Decoupled controller for mixed exhausts turbofan engine

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ABSTRACT

This paper points out the capabilities of fully decoupled fuzzy controller which introduces simple design approach to deal with the coupling effects in controlling two spools, mixed exhausts turbofan engines. The decoupling is performed through proper selection of input parameters to the controller. Digital nonlinear engine/control system simulation is used to construct the fuzzy rules depending on simple logic. The performance of this controller is compared with that of an optimal controller representing efficient classical and conventional techniques. The decoupled fuzzy control system produces favorable transient strategies that other conventional controllers can not attempt due to its inherent proportionality characteristics. It displays improvements in surge margin for both fan and compressor, and temperature margin with almost similar response time during acceleration. Also, the proposed controller has the capabilities to increase the response speed during deceleration independently from acceleration transient.

NOMENCLATURE

AN	area of nozzle [m^2]
$(A/L)_{vol}$	area to length ratio of volume
E	error
$\dot{E}$	derivative of error
F	thrust [kN]
FAR	fuel to air ratio
I	polar moment of inertia [N.m.s^2]
K_P, K_I, K_D	proportional, integral, and derivative controller gains
$\dot{m}$	mass
m	mass flow rate [kg/s]
MFP	mass flow parameter
N	spool speed [rpm]
P	pressure [Pa]
PIC	compressor pressure ratio
PIF	fan pressure ratio
Q	torque [N.m]
R	gas constant [J/(kg K)]
t	time
T	temperature [K]
V	volume
γ	specific heat ratio

Subscripts

2, 2.5,….	engine station numbering, defined in Fig. 1
A	nozzle Area
F	fuel
H	high pressure spool

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i	input
in	initial
L	low pressure spool
Lim	limit
max	maximum
min	minimum
N	spool speed
O	output
P	pressure
rel	relative
S	static
t	total

Abbreviations

CSM	compressor surge margin
FSM	fan surge margin
HPC	high pressure compressor
PID	proportional, integral, and derivative controller
PLA	power lever angle
SLS	sea level static
SSL	steady state line
TIT	turbine inlet temperature
TM	temperature margin, $TM = (TIT_{LIM} - TIT)/TIT_{LIM}$
TSFC	thrust specific fuel consumption

1.0 INTRODUCTION

Engine dynamics and limits preservation are of main concern for any aircraft engine controller. There are many control strategies that can be applied in the aircraft engine control system, beginning from simple acceleration built in schedules to the sophisticated control schemes such as nonlinear optimal and fuzzy logic controllers. The nonlinear conventional control methods[1-4] applied on two spools, variable nozzle turbofan engines suffer from the coupled effects of fuel flow and nozzle area as control actions. These control systems can not deal with the coupling effects due to its inherent proportionality characteristics. As an example, when the error in fan duct Mach number is negative (case of acceleration) the nozzle must be closed, i.e., negative input error leads to negative change in output and the opposite action can't be produced due to proportionality characteristics of these controllers. This will cause decrease in fan surge margin and increase in turbine inlet temperature. These effects are also caused by increasing fuel flow (the second control action) as a result of positive error in engine speed. The conventional control strategies have no method to reverse the action of nozzle on the beginning of acceleration such that the fan surge margin can be increased and/or the turbine inlet temperature can be decreased during acceleration transient as possible while maintaining the time of response.

The application of fuzzy logic in controlling the aircraft engines is still limited, and most of this effort focuses on the control of fuel flow of jet engines. References 5-7 introduce fuzzy controllers dealing with single input-single output fuel control systems. However, the authors, employed fuzzy logic on two spools variable nozzle turbofan engines[8-9], emphasise on tuning fuzzy system parameters to enhance engine performance. Nevertheless, the proposed fuzzy controllers still experience the coupling criticism, which complicates the controller design and limit the performance improvements. In this paper, a fuzzy controller is built with distinct selection of input parameters to the controller such that the coupling between fuel flow and nozzle area effects during transients are decreased or completely removed. This decoupling can enhance the engine safety margins during transient response and/or decrease the total time of response. The results of the proposed controller are compared with optimal PID controller with scheduled gains, as strong, complicated, and conventional control approach, for various flight conditions inside the flight envelope.

2.0 STEADY STATE SCHEDULES

The first step in designing engine control system is to build the schedule which determines the steady state operating points on which the controller has to realise engine running. Figure 1 shows typical advanced variable cycle, F110-GE, turbofan engine[10]. Such engines are characterised by a number of variable geometry features and have optimum steady state schedules with significant coupling between the actions of these variables. The fuel flow and nozzle area are only considered in this paper to demonstrate the concept, which can be applied to engines with more control actions.

These schedules are built using nonlinear dynamical model such as that in references[12-14]. Hereafter, this model is presented briefly. The performance maps are used to represent steady state operation of engine components. The effects of mass, momentum and energy storage of the flow are allowed for using inter-component volumes. Integral forms of continuity, energy, and state equations are written for each volume and solved for the stored mass, temperature, and pressure in the volume, respectively.

Continuity equation: $$m = \int \left(\dot{m}_i - \dot{m}_O \right) dt + m_{in} \quad \ldots (1)$$

Energy equation (for no work added or subtracted):

$$T = \frac{\gamma}{m} \int \left(\dot{m}_i T_i - \dot{m}_O T_O \right) dt + T_{in} \quad \ldots (2)$$

When mixing of gases is not involved, a simple first-order lag form of the energy equation is used. The time constant for each lag is

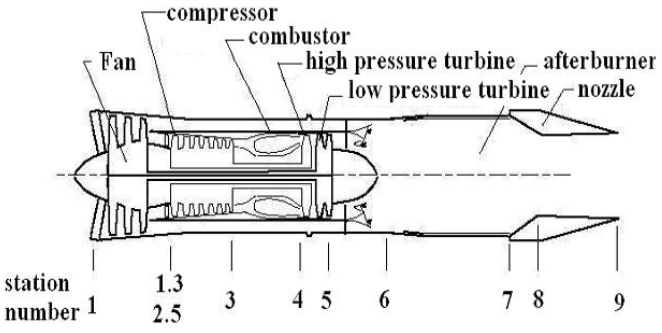


Figure 1. Typical F110-GE-129 turbofan engine.

