SELF-TUNING CONTROLLER FOR THE ENGINE OF AUTOGUIDED AIRCRAFT

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ABSTRACT

The jet engine of autoguided aircraft is represented by different state models in its three operating conditions i.e take-off,normal cruise and landing conditions . This paper deals with a design of a computer controlled feedback loop that searches for optimum controller which minimizes the steady state errors of the engine thrust and turbine inlet temperature and also minimizes the overshootings and oscillations in both variables. This reflects to a better performance of the engine, decreasing or eliminating the surge pressure and oscillations in the speed of the high and low pressure compressors. The obtained optimum controller during the take-off is not the best for the normal cruise operating conditions so it must be tuned to obtain optimum engine performance during the case of normal cruise. In this work this has been realised using the strategy of Zettle [1]. The controller used is a multivariable proportional controller .The method is applied for the linear model suggested by Mahmoud [2] representing the P&W F 100 jet engine.

Keywords: Autoguided aircraft, Jet engine control, Multivariable controller, Optimal control.

NOMENCLATURE

A Transfer matrix of the state variables.
B Transfer matrix of the control signal inputs.
C Transfer matrix between outputs and the state variables
D Transfer matrix between inputs and output variables
X State vector matrix.
Y Output vector matrix.
U Open loop input vector.
J Objective function.
V Input vector matrix.
x_1 Speed of the high pressure compressor.
x_2 Speed of the low pressure compressor.
x_3 Combustor internal pressure.
x_4 After burner pressure.
x_5 Combustor internal energy.
y_1 Engine thrust.
y_2 Turbine inlet temperature.
y_3 High pressure compressor surge margin.
y_4 Low pressure compressor surge margin.
u_1 Combustor fuel flow rate.
u_2 Exhaust nozzle area.
w_i Weighing factors for the objective function.

INTRODUCTION

The control problem of the twin spool jet engine of aircraft is treated from different points of view. Gray and Taylor [3] applied the frequency domain methods in the design of nonlinear feedback loops. Mahmoud and McLean[2] used a single control law in regulating the dynamic responses of a linear and nonlinear model for jet engine as an application of multivariable system. Al-Bahi and Abdelrahman[4] tried to find a single control law suitable for the different operating conditions of an aircraft engine. Awad[5] applied the optimization techniques and obtained optimal PI and PID controllers for aircraft with twin spool gas turbine modelled by Mueller[6]. This work aims to obtain for autoguided aircraft a proportional multivariable selftuning controller which realizes optimum performance for the engine in the take-off operating condition and tunes this controller to fit the normal cruise case. During the tuning stage of the controller, rapid and nonoscillating response of the gas turbine engine variables must be guaranteed.The limits of the compressors surge pressures must not be exceeded.

PROBLEM FORMULATION

Starting from the linear state variable mathematical model of the P&W F100 engine given in [2] and modified by [4].

$$\dot{\mathbf{X}} = \mathbf{A}\,\mathbf{X} + \mathbf{B}\,\mathbf{U} \qquad (1)$$

$$\mathbf{Y} = \mathbf{C}\,\mathbf{X} + \mathbf{D}\,\mathbf{U} \qquad (2)$$

The matrices A, B, C and D depend upon the particular aircraft and engine operating conditions. In this work the linear model suggested by Mahmoud [2] for the Pratt and Whitney F 100 in both take-off and normal cruise is considered (see the appendix).

The control system presented in Figure (1) is suggested with the following control equation:

$$\mathbf{U} = \mathbf{V} - \mathbf{P}\ \mathbf{Y} \qquad (3)$$

Where P is the proportional controller matrix [2x2]. It is required to find the values of the matrix elements that minimize the steady state errors,the oscillations and the overshooting of y_1 ,y_2. In the same time guarantee rapid response of the outputs and maintaining the surge pressure in the compressors within the permissible limits.

