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COMPLEX CONTROL SYSTEM FOR A JET ENGINE WITH AFTERBURNING AND MULTI-RAMP FUEL SYSTEM

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Abstract: *This paper deals with a complex control system for an aircraft engine with afterburning. The paper is based on other papers, which have studied individually some control systems. Engine's mathematical model was built from VK-1F engine, which was considered as using an afterburning system with multiple fuel injector ramps. The embedded control system uses also three controllers (for engine's speed, for the exhaust nozzle and for afterburner's fuel injection). The author has performed some simulation, based on the combined mathematical models of system's main parts, concerning system's quality (system time behavior for throttle position step input). The simulation results were presented as graph(s); several useful conclusions were drawn, regarding system's behavior. System's mathematical model and its time behavior, as well as the conclusions, may be useful in similar further studies.*

Keywords: *afterburning, fuel, control, throttle, turbine, exhaust-nozzle, jet-engine, speed*

1. INTRODUCTION

One of the most efficient aircraft engine's thrust augmentation method is the after-burning, which means the controlled fuel injection and burning in a special kind of combustor, mounted after the engine's gas turbine, before the exhaust nozzle, called "afterburner".

Gas-dynamic principles and the equations, for both of the basic jet engine as well as the afterburning system, are presented in [4], [5] and [9]. Meanwhile, the basic single-spool single jet engine and the afterburning system as controlled objects are depicted in [7], [9] and [10]; a possibility for the afterburner's fuel pump automatic control was presented by the author in [12] and a similar simplified system in [10]; a complex integrated system (engine-afterburner) was also presented by the authors in [13].

This paper has as main purpose to identify the embedded system (single-spool jet-engine and afterburning system, also called EAS, with specific controllers) as controlled object and to determine its simplified mathematical model, as well as its time behavior.

One can affirm that EAS is an inter-connection between two propulsion systems, the basic engine and the afterburning, both from gas-dynamic and control point of view. Both of EAS main parts are supplied with the same fuel type but by different pumps; these pumps are driven by the basic jet engine's shaft, through an appropriate gear, so each pump speed is proportional (sometimes equal) to the engine's speed *n*, which is the engine's most frequently controlled parameter; between these two fuel-systems there are several principles differences, such as input and output parameters, as well as control type and equipment.

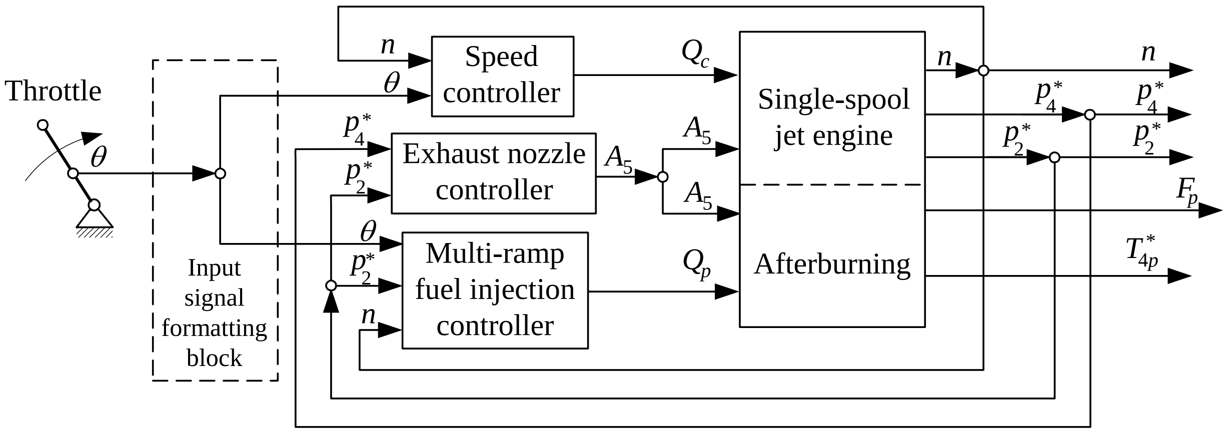


Fig. 1. Single-jet single-spool jet engine with afterburning operational block diagram

Aircraft jet engines as controlled objects are depicted and studied in [8], [9] and [10], where the authors have identified, amongst a multitude of parameters, possible control parameters (inputs), possible controlled parameters (outputs), as well as several command laws. As input parameters, one has identified only three: a) the combustor fuel flow rate Q_c (for all engine types); b) the exhaust nozzle's opening A_5 (for engines with variable-area nozzles); c) the afterburner fuel flow rate Q_p (for engines with afterburning systems).

