FUEL PUMP WITH INJECTION PRESSURE CHAMBER FOR A JET ENGINE AFTERBURNING SYSTEM

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Abstract – **This paper deals with a fuel pump with injection chamber, used as main fuel supplying system for an afterburning system, which can be able to serve on a jet engine (single-jet or twin-jet). The fuel system consists of: fuel pump with actuator, pressure ratio transducer, fuel injection chamber and on/off switching system. The author has established the mathematical model of this fuel system, which means the non-linear form, the linearised form as well as the non-dimensional form, based on the small perturbations method. This mathematical model, after the Laplace transformation applying, represents the system's description as controlled object, as well as the basic elements of the block-diagram with transfer functions building. Furthermore, the author has realized some studies about the system's stability and quality; the conditions for the system's stability leads to some interesting results, concerning the criteria for the injection chamber's parts choice. System's quality studies consist of the system step response for the main controlled parameters, offering an image about the system's behavior, as well as about its operability and possibility of interconnection with other systems. The paper is based on some similar works of the author, as well as on similar works presented in the reference list, about aircraft jet engines and engines' main parts as controlled object(s).**

Keywords: *Fuel, Pump, Injection, Afterburning, Jet-engine.*

1. INTRODUCTION

For the aircraft jet engines, the most efficient thrust augmentation method is the afterburning, in spite of its huge fuel consumption.
The gas-dynamic principles, as well as the equations of the afterburning system are presented in [2], [3] and [6]. Meanwhile, the afterburning system as controlled object is depicted in [7], [9] and [11]; a possibility for the afterburner's fuel pump automatic control was presented by the author in [14] and a similar simplified system in [11].
The purpose of this paper is to identify the afterburning fuel pump in fig.1 as controlled object, by describing it through its mathematical model as well as through its transfer function and performing some stability and quality studies, which can be extended for a whole class of such fuel systems, useful for different afterburners.

The fuel system in fig. 1 consists of the following main parts: I-fuel pump; II-pump's actuator; III-injection pressure chamber; IV-engine's gas turbine pressure ratio transducer; V-afterburning on/off switching system.
One can observe that the fuel flow-rate depends on the pump's rotor speed as well as on the pump's plate position (cline angle); fuel's pressure is kept constant by the valves in the injection chamber, so the controlled parameter is the injection fuel flow-rate Q_i, as well as the injection pressure p_i. The control parameters are the pressures before and after the engine's gas turbine, that means the turbine's total pressure ratio δ_T^*. The system must assure the co-relation between the turbine's pressure ratio and the injected fuel flow-rate during the engine's operation, no matter the flight regime is.
The pump is permanently turned round by the engine's shaft, but the afterburning operates only by command, so, when the afterburning is switched-off, the fuel pump only re-circulates the fuel, without injection and burning. This manner of operating is realized by the on/off switch valve and its command equipment (V): when the afterburning is switched-off the electro-magnet 41 moves the slide-valve 42 to the right, so the 38 actuator's B-chamber is supplied with high pressure fuel. Consequently, the spring 40 moves the piston 39 and the slide valve 37 to the left, so the injection pressure chamber (III) supplying main pipe 32 is cut-off (so the afterburner's injectors become inactive). Meanwhile, the pump actuator's B-chamber is supplementary discharged, so the piston 23 moves to the right and its rod 22 reduces the mobile plate's angle to the minimum value, which assures only the fuel re-circulation through the system's components. When the afterburning is switched-on, the mobile plate's angle is established by the actuator's piston 23 positioning, commanded by the pressure balance in the actuator's command block.