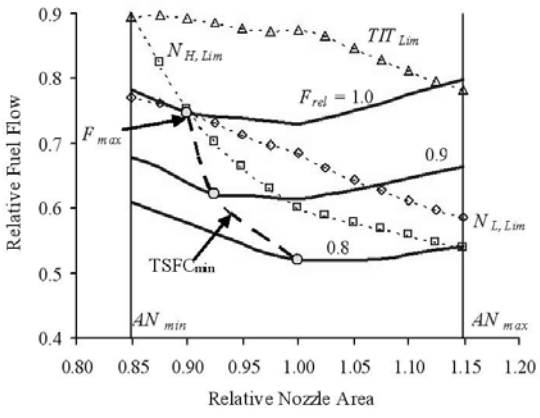


Figure 2. Global optimum at sea level static conditions.

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estimated to be equal to the ratio of the stored mass in the volume to the flow through the volume. This reduces to the integral form:

$$T = \frac{\gamma\ \dot{m}_O}{m}\int\left(T_i - T_O\right)\ dt + T_{in} \quad \ldots (3)$$

State equation:

$$P = m\ R\ T / V \quad \ldots (4)$$

The inclusion of the fluid momentum in the simulation serves to eliminate iterative loops (when the mass flow is required to address the variables in a performance map). It is applied for the flow through the fan duct, the high pressure compressor, the combustor, and mixer. This equation can be expressed as:

$$\dot{m}_i = \left(A / L\right)_{vol}\int\left(P_i - P_O\right)dt + \dot{m}_{i\ in} \quad \ldots (5)$$

The rotor angular momentum equation is given by:

$$N = \frac{1}{I}\int\left(Q_{turbine} - Q_{compressor}\right)dt + N_{in} \quad \ldots (6)$$

The details and solution scheme of the above model are given in[13-14]. Figure 2 shows an example of how to get the steady state fuel flow-nozzle area schedule. This figure presents the values of fuel flow and nozzle area required to get certain thrust at sea level static conditions. All values are scaled to design conditions. Three lines of constant relative thrust at SLS conditions are presented. Also shown on the figure are the loci of maximum low pressure spool speed (N_L), high pressure spool speed (N_H), and turbine inlet temperature (*TIT*). These parameters are that may constrain the minimum TSFC at maximum thrust point.

Other steady state limits and the optimum schedule building are outlined in Ref. 11. The point with the lowest fuel flow rate on each line is the optimum schedule (minimum *TSFC*) within geometrical constraints (maximum and minimum nozzle opening) and safety constraints (maximum and minimum N_H, N_L, etc.). The resulting nozzle area schedules for SLS, cruise, and minimum airflow flight conditions are plotted in Fig. 3 from idle to maximum available thrust for each case. The figure indicates the diversity of the optimum schedules.

3.0 FUZZY CONTROLLER DESIGN

Figure 4 shows the control loop for the two spools, mixed exhausts turbofan engine. The power lever angle and engine inlet conditions (inlet total pressure, P_{t2}, and inlet total temperature, T_{t2}) are inputs to the steady state schedule, while N_L and fan duct Mach number (represented by $(P_{t1.3} - P_{S1.3})/(P_{S1.3})$ are the outputs from this schedule. The utilisation of these two regulating parameters is in consistent with that of manufacturers such as SNECMA[3] and GE[10]. Generally, when applying fuzzy logic in fuel control systems, the speed error (E_N) and its first derivative are used as inputs to the controller[6].

On the other hand, the speed error and the error in fan duct Mach number are used as inputs to the nozzle area controller. Including the error in N_L with that of the fan duct Mach number in fuzzy logic for the nozzle controller facilitates opening the nozzle at high positive speed error regardless of the error in pressure (representing the fan duct Mach number). This increases the fan surge margin at the beginning of acceleration transient and thus increases engine safety and/or increases the controller capability to accelerate the engine faster. This algorithm helps in controlling the engine safety margins by the nozzle opening independently of the effect of fuel flow, which controls the spool speed.

During deceleration the action is reversed to keep the fuel to air ratio as high as possible to prevent flameout. Explicitly, the nozzle is closed at negative speed error despite the value of pressure error to maintain the fuel to air ratio as high as possible during deceleration transient and it is opened at positive speed error despite the value of pressure error to increase engine safety during acceleration transient. Near the required steady state value of engine speed, the nozzle is changed in direct proportion to pressure error to arrive at the value demanded by the steady state schedule. This decoupling between fuel flow controller and nozzle area controller helps in increasing the engine safety during transients without affecting the speed of response.

Scale factors are used for all errors and actuating signals. The scale factor for changing fuel flow is scheduled with flight conditions to adapt for the level of fuel variations with Mach number and altitude. The minimum value of the fuel change scale factor is selected at high altitudes-low Mach number; while the maximum value is determined at low altitudes-high Mach number flight conditions. The rest of the scale factors are constant used only to normalise the range of each parameter. Figure 5 shows the fuzzy sets of the universe of discourse employed in both fuel and nozzle area controllers, and the definition of the membership functions is given in Table 1. Two membership functions near zero were added (Negative Zero: NZ and Positive Zero: PZ) to improve engine stability.