However, aircraft pilots have at their disposal only the throttle (as single possibility to control the engine/propulsion system). Consequently, the throttle has to generate somehow, by its displacement, the input signals formatting, which means that EAS input parameters should be determined as some other control sub-systems' outputs.

2. SYSTEM'S PRESENTATION

Fig. 1 presents an operational block diagram of an EAS, assisted by three controllers, each one giving an EAS input parameter, respectively Q_c, A_5 and Q_p.

One can observe that A_5 is involved both in the basic single-jet engine control and in the afterburning control, while the fuel injection operates separately for each one of the EAS sub-systems.

Main output parameter of the above-depicted EAS is the total thrust F_p (that means the thrust of basic engine and afterburning operating simultaneously). Total thrust depends on air flow rate Q_a and on specific thrust F_{sp_p}, which depends on afterburner's temperature T_{4p}^*. One can assume, according to [4] and [5] that between basic engine specific thrust and afterburning specific thrust there is a mathematical relation (being proportional to the square root of the temperature ratio). Consequently,

$$F_p = Q_a F_{sp_p} \approx Q_a F_{sp} \sqrt{\frac{T_{4p}^*}{T_4^*}}, \tag{1}$$

where F_{sp} is basic engine specific thrust.

As secondary output parameters may be considered engine's speed n, engine's combustor temperature T_3^*, afterburner's temperature $T_{4_p}^*$, as well as any other parameter involved in a control scheme.

One has chosen a control scheme, which uses two independent fuel control systems and an exhaust nozzle control system. As far as EAS may have only a single input, which is throttle's displacement, it is compulsory to include a complex input signal-formatting block; its essential role is to establish the reference or input parameter(s), with respect to throttle position, for the control systems which use throttle's positioning in their structure. Consequently, for this EAS, one uses:

a) a fuel injection control system for the basic engine, which operates as engine's speed controller;
b) a multi-ramp fuel injection system for the afterburning, which operates as follower system, with respect to the

throttle's position, in correlation with air (or burned gases) flow rate;

c) an exhaust nozzle opening control system, which operates with respect to the engine's turbine pressure ratio (in order to keep it constant and keep the basic engine stable, even when the afterburning is operating).

Furthermore, both fuel pumps are driven by the engine's shaft, so engine speed becomes an inner feedback parameter (as fig. 1 shows). Consequently, during EAS dynamic regimes, all input parameters are modifying.

One has chosen, for a quantitative study, as EAS a VK-1F-type engine, as speed controller a system with constant pressure chamber [11], as afterburning fuel injection system a multi-ramp fuel injection follower system [14] and as exhaust nozzle controller a constant turbine pressure ratio system [2]. Embedded system (consisting of EAS and controllers) should be modeled and studied as controlled object.

3. SYSTEM'S MATHEMATICAL MODEL

Embedded system mathematical model consists of joined mathematical models of the above-mentioned main parts: EAS, input formatting block, speed controller, exhaust nozzle controller and afterburning fuel injection controller.

3.1. Jet engine with afterburning model

EAS linearised adimensional mathematical model is expressed by a matrix equation (as determined in [7] and [9])

$$A \times u = b, \tag{2}$$

where A is the engine's matrix, u – controlled parameters vector and b – control parameters vector, as follows

$$A = \begin{bmatrix} \tau_1 s + \rho_1 & -k_{1T3} & -k_{1p2} & -k_{1p4} & 0 & 0 \\ k_{2n} & -k_{2T3} & k_{2p2} & 0 & 0 & 0 \\ 0 & -1 & -k_{3p2} & k_{3p4} & 0 & 1 \\ 0 & k_{4T3} & k_{4p2} & k_{4p4} & -k_{4Tp} & 0 \\ k_{5n} & k_{5T3} & k_{5p2} & 0 & 0 & 0 \\ 0 & k_{6T3} & k_{6p2} & 0 & k_{6Tp} & k_{6T4} \end{bmatrix}, \tag{3}$$

$$u^{\mathrm{T}} = \begin{pmatrix} \overline{n} & \overline{T_3^*} & \overline{p_2^*} & \overline{p_4^*} & \overline{T_{4p}^*} & \overline{T_4^*} \end{pmatrix}, \tag{4}$$

$$b^{\mathrm{T}} = \begin{pmatrix} 0 & 0 & 0 & k_{4A}\overline{A_5} & k_{5Qc}\overline{Q_c} & k_{6Qp}\overline{Q_p} \end{pmatrix}, \tag{5}$$

where the involved coefficient forms are those presented in [7].