2. SYSTEM'S MATHEMATICAL MODEL

The studied system's mathematical model consists of the motion equation for each of its parts. The non-linear equation will be transformed, in order to bring them to an acceptable form for further studies and

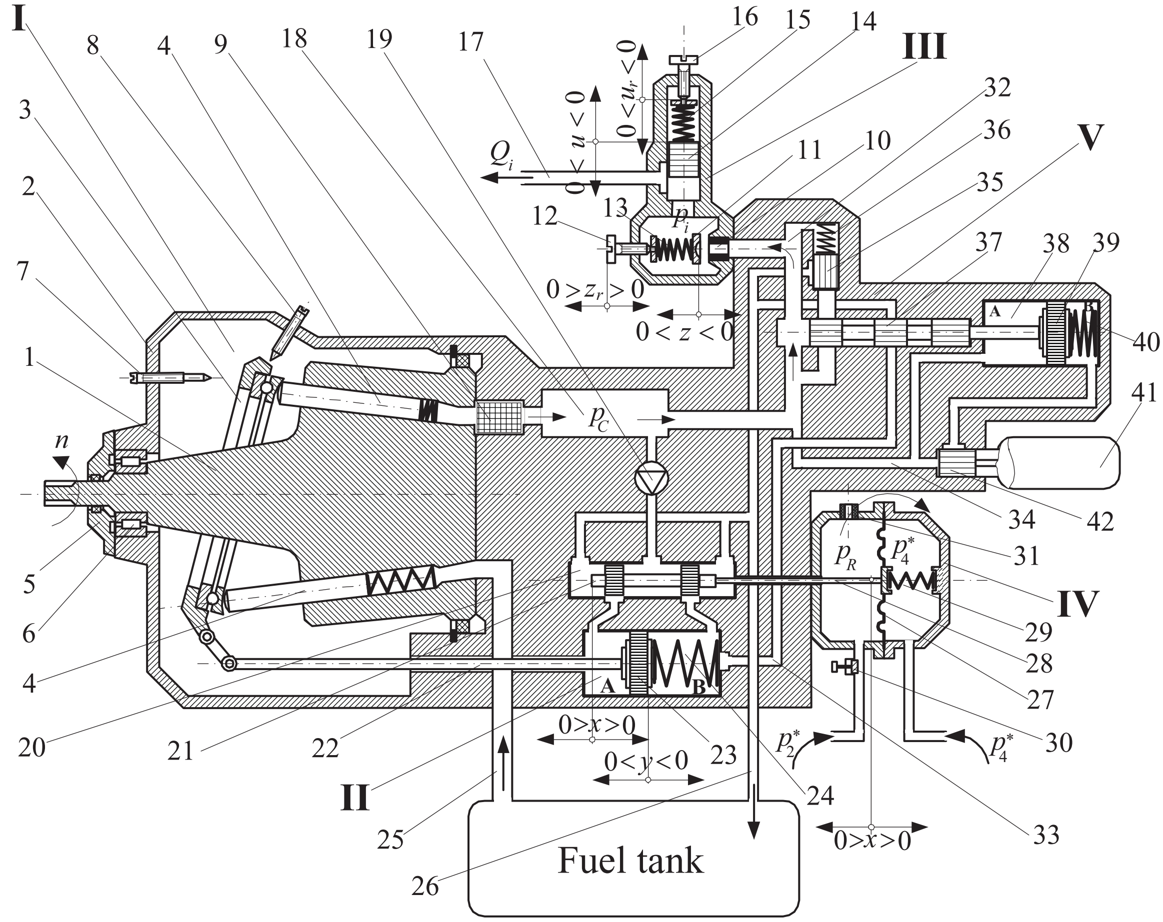


Figure1: Fuel system's constructive and operating schematic

I-fuel pump; II-pump's actuator; III-injection pressure chamber; IV-engine's gas turbine pressure ratio transducer; V-afterburning on/off switching system; 1-pump rotor; 2-pump cradle; 3-mobile plate; 4-plunjers, 5-lid; 6-bearing; 7,8-limitators; 9-fuel filter; 10-drossel; 11-hemispherical valve; 12,16-adjustment bolts; 13,15-springs; 14-slide-valve;17-injection pipe; 18-pump pressure chamber; 19-constant pressure valve; 20-actuator's supplying block; 21-slide-valve; 22-actuator's rod; 23-actuator's piston; 24-actuator's spring; 25-pump supplying pipe; 26-main discharging pipe; 27-transducer's elastic membrane; 28- transducer's rod; 29- transducer's spring; 30-variable fluidic resistance; 31-drossel; 32-main fuel pipe; 33-actuator's supplementary discharging pipe; 34-switching system's supplying pipe; 35, 42-on/off-valves; 36, 40-springs; 37-switching system's main slide valve; 38- switching system's actuator; 39-piston; 41-electro-magnet.

simulations.