This can be achieved by minimizing the following objective function using the strategy of Zettle[1] based on the gradient method coupled with a random search method to find a good estimation of the controller parameters.

$$J = \sum_{i=1}^{i=2} \sum_{n=1}^{n=2000} w_i\, v_i\, ABS(v_{i,n} - y_{i,n}) \text{ penalty function} \qquad (4)$$

Where n is the number of calculated points on the output curves. To assure good accuracy 2000 points for each curve are calculated for maximum response time equal to 1 second. The weighing factors w_1=0.0001,w_2=0.01 are used in the calculation of the objective function. These factors make the values $w_1.v_1.ABS(v_1-y_1)$ of the same order as $w_2.v_2.ABS(v_2-y_2)$ for all calculated points,since y_1 the engine thrust and y_2 the inlet temperature to the turbine are of different orders i.e make them equally weighted in the objective function.

The penalty function increases the objective function rapidly when the pressures exceed the permissible surge margins of the engine and equals to 1/summation of their differences .

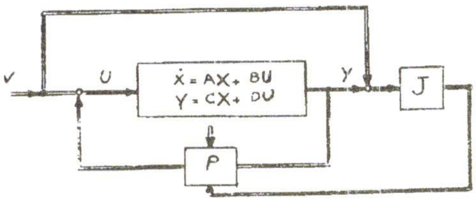


Figure 1. Control system.

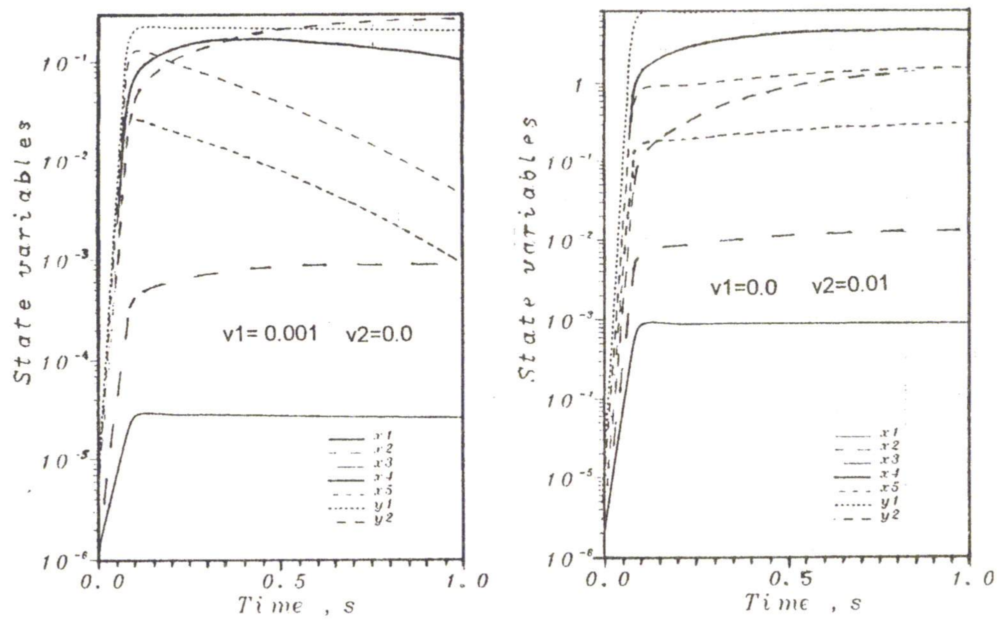
RESULTS AND DISCUSSION

Starting by a value equal to 0.00001 for all elements of the controller matrix P and applying a random search method , better initial guess for the parameters are obtained and shown in Table (1), then the optimization method of Zettle[1] is proceeded to find the optimal controller for the condition of the take-off taking into consideration the following two cases for the input signals:

