrix

DE

	U	NB	NM	NS	ZO	PS	PM	PB
	NB	NB	NB	NB	NM	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NM	NM	NS	ZO	PS	PM
E	ZO	NB	NS	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PM	PB	PB	PB

The fuzzy addition property can be used to generate the PD fuzzy controller rules by considering that the control action is the sum of the error and change of error with scaling factors k_p and k_d. This method can be used to generate the rules of the three term controller (PID). By inference we mean obtaining the controller output fuzzy set from the controller input and the control rules by the compositional rule of inference. The two main operators defined before are the max-min (Zadeh) and the max-product, Fig.4, and Fig.5.

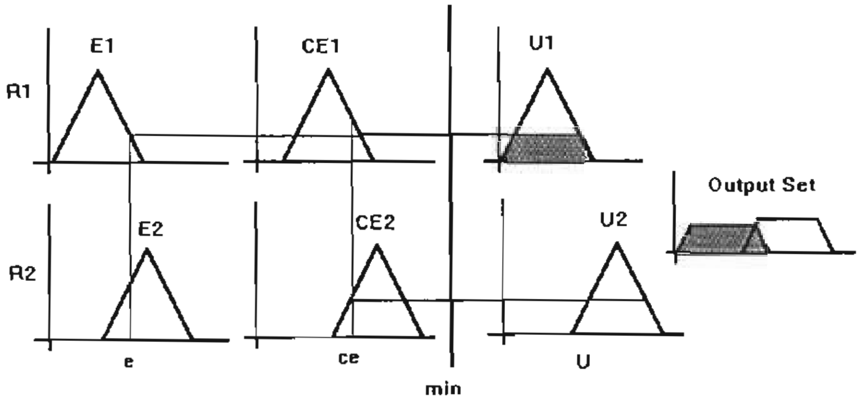

Fig. 4 Graphical interpretation for rule by rule fuzzy decision making using min. fuzzy implication

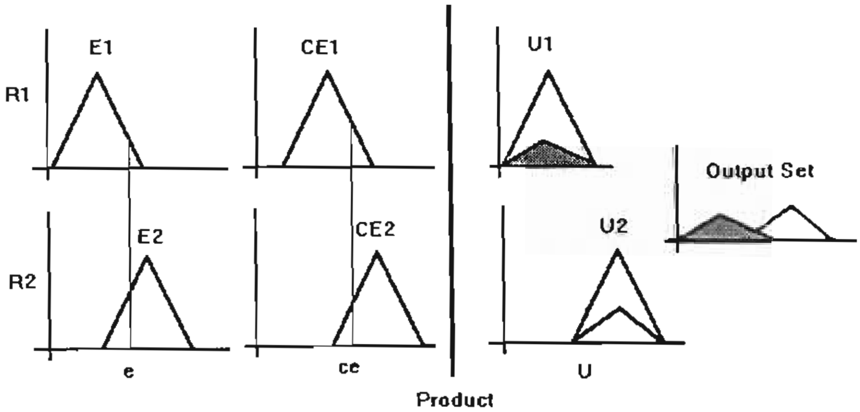

Fig. 5 Graphical interpretation for rule by rule fuzzy decision making using product fuzzy implication

3.6 Defuzzification

It is the process by which the fuzzy output from the decision making part is converted to crisp values suitable for the physical situation. There are three commonly used strategies for defuzzification, the max. method, mean of maximum (MOM), and center of area method (COA), Fig. 6.

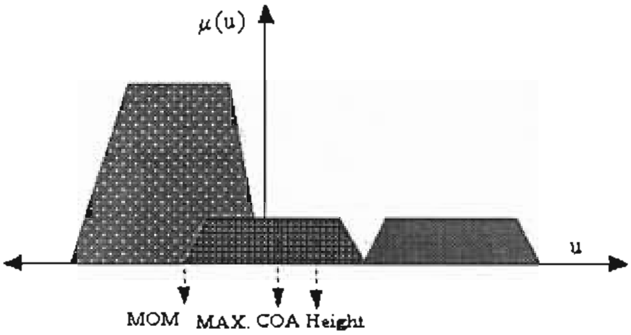

Fig. 6 Defuzzification Methods

3.7 FLC Algorithm

Without loss of generality we consider the PD FLC in which the controller inputs are the error *(E)* and error derivative *(CE)* [CE = E(k) - E(k-1)], and the controller output is the process input *(U)*.