Amongst the output parameters there are several of them usable in the control schemes, or important as output parameters, such as $\overline{n}, \overline{p}_2^*, \overline{p}_4^*$ and $\overline{T}_{4_p}^*$. Their expressions will be determined solving the matrix equation by the Cramer method.

Particularly, for VK-1F engine with afterburning,

$$A = \begin{bmatrix} \begin{matrix} 0.83s + \\ +3.15 \end{matrix} & -0.5 & -2.25 & -1.2 & 0 & 0 \\ 3.1 & 0.5 & -1.9 & 0 & 0 & 0 \\ 0 & -1 & 0.25 & -0.25 & 0 & 1 \\ 0 & -0.5 & 1 & -1 & -1 & 0 \\ 3.1 & 1.8 & -1.17 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & -1 \end{bmatrix}, \tag{6}$$

and the input parameters' coefficients are

$$k_{4A} = 1, k_{Q_c} = 1, k_{Q_p} = 1. \tag{7}$$

After applying the solving Cramer method, one has obtained, in the case of VK-1F (considered at engine maximum operating regime) for the above-mentioned parameters the following expressions

$$\overline{n} = \frac{3.402\overline{A}_5 + 2.3837\overline{Q}_c + 3.402\overline{Q}_p}{2.9413s + 13.486}, \quad (8)$$

$$\overline{p}_2^* = \frac{4.836\overline{A}_5 + (0.5187s + 5.7633)\overline{Q}_c}{2.9413s + 13.486} + \\ + \frac{6.3182\overline{Q}_p}{2.9413s + 13.486}, \quad (9)$$

$$\overline{p}_4^* = \frac{1}{2.9413s + 13.486}\left[-(2.3531s + 0.9942)\overline{A}_5 + \right. \\ \left. + (0.1452s + 7.5263)\overline{Q}_c - (2.3531s + 0.9942)\overline{Q}_p\right] \quad (10)$$

$$\overline{T}_{4p}^* = \frac{1}{2.9413s + 13.486}\left[(0.5883s + 6.2936)\overline{A}_5 - \right. \\ \left. - (0.6121s + 5.3263)\overline{Q}_c + (2.3531s + 7.1188)\overline{Q}_p\right] \quad (11)$$

One can observe that each output parameter is a function of input parameters, but they have a different dependence.

In terms of total thrust, it shall be treated by the same method. According to [7] and [10], one can assume that $Q_a = Q_a\left(p_2^*\right)$, respectively $F_{sp} = F_{sp}\left(T_3^*, p_2^*, T_4^*\right)$; applying the same linearisation method for Eq. (1), one obtains

$$\overline{F}_p = k_{FT3}\overline{T}_3^* + k_{Fp2}\overline{p}_2^* + k_{Fp4}\overline{p}_4^* + k_{FT4}\overline{T}_4^* + \\ + k_{FTp}\overline{T}_{4p}^*. \quad (12)$$

Finally, one has to complete *A*-matrix with a seventh line, given by Eq. (12) and with a column given by vector (5), where the coefficients are keeping their expressions. It results, for the last line

$$\begin{bmatrix}0 & -1.2 & -0.13 & -2.2 & 0.5 & 0.5 & 0\end{bmatrix}, \quad (13)$$

which completes *A*-matrix in (6). It results, for the total thrust

$$\overline{F}_p = \frac{-(4.4883s + 1.3816)\overline{A}_5 + 2.1196s\,\overline{Q}_c}{2.9413s + 13.486} + \\ + \frac{24.7434\,\overline{Q}_c + (6.0591s + 6.3248)\overline{Q}_p}{2.9413s + 13.486}. \quad (14)$$

Equations (8), (9), (10), (11) and (14) are the EAS linear mathematical model.

