COMPLEX ROTATION SPEED CONTROL SYSTEM FOR TWO SHAFTS JET ENGINES

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***Abstract* - This paper deals with a control system for two-shafts turbo engines. The complex system consists of two rotation speed controllers (two control closed loop sub-systems), having a single input - the throttle's position. One establishes the mathematical model, the block diagram with transfer operators and one performs some computer simulations regarding the system's behavior and stability, based on some practical determined co-efficient. The results could be extended for all types of two-spool engines .**

***Keywords*:** *rotation speed, jet engine, turbo-compressor, fuel flow rate, exhaust nozzle, control system.*

1. INTRODUCTION

Most aircraft jet engines are two- or multi-shaft type, so each of its spools (turbo-compressor group) has its own rotation speed; there is no mechanical bondage between them, being only gas-dynamic bounded.

Consequently, there are more possible controlled parameters then control factors (inputs), so a new combination between them is strongly necessary in order to assure the complete and correct aircraft's engine's operating control.

This paper deals wits a two-shaft jet engine, a low-pressure turbo-compressor spool (LPS) and a high-pressure one (HPS); so, the controlled parameters could be their rotation speeds n_1, n_2 and the engine's combustor temperature T_3^*. The control parameters are only two: the fuel flow rate $\dot{M}_c$ and the exhaust nozzle's opening (surface area) A_5, which means that there will be only two directly controlled parameters, chosen of the above mentioned three.

The flight regime (flight speed V and flight altitude H), considered as disturbance, is represented and modeled by the air pressure p_1^* after the intake.

Although, the pilot has only one possibility to control the engine - the throttle's positioning, so this one must "generate" the input signals for both of control parameters ($\dot{M}_c$ and A_5).

Some rotation speed control systems are studied in [3],[7] and [9], which are using as control parameter the fuel flow rate. Such a system, for a single-shaft jet engine, is presented in fig. 1. The exhaust nozzle's flaps position, that means the A_5 value, is one of the control parameters for the multi-shaft engines, but, in the same time, it is a controlled parameter, with respect to the throttle's position (see [1], [5] and [10]), as shown in fig. 2[1].

2. SYSTEM’S STRUCTURE

The complex system presented in this paper has some particular properties:

- it consists of two apparently independent closed-loop control sub-systems;
- it has a single input -throttle's position α, which commands a complex input mechanism (complex input signals forming block);

