Fuel Injection Controller for Aircraft Jet Engine Based on Injection Pressure Control

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Abstract: -This paper deals with a fuel flow rate controller meant to assist a turbo-jet engine. The author has established the non-linear motion equations for the integrated control system (controller+fuel pump+engine); based on it, assuming the small perturbations hypothesis, these equations were transformed into a linear system and, after the Laplace transformer applying, into a non-dimensional mathematical model. Its block diagram with transfer functions also described the control system. Some simulations were performed, considering this kind of system description, concerning the system time behavior for different situations. Based on these studies, the author has presented some useful conclusions, as well as some considerations regarding the system's operating limits.

Key-Words: jet engine, control, fuel, airflow rate, pressure, actuator, throttle, speed.

1. Introduction

Jet engines for aircraft are built in a large range of performances and types. Different types of fuel pumps assure their fuel supply: with plungers, with pinions (toothed wheels), or with impeller. For all of them, the output fuel flow rate depends on their rotation speed and on their actuator's position; for the pump with plungers the actuator gives the plate's cline angle, but for the other pump type the actuator determines the by-pass slide-valve position (which gives the size of the discharge orifice, that means the amount of the discharge fuel flow rate).

Usually, the fuel pumps are integrated in the jet engine's control system; more precisely: the fuel pump is turned round by the engine's shaft (obviously, through a gear box), so the pump speed is proportional (sometimes equal) to the engine's speed *n*, which is the engine's most frequently controlled parameter. So, the other pump control parameter (the plate angle or the discharge orifice width) must be commanded by the engine's speed controller.

Engine's speed controllers are built based on various operating principles, in a large range of types. Mostly all of them are controlling the engine speed using as main parameter the injected fuel flow rate, through direct or indirect methods.

The control system presented in fig. 1 uses an indirect method, being based on the fuel injection pressure control. It is a different method, comparing to the one studied in [12], where the injection pressure (or the injection differential pressure) must be kept constant, meanwhile the engine's useful fuel flow rate being given by the fuel dosing valve's opening.

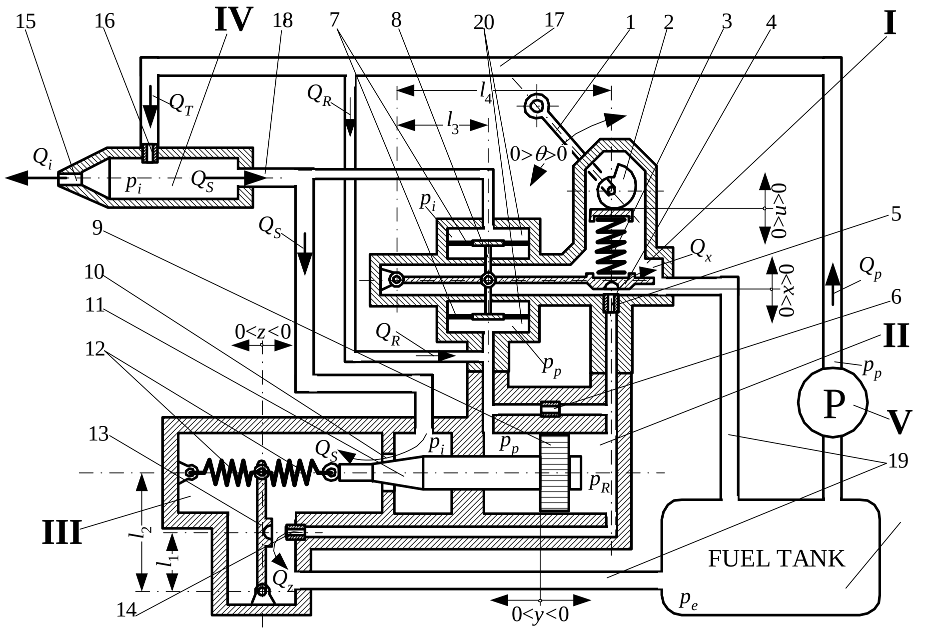
2. Controller presentation

Control system's main parts are presented in fig.1. The controller has four main parts (the pressure transducer, the actuator, the actuator's feed-back and the fuel injector); it operates together with the fuel pump and, obviously, with the turbo-jet engine.

Controller's duty is to assure, in the injector's chamber, the appropriate p_i value, enough to assure the desired value of the engine's speed, imposed by the throttle's positioning, which means to co-relate the pressure difference $p_p - p_i$ to the throttle's position (given by the 1 lever's θ angle).

The fuel flow rate Q_i, injected into the engine's combustor, depends on the injector's diameter (drossel no. 15) and on the fuel pressure in its chamber p_i. The difference $p_p - p_i$, as well as p_i, are controlled by the level of the discharged fuel flow Q_S through the calibrated orifice 10, which diameter is given by the profiled needle 11 position; the profiled needle is part of the actuator's rod, positioned by the actuator's piston 9 displacement.

