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AN ADVANCED CONTROL SYSTEM FOR TURBOFAN ENGINE : MULTIVARIABLE CONTROL AND FUZZY LOGIC. (APPLICATION TO THE M88-2 ENGINE)

Alain GARASSINO
Control and Accessories Division
SNECMA
MELUN-VILLAROCHE
FRANCE

ABSTRACT :

The search for better performance of present and future turbofan engine involves an increase on the number of variable geometries and thus of control loops.

As we can not or do not want to disregard the interaction between loops any more, the future control systems will therefore be multivariable. The aim of the architecture of multivariable control presented here is to optimize a performance index during transients.

This architecture consists of an inner loop which optimizes the performance index taking in account the limitations, an outer loop which brings the nominal steady-state offsets to zero and a trajectory which allows to take into account the topping schedule limitation.

This basic architecture can be improved by fuzzy supervisor.

Indeed, two control outputs are generated according to the description above :

- the first one optimizes the thrust and does not care very much about LP stall margin limitation,
- the second one optimizes again the thrust and strongly takes low pressure stall margin limitation into account.

The fuzzy logic then allows to do a compromise between these two control outputs according to the engine state.

Simulation results showing the efficiency of the method are given.

Symbols and Notations :

A8	Exhaust Nozzle Area
C	Combustion Chamber
ΔP/P	Pressure Ratio
Fn	Thrust
H/LP	High/Low Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
LQ	Linear Quadratic
SM	Low Pressure Stall Margin
WF32	Main Fuel Flow
XN2	Fan speed
X*	the desired value of X

1 - INTRODUCTION :

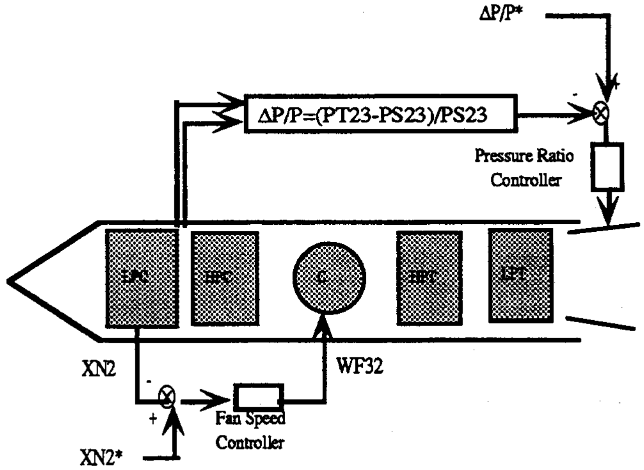
1.1 - Control Architecture of the M88-2 engine :

In order to manage thrust, two engine parameters are controlled: the fan speed, XN2, which is an estimator of the fan airflo and the pressure ratio, ΔP/P=(PT23-PS23)/PT23, where PT23 is the total pressure and PS23 the static pressure beetween the LP and HP compressors, DP/P is an estimator of the mach beetween the two compressors. The LP stall margin,SM, can be computed versus DP/P by :

SM = f(DP/P,XN2R)

where the corrected fan speed XN2R has a very low influence.

Usualy, the fan speed XN2 is controlled by the main fuel flow, WF32, and the pressure ratio ΔP/P is controlled by the exhaust nozzle area, A8 :



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1.2 - Application of the Linear Quadratic Regulator :

In Linear Quadratic (L.Q.) multivariable control, the controller gains are computed in order to minimize a performance index. The choice of this performance index depends on the requirements for an operationnal mode.

In the thrust mode, the thrust Fn must be optimized and the performance index is :

$$J = \int Fn^2 dt$$

An engine having physic limitations, the actual optimization must take into account constraints. The low pressure (LP) stall margin is one of the main limitations for transients. Thus, the performance index becomes :

$$J = \int (FN^2 + a\,SM^2)\,dt$$

where SM is the LP stall margin, a a parameter used to manage the compromise between performance and the available LP stall margin.