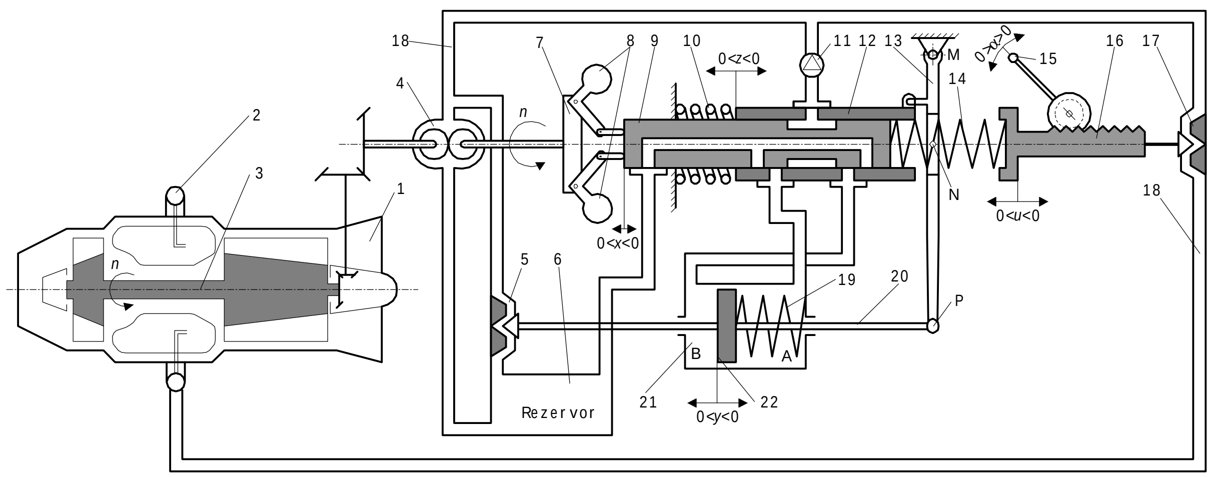


Figure 1. Single shaft engine control system

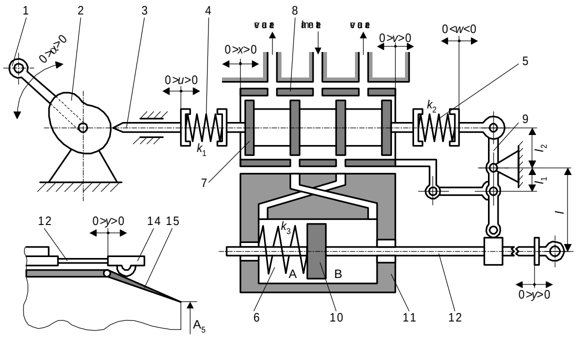


Figure 2. Exhaust nozzle's flaps' positioning system

- the two sub-systems are intrinsic inter-connected, because of the fuel pump, which is turned round by the high pressure shaft and the rotation speed transducer is relayed at the low pressure shaft;
- the combustor's temperature T_3^* is not a *controlled* parameter, but a *limited* parameter, through the fuel flow rate control. That means that the system could have a T_3^* value controller, which reduces the fuel injection when the maximum T_3^* value is overlapped [11];
- a rotation speed limitation is possible , using the same control parameter(s), e.g. fuel flow rate. Both limitations induce rotation speeds, n_1 and n_2, decreasing.

System's functional block-diagram lays in fig. 3.

2.1. Fuel injection control sub-system

For the system in fig. 1, the components are: 1-jet engine; 2-fuel injectors ramp; 3-turbo-compressor spool; 4- fuel pump; 5-shortcutting valve; 6-fuel tank; 7-rotating plate; 8-centrifuge weights; 9-slide valve; 10, 14, 19-springs; 11-pressure equalizing valve; 12-negative feed-back's glider; 13-negative feed-back's lever; 15-throttle; 16- glider; 17- fuel injection cutting valve; 18-main fuel pipeline; 20-servo-amplifier's rod; 21-servo-amplifier; 21-servo-amplifier's piston. Its operating mode, described in [9] and [12], assures the rotation speed control by the fuel injection dosage.

System's non-dimensional linear equations are [9]:

$$(T_M \mathrm{D}+1)\overline{n} = k_c \overline{\dot{M}_c} - k_{p1}\overline{p_1^*}, \quad (1)$$

$$\overline{\dot{M}_c} = k_{pn}\overline{n} + k_{py}\overline{y}, \quad (2)$$

$$(T_m^2 \mathrm{D}^2 + T_x \mathrm{D} + 1)\overline{x} = k_u\overline{u} - k_{es}\overline{n}, \quad (3)$$

$$k_{sx}\overline{x} - k_{sz}\overline{z} - k_{sy}\mathrm{D}\overline{y} = \frac{1}{k_{ap}}\left(T_{sp}\mathrm{D}+1\right)\left(\overline{p}_A - \overline{p}_B\right), \quad (4)$$

$$\overline{y} = \frac{k_{yp}}{T_{mp}^2 \mathrm{D}^2 + T_{xp}\mathrm{D} + 1}\left(\overline{p}_A - \overline{p}_B\right), \quad (5)$$

$$\overline{z} = r_l \frac{y_0}{z_0}\overline{y}, \quad (6)$$

$$\overline{u} = k_{ua}\overline{a}\ , \quad (7)$$

where the equations' arguments, time constants and amplifying co-efficient are given by the formulas in [9] and [12].

Particularly, when this kind of control system is integrated in a two-shaft engine control system, it has the fuel pump's rotor turned round by the HPS and the transducer's plate 7 by the LPS.

