Aircraft Double-Spool Single Jet Engine with Afterburning System

ALEXANDRU NICOLAE TUDOSIE
Avionics Department, Faculty of Electrical Engineering
University of Craiova
105-107 Decebal Blvd., Craiova, Dolj
ROMANIA
atudosie@elth.ucv.ro, antudosie@yahoo.com, http://www.elth.ucv.ro/catedre/avionica/.

CONSTANTIN LUCIAN SEPCU
Avionics Department, Faculty of Electrical Engineering
University of Craiova
105-107 Decebal Blvd., Craiova, Dolj
ROMANIA
lsepcu@elth.ucv.ro, sepcu_lucian@yahoo.com, http://www.elth.ucv.ro/catedre/avionica/.

Abstract: -In this paper the authors have studied an aircraft engine for high thrust, the double spool single jet engine with afterburning. The authors have identified the control and the controlled parameters of the integrated propulsion system and they have also established the non-dimensional mathematical model for the integrated system (jet engine+afterburning), starting from earlier determined models; based on it, one has built the system’s block diagram with transfer functions. Some simulations were performed, considering this kind of system description, concerning the system time behavior, such as step response of its main outputs (engine speeds and temperatures, as well as the estimated augmented thrust), for different inputs (throttle’s positioning and flight regime’s variation).

Key-Words: Jet-engine, Double-spool, Afterburner, Control, Fuel flow rate, Speed, Flight regime, Temperature.

1. Introduction

Modern aircraft engines, especially the combat aircraft engines must assure high level of thrust, low time response and maneuverability. For a high thrust level, there are necessary high compressors’ pressure ratios $\pi_c$ and/or high combustors’ temperatures $T_3$. For high values of $\pi_c$, the compressor must be “split” in two or more parts, coupled to the same number of gas turbines (turbo-compressor groups or spools), which means that the engine become a multi-shaft or a multi-spool one; each one of these spools has its own rotation speed, all of them being gas-dynamic, but not mechanical, related (coupled).

In order to obtain a supplementary thrust, these engines can be completed with afterburning, which is one of the most effective aircraft engine’s thrust augmentation method, being the controlled fuel injection and burning in a special kind of combustor, called “afterburner”, mounted after the engine’s last gas turbine, before the exhaust nozzle.

Such a jet engine is represented in fig.1, its main parts being: a) the air inlet; b) the low pressure spool (L.P. compressor + L.P. turbine); c) the high pressure spool (H.P. compressor + H.P. turbine); d) the engine’s combustor; e) the afterburner with fuel injectors and flame stabilizers; f) the adjustable exhaust nozzle.

This kind of engine assures higher thrust because of a higher $\pi_c$, as well as because of the afterburning.

![Fig. 1. Double-spool jet engine with afterburning](image-url)
2. System presentation
As fig. 1 and 2 shows, the system consists of two interconnected jet propulsion engines: a double-spool turbo-engine and an afterburner, each one of them having its own control and controlled parameters.

As control parameters (inputs) for a single-jet double spool engine, only two inputs can be identified: the fuel flow rate \( Q \) (which is the most important control parameter) and the exhaust nozzle opening \( A_5 \) [4],[13]. The controlled parameters are, obviously, the spools’ speeds \( n_1 \) and \( n_2 \); meanwhile, the combustor’s temperature \( T_3^* \) is a limited controlled parameter, its limitation being realized through the fuel flow-rate control [13].

The engine has, eventually, a single input parameter, which is the throttle’s position \( \alpha \). The throttle is the unique command that the pilot can use, but it generates, by a complex input mechanism, the two input signals (presetting the reference signals for \( Q \) and \( A_5 \)). Engine’s fuel pump’s rotor is turned round by the high pressure shaft, but the centrifuge speed transducer is turned round by the low pressure shaft; the execution element is an actuator, which realizes the fuel pump plate (or the discharging valve) positioning [11,15]. Meanwhile, the exhaust nozzle’s opening is controlled by a follower system [2].

The afterburner is supplied by a fuel pump (turned round by the high-pressure shaft) and controlled by an actuator, which co-relates the fuel flow rates to the engine’s operating regime and the flight regime. The afterburning control system [12] is integrated to the engine’s control system, because it uses the same control parameters \( (n_2 \text{ and } A_5) \), that means the unique input parameter, which is the throttle’s position, as well as the flight regime (considered as disturbance), given by the inlet air pressure \( p_1^* \).