Thrust optimization and keeping LP stall margin nearly constant are contradictory: the best accelerations involve lower LP stall margins at the begining of transient.

Therefore, it would be very interesting to adapt a versus time, in order to optimize the LP stall margin in the begining and thrust at the end.

Unfortunately, the linear quadratic method does not allow that variable weighting.

2 - SUPERVISED ARCHITECTURE :

In order to perform this variable weighting, the gains of two multivariable controllers are computed by L.Q. method :

- Ksecu which optimizes the LP stall margin rather than thrust (a big)
- Kperf which optimizes the thrust rather than LP stall margin (a small)

The actual control outpout is then computed by the weighted sum :

$$u = [\,(1-\lambda)\,Kperf + \lambda\,Ksecu\,]\,X$$

where

u is the control output vector
X is the states vector
λ a weighting factor.

- when λ --> 0, performance is improved rather than LP stall margin.
- when λ --> 1, the LP stall margin is optimized rather than performance.

The management of λ becomes the critical point in this concept. Therefore we use fuzzy logic because :

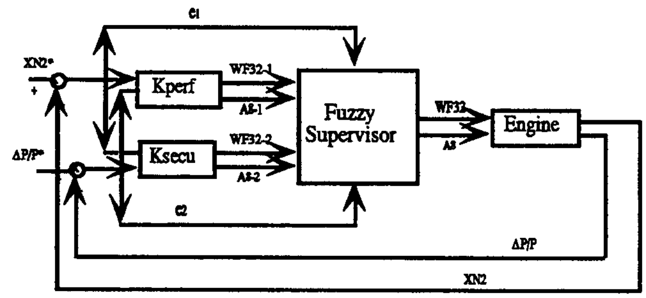
- the λ computation can be evaluated by rules such as :

" If the difference between $\Delta P/P$ * (desired) and $\Delta P/P$ is big then λ --> 0 "

where $\Delta P/P$ is an estimator of the LP stall margin.

- fuzzy logic allows smooth and continuous evolutions of λ.

So, the following control architecture is selected :



where

XN2 is the LP rotor speed,
$\Delta P/P$ the pressure ratio
WF32 the fuel flow
A8 the exhaust nozzle area
e1 = XN2* - XN2 with XN2* the desired LP rotor speed,
e2 = $\Delta P/P^*$-$\Delta P/P$ with $\Delta P/P^*$ the desired pressure ratio.

3 - APPLICATIONS :

3.1 - L.Q. Gains computation :

The Kperf and Ksecu gains are classicaly computed by LQ method optimizing the thrust and LP stall margin, respectively.

3.2 - λ computation :

3.2.1 - Approach :

λ is computed with both differences between :

- the LP rotor speed : e_1 = XN2* - XN2, what we call the LP rotor speed error,
- the pressure ratio : $e_2 = \Delta P/P^* - \Delta P/P$, what we call the Pressure Ratio error,

$$\lambda = f(e_1, e_2)$$

Then it is necessary to :

- define a domain of variation (called universe of discourse) for each variable e_1, e_2 and λ.
- divide each universe of discourse in sub-parts called fuzzy sets.
- define rules as :

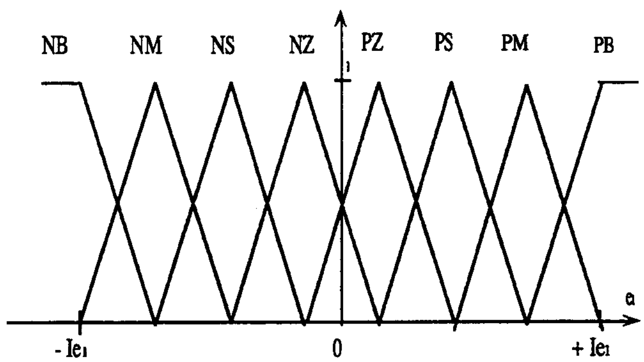
IF (e_1 is ...) and (e_2 is ...) THEN (λ is...)