The control rules takes the form :

If E is E_i and CE is CE_i then U is U_i

where E_i, CE_i, U_i are linguistic terms of error, change in error and process input, respectively. Then, the scaling factors that scale the real universe of discourse into the normalized universe are **Ge, Gce, Gu,** where :

$$E_n = F_m(E * Ge),$$

$$CE_n = F_m(CE * Gce) \tag{8}$$

F_m is the mapping function that is usually linear or nonlinear logarithmic.

$$U_n = U * Gu; \tag{9}$$

The control action in the linear controller shown in Fig. 7, is taken as :

$$u = G_u(G_e * e + G_{ce} * ce) \tag{10}$$

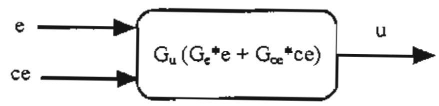

Fig. 7 PD-FLC model

which is similar to the classical PD controller, (u = Kp * e + Kd *ce) except that the fuzzy PD control action has a limit that is physically true.

For PI controllers, the output from the classical PD controller is given by :

$$u = k_p e + k_d \dot{e} \qquad (11)$$

integration of the above relation gives :

$$\int u\,dt = kp \int e\,dt + k_d e \qquad (12)$$

which is a PI controller. We can then use the PD controller as a PI and considering the output from the PD as an incremental change to the control action not the control action itself. Therefore, the same method can be applied to the fuzzy controller. The control action from the fuzzy PI controller at any step k is

$$u(k) = u(k-1) + f(e, \Delta e) \qquad (13)$$

where $f(e, \Delta e)$ is the output from the PD controller. The PI controller is primarily used to reduce the steady state error as the type of the system is increased. An attractive application of this controller is the system with time delay.

4. SIMULATION RESULTS

The static fuzzy logic control for single control input was applied. Several simulations were carried out to obtain the scaling factors that give the reasonable response. These scaling factors were switched to smaller values when the error was less than certain value. The simulation results which represent the response of the two spool speeds, the fuel flow rate, the cobustor pressure, and the turbine inlet temperature are shown in Fig. 8, Fig. 9, Fig. 10, and Fig. 11. Fig. 8 shows simulation results of PD fuzzy controller for the take off condition, while results o f PI controller are shown in Fig. 9. It is shown that the response of PD controller is oscillatory and the fuel consumption initially shows a too high overshoot. The speed of response of PI controller is slower than that of the PD, while, on the other hand, the fuel consumption is acceptable as well as the steady state performance. Several simulations was carried out to obtain the