EAS has a single input, which is throttle's position θ. One can affirm that throttle's positioning has two operation intervals:

- from "idle" to "maximal" (or "full"), when it controls the basic engine's speed, θ being proportional to the speed reference n_{ref};
- beyond "maximal", into afterburning domain, when θ is conceived to be proportional to F_p total thrust. In fact, it can be assumed as proportional to Q_p (consequently, to T_{4p}^*).

Such a throttle assisting system (input signal formatting block) is presented in [3]; a similar system is described in [10], but operating after a different command law, $A_5 = A_5(\theta)$.

3.2. Engine speed controller model

Fuel system for the basic engine consists of a fuel pump with constant pressure chamber, pump's actuator and fuel valve (commanded by the throttle); a correction with the flight regime ($\overline{p}_1^*$) may be used, if a capsules system is added. This kind of fuel system is the speed controller and it was studied in [11]; its simplified mathematical model is reduced at a single equation, as follows

$$\overline{Q}_c = \frac{0.683\overline{\theta} - (0.125s + 0.836)\overline{p}_1^*}{0.078s^2 + 1.813s + 5.3068} + \\ + \frac{(0.9065s + 2.4795)\overline{n}}{1.6183s + 6.308}. \quad (15)$$

The fuel flow rate (supplied by the engine's main pump) depends on the throttle's position, on the flight regime, as well as on the effective engine's speed. If one assumes the flight regime as constant, the term in (15) containing the air inlet pressure parameter $\overline{p}_1^*$ becomes null.

3.3. Exhaust nozzle's controller model

For EAS', no matter their constructive solution were, it is compulsory that exhaust nozzle has variable exhaust area.

Exhaust nozzle's effective area is both an engine input parameter and an afterburning input parameter, but it is also a controlled parameter, from its controller point of view.

During afterburning operation, fluid pressure and temperature behind the turbine may significantly increase, which leads to an engine speed decrease; in order to keep it constant, exhaust nozzle must be open. Consequently, exhaust nozzle's control law has to be engine's turbine pressure ratio constancy; in order to "separate" the basic engine operation from the afterburning operation, more precisely, to keep the basic engine at maximum regime, no matter the afterburning regime were.

Such a controller was depicted and studied in [2] (and partially in [13]). It works with respect to the gas pressure before and behind the turbine ($\overline{p}_3^*$, respectively $\overline{p}_4^*$), but because of the very high gas temperature before the turbine, one has to use the air pressure behind the compressor $\overline{p}_2^*$ instead of $\overline{p}_3^*$, those two pressure values being close enough to make possible this replacement.

Exhaust nozzle's simplified mathematical model is

$$\overline{A}_5 = \frac{0.2524s^2 + 1.6634s + 1.5816}{(0.81s+1)(0.187s+1)(0.23s+5.17)} \times \left(\frac{0.234}{0.187s+1} \overline{p}_4^* - \overline{p}_2^* \right), \tag{16}$$

which is a 3-rd order system, but a stable one, because of characteristic polynomial's roots, which are all real and negative (as the denominator in Eq. (16) shows).

3.4. **Afterburning multi-ramp fuel injection controller** was depicted and studied in [14]. Fuel injection controller is a follower system, which operates with respect to the throttle's position, fuel flow rate Q_p being correlated to the air flow rate (air pressure behind the compressor), in order to assure an optimum air-fuel mixture.

Simplified mathematical model, determined in [14] as particular system for a VK-1F type engine, has the following form

$$\overline{Q}_p = \frac{4.957}{s^4 + 15.01s^3 + 88.93s^2 + 172.11s + 119.94} \times \left[0.448\overline{\theta} - 0.397\overline{p}_2^* + \left(0.023s^2 + 0.062s + 0.076\right)\overline{n} \right], \tag{17}$$

where the term containing $\overline{n}$ may be neglected, if one considers that afterburning fuel pump is driven at constant speed, or if the fuel supplying is made through a constant pressure valve.

Embedded system's mathematical model consists of Eqs. (8), (9), (10), (11), (14), (15), (16) and (17).

4. EMBEDDED SYSTEM"S QUALITY

System's quality study consists of system's step response analysis, for a step input (step throttle displacement). One has considered as studied regime the maximal engine's operating regime (full thrust regime), when afterburning may be switched on.