3.2.2 - Universes of discourse :

. *Universe of discourse of the Rotor speed error* :

The universe of discourse of e1 is divided in six fuzzy sets :

NB : Negative Big
NM : Negative Medium
NS : Negative Small
NZ : Negative Zero
NP : Positive Zero
PS : Positive Small
PM : Positive Medium
PB : Positive Big

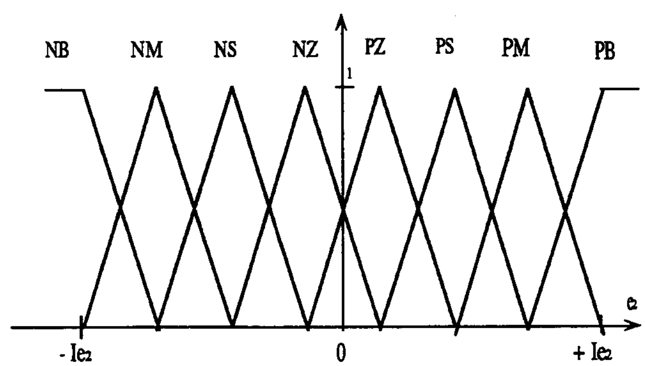


Ie1 is a tuning parameter. An obvious value of Ie1 is the transient amplitude :

$$Ie1 = XN2^* - XN2\ (T=0)$$

. *Universe of discourse of the Pressure Ratio error :*

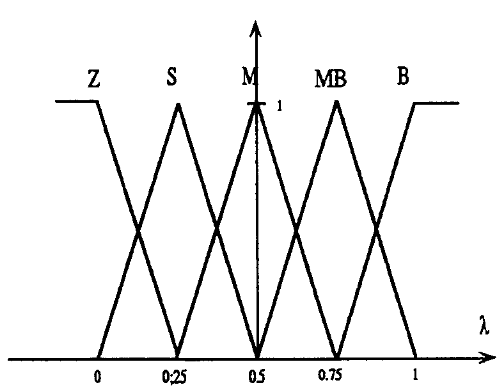
The universe of discourse of e2 is also divided in six fuzzy sets :



In the same way, Ie2 is a tuning parameter. Ie2 can be chosen as the biggest value of the difference between $\Delta P/P^*$ and DP/P during the transient : flight idle --> full power.

. *Universe of discourse of λ :*

λ must be included in [0 ; 1], its universe of discourse is divided into five fuzzy sets :



where: Z stands for Zero,
S for smal,
M for medium,
MB for medium big,
B for big.

3.2.3 - The Rules :

Keeping in mind e1 and e2 expressions :

$$e_1 = XN2^* - XN2$$

$$e_2 = \Delta P/P^* - \Delta P/P$$

we know that during an acceleration :

IF e1 > 0 or e2 < 0 : quite normal behaviour

IF e2 > 0, the LP stall margin becomes smaller

IF e1 < 0, there is an overspeed

The following look-up table can be deduced :

e2 \ e1	NB	NM	NS	PS	PM	PB
NB	Z	Z	Z	S	MB	B
NM	Z	Z	S	S	MB	B
NS	Z	Z	S	S	MB	B
PS	Z	Z	S	S	MB	B
PM	Z	Z	S	S	MB	B
PB	Z	Z	Z	S	MB	B

Overspeed (rows NB–NS) ; Performance Seeking (rows PS–PB)

Performance Seeking (columns NB–NS) ; Stall Margin lost (columns PS–PB)

The middle square of this table stands for nearly steady-state behaviour.

The choice of λ value for the steady state (λss) is also a tuning parameter.

A choice of λss=0,25 implies a controller that performs a compromise between thrust and LP stall margin optimization at the end of transients.

Physically, this choice makes no sense and the choice of λss = 0, which implies a controller which performs a complete thrust optimization at the end of transients, would lead to better performance. But a complete thrust optimization at the end of transients could involve an overspeed due to the integral control.