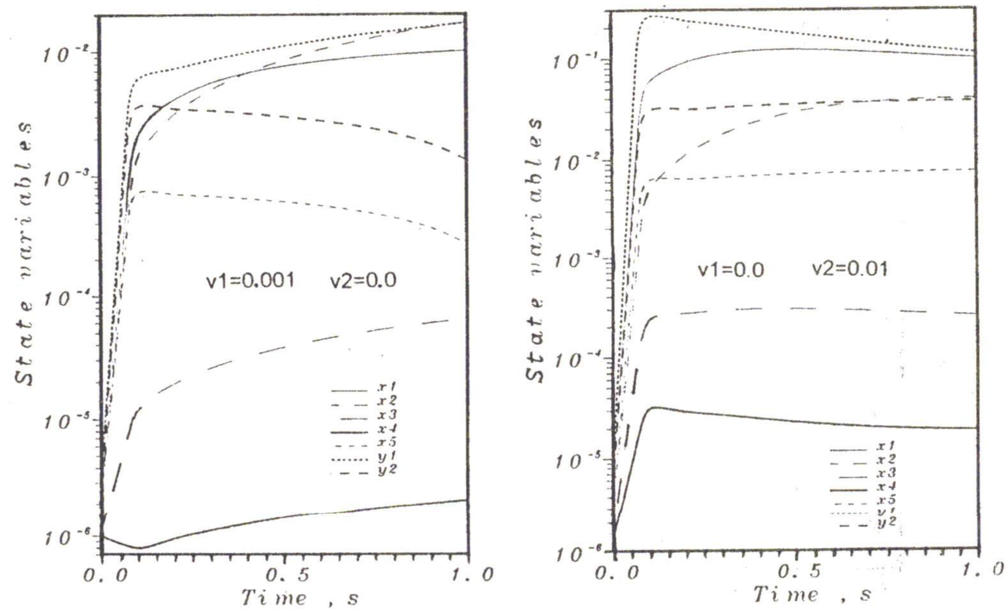
a- Step input v_1=0.001 and v_2= 0.
b- Step input v_2=0.01 and v_1= 0.

It is required to find the optimal controller elements that minimize the overshootings and the steady state errors for the two outputs y_1 and y_2 in the take-off condition.

Then transferring to the normal cruise condition the elements of the P matrix must be tuned to maintain optimality of the two outputs. Table (1) shows the objective function for the initial guess of the controller and for the optimum controllers in the take-off and normal cruise operating conditions. Figures (2a, b) show the state variable responses x_i,[i=1,5] and the outputs y_1 and y_2 before and after optimization for the two different inputs v_1 and v_2. Due to the great differences in the values of the state variables , they are represented on a semi-logarithmic sheet with the absolute values only. Figures (3a, b) show the same variables and outputs for the case of normal cruise before and after the optimization of the controller parameters.