Fuel’s flow rate of the afterburner determines the level of the afterburning temperature \( T_{4p}^* \). Eventually, system’s outputs are: spools’ speeds \( (n_1 \text{ and } n_2) \) and afterburning temperature \( T_{4p}^* \).

The afterburner’s fuel pump is permanently turned round by the engine’s high pressure shaft, but the afterburning operates only by the pilot’s command; so, when the afterburning is switched-off, the fuel pump only re-circulates the fuel, without injection and burning.

---

**Fig. 2. Block diagram of the double-spool single-jet engine with afterburning**
3. System’s mathematical model

The studied system’s mathematical model consists of the motion equation for each of its parts, brought to an acceptable form for studying and simulations. A simplified mathematical model, based on the joining of the engine and afterburning simplified models, can be obtained and used for further studies.

The authors have used the models presented in [2], [4], [8], [11] and [13], as follows:

a) for the double-spool engine

\[(\tau_{rs} s + 1) \bar{n}_1 = k_{c_1} \dot{Q}_c + k_{n12} \bar{n}_2 + k_{n1} A_5 - k_{ple} \frac{p_*^1}{\bar{n}_1}, \quad (1)\]

\[(\tau_{rs} s + 1) \bar{n}_2 = k_{c_2} \dot{Q}_c + k_{n21} \bar{n}_1, \quad (2)\]

where the used annotations are:

\[K_{ Ri} = \frac{1}{\left(\frac{\partial M_{ Cl}}{\partial n_{ i}^0}\right) - \left(\frac{\partial M_{ Ci}}{\partial n_0}\right)} , \quad \tau_{ ri} = \frac{\pi L_i}{30} K_{ Ri} , \quad i = 1,2, \]

\[k_{c_i} = K_{ Ri} \frac{Q_{ c0}}{n_{ i0}} \left(\frac{\partial M_{ Cl}}{\partial Q_{ c0}}\right) , \quad k_{n_{ i0}} = K_{ Ri} \frac{Q_{ c0}}{n_{ i0}} \left(\frac{\partial M_{ Ci}}{\partial \bar{n}_0}\right) , \quad \]

\[k_{n_{ i2}} = K_{ Ri} \frac{n_{ i0}}{n_{ i0}} \left(\frac{\partial M_{ T2}}{\partial \bar{n}_0}\right) - \left(\frac{\partial M_{ Cl}}{\partial \bar{n}_0}\right) \]

\[k_{p_{ ple}} = k_{c_1} \left(\frac{p_*^1}{Q_{ c0}^*}\right) \left(\frac{Q_{ c0}^*}{p_*^1}\right)_{\bar{H}=0, \bar{Y}=0} , \quad (3)\]

their expressions being explained in [4].

Both speeds have similar expressions, but some important particularities are occurred. Each spool can be assimilated to an independent spool of a single-jet single-spool engine, but operating as a couple, being gas-dynamic bounded. Consequently, analyzing the (1) and (2) forms, an observation can be made, concerning the existence of a mutual influence between the spool’s speeds, accomplished by the coefficient \(k_{n_{ i2}}\) and \(k_{n_{ i1}}\) which appear in (1) and (2). These co-efficient are the mutual co-efficient and have a lot of influence in the engine’s stability (as controlled object); these mutual co-efficient are not constant, but they depends on the flight regime (altitude \(H\) and speed \(V\)).

Another observation is that the exhaust nozzle’s opening \(A_x\) influences only the LPS speed, as (1) shows, being the consequence of the burned gas flow rate’s dependence on the above mentioned parameter \(A_x\).