Therefore, simulation results of two controllers (λss = 0.5 and λss =0.25) are shown and the consequences of the choiced lss on performance is exhibited.

4 - Results :

The following results are obtained with linear models of the engine.

The method is tested at two points :

- M1: near flight idle with $\lambda ss = 0.5$ and $\lambda ss = 0.25$.
- M3: near full power with only $\lambda ss=0.5$.

For each variable X, the response was simulated for an input step :

- with a classical multivariable controller which performs the best compromise between the thrust and LP stall margin optimizations, Xref.
- with a classical multivariable controller which performs only the LP stall margin optimization , Xsecu.
- with a classical multivariable controller which performs only the thrust optimization , Xperf.
- with a controller supervised by fuzzy logic, Xfuzzy.

The last controller leads to a minimum loss of LP stall margin: it is the same as those obtained with only LP stall margin optimization. On the other hand this controller also leads to a significant gain of thrust compared with the first one.

These results are mainly due to the desired response of the nozzle area, more efficient in the begining of transients.

5 - Conclusion :

The results exhibit a significant gain in thrust response for an equivalent LP stall margin loss.

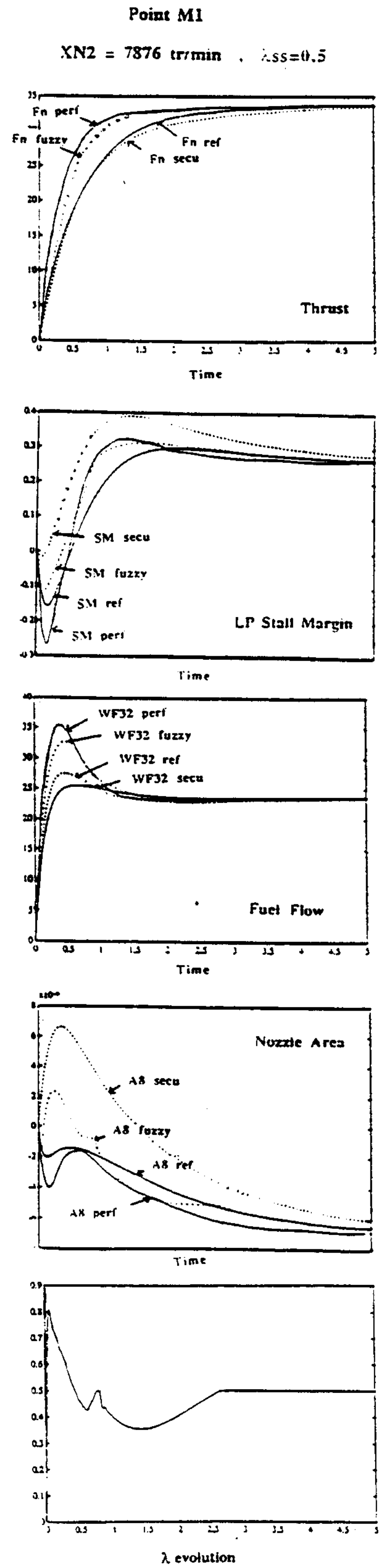
Of course, this method will have to be evaluated with non-linear models. But its application with non-linear models may not introduce particular problem because non-linearities are managed by LQ architecture itself.

On the other hand, stability must be proved at each time:

If u1 and u2 are stable control outputs, $(1-\lambda)\ u1 + \lambda\ u2$ is not automatically stable.

In consequence, when Kperf and Ksecu are computed, it must be necessary to verify that $(1-\lambda)$ Kperf+λ Ksecu is also stable for $\lambda \in [\,0\,;1\,]$

This architecture implement in a real ECU also involves the computation of control outputs twice plus the computation of λ using fuzzy logic.