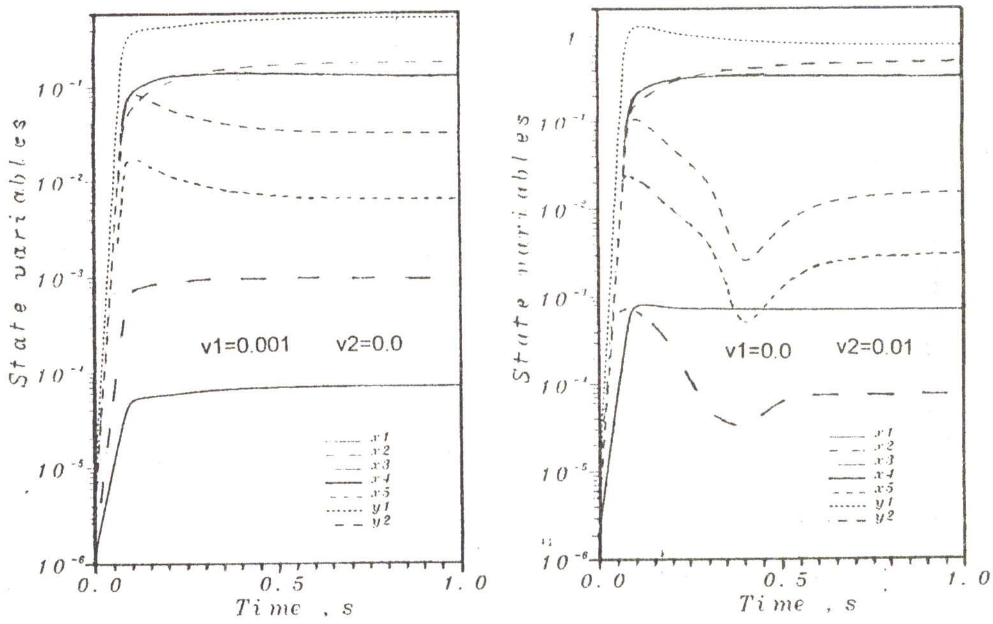


a- For the initial guess controller.

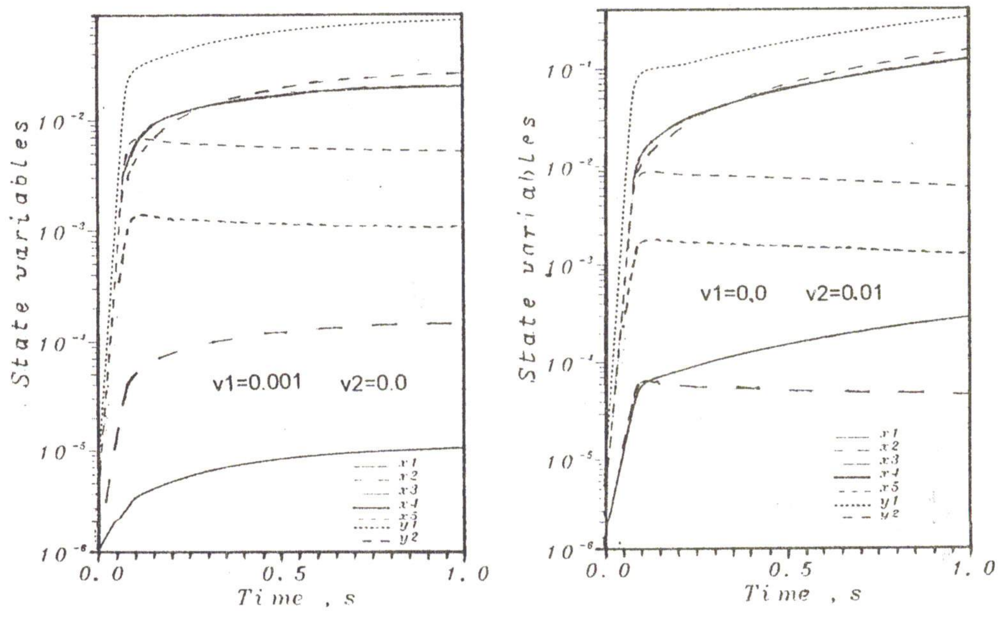


b-For the optimum controller.

Figure (2) State variables and outputs before and after optimization for take-off operating condition.