2.1. System's non-linear equations

The system non-linear motion equations are
a) fuel pump equations

$$Q_p = Q_p(n, y), \tag{1}$$

$$Q_C = Q_p - Q_a, \tag{2}$$

where Q_p is the pump's fuel flow rate, n – rotor speed, y – actuator's rod displacement, Q_a – command fuel flow rate, Q_C – effective fuel flow rate;

b) fuel pump actuator equations

$$Q_B = \beta V_{B0}\frac{\mathrm{d}p_B}{\mathrm{d}t} + S_B\frac{\mathrm{d}(y+y_s)}{\mathrm{d}t}, \tag{3}$$

$$-Q_A = \beta V_{A0}\frac{\mathrm{d}p_A}{\mathrm{d}t} - S_A\frac{\mathrm{d}(y-y_s)}{\mathrm{d}t}, \tag{4}$$

$$Q_A = \mu_a b_a x\sqrt{\frac{2}{\rho}}\sqrt{p_A - p_a}, \tag{5}$$

$$Q_B = \mu_a b_a x\sqrt{\frac{2}{\rho}}\sqrt{p_B - p_0}, \tag{6}$$

$$p_A S_A - p_B S_B = m_a\frac{\mathrm{d}^2}{\mathrm{d}t^2}(y+y_s) + \xi\frac{\mathrm{d}}{\mathrm{d}t}(y+y_s) + k_{ea}(y+y_s), \tag{7}$$

where Q_A, Q_B – actuator's chambers fuel flow rates, through the slide valve's slots; p_A, p_B – fuel pressure in actuator's chambers; V_{A0}, V_{B0} – actuator chambers' volumes; S_A, S_B – pump actuator piston's surfaces areas; β – fuel's isotherm compressibility co-efficient; μ_a – flow rate co-efficient; b_a – slot's width; y – actuator's rod displacement; p_a – supplying pressure; p_0 – low pressure fuel circuit pressure; x – slide valve's displacement; m_a – actuator piston+ rod ensemble's mass; k_{ea} – actuator spring elastic constant; ξ – viscous friction co-efficient; ρ – fuel density; t – time;

c) pressure ratio transducer equations

$$S_m\left(p_R - p_4^*\right) = m_t \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + \xi \frac{\mathrm{d}x}{\mathrm{d}t} + k_{et}(x + x_r), \quad (8)$$

$$p_R = \frac{S_2}{S_1} p_2^*, \quad (9)$$

where S_m – transducer membrane surface area; p_4^* – gas pressure after the engine's turbine; p_2^* – air pressure after the engine's compressor (considered proportional to the pressure before the turbine p_3^*, so the turbine pressure ratio δ_T^* can be determined by $\delta_T^* = \frac{p_3^*}{p_4^*} \approx \frac{p_2^*}{p_4^*}$); p_R – corrected p_2^* pressure, given by (9), because of the critical flow regime through the 31 and 31 fluidic resistances; S_1, S_2 – effective areas of the fluidic resistances 30 and 31; m_t – transducer's rigid center+rod ensemble's mass; k_{et} – transducer spring's elastic constant; x_r – spring's displacement preset (pre-tensioning);

d) injection pressure chamber equations

$$Q_C = \mu_{10} \pi d_{10} z \sqrt{\frac{2}{\rho}} \sqrt{p_C - p_i}, \quad (10)$$

$$Q_i = \mu_b b u \sqrt{\frac{2}{\rho}} \sqrt{p_i - p_f}, \quad (11)$$

$$Q_C - Q_i = \beta V_{i0} \frac{\mathrm{d}p_i}{\mathrm{d}t} + S_D \frac{\mathrm{d}(u + u_s)}{\mathrm{d}t}, \quad (12)$$