Most important output parameter is total thrust; although, one has also studied some other important input/output parameters behavior (such as speed, fuel flow rates, exhaust nozzle's area, turbine's pressures).

As presented in section 1 and 2, EAS effective inputs are exhaust nozzle's area and fuel flow rates; main output is total thrust (as well as afterburner's temperature), while secondary outputs are engine's speed and turbine pressures, which are used as inputs or feed-back in controllers' operating block diagrams.

System's quality (its time behavior) was studied in two different cases:

a) constant flight regime ($\overline{p}_1^* = \text{const.}$) and throttle step input;
b) constant throttle position ($\overline{\theta} = \text{const.}$) and step input for $\overline{p}_1^*$ (flight regime).

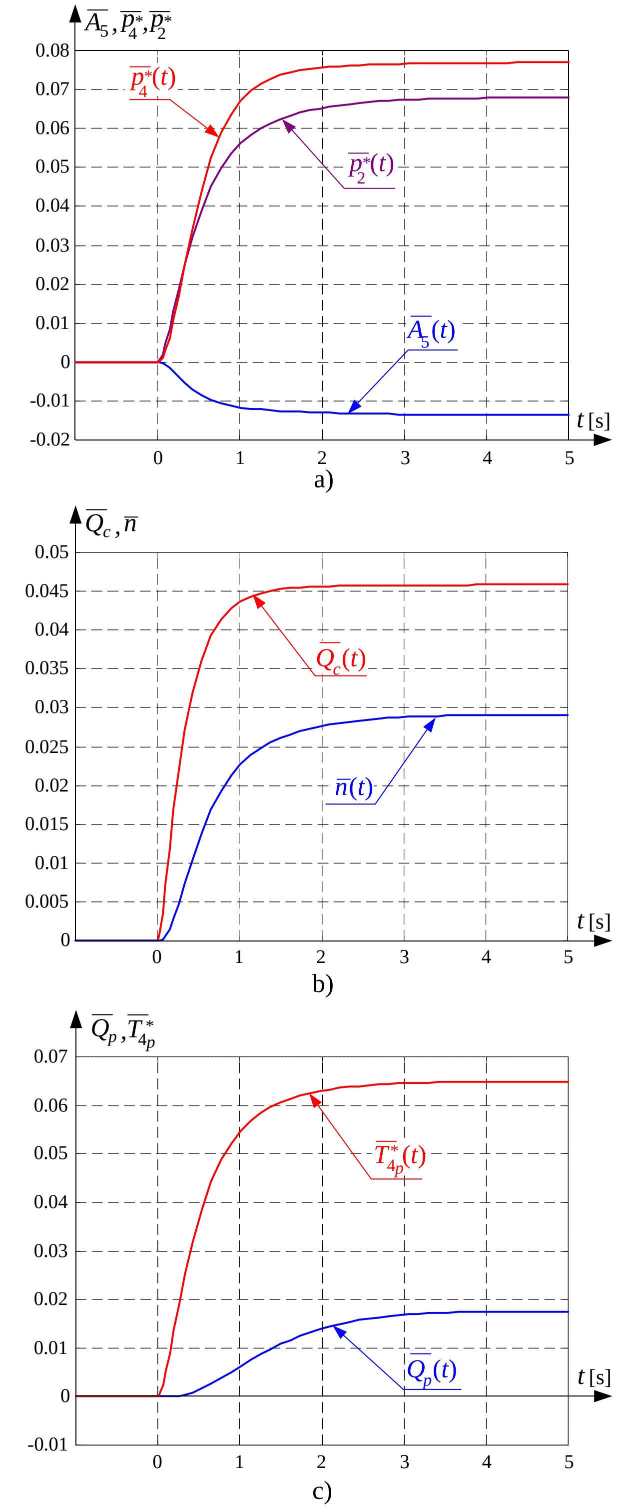


Fig. 2. System step response for $\overline{\theta}$ throttle position parameter step input and constant $\overline{p}_1^*$ air pressure parameter