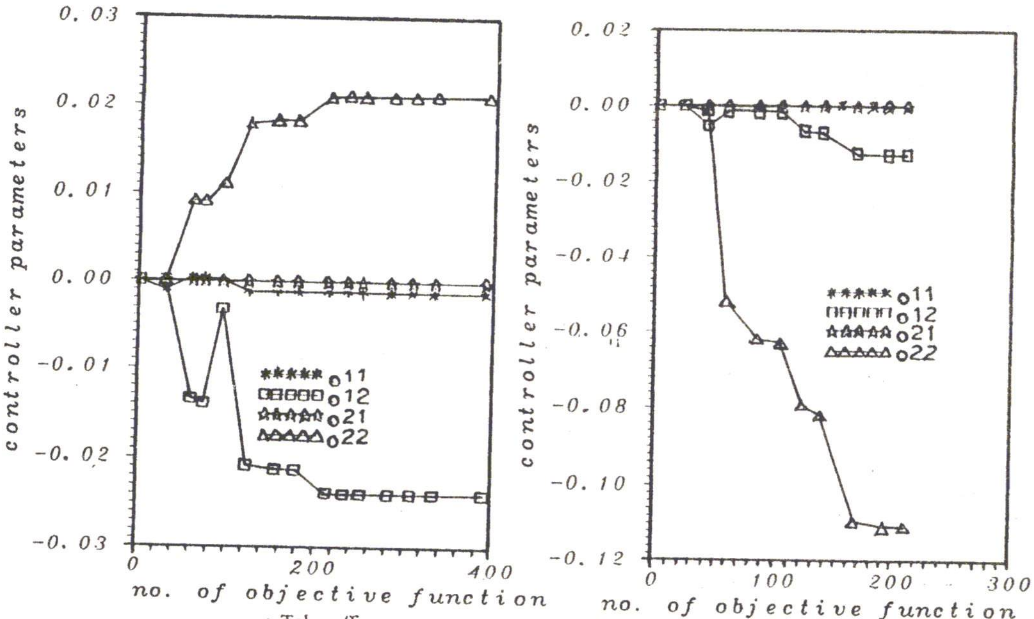


a- For the initial guess controller



b-For the optimum controller.

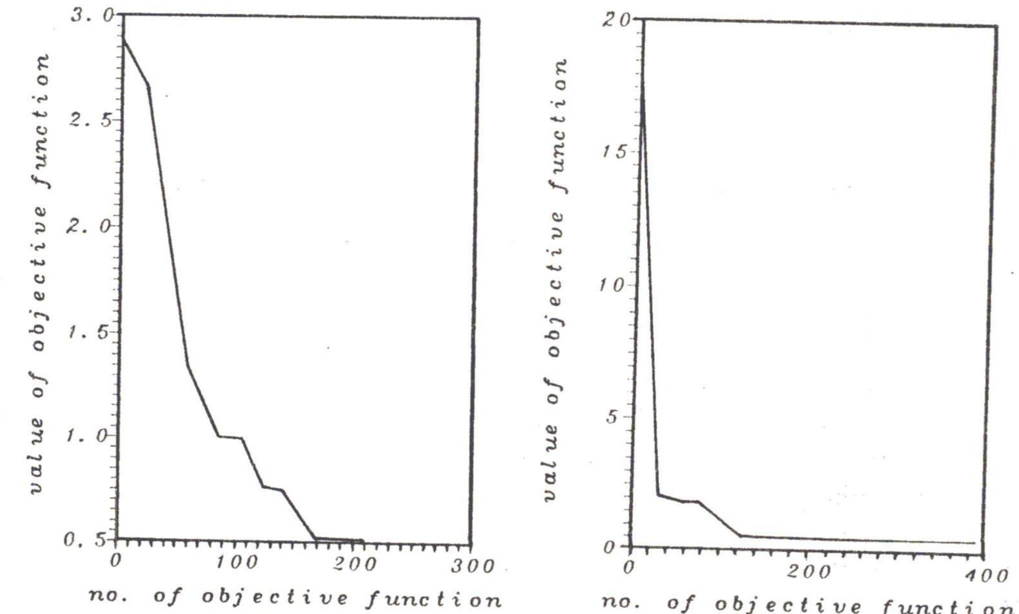
Figure (3) State variables and outputs before and after optimization for the subsonic normal cruising condition.



a-Take-off

b-Normal cruise

Figure (4) The controller parameter change in the optimization process.



a-Take-off

b-Normal cruise

Figure (5) Objective function change in the optimization process.

For the take-off, the controller with its initial guess gives the following steady state response for step inputs v_1=0.001 and v_2 = 0:
y_1 = 0.2 and y_2 = 0.001. The settling time of y_2 is more than one second.
For v_1= 0. and v_2 = 0.01 , the steady state of y_1 =8. and y_2 =1.1 .