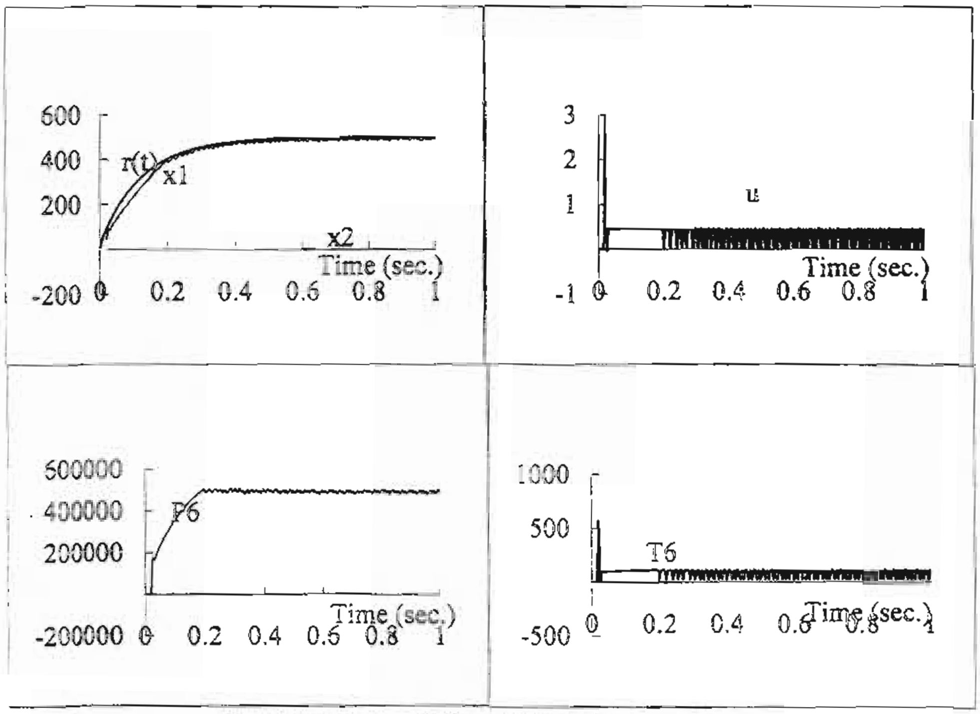

Fig. 8 Simulation results of take off using PD controller.

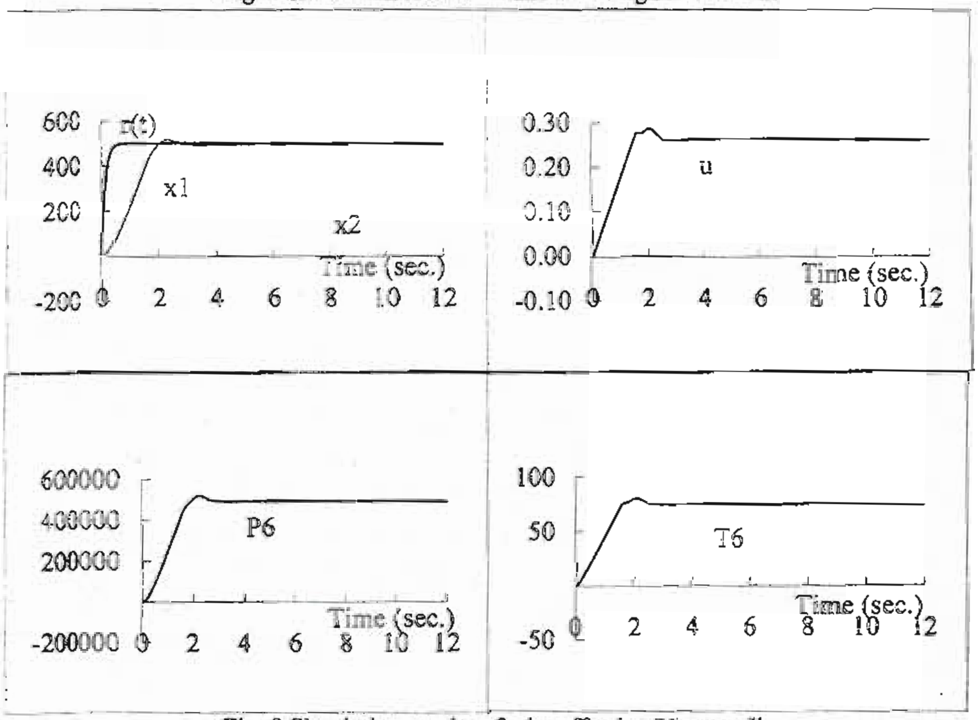

Fig. 9 Simulation results of take off using PI controller.