The proposed decoupling facilitates to a great extent the fuzzy rules development as they rely on a simple logic using the nonlinear dynamical model of the engine[13-14] as a test bed. Tables 2 and 3 present the rule bases for fuel and nozzle area controllers, respectively. The fuzzy rules of the fuel controller are built such that the controller prevents oscillations near the required steady state point while a proportional controller approximation is employed at large errors in spool speed. It is obvious that the performance of this controller during deceleration can be altered by changing the rules in the left columns of Table 2 (negative speed error) independently of the rules that govern the response during acceleration transient (positive speed error).

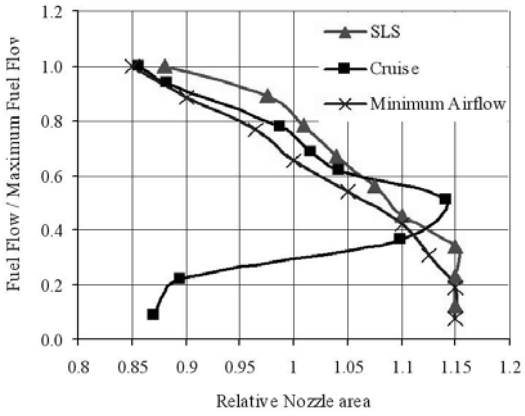


Figure 3. Optimum schedules at various flight conditions.

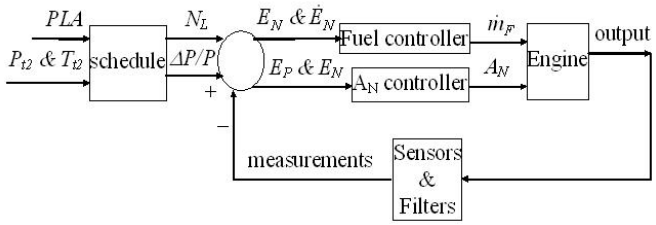


Figure 4. Decoupled control loop filters turbofan engine.

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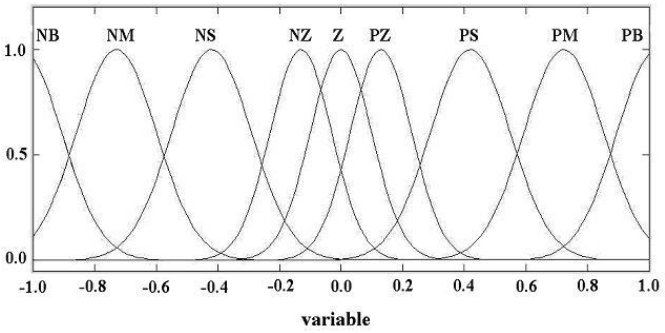


Figure 5. Decoupled control loop filters turbofan engine.

Table 1
Definition of membership functions

NB	Negative Big	PB	Positive Big
NM	Negative Medium	PM	Positive Medium
NS	Negative Small	PS	Positive Small
NZ	Negative Zero	PZ	Positive Zero
Z	Zero		

The nozzle area controller set of rules is built such that a substantial surge margin is available at the beginning of acceleration transient by opening the nozzle regardless of the error in duct Mach number. Conversely, a minimum airflow is maintained at the beginning of deceleration transient by closing the nozzle despite the error in fan duct Mach number. For the situation when speed error is small or near zero, the fan duct Mach number controls the nozzle area like a variable proportional gain to arrive at the opening determined by steady state schedule. This simple logic seems to yield excellent performance, which is the striking feature of the proposed decoupled fuzzy controller.

4.0 OPTIMAL CONTROLLER DESIGN

The optimal control is powerful and conventional tool for complicated nonlinear systems such as turbofan engines[15]. The objective function is the total time of response, which is a function of the controller gains. These gains represent the independent parameters while the minimum compressor surge margin, temperature margin, etc. are the constraints for this optimality problem. Generally, the controller gains are three gains for fuel controller (K_{PF}, K_{IF}, and K_{DF}) and three gains for nozzle controller (K_{PA}, K_{IA}, and K_{DA}). The problem formulation is:

$$\min [\text{Response Time}];\ x \in R^6 \text{ subject to operating steady state and transient limits} \quad \ldots (7)$$

In the above equation, $x = [K_{PF}, K_{IF}, K_{DF}, K_{PA}, K_{IA}, K_{DA}]$, and the optimum solution must satisfy the steady state operating limits in addition to dynamical limits such as surge margins in both fan and high pressure compressor and temperature margin in the high pressure turbine. This safety condition must be fulfilled during the transient response over the flight envelope, thus, these gains must be scheduled with flight conditions to compensate for the variations in engine dynamical characteristics. The use of PID controller with scheduled gains simplifies the application of optimal control methods on the two spool turbofan engine. The use of only proportional and integral controller necessitates the scheduling of the gains with spool speed in addition to scheduling with flight conditions[15]. Thus, it is required to schedule at least six gains with flight conditions compared with one gain (scale factor for changing fuel flow) in the case of decoupled fuzzy controller as mentioned in the previous section.