It is obvious that the steady state errors are great. The optimum controller obtained gives from the computed results steady state responses for step inputs v_1=0.001 and v_2 = 0., y_1 =0.01 ,y_2=0.001 and for v_1=0.0 and v_2=0.01 ,y_1=0.1, y_2 =0.03 (see Figures (2a, b)).

Regarding the same inputs for the normal cruising condition the new optimum controller for that case gives for v_1 =0.001 and v_2 = 0. ,the steady state for y_1=0.05 and y_2 = 0.007 and for v_1=0. and v_2=0.01, y_1=0.1 ,y_2=0.008 (see Figures (3a, b)).

The two optimum controllers give better performance. The state variables have minimum overshootings. The settling time is less than 0.5 second for all variables which fits the operating performance of aircraft.
The percentage of the steady state errors relative to the inputs for all outputs are still great.

Table 1.

Case study	Controller elements				Objective function
	p_{11}	p_{12}	p_{21}	p_{22}	
Initial guess	-1.54E-5	7.2E-5	1.0E-5	6.0E-7	2.879594
Optimum controller for take-off condition .	-2.407E-4	-1.2788E-2	1.0E-5	-1.1076E-1	0.517567
optimum controller for normal cruise condition.	-1.183E3	-2.3857E-2	1.0E-5	2.1115E-2	0.514603

CONCLUSIONS

The method gives good controllers for the take-off and subsonic normal cruising operating condition of an aircraft turbojet engine. The obtained controllers improve the outputs and the state variables responses by minimizing the settling time to less than 0.5 second and nearly eliminating the overshooting. The relative values of the steady state errors can be improved by applying the method to a PID multivariable controller.

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APPENDIX

Linear model for take -off operating condition

$$\mathbf{A} = \begin{bmatrix} -12.5059 & -2.07934 & 1781.71 & 1110.16 & 34.4155 \\ 0.68988 & -5.63152 & 680.035 & 556.384 & 21.8413 \\ 1.34506 & 0.950426 & -393.069 & -245.863 & 6.55716 \\ -0.022174 & 0.0056329 & 6.88068 & -67.8116 & 0.0112172 \\ 2.5498 & -3.3495 & -1991.44 & -1721.09 & -105.891 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 5706.82 \\ 0 & 2591.63 \\ 61.8086 & -1000.59 \\ 0 & -43.1127 \\ 31866.8 & -594.388 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 5.17E{-4} & 0 & 0 & 7623.24 & -.141421 \\ 0 & 0 & 0 & 0 & 4.93119 \\ -1.488E{-4} & -1.272E{-4} & 0.0442066 & 0 & 0 \\ 0 & 1.209E{-4} & -.008275 & 0 & 0 \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} 0 & 4533.5 \\ 0 & 0 \\ 0 & 0.13386 \\ 0 & -0.26245 \end{bmatrix}$$

Linear model for subsonic cruise operating condition

$$\mathbf{A} = \begin{bmatrix} -5.08413 & -5.15966 & 2004.85 & 908.862 & 18.6713 \\ 0.282966 & -1.72003 & 508.627 & 332.326 & 15.3771 \\ 0.329032 & 0.861007 & -302.32 & -137.55 & 2.56234 \\ -0.0045155 & -0.0085174 & 4.65386 & -52.2517 & 0.008293 \\ 3.07623 & -3.15127 & -2968.77 & -1841.25 & -91.5133 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 10648.8 \\ 0 & 84.4355 \\ 34.632799 & 2311.96 \\ 0 & 25.8363 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 4.013e{-4} & 0 & 0 & 7752.54 & -0.160553 \\ 0 & 0 & 0 & 0 & 4.93115 \\ -7.92E{-5} & -4.582E{-4} & .150167 & 0 & 0 \\ 0 & 6.73E{-4} & -.0502946 & 0 & 0 \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} 0 & 845.473 \\ 0 & 0 \\ 0 & 0.768648 \\ 0 & -1.59633 \end{bmatrix}$$