For the temperature \(T_3\) one can obtain the form:

\[\bar{T}_3 = k_{c_3} \frac{\dot{Q}_c}{\bar{c}_p} + k_{3n1} \bar{n}_1 + k_{3n2} \bar{n}_2, \quad (4)\]

where

\[k_{c_3} = \left(\frac{Q_{ c0}^*}{\bar{c}_p^*}\right) \left(\frac{\partial T_3^*}{\partial \bar{T}_3}\right)_{\bar{n}_1}, \quad k_{3n1} = \left(\frac{n_{ 01}}{T_{30}^*}\right) \left(\frac{\partial T_3^*}{\partial \bar{n}_1}\right)_{\bar{n}_2}, \quad k_{3n2} = \left(\frac{n_{ 02}}{T_{30}^*}\right) \left(\frac{\partial T_3^*}{\partial \bar{n}_2}\right)_{\bar{n}_1}, \quad (5)\]

or, the new form

\[\bar{T}_3 = \left(\frac{m_1 s^2 + m_2 s + m_0}{\bar{c}_p^*}ight) \left(\frac{\dot{Q}_c}{\bar{c}_p}\right) + \left(\frac{\tau_{ rs}}{\tau_{ rs} + \tau_{ r2}}\right) s + \left(\frac{\tau_{ rs} + \tau_{ r2}}{\tau_{ rs} + \tau_{ r2}}\right) s_{\bar{c}p\bar{c}p}, \quad (6)\]

with

\[m_1 = k_{c_3} (\tau_{ rs} + \tau_{ r2}) + k_{3n1} (\tau_{ rs} + \tau_{ r2}) + k_{3n2} (\tau_{ rs} + \tau_{ r2}), \quad m_0 = k_{c_3} + k_{3n1} (\tau_{ rs} + \tau_{ r2}) + k_{3n2} (\tau_{ rs} + \tau_{ r2}). \quad (7)\]

If the flight regime must be taken into account, it shall affect the LPS equation, because it is given by the terms containing the pressure in the front of the compressor \(p_*^1\). It has a direct influence above the low pressure compressor’s inlet, as well as above the low pressure turbine’s exhaust, which explains why the flight regime affects only the LPS.

b) for the afterburning

\[k_n (\tau_{ rs} s + 1) \bar{p}_r - k_{ple} \bar{p}_l = (a_2 s^2 + a_1 s + a_0) \bar{Q}_c, \quad (8)\]

where the involved co-efficient are:

\[k_n = k_Q k_{ pr} (k_{ pr} + k_{ pr} k_{ ul}), \quad \tau_n = k_{ yb} \tau_y, \quad (\bar{Y})\]

\[k_{HV} = k_{ R_i} k_{H_1} \left(k_{ CB} k_{ pr} k_{ yb} - k_{ CB} (k_{ pr} + k_{ pr} k_{ ul})\right), \quad a_2 = k_{pr} k_{ pr} (k_{ pr} k_{ pr} - k_{ CB} k_{ pr} k_{ yb} + 1) - k_{ yb} (k_{ pr} k_{ pr} - k_{ CB} k_{ pr} k_{ yb}), \quad (\bar{Y})\]

\[a_1 = k_{ pr} (k_{ pr} - k_{ yb} k_{ pr} k_{ yb} + 1) + k_{ yb} (k_{ pr} k_{ pr} + k_{ pr} k_{ pr} + k_{ pr} k_{ pr} + 1) - k_{ yb} k_{ yb}, \quad a_0 = (1 + k_{ pr}) (k_{ pr} k_{ pr} - k_{ CB} k_{ pr} k_{ yb} + 1) + k_{ pr} (k_{ pr} k_{ pr} - k_{ CB} k_{ pr} k_{ yb} - k_{ CB}), \quad (\bar{Y})\]

their expressions being explained in [12] and [14].

\[\bar{T}_{\bar{Y}} = \left[b_{2s} s^2 + b_{1s} s + b_{0s}\right] \bar{Q}_c - \left[b_{2s} s^2 + b_{1s} s + b_{0s}\right] \bar{Q}_p + \left(b_{2s} s^2 + b_{1s} s + b_{0s}\right) \left[\bar{p}_l k_{pr} \tau_{rs} s^2 + \bar{p}_le \tau_{rs} + \bar{p}_le \tau_{rs} + k_{ple} \tau_{rs}\right] + \bar{r}_{rs} k_{ple} \tau_{rs}, \quad (10)\]

where the co-efficient are the one in [14].