$$\frac{\pi d_{10}^2}{4} p_C = k_e (z_r + z), \quad (13)$$

$$S_D p_i = k_{ei}(u + u_r), \quad (14)$$

where p_C – fuel pressure in pump's chamber; p_i – fuel injection pressure; p_f – pressure in the afterburner chamber; Q_i – injection fuel flow rate; V_{i0} – injection chamber volume; μ_b, μ_{10} – flow rate co-efficient of the injection chamber orifices; d_{10} – injection drossel diameter; b – injection slot width; k_e, k_{ei} – 13 and 15 springs' elastic constants; z, u – 13 and 15 springs' displacement z_r, u_r – 13 and 15 springs' displacement preset (pre-tensioning); S_D – 14 slide-valve frontal area amount.

2.2. Linear equation system

The above determined non-linear equation system is difficult to be used for further studies, so it can be linearized, using the small perturbation method, considering formally any variable or parameter X as $X = X_0 + \Delta X$ and $\overline{X} = \frac{\Delta X}{X_0}$, where ΔX – parameter's deviation, X_0 – steady state regime's value and $\overline{X}$ – non-dimensional deviation.

Introducing the new form of each parameter into the above mentioned equation system and separating the steady state terms, one obtains a new for of the system, as follows

$$\Delta Q_p = k_n \Delta n + k_y \Delta y, \quad (15)$$

$$\Delta Q_C = \Delta Q_p - \Delta Q_a, \quad (16)$$

$$\Delta Q_B = \beta V_{B0} \frac{\mathrm{d}}{\mathrm{d}t} \Delta p_B + S_B \frac{\mathrm{d}}{\mathrm{d}t} \Delta y, \quad (17)$$

$$-\Delta Q_A = \beta V_{A0} \frac{\mathrm{d}}{\mathrm{d}t} \Delta p_A - S_A \frac{\mathrm{d}}{\mathrm{d}t} \Delta y, \quad (18)$$

$$\Delta Q_A = k_{Ax} \Delta x + k_{Ap} \Delta p_A, \quad (19)$$

$$\Delta Q_B = k_{Ax} \Delta x - k_{Ap} \Delta p_B, \quad (20)$$

$$S_A \Delta p_A - S_B \Delta p_B = \left(T_a^2 \frac{\mathrm{d}^2}{\mathrm{d}t^2} + T_{a\xi} \frac{\mathrm{d}}{\mathrm{d}t} + 1\right) \Delta y, \quad (21)$$

$$S_m\left(\Delta p_R - \Delta p_4^*\right) = \left(T_t^2 \frac{\mathrm{d}^2}{\mathrm{d}t^2} + T_{t\xi} \frac{\mathrm{d}}{\mathrm{d}t} + 1\right) \Delta x, \quad (22)$$

$$\Delta p_R = \frac{S_2}{S_1} \Delta p_2^*, \quad (23)$$

$$\Delta Q_C = k_{Cz} \Delta z + k_{Cp}\left(\Delta p_C - \Delta p_i\right), \quad (24)$$

$$\Delta Q_i = k_{iu} \Delta i + k_{ip} \Delta p_i, \quad (25)$$

$$(12) \Delta Q_C - \Delta Q_i = \beta V_{i0} \frac{\mathrm{d}}{\mathrm{d}t} \Delta p_i + S_D \frac{\mathrm{d}}{\mathrm{d}t} \Delta u, \quad (26)$$

$$\Delta p_C = \frac{4 k_e}{\pi d_{10}^2} (\Delta z_r + \Delta z), \quad (27)$$

$$S_D \Delta p_i = k_{ei}(\Delta u + \Delta u_r), \quad (28)$$

where $k_n = \left(\frac{\partial Q_p}{\partial n}\right)_0$, $k_y = \left(\frac{\partial Q_p}{\partial y}\right)_0$, $k_{iu} = \mu_b b \sqrt{\frac{2 p_{i0}}{\rho}}$,

$$k_{ip} = \mu_b b u_0 \sqrt{\frac{1}{2 p_{i0} \rho}}\ ,\ k_{Cz} = \mu_{10} d_{10} \pi \sqrt{\frac{2(p_{C0} - p_{i0})}{\rho}},$$

$$k_{Cp} = \mu_{10} \pi d_{10} z_0 \sqrt{\frac{1}{2(p_{C0} - p_{i0})\rho}},\ k_{Ax} = \mu_a b_a \sqrt{\frac{2 p_{A0}}{\rho}}\ ,$$

$$k_{Ap} = \mu_a b_a x_0 \sqrt{\frac{1}{2 p_{A0} \rho}},\ T_a = \sqrt{\frac{m_a}{k_{ea}}},\ T_{a\xi} = \frac{\xi}{k_{ea}},$$

$$T_t = \sqrt{\frac{m_t}{k_{et}}},\ T_{t\xi} = \frac{\xi}{k_{et}}\ . \tag{29}$$

2.3. Non-dimensional linear equation system

Using some appropriate chosen amplifying terms, the above-determined mathematical model can be transformed in a non-dimensional one. After applying the Laplace transformer, one obtains the non-dimensional mathematical model, as follows

$$\overline{Q_C} = \overline{Q_p} = k_{pn}\overline{n} + k_{py}\overline{y}\ , \tag{30}$$

where one has used the observation that the command fuel flow rate Q_a is very small comparative to Q_C, so $Q_C \approx Q_p$;

$$\overline{p_A} - \overline{p_B} = \frac{1}{k_{SA}(\tau_a \mathrm{s} + \rho_a)}\overline{x}\ , \tag{31}$$

$$\left(T_a^2 \mathrm{s}^2 + T_{a\xi}\mathrm{s} + 1\right)\overline{y} = k_{SA}\left(\overline{p_A} - \overline{p_B}\right). \tag{32}$$

$$\overline{Q_i} = k_{ui}\overline{u} + k_{pi}\overline{p_i}\ , \tag{33}$$

$$k_z \overline{z} = \overline{Q_C} - k_{zc}\overline{p_C} + k_{zi}\overline{p_i}\ , \tag{34}$$

$$\overline{u} = k_{up}\overline{p_i} - k_{rp}\overline{u_r}\ , \tag{35}$$

$$(\tau_i \mathrm{s} + 1)\overline{p_i} = k_{iz}\overline{z} + k_{ic}\overline{p_C} - k_u(\tau_u \mathrm{s} + 1)\overline{u}\ , \tag{36}$$

$$\left(T_t^2 \mathrm{s}^2 + T_{t\xi}\mathrm{s} + 1\right)\overline{x} = k_\delta \overline{\delta_T^*}\ . \tag{37}$$

The used annotations in the above system, based on the annotation presented in (29)-system, are as follows:

$$k_{pn} = \frac{1}{Q_{p0}}\left(\frac{\partial Q_p}{\partial n}\right)_0,\ k_{py} = \frac{1}{Q_{p0}}\left(\frac{\partial Q_p}{\partial y}\right)_0,$$

$$k_{ui} = \frac{k_{iu}u_0}{Q_{i0}},\ k_{pi} = \frac{k_{ip}p_{i0}}{Q_{i0}},\ k_{pz} = \frac{4k_e z_0}{\pi d_{10}^2 p_{C0}},\ k_z = \frac{k_{Cz}z_0}{Q_{p0}},$$

$$k_{zc} = \frac{k_{Cp}p_{C0}}{Q_{p0}},\ k_{zi} = \frac{k_{Cp}p_{i0}}{Q_{p0}},\ k_{ic} = \frac{k_{Cp}p_{C0}}{p_{i0}(k_{ip} + k_{Cp})},$$

$$k_{prz} = \frac{4k_e z_{r0}}{\pi d_{10}^2 p_{C0}},\ \tau_i = \frac{\beta V_{i0}}{k_{ip} + k_{Cp}},\ k_{iz} = \frac{k_{Cz}z_{i0}}{p_{i0}(k_{ip} + k_{Cp})},$$

$$k_u = \frac{k_{iu}u_0}{p_{i0}(k_{ip} + k_{Cp})},\ \tau_u = \frac{S_D}{k_{iu}},\ \tau_a = \frac{S_A y_0}{\mu_a x_0}\sqrt{\frac{\rho}{p_a - p_0}},$$

$$k_{up} = \frac{S_D p_{i0}}{k_{ei}u_0},\ \rho_a = \frac{k_{ea}y_0}{2S_A(p_a - p_0)},\ k_\delta = \frac{p_{40}^* S_m S_2}{k_{et}S_1}\ . \tag{38}$$

Based on some practical observation, one can make some supplementary hypothesis: a) the fuel is a non-compressible fluid ($\beta = 0$), so the terms containing it become null $(\tau_i = 0)$; b) the inertial effects are very small, as well as the viscous friction, so the terms containing $m_{a.}, m_t$ and ξ are becoming null $\left(T_a = T_{a\xi} = = T_t = T_{t\xi} = 0\right)$. Consequently, eq. (31) and (32) give

$$\overline{y} = \frac{1}{\tau_a \mathrm{s} + \rho_a}\overline{x} \tag{39}$$

and from eq. (36) and eq (37) one obtains

$$\overline{p_i} = k_{iz}\overline{z} + k_{ic}\overline{p_C} - k_u(\tau_u \mathrm{s} + 1)\overline{u}\ , \tag{40}$$

$$\overline{x} = k_\delta \overline{\delta_T^*}\ . \tag{41}$$

Meanwhile, the preset operation are realized during the engine or pump ground tests, so the terms containing u_r and z_r (as well as $\overline{u_r}$ and $\overline{z_r}$) become null and shall be eliminated.

The new, simplified, mathematical model is given by the equations (30),(39),(33),(34),(35),(40) and (41). Based on it, the system's block diagram with transfer functions is built and depicted in fig. 2. (This block diagram contains the terms $\overline{u_r}$ and $\overline{z_r}$ too).

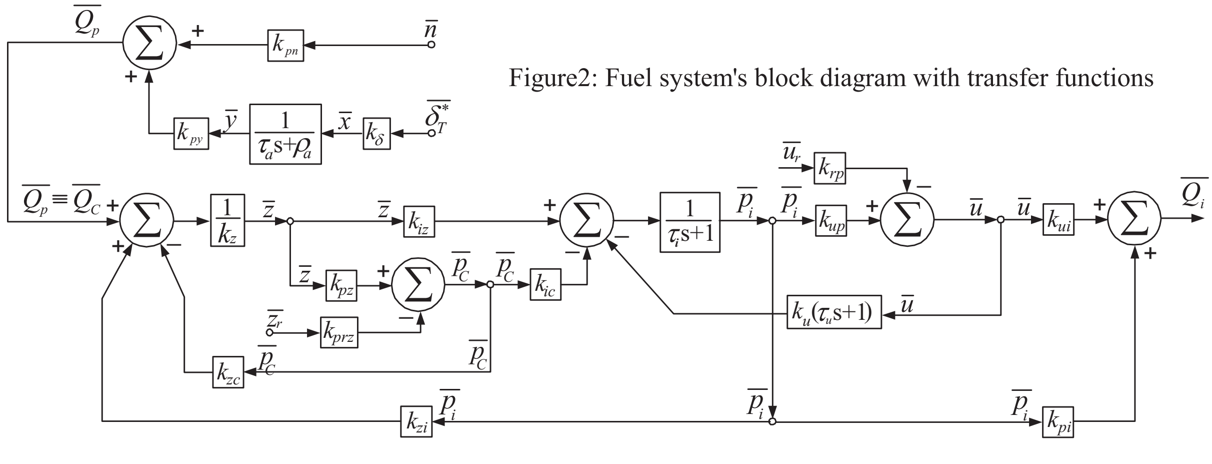


Figure2: Fuel system's block diagram with transfer functions

2.4. System's transfer functions

The block diagram with transfer functions in fig.2 shows that the system has two inputs ($\overline{n}$ and $\overline{\delta_T^*}$) and one output ($\overline{Q_i}$). Using the above-determined mathematical model's equations, one can obtain an equivalent form:

$$\left(\tau_f \mathrm{s} + \rho_f\right)\overline{Q_i} = k_{pn}\overline{n} + \frac{k_\delta k_{py}}{\tau_a \mathrm{s} + \rho_a}\overline{\delta_T^*}, \tag{42}$$

where τ_a and ρ_a are given in (38) and τ_f and ρ_f are:

$$\tau_f = \frac{k_u k_{up}\left(k_z + k_{zc}k_{pz}\right)}{\left(k_{iz} + k_{ic}k_{pz}\right)\left(k_{ui}k_{up} + k_{pi}\right)}\tau_u, \tag{43}$$

$$\rho_f = \frac{\left(k_z + k_{zc}k_{pz}\right)\left(1 + k_u k_{up}\right) - k_{zi}\left(k_{iz} + k_{ic}k_{pz}\right)}{\left(k_{iz} + k_{ic}k_{pz}\right)\left(k_{ui}k_{up} + k_{pi}\right)}. \tag{44}$$

System's transfer functions expressions are:

$$H_n(\mathrm{s}) = \frac{k_{pn}}{\tau_a \mathrm{s} + \rho_a}, \tag{45}$$

$$H_\delta(\mathrm{s}) = \frac{k_\delta k_{py}}{\left(\tau_a \mathrm{s} + \rho_a\right)\left(\tau_f \mathrm{s} + \rho_f\right)}. \tag{46}$$

3. SYSTEM STABILITY, QUALITY AND CONCLUSIONS

3.1. System stability

Taking into account the transfer functions expressions (see (45) and (46)), one can affirm (according the algebraic stability criteria) that for the system's stability the conditions must be:

$$\rho_a > 0, \tag{47$'$}$$

$$\rho_f > 0. \tag{47$''$}$$

While the first condition is always realized,

$$\rho_a = \frac{k_{ea}y_0}{2S_A\left(p_a - p_0\right)} > 0, \tag{48$'$}$$

because all the involved terms are strictly positives, the second condition

$$\frac{\left(k_z + k_{zc}k_{pz}\right)\left(1 + k_u k_{up}\right) - k_{zi}\left(k_{iz} + k_{ic}k_{pz}\right)}{\left(k_{iz} + k_{ic}k_{pz}\right)\left(k_{ui}k_{up} + k_{pi}\right)} > 0, \tag{48$''$}$$

leads to a relation between the injection pressure chamber springs elastic constants, represented by a hyperbolic curve (see dashed curve in fig. 3), which separates the stability domain from the instability domain. The stability domain is the one above the curve, on the right side of the abscissa axis. One can observe that, if the spring 15 and the valve 14 are absent $k_{ei} = 0$, there is a minimum value for the elastic constant of the 13-spring, which means the

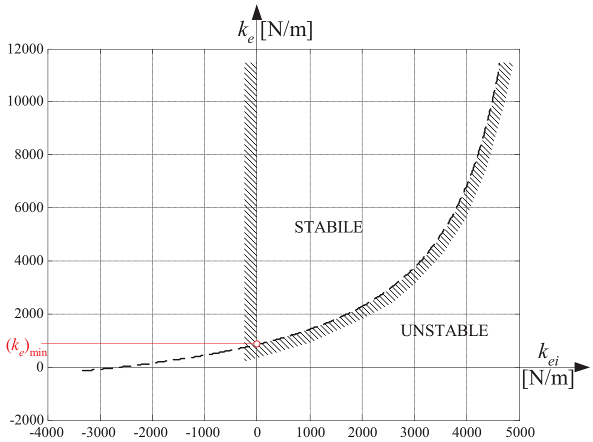


Figure 3: System's stability domain

lowest possible k_e elastic constant value for system stability, $\left(k_e\right)_{\min}$.