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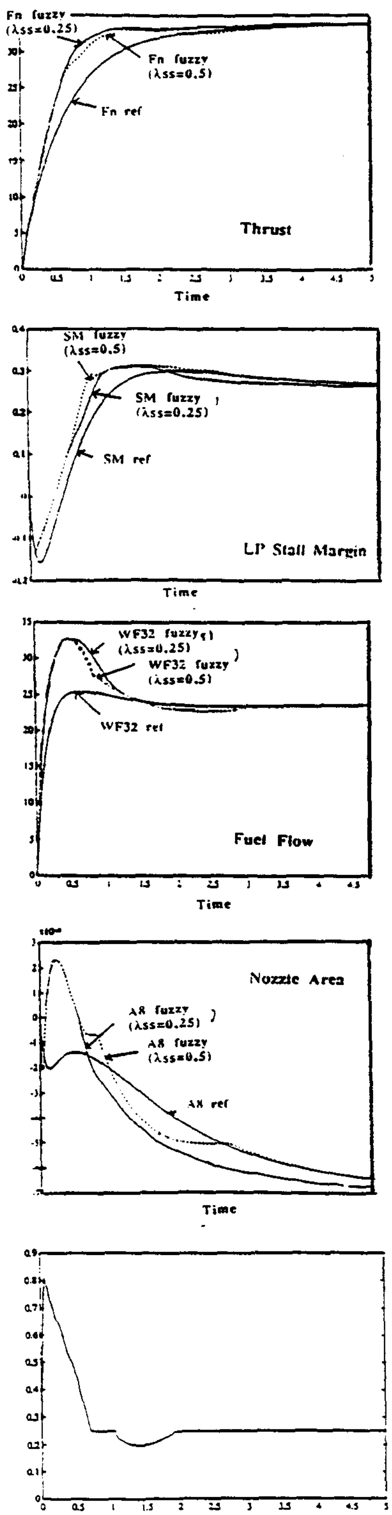
Point M1

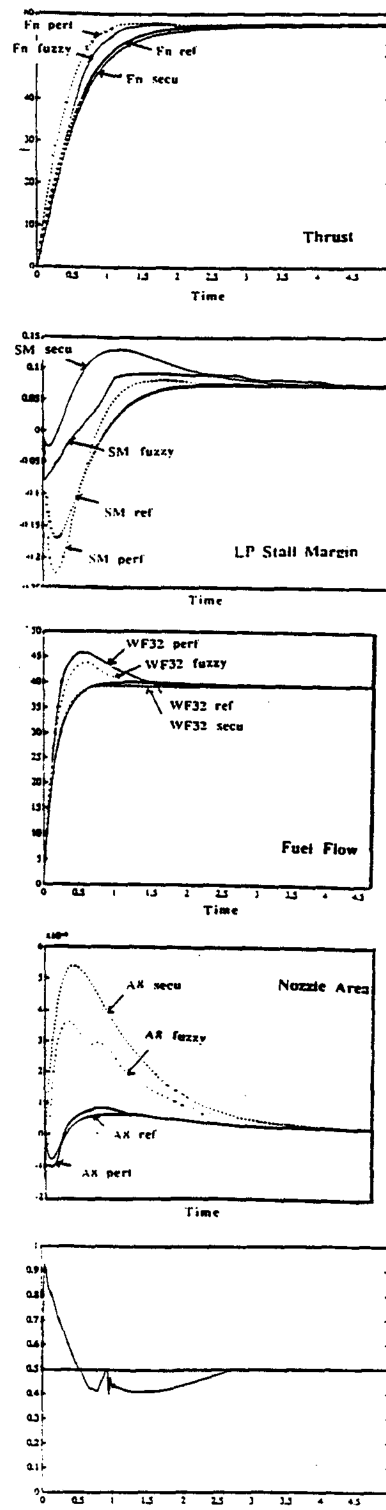
XN2 = 7876 tr/min , λ_{ss}=0.25



λ evolution

Point M3

XN2 = 10042 tr/min , λ_{ss}=0.5



λ evolution