The actuator has also a distributor with feedback link (the flap 13 with its nozzle or drossel 14, as well as the springs 12), in order to limit the profiled needle's displacement speed.



Control system's main parts

I-differential pressure transducer;
II-actuator;
III-actuator's feedback;
IV-fuel injector;
V-fuel pump;
VI-fuel tank;

1-lever (throttle bounded); 2-cam; 3-spring; 4, 13-flap with hemi-spherical lid; 5,6-drossels; 7-elastic membranes; 8-intermembrane rod; 9-actuator's piston; 10-calibrated orifice; 11-profiled rod (needle); 12-springs; 14-drossel; 15-injector final orifice; 16-injector's drossel; 17-fuel pump's exhaust pipe; 18-injector's discharge pipe; 19-low pressure fuel pipes (controller's discharge pipes); 20- transducer's pressure chambers.

Fig.1. Control system's constructive and operating block-diagram

Controller's transducer has two pressure chambers 20 with elastic membranes 7, for each measured pressure p_p and p_i; the inter-membrane rod is bounded to the transducer's flap 4. Transducer's role is to compare the level of the realized differential pressure $p_p - p_i$ to its necessary level (given by the 3 spring's elastic force, due to the (lever1+cam2) ensemble's rotation).
So, the controller assures the necessary fuel flow rate value Q_i with respect to the throttle's displacement, by controlling the injection pressure's level through the fuel flow rate discharging.

3. Controller's mathematical model

The studied controller'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 studying and simulations.

3.1. Non-linear equation system

The system non-linear motion equations are
a) pressure transducer equations

$$S_m\left(p_p - p_i\right)l_3 = l_4 k_{rs}(u + x), \tag{1}$$

$$p_p - p_i = p_d, \tag{2}$$

$$u = k_\theta \theta, \tag{3}$$

b) injector equations

$$Q_T - Q_S - Q_i = \beta V_{i0}\frac{\mathrm{d}p_i}{\mathrm{d}t}, \tag{4}$$

$$Q_T = \mu_d \frac{\pi d_{16}^2}{4}\sqrt{\frac{2}{\rho}}\sqrt{p_p - p_i}, \tag{5}$$

$$Q_S = \mu\ \frac{\pi}{4}\left[d_0^2 - \left(d_1 + 2y\tan\alpha\right)^2\right]\sqrt{\frac{2}{\rho}}\sqrt{p_i - p_e}, \tag{6}$$

$$Q_i = \mu_d \frac{\pi d_i^2}{4}\sqrt{\frac{2}{\rho}}\sqrt{p_i - p_{CA}}, \tag{7}$$

c) actuator equations

$$Q_R - Q_x - Q_z = \beta V_{R0}\frac{\mathrm{d}p_R}{\mathrm{d}t} + S_R\frac{\mathrm{d}y}{\mathrm{d}t}, \tag{8}$$

$$Q_R = \mu_6 \frac{\pi d_6^2}{4}\sqrt{\frac{2}{\rho}}\sqrt{p_p - p_R}, \tag{9}$$

$$Q_x = \mu_5 \pi d_5\left(x - x_s\right)\sqrt{\frac{2}{\rho}}\sqrt{p_R - p_e}, \tag{10}$$

$$Q_z = \mu_{14} \pi d_{14}\left(z - z_s\right)\sqrt{\frac{2}{\rho}}\sqrt{p_R - p_e}, \tag{11}$$

$$z = \frac{l_1}{l_2}y, \tag{12}$$

$$S_R p_R - S_p p_p = m_s\frac{\mathrm{d}^2 y}{\mathrm{d}t^2} + \xi\frac{\mathrm{d}y}{\mathrm{d}t} + \left(k_{r1} + k_{r2}\right)y, \tag{13}$$