An observation can be made, concerning the presence of the afterburner, which affects the LP turbine’s exhaust, so the Eq. (1) shall be completed with a term containing a afterburner’s fuel flow.
rate: \(-k_{up} Q_p\). The value of the co-efficient \(k_{up}\) is a small one, being ten times smaller than the other co-efficient involved in (1), so, for preliminary studies it can be neglected.

Based on the above presented equations, which are the system’s simplified mathematical model, one has built the block diagram with transfer functions, as fig. 3 shows.

4. System’s quality
As one can observe in fig. 2 and 3, the system has two effective inputs: a) engine’s throttle’s position; b) aircraft flight regime (given by the inlet inner pressure \(p_1^*\)). So, the system should operate in case of any changing affecting one or both of the input parameters \((\alpha, p_1^*)\).

A study concerning the system quality was realized (using the co-efficient values for a jet engine, R-11F-300, presented in [8] and [14]), by analyzing its step response (system’s response for step input for one or for both above-mentioned parameters). As outputs, one has considered the engine’s speeds \((n_1, n_2)\), the afterburner’s temperature \(T_{4p}^*\), as well as the afterburning fuel flow-rate and the total thrust \(F_p\).

Concerning the system’s step response for throttle’s step input (high speed pushed throttle), when the flight regime is constant (see fig.4), one can observe that all the output parameters are stables \((n_1, n_2, T_{4p}^*)\), so the system is a stable-one (even an asymptotic stable one, according to the shapes of the curves in fig. 4). All output parameters are stabilizing at their new values with static errors, so the system is a static-one. However, the static errors are acceptable, being fewer than 5% for each output parameter. LP shaft’s speed \(n_1\) has a static error bigger than the HP shaft’s speed \(n_2\); both of them are stabilizing after 5...6 s, characteristic for a slow engine. The afterburner’s fuel flow rate \(Q_p\) has a similar behavior, but the temperature \(T_{4p}^*\) has an initial decreasing, because of the initial exhaust nozzle’s opening and of the air flow rate initial growing (due to the speeds’ growing).

Fig. 3. System’s block diagram with transfer functions

When the throttle is immobile, for a step input of \(p_1^*\) (high speed modifying of the flight regime) system’s behavior is similar (asymptotic stability, see fig. 5), but the static errors are negative and their absolute values are a little lower, being around 4.5% for \(n_1\) and 2% for \(n_2\). Both the afterburner’s fuel flow rate \(Q_p\) and the temperature \(T_{4p}^*\) have similar behavior, being also asymptotic stables.

When both of the input parameters have step variations, the effects are overlapping, so system’s behavior is the one in fig. 6. In this case, some parameters have a smaller or a bigger override, which gives a periodic stability. One can observe that, because of the initial \(n_1\) decreasing, both parameters (the fuel flow rate \(Q_p\) and the temperature \(T_{4p}^*\)) have similar behavior, with an initial decreasing; however, the temperature \(T_{4p}^*\) is more sensitive, so its initial decreasing is bigger (3% static error), but eventually it reaches the 2% level of...
the static error.

Another important output parameter is the total thrust, which means the combined thrust of both of the studied propulsion systems (double-spool engine...
and afterburning). Using the formula given by [14]
\[ F_p = \left[ \left( l_2 s^2 + l_4 s + l_6 \right) Q_v - \left( l_5 s^2 + l_7 s + l_9 \right) Q_v + \left( l_{2p} s^2 + l_{3p} s + l_{4p} \right) Q_v \right] \left( k_{p1e} k_{r1} \tau_2 s^2 + (k_{p1e} k_{r1} + \tau_2 k_{p1q}) s + (k_{p1e} - k_{1a2} k_{2a1}) k_{p1q} \right) \] (11)
one has obtained the behavior in fig.7.

As the figure shows, the total thrust tends to decrease when the flight regime becomes more intense (dash-dot curve); meanwhile, it grows when the throttle is pushed up, as consequence of all involved parameters growing (speeds, fuel flow rates and temperatures), see the dash curve.

For a combined input, one can observe that the flight regime’s influence is smaller than the throttle’s positioning influence, total thrust’s behavior (continuous curve) being very similar to the throttle’s positioning behavior.

The above-described engine’s model can be extended to other multi-spool engines, such as turbofans, or twin-jet engines.

References: