SINGLE-SPOOL JET ENGINE FOR AIRCRAFT WITH AFTERBURNING SYSTEM

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Abstract – **This paper deals with a single-spool single jet engine with afterburner for thrust augmentation. The afterburning system consists of a special combustor with its own fuel pump, turned round by the engine's spool and operating with respect to the gas-turbine's pressure ratio. The authors have built the mathematical model for the interconnected engine-afterburning system (EAS), based on the simplified mathematical models of the main parts of the system, models already determined and presented by other papers mentioned in the references section. The EAS was identified as controlled object and described by its mathematical model, as well as by its block diagram with transfer functions. Based on these elements, the authors have studied EAS time behavior, by studying its quality, which means its time response, performing some computer aided simulations; the simulations were based on some co-efficient, experimentally determined and calculated for the VK-1F jet engine. The paper is based on some similar works of the first author, as well as on similar works presented in the reference list, about aircraft jet engines and engines' main parts as controlled object(s). The used methods, as well as the conclusions and results, can be extended in further works, concerning multi-spool engines with afterburning systems.**

Keywords: *Fuel, Jet-engine, Single-spool, Control, Afterburning*

1. INTRODUCTION

The engines for modern aircraft, especially the ones for combat aircraft, must assure high level of thrust, low time response and maneuverability. For an engine high thrust level, there are necessary high compressors pressure ratios π_c^*, high combustor temperatures T_3^*, as well as alternative thrust augmentation methods. 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; it consists of 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.

The gas-dynamic principles and the equations, for both of the basic jet engine as well as the afterburning system, are presented in [3], [4] and [7]. Meanwhile, the basic single-spool single jet engine and the afterburning system as controlled objects are depicted in [8], [10] and [12]; a possibility for the afterburner's fuel pump automatic control was presented by the author in [15] and a similar simplified system in [12]; a complex integrated system (engine-afterburner) was also presented by the authors in [16].

The purpose of this paper is to identify the system (single-spool jet-engine+afterburning system, also called EAS) as controlled object and to determine its simplified mathematical model, as well as its time behavior.

Such an EAS is represented in fig.1, its main parts being: a) the air inlet; b) the compressor; c) the engine's combustor; d) the gas-turbine, its rotor being connected to the compressor's rotor through the shaft, resulting the engine's spool; e) the afterburner with fuel injectors and flame stabilizers; f) the adjustable exhaust nozzle with actuator.

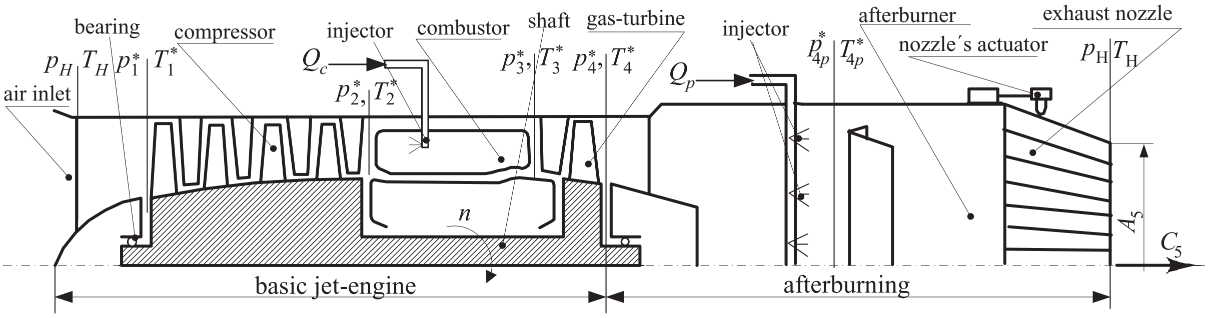


Figure 1: Single-spool single-jet aircraft engine with afterburning and adjustable exhaust nozzle

2. EAS PRESENTATION

According to fig. 1 and fig.2, EAS consists of two interconnected jet propulsion systems (engines): a single-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 single-spool turbo-engine, only two inputs can be identified: the fuel flow rate Q_c (which is the most important control parameter) and the exhaust nozzle opening A_5 (see [5],[14]). The controlled parameter is, obviously, the spool speed n; meanwhile, the combustor's temperature T_3^* is a limited controlled parameter, its limitation being realized through the fuel flow-rate control [14].

The engine has, eventually, a single input parameter, which is the throttle's position θ. 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_c and for A_5). Engine's fuel pump's rotor is turned round by the shaft. Meanwhile, the exhaust nozzle's opening is controlled by a follower system, similar to the one studied in [2].

The afterburner is supplied by a fuel pump (turned round by the same engine's shaft) and controlled by an actuator, which co-relates the fuel flow rates to the engine's gas-turbine pressure ratio. The afterburning control system is integrated to the engine's control system, because it uses the same control parameters (n 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^*. In fact, the input parameters for the afterburning are the pump speed and the gas-turbine pressure ratio δ_T^*. The afterburner fuel flow rate determines the level of the combined thrust, as well as of the afterburning temperature T_{4p}^*.

Eventually, system's main outputs are: spool's speed (n), combustor's temperature T_3^* and afterburning temperature T_{4p}^*. The afterburner's fuel pump is permanently turned round by the engine's shaft, but the afterburning operates only by the pilot's command; so, when the afterburning is switched-off, the afterburning fuel pump only re-circulates the fuel, without injection and burning.

3. EAS MATHEMATICAL MODEL

As fig. 1 and fig. 2 show, main parts of the studied EAS are: a) basic engine; b) fuel flow rate control sub-system; c) exhaust nozzle's flaps positioning

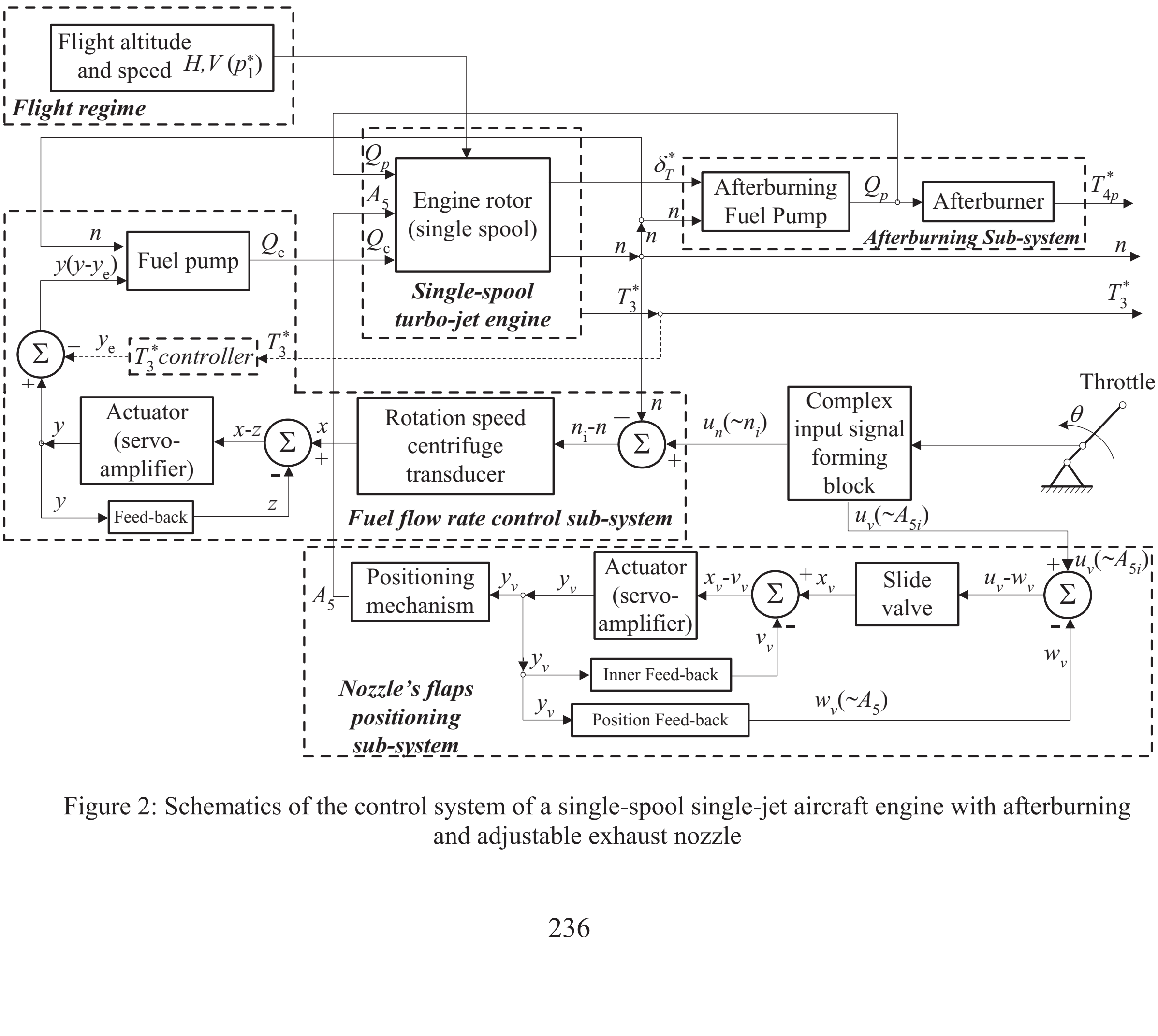


Figure 2: Schematics of the control system of a single-spool single-jet aircraft engine with afterburning and adjustable exhaust nozzle

sub-system; d) afterburning sub-system. Further more, the mathematical model shall be built from the main parts non-dimensional linearized models, as follows.

3.1. Basic engine equations

For an engine with afterburning, the mathematical model was determined and presented in [12] and has the form:

$$A \times u = b\,, \tag{1}$$

where A is the engine's matrix, $u-$controlled parameters vector and $b-$control parameters vector,

$$A=\begin{bmatrix} \tau_1 s+\rho_1 & -k_{1T3} & -k_{1p2} & -k_{1\delta} & 0 & 0 \\ k_{2n} & -k_{2T3} & k_{2p2} & 0 & 0 & 0 \\ 0 & -1 & -k_{3p2} & k_{3\delta} & 0 & 1 \\ 0 & k_{4T3} & k_{4p2} & k_{4\delta} & -k_{4Tp} & 0 \\ k_{5n} & k_{5T3} & k_{5p2} & 0 & 0 & 0 \\ 0 & k_{6T3} & k_{6p2} & 0 & k_{6Tp} & k_{6T4} \end{bmatrix} \tag{2}$$

$$u^{\mathrm{T}}=\left(\overline{n}\quad \overline{T_3^*}\quad \overline{p_2^*}\quad \overline{\delta_T^*}\quad \overline{T_{4p}^*}\quad \overline{T_4^*}\right), \tag{3}$$

$$b^{\mathrm{T}}=\left(0\quad 0\quad 0\quad k_{4A}\overline{A_5}\quad k_{5Qc}\overline{Q_c}\quad k_{6Qp}\overline{Q_p}\right), \tag{4}$$

the co-efficient $\tau_1, \rho_1, k_{1T3}, k_{1p2}, \ldots, k_{6Qp}$, involved in the above-presented equations having the forms determined in [8] and [10].

Solving the system (1) using the Cramer-method, for the main controlled parameters one obtains:

$$(\tau_m s+1)\overline{n}=k_c\overline{Q_c}+k_{nA5}\overline{A_5}+k_{nqp}\overline{Q_p}-k_{p1e}\overline{p_1^*}\,, \tag{5}$$

$$(\tau_m s+1)\overline{\delta_T^*}=k_{\delta c}(\tau_{\delta c}s+1)\overline{Q_c}+k_{\delta A}(\tau_{\delta A}s+1)\overline{A_5}+ \\ +k_{\delta p}(\tau_{\delta p}s+1)\overline{Q_p}\,, \tag{6}$$

$$(\tau_m s+1)\overline{T_3^*}=k_{T3c}(\tau_{TC}s+1)\overline{Q_c}+k_{T3A}(\tau_{TA}s+1)\overline{A_5}+ \\ +k_{T3P}(\tau_{TP}s+1)\overline{Q_p}\,. \tag{7}$$

Actually, the main output parameters are n and δ_T^*, the temperature T_3^* being, if necessary, only a limited output parameter.

3.2. Engine's fuel flow rate control sub-system equations

Engine's fuel pump is controlled by an actuator with inner feed-back, as presented in [11], [14] and [15], its equation being:

$$\overline{Q_c}=k_{pn}\overline{n}+k_{py}\overline{y}\,, \tag{8}$$

$$\tau_{sn}s\overline{y}=\overline{x}-\overline{z}\,, \tag{9}$$

$$\overline{z}=\rho_{sn}\overline{y}\,, \tag{10}$$

$$\overline{x}=\overline{n_i}-\overline{n},\ \overline{n_i}=\frac{k_{u\alpha}}{k_{es}}\overline{u_n}\,, \tag{11}$$

together with the signal forming block equation

$$\overline{u_n}=k_{un\alpha}\overline{\theta}\,. \tag{12}$$

The co-efficient involved in the above-presented equations have the forms determined in [11] and [15].

3.3. Exhaust nozzle's flaps positioning sub-system equations

EAS uses a nozzle tunning sub-system similar to the one described in [2], which equations are

$$\tau_{sv}s\overline{x_v}=\overline{A_5}\,, \tag{13}$$

$$\overline{z_v}=\rho_{sv}\overline{A_5}\,, \tag{14}$$

$$\overline{x_v}=\overline{u_v}-\overline{z_v}\,, \tag{15}$$

together with the signal forming block equation

$$\overline{u_v}=k_{uv\alpha}\overline{\theta}\,. \tag{16}$$

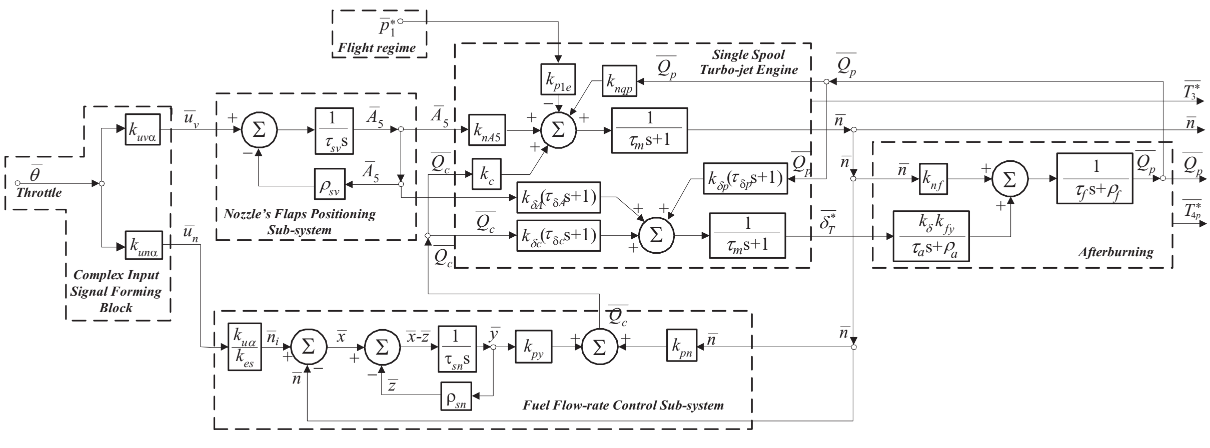


Figure 3: Block diagram with transfer functions of a single-spool single-jet aircraft engine with afterburning and adjustable exhaust nozzle

3.4. Afterburning equations

Afterburning fuel flow rate is given by

$$\left(\tau_f s + \rho_f\right)\overline{Q_p} = k_{nf}\overline{n} + \frac{k_\delta k_{fy}}{\tau_a s + \rho_a}\overline{\delta_T^*}. \qquad (17)$$

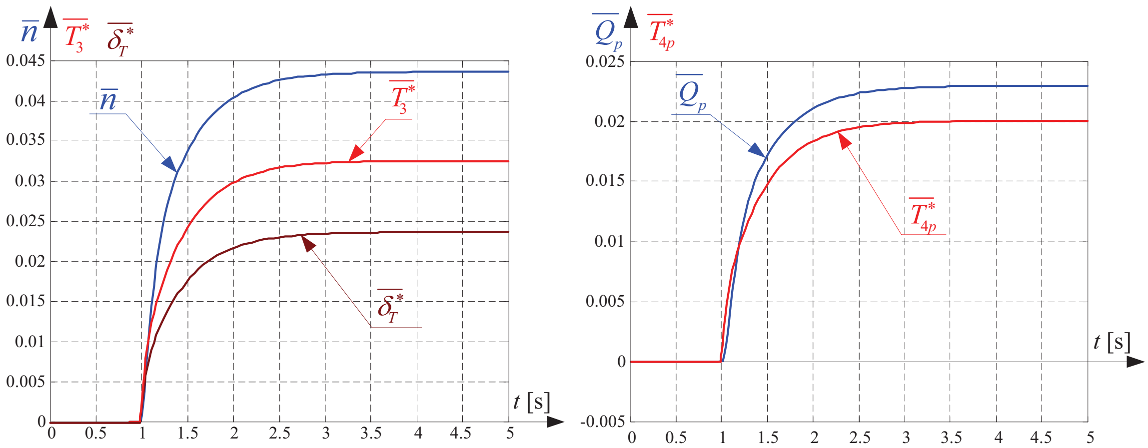
For the afterburner's $\overline{T_{4p}^*}$ non-dimensional temperature, one can use an equation similar to (7):

$$\left(\tau_m s + 1\right)\overline{T_{4p}^*} = k_{Tfc}\left(\tau_{fc}s + 1\right)\overline{Q_c} + k_{TfA}\left(\tau_{fA}s + 1\right)\overline{A_5} + $$
$$+ k_{Tfp}\left(\tau_{fp}s + 1\right)\overline{Q_p}. \qquad (18)$$

EAS mathematical model (non-dimensional linear equations) consists of the equations (5), (6), (8), (9), (10), (11), (12), (13), (14), (15), (16) and (17). Based on these, one has built the block diagram with transfer functions, as depicted in fig. 3.

4. EAS QUALITY

Analyzing the diagrams in figures 2 and 3, one can observe that EAS has, actually, two inputs: throttle's position θ (as input for engine's regime) and air inlet's total pressure p_1^* (as input for the flight regime, that means flight altitude H and speed V).
So, EAS should operate in case of any changing affecting one or both of the input parameters $\left(\overline{\theta}, \overline{p_1^*}\right)$.
A study concerning the system quality was realized (using the co-efficient values for a single-jet single spool engine, VK-1F, presented in [8] and [12]), 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 speed n, the engine combustor's temperature T_3^*, the engine gas-turbine pressure ratio δ_T^*, the afterburning fuel flow-rate Q_p, as well as the afterburner's temperature T_{4p}^*.
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 stabiles (both basic engine parameters n, δ_T^*, T_3^* and afterburning parameters Q_p, T_{4p}^*), so the system is a stabile-one (even an asymptotic stabile one, according to the shapes of the curves in fig. 4.a and, respectively, 4.b). 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; the biggest static error is of the engine speed parameter, 4.3%, and the lowest is for the turbine pressure ratio, 2.4%. The afterburner flow rate parameter $\overline{Q_p}$, as well as the afterburner temperature parameter $\overline{T_{4p}^*}$, has small static errors, 2.2%÷2.4%. All of the above-mentioned parameters are stabilizing after 3÷4 s, characteristic for a slow engine.
When the throttle is immobile (constant engine regime), for a step input of $\overline{p_1^*}$ (high speed modifying of the flight regime) system's behavior is a little different (see fig. 5.a and 5.b); all studied parameters are stabile, but periodic stabile, the curves in fig.5 having all small overrides. The static error of the speed parameter is negative and its absolute value is lower, being around 1.55 %, as well as the static error of the afterburning fuel flow rate parameter, which static error is also negative but smaller (around 0.7%). The periodical character is more visible for the temperature parameters, $\overline{T_3^*}$ and $\overline{T_{4p}^*}$, but their



a) b)

Figure 4: EAS step response for constant flight regime $\overline{p_1^*} = 0$ and throttle positioning $\overline{\theta}$ step input

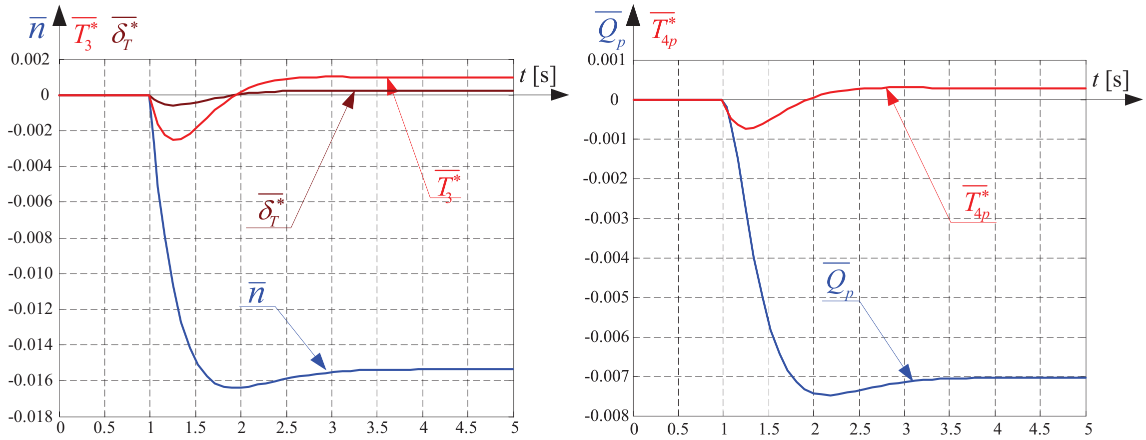


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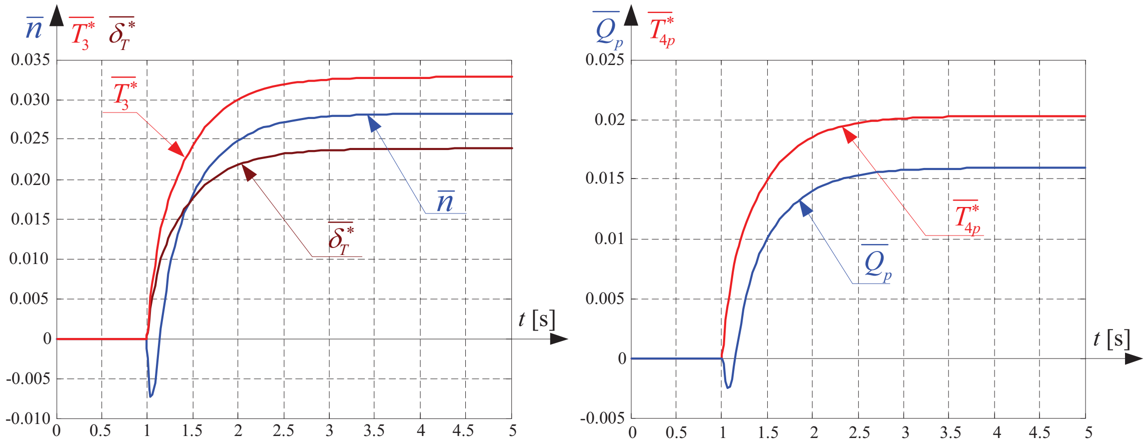
Figure 5: EAS step response for constant throttle position $\overline{\theta} = 0$ and flight regime $\left(\overline{p_1^*}\right)$ step input



a) b)

Figure 6: EAS step response for combined (throttle position and flight regime) step input

static errors are positive and very small, under 0.1%. Gas-turbine pressure ratio parameter $\overline{\delta_T^*}$ has similar behavior, but its static error is insignificant, being practically null. The time of stabilization is a little longer for each parameter, being 4÷4.5 s.

When both of the input parameters have step variations, the effects are overlapping, so system's behavior is the one in fig. 6.a and 6.b. All studied parameters are asymptotic stabile, except the engine speed and the afterburning fuel flow rate, which have small initial decreasing (due to the initial exhaust fast opening). As result of the effects overlapping, the static errors have decreased, being smaller than 3.3%; the biggest static error is the one for temperature parameters.

One of the most important output parameter is the total thrust, which means the combined thrust of EAS (both of the studied propulsion systems, which means the combination single-jet single-spool engine and afterburning). Using the formula given by [12]

$$(\tau_m s+1)\overline{F_p} = k_{Fc}\left(\tau_{fpc}s+1\right)\overline{Q_c} + k_{fpA}\left(\tau_{fpA}s+1\right)\overline{A_5} + + k_{fpp}\left(\tau_{fpp}s+1\right)\overline{Q_p}\ , \qquad (19)$$

one has obtained the behavior in fig.7.

As the figure 7 shows, the total thrust, when the flight regime becomes more intense, has a periodical behavior (dash-dot curve); it tends initially to decrease, but, eventually, it grows slowly and stabilizes itself with a very small static error, around 0.4%. Meanwhile, when the throttle is pushed up, the total thrust grows, as consequence of all involved parameters growing (engine speed, fuel flow rates and temperatures); system's total thrust for constant flight regime and throttle repositioning is represented by the dash curve in fig. 7. EAS stability is a non-periodic one, and the static error is around 4%.

For a combined step input, one can observe that the

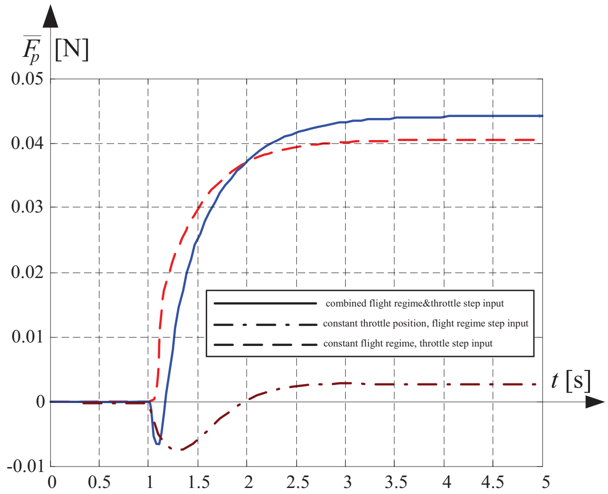


Figure 7: Total thrust of the engine with afterburning system (EAS combined thrust)

flight regime's influence is smaller then the throttle's positioning influence, total thrust's behavior (continuous curve) being very similar to the throttle's positioning behavior; static error is 4.5% and the time of stabilization – around 4.5 s.

5. CONCLUSION

As a final conclusion, one can affirm that the afterburning is an efficient method for thrust augmentation. Although, coupling a fuel pump to the basic engine's shaft has as consequence the appearance of a new feedback in the engine's model, involving the afterburning fuel flow rate; meanwhile, in order to keep unchanged the basic engine regime during the afterburning operation, one has to control the engine's fuel flow rate and its exhaust nozzle opening in order to keep constant the gas-turbine pressure ratio.
The method an the results can be extended for other types of jet engines, such as double-spool or multi-spool jet engines, or even twin jet engines.

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