d) fuel pump equation

$$Q_p - Q_R - Q_T = \beta V_{p0}\frac{\mathrm{d}p_p}{\mathrm{d}t}, \tag{14}$$

$$Q_p = Q_p(n), \tag{15}$$

where Q_i is the injection fuel flow rate, Q_p – pump's fuel flow rate, Q_S – discharging fuel flow rate, Q_R, Q_T, Q_x, Q_z – controller's fuel flow rates, S_m – elastic membranes' surface areas, p_p – fuel's pumping pressure, p_i – fuel's injection pressure, p_d – fuel's differential pressure, l_3, l_4 – 4-flap arms length, u – spring's upper side displacement (depending on the 2-cam profile), x – 4-flap's displacement, θ – lever's angular displacement (given by the throttle's displacement), k_{rs} – transducer's spring elastic constant, β – fuel's compressibility co-efficient, V_{i0} – injector's pressure chamber volume, μ, μ_d, μ_5, μ_6, μ_{14} – flow rate co-efficient, d_5, d_6, d_{14}, d_{16} – drossels diameters, d_0 / d_1 – 10-calibrated orifice maximum/minimum diameter, α – profiled needle's angle, ρ – fuel's density, y – actuator's rod displacement, p_e – evacuation pressure value (of the low pressure circuit), p_R – command pressure value, V_{R0} – actuator's chambers volumes, m_p – piston+rod mass, ξ – viscous friction co-efficient, S_R, S_p – actuator's piston surfaces areas, z – 13-flap's displacement, l_1, l_2 – 13-flap arms length, k_{r1}, k_{r2} – 12-springs elastic constants, V_{p0} – pump chamber volume, n – engine and fuel pump rotation speed.

The (1) to (15) equation system represents the controller's non-linear mathematical model.

3.2. Linearized 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. Furthermore, the flow rate expressions for $Q_T, Q_S, Q_i, Q_R, Q_x, Q_z$ are introduced into the other equations, so the system becomes

$$\Delta x = \frac{S_m l_3}{l_4 k_{rs}}\left(\Delta p_p - \Delta p_i\right) - \Delta u, \qquad (16)$$

$$\Delta p_p - \Delta p_i = \Delta p_d, \qquad (17)$$

$$\Delta u = k_\theta \Delta\theta, \qquad (18)$$

$$\Delta Q_i = k_{Qi}\Delta p_i, \qquad (19)$$

$$k_{PT}\left(\Delta p_p - \Delta p_i\right) - k_{sy}\Delta y - k_{si}\Delta p_i - k_{Qi}\Delta p_i = \beta V_{i0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta p_i, \qquad (20)$$

$$k_{RP}\left(\Delta p_p - \Delta p_R\right) - k_{xx}\Delta x - k_{xR}\Delta p_R - k_{zz}\Delta z - k_{zR}\Delta p_R = \beta V_{R0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta p_R + S_R\frac{\mathrm{d}}{\mathrm{d}t}\Delta y, \qquad (21)$$

$$\Delta z = \frac{l_1}{l_2}\Delta y, \qquad (22)$$

$$\Delta Q_p - k_{RP}\left(\Delta p_p - \Delta p_R\right) - k_{PT}\left(\Delta p_p - \Delta p_i\right) = \beta V_{p0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta p_p, \qquad (23)$$

$$S_R\Delta p_R - S_p\Delta p_p = \left[m_s\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \xi\frac{\mathrm{d}}{\mathrm{d}t} + \left(k_{r1} + k_{r2}\right)\right]\Delta y \qquad (24)$$

which are completed by the fuel pump equation

$$Q_p = Q_p(n), \qquad (25)$$

and the engine's speed equation

$$n = n(Q_i), \qquad (26)$$

where the used annotations are

$$k_{PT} = \mu_d\frac{\pi d_{16}^2}{4}\frac{1}{\sqrt{2\rho\left(p_{p0} - p_{i0}\right)}},\ k_{xx} = \mu_4\pi d_4\sqrt{\frac{2p_{R0}}{\rho}},$$

$$k_{Qi} = \mu_d\frac{\pi d_i^2}{4}\frac{1}{\sqrt{2\rho p_{p0}}},\ k_{zz} = \mu_{11}\pi d_{11}\sqrt{\frac{2p_{R0}}{\rho}},$$

$$k_{RP} = \mu_7\frac{\pi d_7^2}{4}\frac{1}{\sqrt{2\rho\left(p_{p0} - p_{R0}\right)}},$$

$$k_{sy} = \mu\frac{\pi}{4}\left[d_0^2 - d_1^2 - 4\left(d_1 - y_0\tan\alpha\right)\tan\alpha\right]\sqrt{\frac{2p_{i0}}{\rho}},$$

$$k_{si} = \mu\frac{\pi}{4}\left[d_0^2 - d_1^2 - 4\left(d_1 - y_0\tan\alpha\right)\tan\alpha\right]\frac{1}{\sqrt{2\rho p_{i0}}},$$

$$k_{zR} = \mu_{11}\pi d_{11}(z_0 - z_s)\sqrt{\frac{1}{2\rho p_{R0}}},$$

$$k_{xR} = \mu_4\pi d_4(x_0 - x_s)\sqrt{\frac{1}{2\rho p_{R0}}}. \qquad (27)$$

3.2. Non-dimensional linear mathematical model

Using the generic annotation $\overline{X} = \frac{\Delta X}{X_0}$ and some favorable chosen amplifying terms, the above mathematical model can be transformed in a non-