5.0 RESULTS AND DISCUSSION

The engine is tested at three cases: at SLS conditions being the common reference case, at cruise flight conditions, and at minimum airflow flight conditions being the severest case regarding the engine dynamic performance indices and limits. Figures 6-10 show the

Table 2
Rule base for fuel fuzzy controller

$\dot{E}_N$ \ E_N	**NB**	**NM**	**NS**	**NZ**	**Z**	**PZ**	**PS**	**PM**	**PB**
NB	NB	NB	NM	NB	NZ	NZ	PS	PM	PB
NM	NB	NB	NM	NB	NS	Z	PS	PM	PB
NS	NB	NB	NM	NM	NZ	PZ	PS	PM	PB
NZ	NB	NB	NM	NM	NZ	PZ	PS	PM	PB
Z	NB	NB	NM	NS	Z	PS	PS	PM	PB
PZ	NB	NB	NM	NZ	PZ	PM	PS	PM	PB
PS	NB	NB	NM	Z	PZ	PB	PS	PM	PB
PM	NB	NB	NM	Z	PS	PB	PS	PM	PB
PB	NB	NB	NM	PZ	PS	PB	PS	PM	PB

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Table 3
Rule base for nozzle area fuzzy controller

E_P \ E_N	NB	NM	NS	NZ	Z	PZ	PS	PM	PB
NB	NM	NS	NZ	NM	NB	NM	PZ	PS	PM
NM	NM	NS	NZ	NM	NB	NM	PZ	PS	PM
NS	NM	NS	NZ	NS	NM	NS	PZ	PS	PM
NZ	NM	NS	NZ	NZ	NS	NZ	PZ	PS	PM
Z	NM	NS	NZ	Z	Z	Z	PZ	PS	PM
PZ	NM	NS	NZ	PZ	PS	PZ	PZ	PS	PM
PS	NM	NS	NZ	PS	PM	PS	PZ	PS	PM
PM	NM	NS	NZ	PM	PB	PM	PZ	PS	PM
PB	NM	NS	NZ	PM	PB	PM	PZ	PS	PM

transient response for both optimal and fuzzy controllers at SLS conditions for step acceleration demand from idle to maximum operating thrust. As shown in Fig. 6, the optimal controller closes the nozzle at a high rate as there is large error in fan duct Mach number at the beginning of the acceleration transient.

On the other hand, the fuzzy controller keeps the nozzle open until the spool speed is increased and then closes the nozzle area to diminish the error in fan duct Mach number after passing the critical zone for fan surge margin. The optimal controller and also the other conventional control systems can not reverse the action of closing the nozzle with large error in fan duct Mach number, but they can only delay it but with drawbacks in response time. The fuzzy controller can easily reverse the action of the nozzle according to the error in spool speed and then can put a nonlinear variation in nozzle area to accelerate the response.

Figure 7, which shows the time variation of thrust, indicates that the responses of the two controllers are very close to each other and result in almost same settling time. However, the time to reach 50% of the demanded thrust for the optimal controller is slightly smaller that that for the fuzzy controller. The difference is only ~0·2 second, which does not affect the controller capability in accelerating the engine as the order of magnitude of the engine dynamics is generally smaller than that of the aircraft.

The variation of TIT with time is plotted in Fig. 8, which shows that the fuzzy controller decreases the maximum temperature of the engine and results in higher temperature margin than the optimal controller. The optimal controller results in almost zero temperature margins while the fuzzy controller increases it to more than 3%.

The transient responses of the two controllers on the fan and compressor characteristic maps are given in Fig. 9 and Fig. 10 respectively. The effect of nozzle opening for the fuzzy controller appears in traveling of the transient path away from the surge line of fan map. On the compressor map, it is clear that the fuzzy controller increases the minimum detected surge margin during the transient to obtain nearly 6·5% minimum surge margin rather than 3·3% for the optimal controller. For this flight condition, it is obvious that one can increase the change in fuel during transient for the fuzzy controller until the transient margins (surge and temperature) reach the lowest values and thus decrease the time of response more than the optimal controller.

Hence, the decoupled fuzzy controller can be employed either to increase the speed of response and maintain safety or to increase

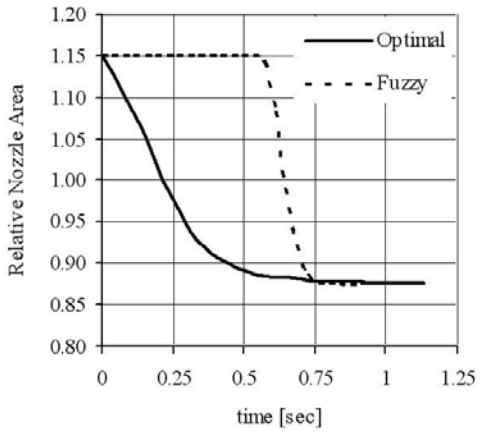


Figure 6. Nozzle area variation at SLS conditions.

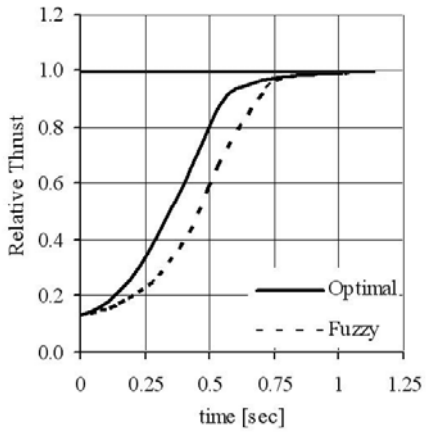


Figure 7. Thrust variation at SLS conditions.

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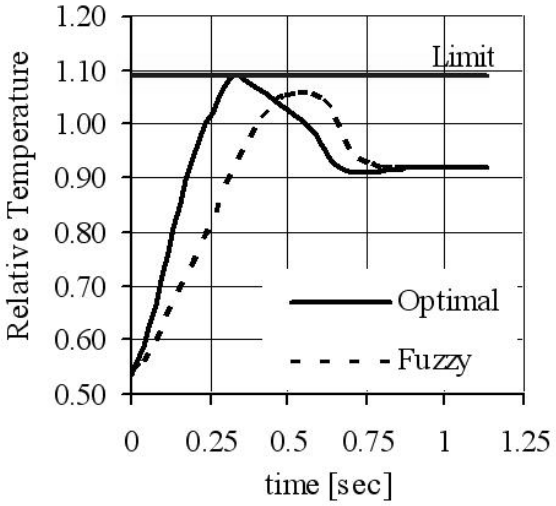


Figure 8. TIT variation at SLS conditions.

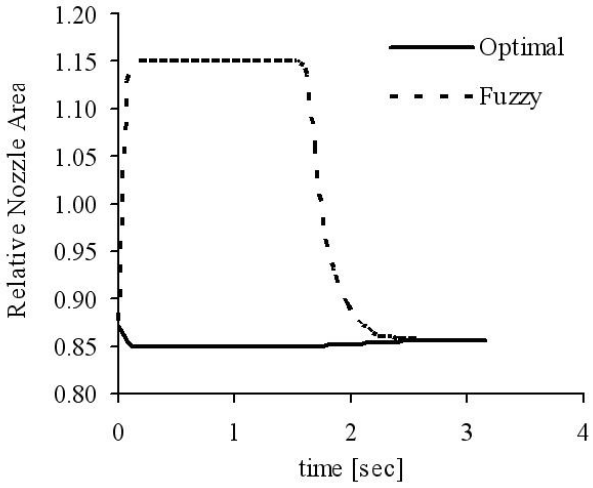


Figure 11. Nozzle area variation at cruise conditions.

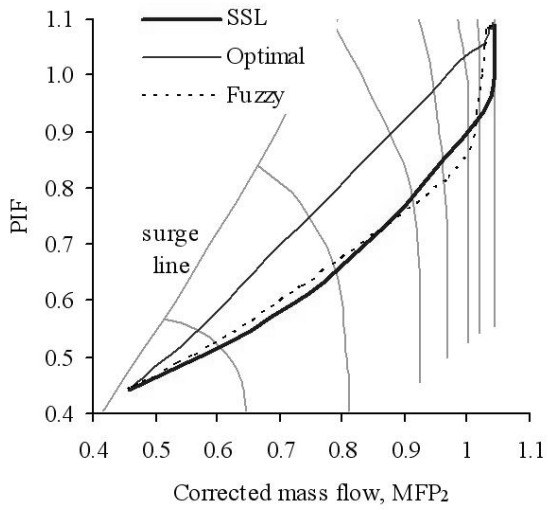


Figure 9. Fan response at SLS conditions.

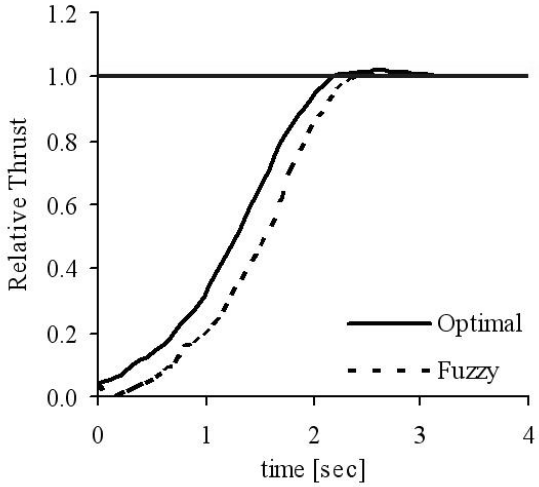


Figure 12. Thrust variation at cruise conditions.

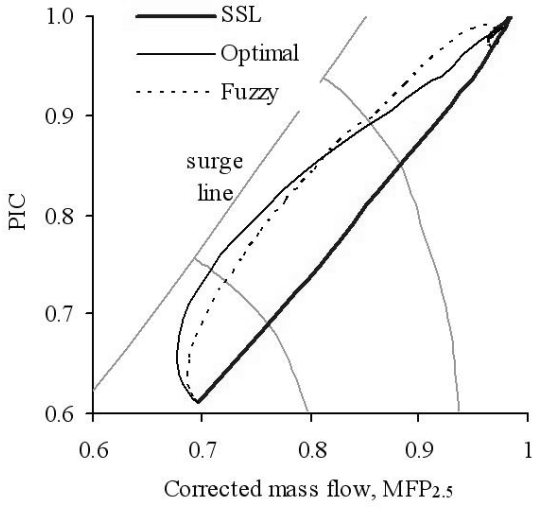


Figure 10. HPC response at SLS conditions.

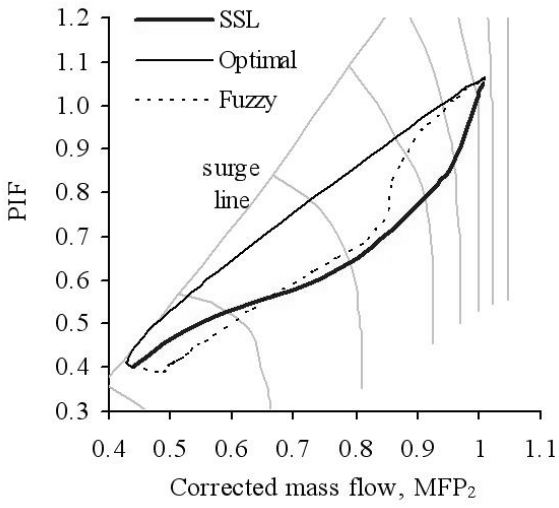


Figure 13. Fan response at cruise conditions.

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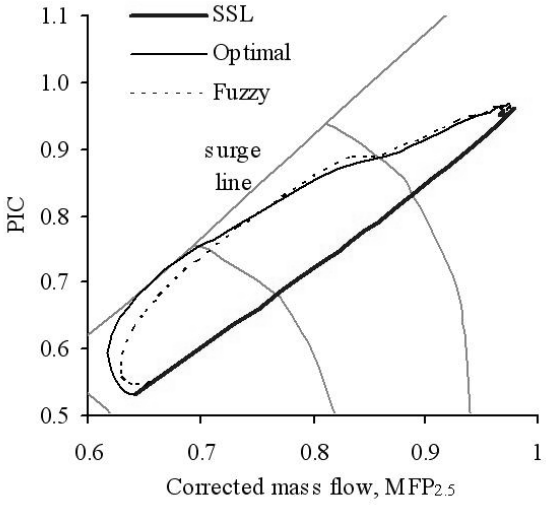


Figure 14. HPC response at cruise conditions.

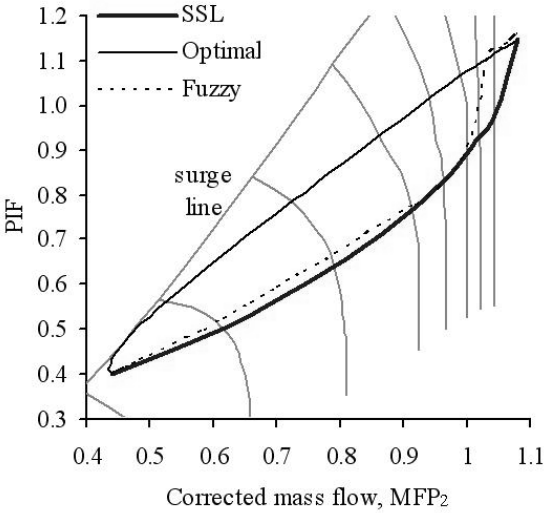


Figure 15. Fan response at minimum airflow.

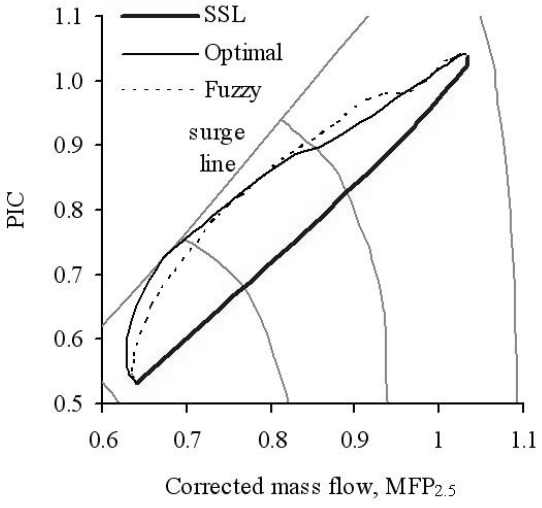


Figure 16. HPC response at minimum airflow.

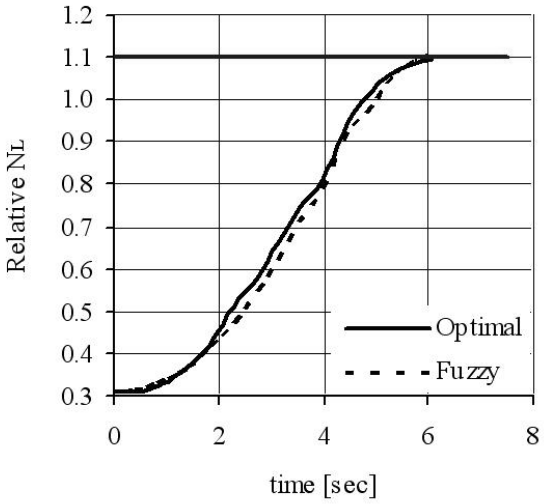


Figure 17. NL variation at minimum airflow.

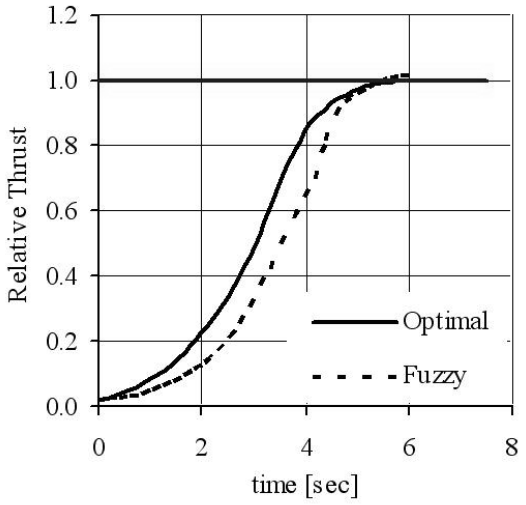


Figure 18. Thrust variation at minimum airflow.

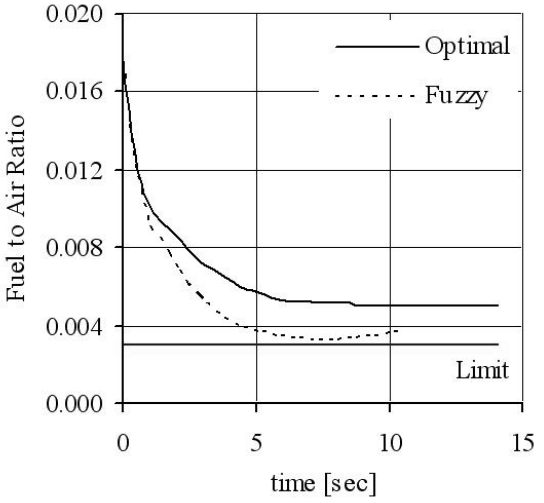


Figure 19. Fuel/air ratio at minimum airflow.