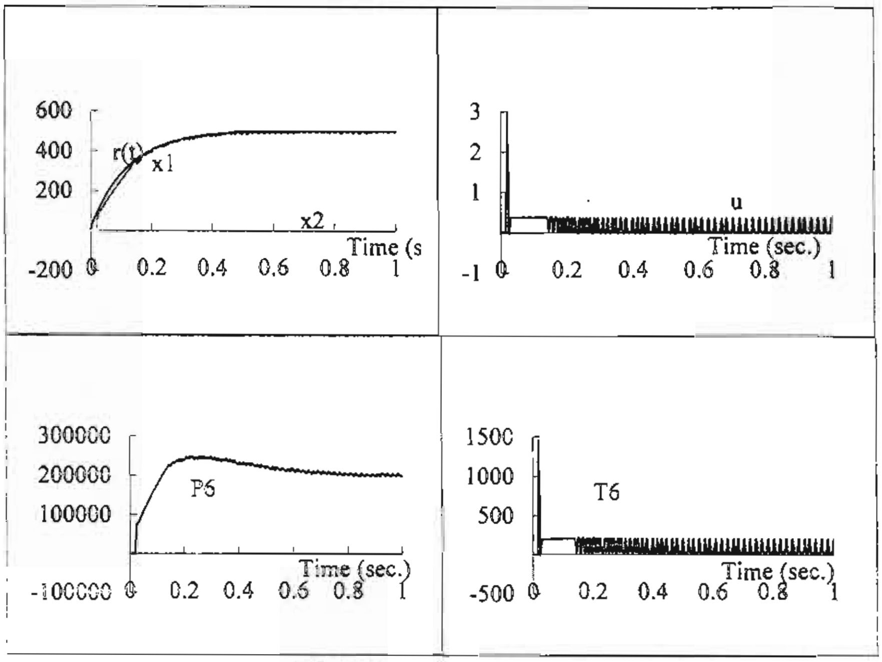

Fig.10 Simulation results of cruise using PD controller

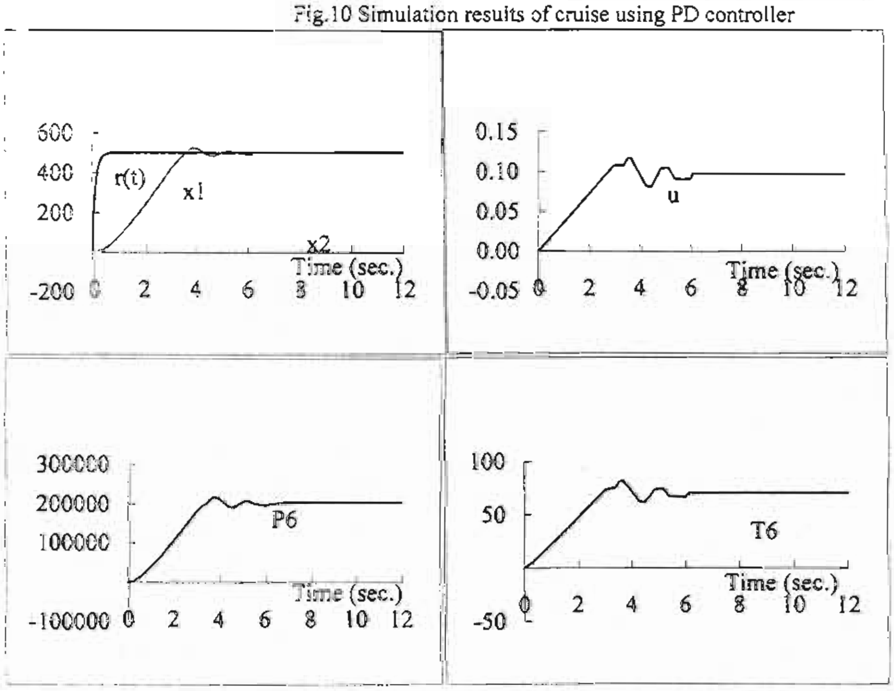

Fig.11 Simulation results of cruise using PI controller.

best scaling factors. These scaling factors were switched to smaller values when the error is less than certain value. Fig. 10, and Fig. 11 shows the simulation for the cruise condition. The same conclusions of the take off condition are valid here also. It is also shown that the system in cruise is faster than in the cruise condition.

5. CONCLUSIONS

Static fuzzy logic control is applied to the control of a high bypass turbofan engine. Two models of the engine are used, namely take off, and cruise conditions. Both fuzzy PI and PD controllers are applied. It is found that the PI one is more suitable than the PD one, since the former give less fuel consumption (consequently temperature), and less overshoot, while the time constant increases. The system at take off is faster than in cruise condition. This may be because the energy level of the engine is higher at take off which raises the excess torque and consequently forces the engine to accelerate faster.

REFERENCES

1. W.K. Tervo, and J.M. Tringali, "Control Design Consideration for Variable Geometry Engines", Power Plant Control for Aero-Gas Turbine Engine, AGARD, 1974.