2.2. Exhaust nozzle's opening control sub-system

For the system in fig. 1, the components are: 1-lever

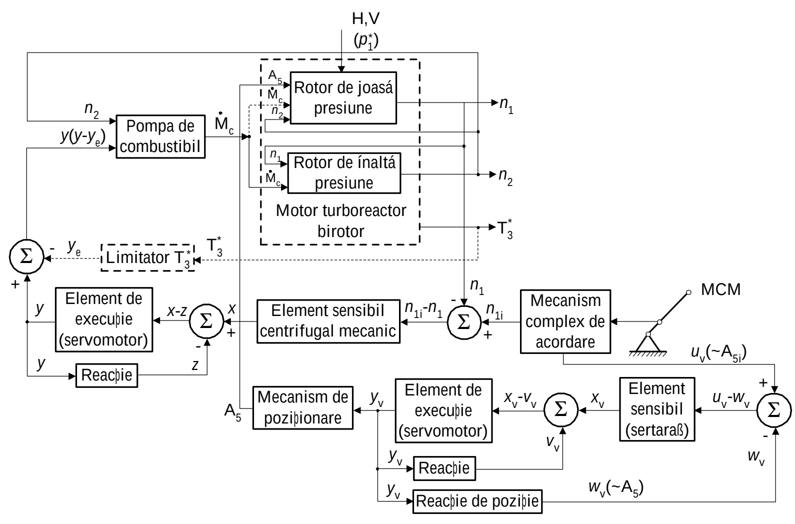


Figure 3. System's functional block-diagram

displaced by the throttle; 2-cam; 3-cam follower; 4,5-springs; 6-servo-amplifier's spring; 7-slide valve; 8-glider; 9-feed-back lever; 10- servo-amplifier's piston; 11- servo-amplifier (actuator); 12-rod; 13-lever; 14-flap positioning ring; 15-exhaust nozzle's flap.

System's non-dimensional linear equations are [1]:

$$K_a \overline{a} - K_{2y}\overline{y} = \left(T_S^2 \mathrm{D}^2 + T_{xS}\mathrm{D} + 1\right)\overline{x}, \tag{8}$$

$$K_x \overline{x} - \frac{1}{K_{1y}}\left(T_y \mathrm{D} + 1\right)\overline{y} = \frac{1}{K_p}\left(T_p \mathrm{D} + 1\right)\left(\overline{p}_A - \overline{p}_B\right), \tag{9}$$

$$\overline{p}_A - \overline{p}_B = \frac{1}{K_{3y}}\left(T_R^2 \mathrm{D}^2 + T_{xR}\mathrm{D} + 1\right)\overline{y}, \tag{10}$$

$$\overline{A}_5 = K_{5y}\overline{y}, \tag{11}$$

where the equations' arguments, time constants and amplifying co-efficient are given by the formulas in [1] and [12].

2.3. Combustor’s temperature limiting sub-system

This sub-system is optional, being used when the thermal overlap hazard really exists. The main control parameter is the fuel flow rate, and when the combustor's maximum temperature is overlapped, the fuel injection is reduced imposing a supplementary discharging of the fuel's control's servo-amplifier's active chambers [11], which means a reduced rod displacement ($y - y_c$, see fig. 3) and less fuel injected, y_c given by [1]:

$$\overline{y}_c = k_{Ty}\overline{T}_3^*; \text{if } T_3^* \geq \left(T_3^*\right)_{\max}. \tag{12}$$

3. MATHEMATICAL MODEL

The mathematical model consists of the reunion of the sub-system's equations:

- engine's shafts' equations [8];
- fuel flow rate equations [9];
- fuel pump's command element equation [9];
- exhaust nozzle's flaps' positioning [1].

In order to simplify the system's study, one can assume some supplementary hypothesis, such as the absence of the inertial phenomena, the neglecting of the scrubbing effects and the viscous flow effects etc. Consequently, some co-efficient and time constants become null, so one can obtain a simplified linearised equation system form.