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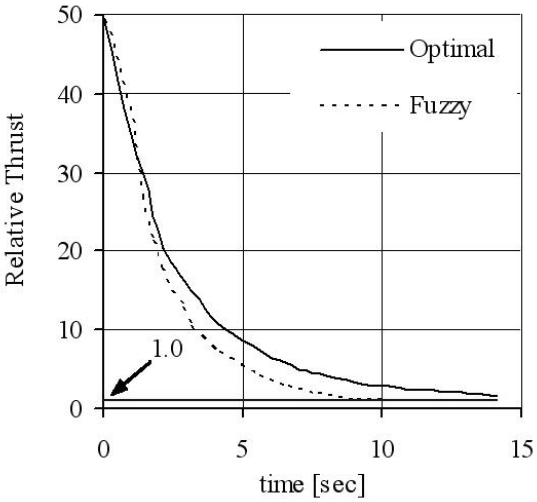


Figure 20. Deceleration at minimum airflow

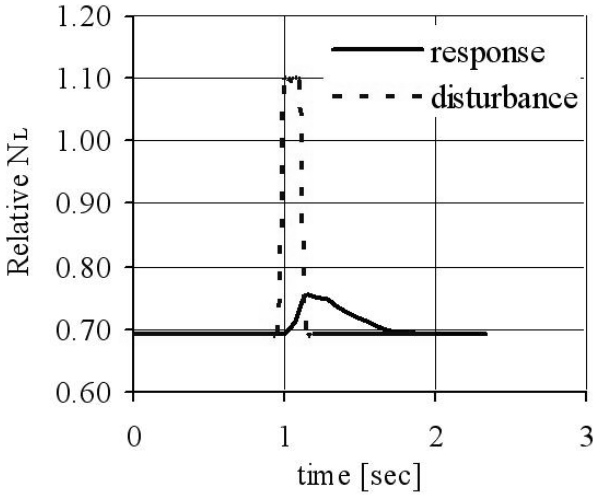


Figure 21. Fuzzy controller stability test at SLS conditions.

safety margins and maintain the speed of response. However, it is preferred to employ this algorithm in increasing the safety margins and maintain the speed of response as possible because the engine dynamics is generally faster than that of the aircraft. It is believed that any effort on improving the engine dynamics is ineffective. Alternatively, the improvement in engine safety is desirable especially to enhance engine life time and decrease the maintenance cost.

The cruise flight conditions is an attractive case because the steady state nozzle area at idle and at maximum thrust is near its minimum value as can be seen from Fig. 3. The results of the two controllers at cruise flight conditions are plotted in Figs 11-14. Figure 11 illustrates the benefit of the nozzle variation and clears the idea of the decoupled fuzzy controller. The decoupled fuzzy controller opens the nozzle to the greatest extent at the beginning of the acceleration as there is large positive speed error regardless of the error on fan duct Mach number. On the other hand the optimal controller closes the nozzle as there is negative error in fan duct Mach number. The thrust responses of the two controllers are given in Fig. 12, which indicates that the fuzzy controller results in almost the same response time as the optimal controller. It is noted from this figure that the thrust is decreased at the beginning as a result of nozzle fast opening. It is important to mention that there was no flameout because the fuel is added in large amounts simultaneously with nozzle opening.

The transient responses of the two controllers on fan and compressor maps are plotted in Fig. 13 and Fig. 14 respectively. Figure 13 shows how the decoupled fuzzy controller can increase the fan surge margin at the beginning of the acceleration transient inversely to the optimal controller, which decreases the fan surge margin to a danger value to increase the speed of response. Also, the decoupled fuzzy controller increases the compressor surge margin during acceleration transient as can be seen from Fig. 14. The fast opening of the nozzle moves the point on the compressor map up as a result of decreased pressure and temperature on the fan duct and hence on front of the compressor (station 1·3 or 2·5 on Fig. 1). The decoupled fuzzy controller improves the compressor surge margin at these flight conditions to about 3·1% rather than almost zero for the optimal controller.

Regarding the dynamical characteristics of the engine, the severest flight conditions are the minimum airflow conditions at very high altitude and very low Mach number. At these flight conditions, engine dynamics are very slow and the minimum fuel to air ratio limit is critical during deceleration. The transient performance of the two controllers at these flight conditions are plotted in Figs 15-18 for acceleration from idle to maximum and plotted in Figs 19-20 for deceleration from maximum thrust to idle as step command. Again, the decoupled fuzzy controller can easily maintain large surge margins in both fan and high pressure compressor as can be seen from Fig. 15 for the fan and Fig. 16 for the compressor. The minimum detected fan surge margin for the decoupled fuzzy controller is about 7·5% compared with about 0·4% for the optimal controller. The minimum compressor surge margin is improved from 0·3% for the optimal controller to about 3·4% by employment of the decoupled fuzzy controller. These improvements are obtained without affecting the transient characteristics of the low pressure spool as can be observed from Fig. 17 and with almost the same response time as can be proved by Fig. 18. It is thought that improving fan and compressor surge and temperature margins will enhance the components life time and hence the engine life time, and this in turn will considerably decrease the maintenance cost.

Another advantage for the decoupled fuzzy controller over the optimal PID controller with scheduled gains is the ability of the designer to construct the fuzzy rules applied during deceleration (negative spool speed error) independent from that applied during acceleration transient. The gains of the optimal PID controller are usually optimised for acceleration transient and checked only for safety of the fuel to air ratio and other limits during deceleration transient. Thus, this controller generally has sub optimal transient response during deceleration in terms of large response time and unused safety margins.