2. M.A. Shaker, "Turbofan Engine Modeling & Control",, Ph.D. Thesis, Cairo University, 1989.

3. J.M. Watts, and T.E. Dwan, and C.G. Brockus, "Optimal State Space of a Gas Turbine Engine", ASME, Vol. 114, pp. 763.-767, October 1992

4. T.R. Nada, "Implication of Turbofan Engine Dynamics and Operating Limits on Fuel Combuster Design", M.Sc. Thesis, Cairo University, 1997.

5. M.H. Gobran, "Analytical Approach to Turbofan Engine Modeling Control and Nonlinear Simulation:, Ph.D. Thesis, Cairo University, 1995.

6. C.C Lee, "Fuzzy Logic in Control Systems, Part I", IEEE Trans. on syst. , man, and cybern., SMC-20,1990, pp. 404-418

7. C.C Lee, "Fuzzy Logic in Control Systems, Part II", IEEE Trans. on syst. , man, and cybern., SMC-20, 1990, pp. 419-435

8. Mamdani, "Applications of fuzzy algorithms for control of simple dynamic plant", IEE Proc. Control Theory Appl., 121, 1974, pp. 1585-1588

9. Mamdani "Twenty years of Fuzzy Control: Experiences Gained and Lessons Learnt", IEEE Procd. 1993, pp. 339-344

10. Zadeh, "Fuzzy Sets", Inform and Control 1965, pp. 28-44

APPENDIX A

LINEARIZATION OF THE ENGINE COMPONENTS CHARACTERSISTICS

As stated in sec.2, the excess power is function of the mass flow rate (air and gas) and the thermodynamic states (pressures and temperatures) at inlet and exit of the engine components (turbine and corresponding compressor). Through the component characteristics, these states are related to the speeds of the two spools, and fuel flow rate. The produced relations are then linearized to deduce the engine linear model. .

1-Intake: The Total temperature and pressure and their linearized forms (for certain flight speed) at the outlet of the intake are,

$$T_{to} = T_a + C^2/2C_p \qquad P_{to} = P_a(T_{to}/Ta)^{3.5}\eta_i$$

$$\Delta T_{to} = \Delta T_a \qquad \Delta P_{to} = (P_{to}/P_a)\Delta P_a - 3.5(P_{to}/T_{to})(C^2/2C_pT_a)\Delta T_a$$

2- Compression components: Theses components are fan, low pressure and high-pressure compressor. The characteristics of each, mathematically, can be expressed as,

$$\frac{P_{to}}{P_{ti}} = \pi = (C_1 + C_2 m + C_3 m^2)N^S$$

Where C_1, C_2, C_3, and S are constants, P_{to} and P_{ti} are the outlet and inlet total pressure respectively, m is the air mass flow rate, and N is the spool speed. Neglecting the change of mass flow rate m, the above equation and its corresponding temperature equation can be written in the linearized form as

$$\Delta P_{to} = \pi.\Delta P_{ti} + S.(\frac{P_{to}}{N})\Delta N \qquad \Delta T_{to} = \frac{T_{to}}{T_{ti}}.\Delta T_{ti} + S.\frac{(\gamma-1)T_{to}}{\eta_c \gamma N}.\pi^{(\frac{\gamma-1}{\gamma})}\Delta N$$

3-Combustion chamber: The heat balance through this component can be expressed as, $m_f.\,HV.\eta_b = m\,C_p\,(T_{to}-T_{ti})$

In the linearized form the above equation can be linearized to become,

$$\Delta T_{to} = \Delta T_{ti} + \frac{HV.\eta_b}{mc_p}.\Delta m_f$$

The pressure drop across the combustor is assumed to be constant then,

$$\Delta P_{to} = \frac{P_{to}}{P_{ti}}.\Delta P_{ti}$$

4-Expansion components: These comprise low and high-pressure turbines. When choked exhaust nozzle assumption is made, the two turbines are considered operate at single operating point. This assumption leads to constant pressure (temperature) ratio across each turbine. In the linearized form this can be formulated as,

$$\Delta P_{to} = \frac{P_{to}}{P_{ti}}\Delta P_{ti} \qquad \Delta T_{to} = \frac{T_{to}}{T_{ti}}\Delta T_{ti}$$