3.1. Linearised equations system

The new form of the mathematical model is:

$$(T_{R1}\mathrm{D} + 1)\overline{n}_1 = k_{c1}\overline{\dot{M}_c} + k_{1n2}\overline{n}_2 + k_{1A5}\overline{A}_5 - k_{HV}\overline{p_1^*}, \tag{13}$$

$$(T_{R2}\mathrm{D} + 1)\overline{n}_2 = k_{c2}\overline{\dot{M}_c} + k_{2n1}\overline{n}_1 \tag{14}$$

$$\overline{\dot{M}_c} = k_{pn2}\overline{n}_2 + k_{py}\overline{y}, \tag{15}$$

$$\overline{u}_n = k_{una}\overline{a}, \tag{16}$$

$$\overline{x} = k_{un}\overline{u}_n - k_{es}\overline{n}_1, \tag{17}$$

$$\overline{z} = r_{sn}\overline{y}, \tag{18}$$

$$t_{sn}\mathrm{D}\overline{y} = \overline{x} - \overline{z}, \tag{19}$$

$$\overline{u}_v = k_{uva}\overline{a}, \tag{20}$$

$$\overline{A}_5 = \frac{1}{t_{sv}\mathrm{D} + r_{sv}}\overline{u}_v. \tag{21}$$

The system could be completed by the combustor's temperature equation:

$$\left(T_2^2\mathrm{D}^2 + T_1\mathrm{D} + 1\right)\overline{T}_3^* = \left(l_{3cT}\mathrm{D}^2 + l_{1cT}\mathrm{D} + l_{0cT}\right)\overline{\dot{M}_c} -$$

$$-\left(l_{1AT}\mathrm{D} + l_{0AT}\right)\overline{A}_5, \tag{22}$$

where the equations' arguments, time constants and amplifying co-efficient are given by the formulas in [1], [7], [9] and [12].

Based on these equations, one can elaborate the system's block diagram with operators, as presented in figure 4.

3.2. System’s transfer operators

Based on the above presented mathematical model and the block diagram in fig. 4, one can define the system's transfer operators: $H_{1a}(\mathrm{D})$ and $H_{2a}(\mathrm{D})$ with respect to the throttle position, respectively $H_{1p}(\mathrm{D})$ and $H_{2p}(\mathrm{D})$ with respect to p_1^*, that means to the flight regime. Their forms are:

$$H_{1a}(\mathrm{D}) = \frac{b_{21}\mathrm{D}^2 + b_{11}\mathrm{D} + b_{01}}{a_{41}\mathrm{D}^4 + a_{31}\mathrm{D}^3 + a_{21}\mathrm{D}^2 + a_{11}\mathrm{D} + a_{01}}, \tag{23}$$

$$H_{2a}(\mathrm{D}) = \frac{b_{41}\mathrm{D}^4 + \ldots + b_{12}\mathrm{D} + b_{02}}{a_{62}\mathrm{D}^6 + a_{52}\mathrm{D}^5 + \ldots + a_{12}\mathrm{D} + a_{02}}, \tag{24}$$

$$H_{1p}(\mathrm{D}) = \frac{c_{31}\mathrm{D}^3 + c_{21}\mathrm{D}^2 + c_{11}\mathrm{D} + c_{01}}{a_{41}\mathrm{D}^4 + a_{31}\mathrm{D}^3 + a_{21}\mathrm{D}^2 + a_{11}\mathrm{D} + a_{01}}, \tag{25}$$

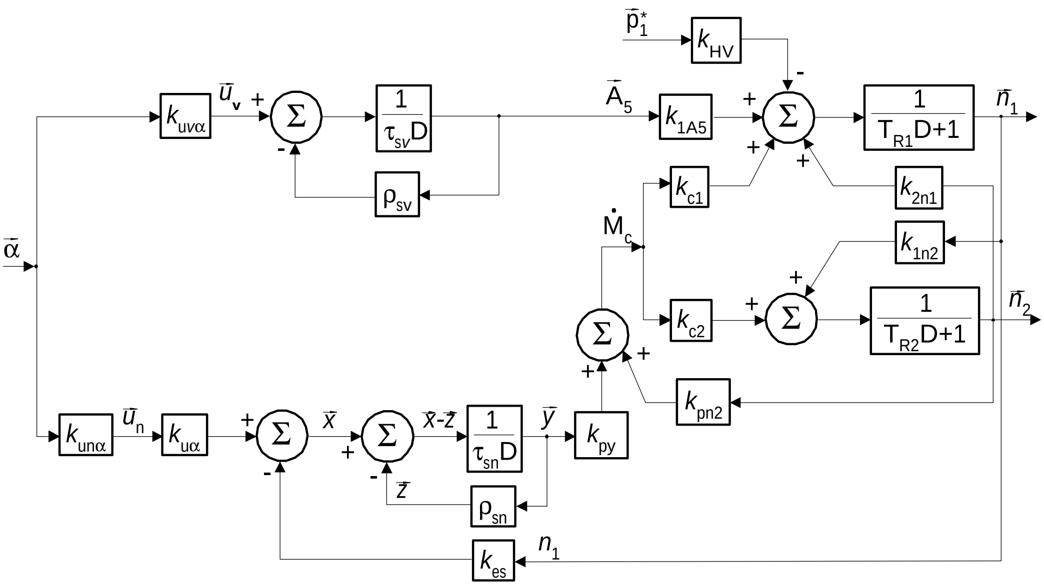


Figure 4. System's block diagram with transfer operators

$$H_{2p}(\mathrm{D}) = \frac{c_{42}\mathrm{D}^4 + \ldots + c_{12}\mathrm{D} + c_{02}}{a_{62}\mathrm{D}^6 + a_{52}\mathrm{D}^5 + \ldots + a_{12}\mathrm{D} + a_{02}}; \qquad (26)$$

the formulas for the co-efficient $a_{41},\ldots,a_{01},a_{62},\ldots,a_{02}$, $b_{21},\ldots,b_{01},b_{42},\ldots,b_{02},c_{31},\ldots,c_{01},c_{42},\ldots,c_{02}$ are given in [12], with respect to the mathematical model equations' [eq. (13) to eq. (21)] co-efficient.
For a steady state regime, one obtains:

$$\bar{n}_1(t) = \frac{b_{01}}{a_{01}}\bar{\alpha}(t), \qquad (27)$$

$$\bar{n}_2(t) = \frac{b_{02}}{a_{02}}\bar{\alpha}(t) = k_{n2a}\bar{\alpha}(t) + k_{n21}\bar{n}_1(t), \qquad (28)$$

$$\bar{n}_1(t) = \frac{c_{01}}{a_{01}}\overline{p_1^*}(t), \qquad (29)$$

$$\bar{n}_2(t) = \frac{c_{02}}{a_{02}}\overline{p_1^*}(t) = -k_{HV}k_{n2p1}\overline{p_1^*}(t). \qquad (30)$$

One can observe that both of the throttle's position and the flight regime the system is a static one, the rotation speeds having static errors, as the above formulas are showing.

4. ABOUT THE CONTROL SYSTEM'S STABILITY AND QUALITY

Analyzing the transfer operators form, one can observe that their characteristic polynoms have 4$^{\text{th}}$ degree (for H_{1a} and H_{1p}), respectively 6$^{\text{th}}$ degree (for H_{2a} and H_{2p}). Because of the complicated co-efficient forms and of the high degree of the characteristics polynoms, it is difficult to use Routh-Hurwitz stability criteria for study.
One has performed a study using data about a two-shaft turbo-jet engine R-11F-300, which permitted the co-efficient values calculus ([4], [12], [8]): $T_{R1} = 0.3087\,\mathrm{s}$; $T_{R2} = 0.453\,\mathrm{s}$; $k_{c1} = 0.3506$; $k_{c2} = 0.398$; $k_{1n2} = 0.296$; $k_{2n1} = 0.182$; $k_{1n2} = 0.2963$; $k_{1A5} = 0.585$; $k_{pn2} = 0.932$; $t_{sn} = 0.0921\,\mathrm{s}$; $r_{sn} = 1.82$; $t_{sv} = 1.183$; $r_{sv} = 2.627$; $T_2^2 = 0.1181\,\mathrm{s}^2$; $T_1 = 0.788\,\mathrm{s}$; $l_{2ct} = 0.092$; $l_{1ct} = 0.4181$; $l_{0ct} = 0.412$; $l_{1At} = 0.1042$; $l_{0At} = 0.212$; $k_{py} = 1.1683$; $k_{HV} = 0.297$. Using these values and the equations above described, one can configure the characteristic polynoms.
System's stability is estimated using the root locus method, for both of characteristic polynoms, as fig. 5 shows. One can observe that the roots for both of the characteristic polynoms are positioned in the left semiplane, being real and negatives, or being complex and having negatives real parts. So, for all the operating regimes, the rotation speeds n_1 and n_2 are stable.
Concerning the system's quality, that means the system's behavior for some different inputs, one has performed some simulations for the maximum engines regime using as input the step function. One has obtained the rotation speeds behavior, as well as the combustor's temperature behavior for an assumed step input for the throttle's position (that means an instantly throttle displacement between the minimum and the maximum position).

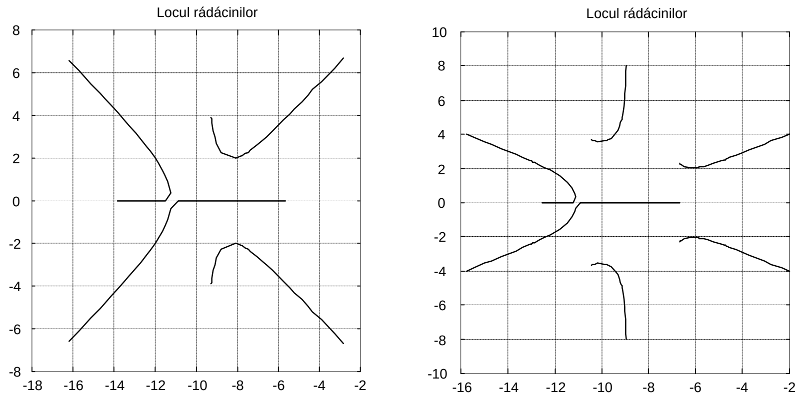
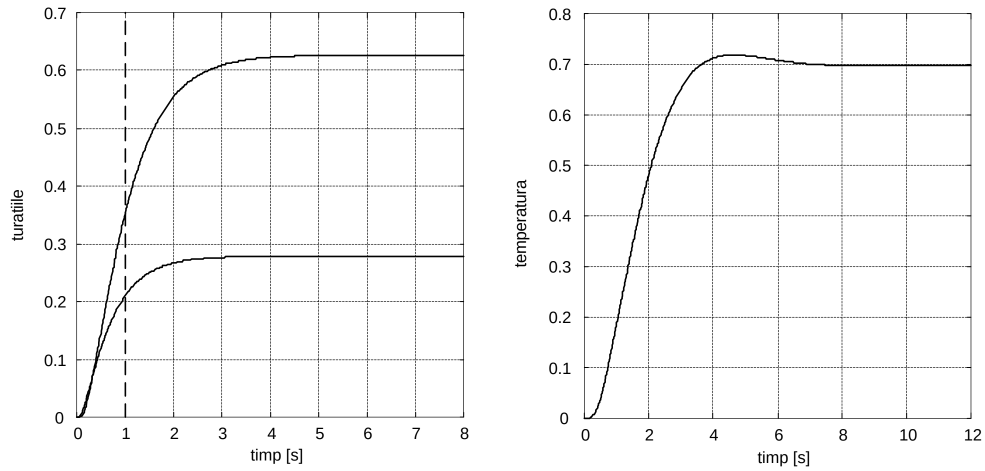


Figure 5. Characteristic polynoms roots-locus diagrams



A. Rotation speed B. Temperature

Figure 6. System's step response for constant flight regime

According to fig. 6.A., for a constant flight regime, both of the rotation speeds are non-periodic asymptotic stable; system's response time varies between 3 s for n_2 and 6 s for n_1, which is perfectly correct for such a two-shaft turbo jet engine. The combustor's temperature stabilizes too, but after a longer time period, about 8.5 s, and with a small initial overlap (see fig. 6.B.), about 4%; this delay's explanation is the delay between the moment of the fuel flow rate stabilization and the air flow rate stabilization.

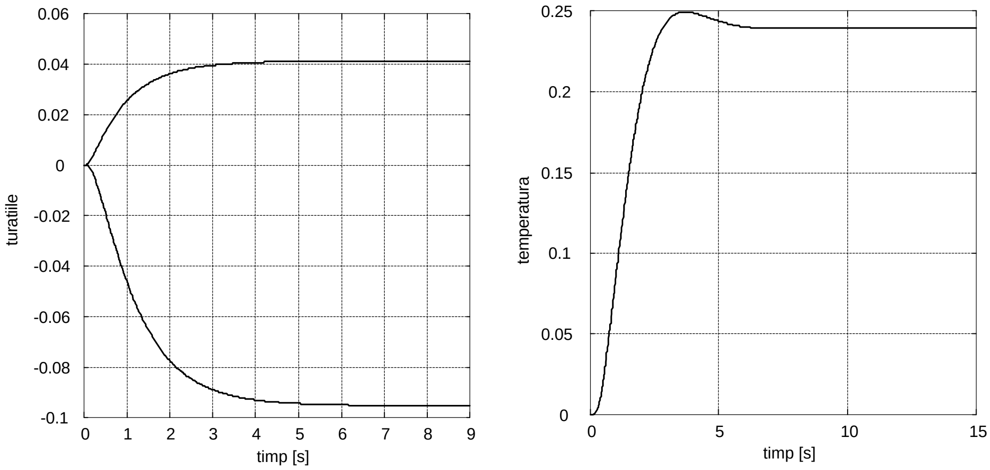
Similarly, one has performed a simulation for a constant engine's regime (fix throttle's position) and a step input for the flight regime (step variation for p_1^*, that means flight speed V grows and/or flight altitude lowers). The graphic results are shown in fig. 7.A. for the rotation speeds and in fig. 7.B. for the combustor's temperature. The rotation speeds have different behaviors, for the same flight regime's variation; although, both speeds stabilize itself, after 4…5 s, but not to the initial value (static errors), because of the system's static properties: the LPS speed gets lower, but the HPS speed gets bigger. The mathematical explanation is that the numerator of the equation (29) is negative, for all value combinations.

As for the T_3^* combustor's temperature, it stabilizes too, but after an overlap, in 6...7 s, because of the necessity of rotation speeds constant mentaining durring the reaccording to a new flight regime.

5. CONCLUSIONS

Based on some earlier results, concerning jet engine's control methods, this paper has realized a modeling of a complex two-shaft engine controller. The linear non-dimensional mathematical model was established and, using some co-efficient values for existent constructive solutions. System's stability and time behavior was estimated using computer simulations for root-locus and step input.

The studied system is a static one, its behavior being affected by static errors. A certain behavior improving could be obtained, if one uses closed loops with elastic feed-back, instead of rigid feed-backs, in



A. Rotation speed B. Temperature

Figure 7. System's step response for constant engine regime

the sub-system's structure; this kind of measures should transform the control sub-systems (for the fuel flow rate and for the exhaust nozzle's flaps positioning) in astatic sub-systems, but, because of the gas-dynamic turbo-compressors' coupling, and the presence of the fuel pumps mechanical coupling (see the presence of the mutual co-efficient k_{1n2}, k_{2n1} in the mathematical model), the main system remains a static one, but with a reduced static error.

The presented results were obtained for a single jet two-shaft turbo-engine, but they could be extended for twin-jets engines, turbo-fan engines etc., for any type of engines which has two spools (two turbo-compressor groups).

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