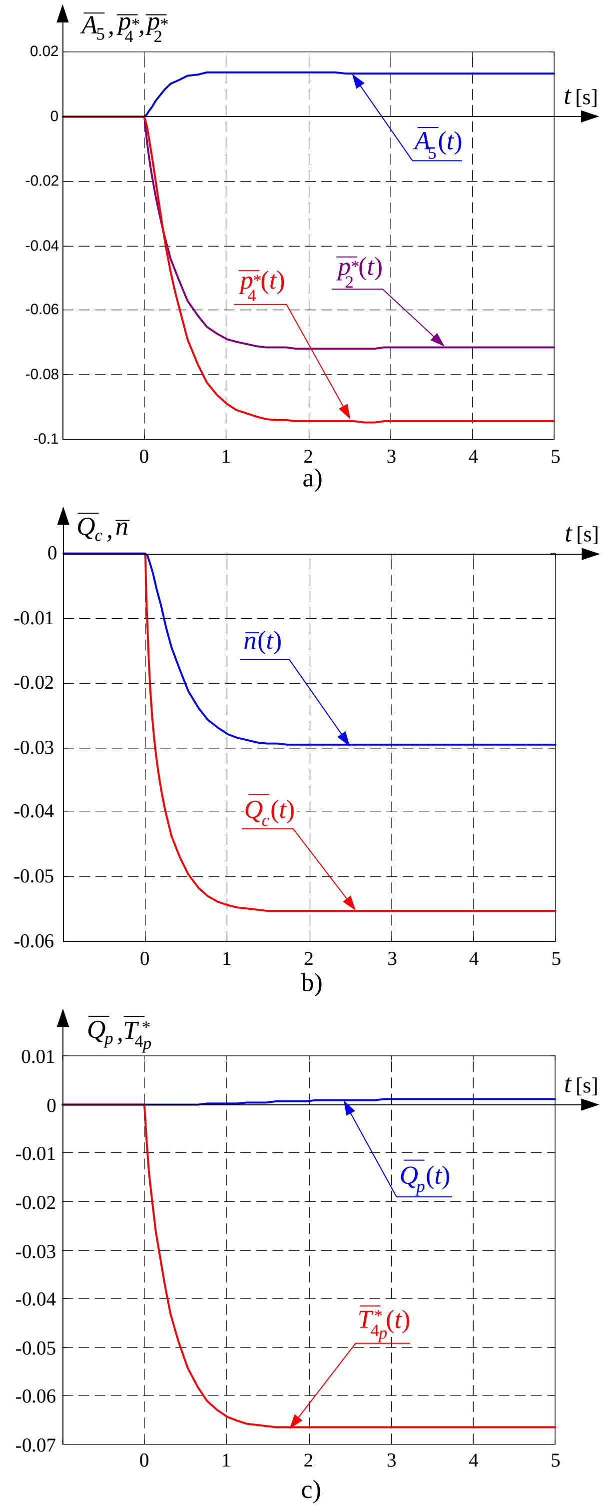


Fig. 3. System step response for $\overline{p}_1^*$ air pressure parameter step input and constant $\overline{\theta}$ throttle position parameter

System behavior for the throttle's position step input is presented in fig. 2.

Fig 2.a shows the exhaust nozzle's opening parameter behavior, as well as turbine pressures' parameters behavior. All of the studied parameters have an asymptotic stabilization, which is an appropriate behavior, but with static errors. Although both of pressures' parameters have large positive static errors (7% to 8%), exhaust nozzle's opening has a very small, but negative, static error (-1.4%). In terms of response time, pressures' stabilization is realized in 3 to 4 s, while exhaust opening response time is around 2.5 s.

Basic engine's speed $\overline{n}$ parameter's behavior, as well as main engine's input parameter $\overline{Q}_c$ are shown in fig. 2.b, both of them having aperiodic behavior and acceptable static errors (4.6% for $\overline{Q}_c$ and 2.8% for $\overline{n}$), as well as acceptable response times (around 3 s).