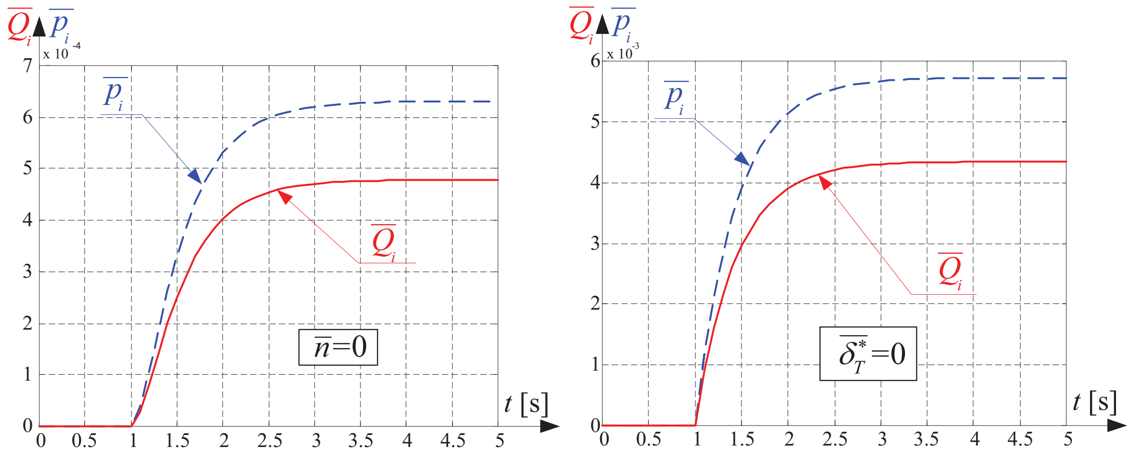
3.2. System quality

As one can see in fig. 1 and 2, the studied system has two input parameters: a) engine's operating regime - (given by the engine's speed *n*); b) gas turbine's pressure ratio $\left(\delta_T^*\right)$. So, the system should operate in case of any changing affecting one or both of these input parameters.

A study concerning the system quality was realized using the co-efficient values for a pump of a VK-1F jet engine, by analyzing its step response, based on the simulated block-diagram in fig. 2 (system's response for step input for one or for both above-mentioned parameters). As output, one has considered the fuel flow rate $\overline{Q_i}$ as main parameter, as well as the pump injection pressure $\overline{p_i}$ as secondary parameter.

Output parameters' behavior is presented by the graphics in fig. 4 and 5; the situation in fig. 4.a has as input gas turbine's pressure ratio, for constant engine speed; meanwhile the situation in fig. 4.b has as input the engine's regime (step acceleration or step throttle's repositioning). System's behavior for both input parameters step input is depicted in fig. 5 .

One can observe (in each figure, from 4 to 5) that all the output parameters are asymptotic stables, so the system is a stable-one. 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, having values smaller than 1%. When both of the input parameters have step variations, the effects are overlapping, so system's behavior is the one in fig. 5.Concerning the stabilization time, both for $\overline{Q_i}$ and for $\overline{p_i}$ its value is somewhere around $3.5 \div 4\,\mathrm{s}$, which is an acceptable value for usual fuel systems (pumps).



a) step input of $\overline{\delta_T^*}$ and $\overline{n}=0$; b) step input of $\overline{n}$ and $\overline{\delta_T^*}=0$;

Figure 4: System step response for different step inputs

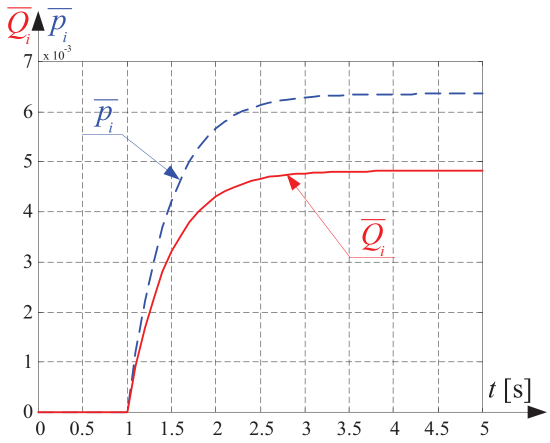


Figure 5: System step response for combined step input

This kind of fuel systems (pumps with plunjers and mobile plate) can be used both for basic jet engines (single jet, single or double spool) and for their afterburning systems. The interconnection engine-afterburner must be carefully realized, in order to keep them in the stability area of operability.

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