Figure 19 shows the transient response of the fuel to air ratio for the two controllers during step deceleration command from maximum thrust to idle at minimum airflow flight conditions. It is clear from this figure that the fuzzy controller can benefit from the available margin in fuel to air ratio (FAR_{Lim} = 0·003) to decrease the response time as possible, while the transient response of optimal controller is limited by the gains optimised during acceleration. Thus, the optimal controller results in steady state error in the fuel to air ratio and hence in thrust as shown by Fig. 20, which presents the thrust variation for deceleration case at these flight conditions. The response time for the decoupled fuzzy controller is less than 10 seconds compared with 15 seconds in addition to some steady state error for the optimal controller.

Table 4 summarises the results of optimal and fuzzy controllers for SLS, cruise, and minimum airflow flight conditions in both acceleration and deceleration. It is worth to note that the response time mentioned here is the settling time (time for the output to reach 95% of the steady state value). The response time of the engine is generally much smaller than that of the aircraft and thus engine response time in the order of 1·0 to 5·0 seconds at different flight conditions is reasonable. It is not needed to do much effort in decreasing this level of engine response time as it will not affect the overall system (engine

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Table 4
Comparisons between optimal controller and fuzzy controller

Flight Condition	Controller	Acceleration				Deceleration	
		time	Minimum FSM	Minimum CSM	Minimum TM	time	Minimum fuel/air ratio
SLS	Optimum	0.8	4.9	3.3	0.2	1.7	0.0085
	Fuzzy	0.8	5.3	6.5	3.2	1.4	0.0073
Cruise	Optimum	2.2	0	0.2	21	4	0.0046
	Fuzzy	2.3	6.3	3.1	22	2.9	0.003
Minimum airflow	Optimum	5.1	0.4	0.3	28	15	0.005
	Fuzzy	5.2	7.5	3.4	29	9	0.0032

with the aircraft) dynamics. Alternatively, the safety margins (surge and temperature) are much more important for the designer of engine control system especially with the expected inlet flow distortions.

It is obvious from this Table that the minimum detected fan and compressor surge margins during acceleration transients are generally higher for decoupled fuzzy controller than that for the optimal controller with similar response time. Also, the response time for deceleration is generally smaller for fuzzy controller than that for the optimal one.

The decoupled fuzzy controller introduced in this work has fixed rules and parameters of the membership functions. It is believed that tuning these rules and parameters of the membership functions to optimise a response index, will produce more competent fuzzy controller with the optimal and other conventional controllers. This tuning can be completed through techniques such as self-organising control[16] or adaptive neuro-fuzzy control[17]. This will cause loss of simplicity for the proposed fuzzy controller, however, it is thought that gains well be practically limited.

6.0 SYSTEM STABILITY

The main concern on fuzzy controller is that there is no related stability theory to assure settled performance during various circumstances and disturbances. However, the complete nonlinear simulation is employed to test system stability throughout the entire operating range and for various flight conditions inside the flight envelope. This represents a good and adequate substitute. The engine is subjected to step disturbances in low pressure spool speed for short period at some steady state point at various flight conditions. The closed loop performance of the engine/controller system is shown in Fig. 21 at SLS conditions and similar responses are obtained at other flight conditions. It is observed from this figure that the system can without difficulty reserve the steady state point in less than two seconds. Neither limit cycles nor hysteresis are observed and good stability running is visible with the proposed fuzzy controller.

It was seen that, compared with optimal PID controller, the proposed controller has the same steady state stability characteristics, and no limit cycles or hysteresis were observed throughout the flight envelope with the application of severest expected command (step command from idle to maximum and vice verse). Also, the derivative nature of the rules near the steady state point and the two membership functions (PZ: Positive Zero and NZ: Negative Zero) help in improving closed loop stability. Actually, if the controller is designed without these near zero membership functions it is expected to exhibit limit cycles or even hysteresis. This is the weakest character of the fuzzy logic control systems. It is recommended that the system stability when applying fuzzy logic on control systems has to be studied in more details on future work.

Moreover, the proposed technique increases the aerodynamic stability margin (surge margins in both fan and high pressure compressor) without affecting the overall time of response. Improvement of this type of stability is rather important. Another type of stability is the combustor flam stability, which is preserved during rapid deceleration demands by closing the nozzle until the airflow is reduced by the rotor speed controller. It is thought that these stability criteria characterising the decoupled fuzzy controller are adequate for its application on the control system of turbofan engines.

7.0 CONCLUSIONS

Coupling effects of the action parameters in multi-variable control systems applied to two spool, mixed exhausts turbofan engine are considered. The decoupling of the action parameters can be achieved by employing Mach number in the fan duct and the speed of the low pressure spool as input parameters to the nozzle area fuzzy controller. While, the fuel fuzzy controller utilises low pressure spool speed error and its first derivative as input parameters. A simple logic is applied to construct the fuzzy rules on a digital nonlinear engine/control system simulation. The comparison between optimal controller, representing efficient classical and conventional techniques, and the proposed decoupled fuzzy controller indicates promising responses for the fuzzy controller at various flight conditions. It displays increase in fan surge margin to about 7%, while for high pressure compressor the surge margin can be increased by about 3%. Also, the temperature margin is increased by about 3% with similar response time during acceleration. Moreover, the proposed controller has the capability to decrease the response time during deceleration by about 40% without affecting the acceleration transient inversely to the optimal controller. The stability characteristics of this controller were tested throughout the flight envelope and neither limit cycles nor hysteresis were obtained. Additionally, the decoupled fuzzy controller is simpler in building and implementation than the optimal controller.

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