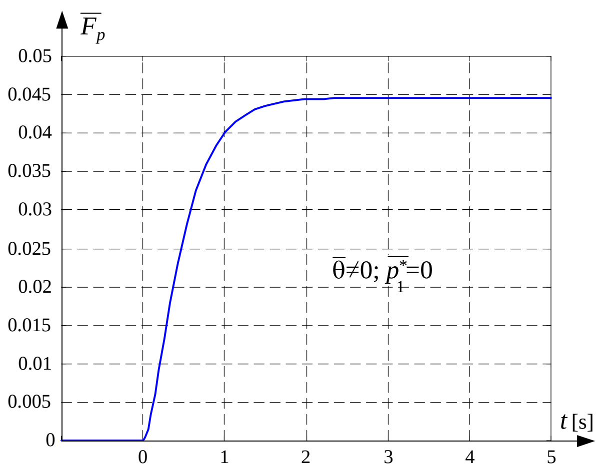
Afterburning characteristic parameters' behavior (fuel flow rate $\overline{Q}_p$ and afterburner's temperature $\overline{T}^*_{4_p}$) are presented in fig. 2.c. Both of studied parameters are asymptotic stable, with acceptable static errors (1.8% for $\overline{Q}_p$ and 6.3% for $\overline{T}^*_{4_p}$), but with a little large response times, $(3 \div 4)$ s.

EAS main output parameter, total thrust $\overline{F}_p$, has also asymptotic stability with static error (4.4%) and a short response time (2.2 s), as fig. 3.a shows.

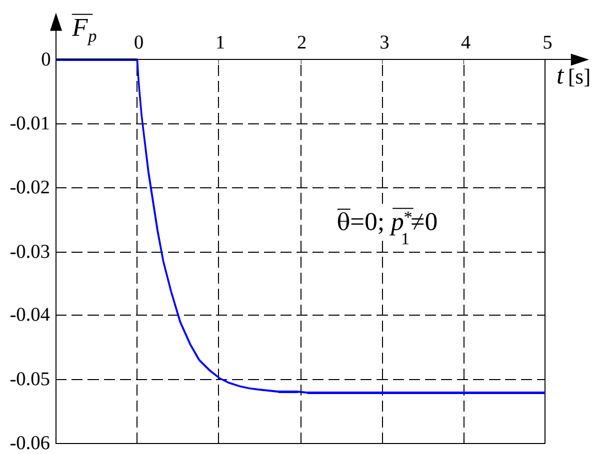
Second studied case, when engine's throttle is held fixed and flight regime is considered as step input, is presented in figures 3.a, b, c and 4.b. One can observe that flight regime's involving (through the air pressure parameter $\overline{p}^*_1$) is effective only for basic engine's fuel flow rate, as shown in Eq. (15). Furthermore, as far as $\overline{Q}_c$ is an input parameter, one can observe different levels of influence above the rest of parameters.

Thus, most of all parameters have negative static errors, having an opposite behavior than in the other studied case. Static errors, as well as response times, are very near to the other case; static errors are larger and negative, excepted exhaust nozzle's area and afterburning fuel flow rate. In terms of $\overline{Q}_p$, one can observe an insignificant positive static error, which means that aircraft (and engine) flight regime has no influence on it.

Total thrust, as fig. 4.b shows, makes no exception, being asymptotically stable, but with a negative larger static error (5.2%). One can affirm that flight regime (given by $\overline{p}^*_1$) has contrary influence than engine's regime (given by $\overline{\theta}$) and generates larger static errors.



a)



b)

Fig. 4. EAS total thrust time behavior

5. CONCLUSION

This paper has studied an aircraft jet engine with afterburning as controlled object. Jet engine VK-1F was considered as basic engine and three controllers were theoretically adapted to it. Control laws were established in order to keep the embedded system stable running, no matter its operation regime and/or flight regime were. Those control laws were determined and verified for different cases and presented in some other papers.

Afterburning must be switched on only when basic engine has reached its maximal regime and should operate without influence above the basic engine's regime. Therefore, one has emphasized the inner feedback involving in the exhaust nozzle opening control, as well as in other main input parameters generating.

Some simulations were performed, using the mathematical model(s), for each system part, as well as for whole embedded system; two cases were studied, respectively the engine operation influence and the flight regime influence. Based on it, one has established system's quality, which has proved itself to be a stable one.

One also has considered the afterburning fuel pump driven by the engine's shaft. If one chooses to neglect it (because of its small speed variation range), one obtains insignificant differences, as shown in fig. 4.a, where the dashed line corresponds to this new situation.

The paper subject and used method can be extended for multi-spool jet engines with afterburning, as well as for further improved studies, concerning other engines, with different coefficient values.

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