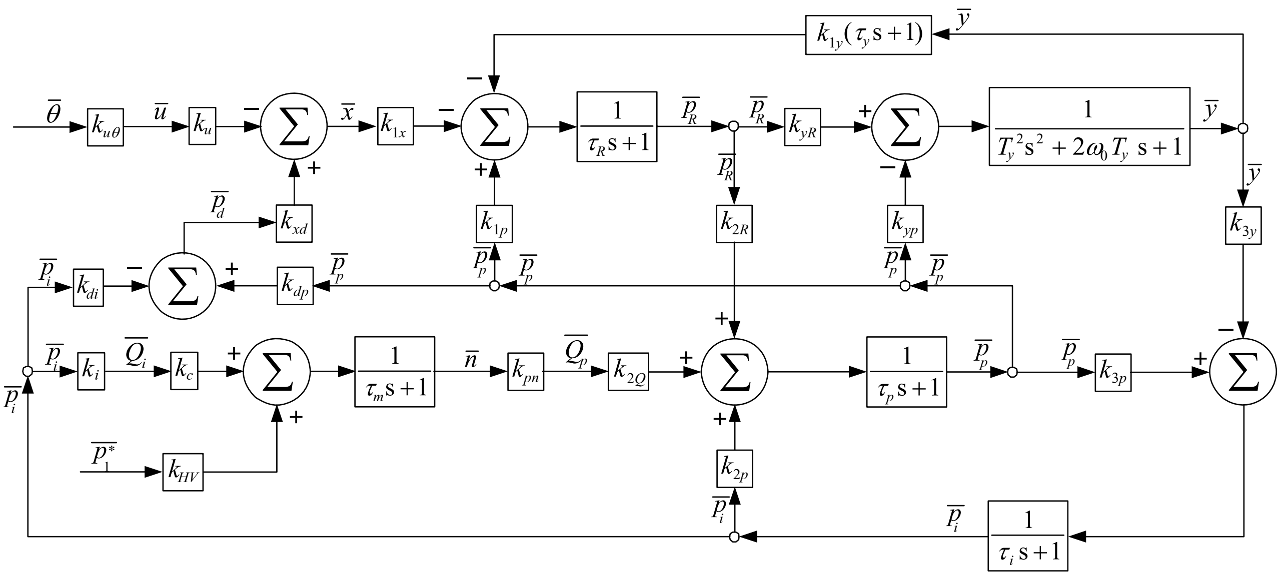


Fig.2. Control system's block-diagram with transfer functions

dimensional one. After applying the Laplace transformer, one obtains the non-dimensional linearized mathematical model, as follows

$$\overline{u} = k_{u\theta}\overline{\theta}\ , \tag{28}$$

$$\overline{p_d} = k_{dp}\overline{p_p} - k_{di}\overline{p_i}\ , \tag{29}$$

$$\overline{x} = k_{xd}\overline{p_d} - k_u\overline{u}\ , \tag{30}$$

$$(\tau_R s+1)\overline{p_R} = k_{1p}\overline{p_p} - k_{1x}\overline{x} - k_{1y}(\tau_y s+1)\overline{y}\ , \tag{31}$$

$$(\tau_p s+1)\overline{p_p} = k_{2p}\overline{p_i} + k_{2R}\overline{p_R} + k_{2Q}\overline{Q_p}\ , \tag{32}$$

$$(T_y^2 s^2 + 2\omega_0 T_y s+1)\overline{y} = k_{yR}\overline{p_R} - k_{yp}\overline{p_p}\ , \tag{33}$$

$$(\tau_i s+1)\overline{p_i} = k_{3p}\overline{p_p} - k_{3y}\overline{y}\ , \tag{34}$$

$$\overline{Q_i} = k_i\overline{p_i}\ , \tag{35}$$

together with the fuel pump and the engine's speed non-dimensional equations ([8],[10])

$$\overline{Q_p} = k_{pn}\overline{n}\ , \tag{36}$$

$$(\tau_m s+1)\overline{n} = k_c\overline{Q_i} + k_{HV}\overline{p_1^*}\ . \tag{37}$$

The above used annotations are

$$k_{u\theta} = k_\theta\frac{\theta_0}{u_0},\ k_{xd} = \frac{S_m l_3 p_{d0}}{k_{rs} l_4 x_0},\ k_u = \frac{u_0}{x_0},\ k_{dp} = \frac{p_{p0}}{p_{d0}},$$

$$k_{di} = \frac{p_{i0}}{p_{d0}},\ \tau_R = \frac{\beta V_{R0}}{k_{RP}+k_{xR}+k_{zR}},\ \tau_p = \frac{\beta V_{p0}}{k_{RP}+k_{PT}},$$

$$k_{1p} = \frac{k_{RP}p_{p0}}{(k_{RP}+k_{xR}+k_{zR})p_{R0}},\ \tau_y = \frac{S_R l_2}{k_{zz} l_1},\ k_{1y} = \frac{k_{zz} l_1 y_0}{p_{R0} l_2},$$

$$k_{1x} = \frac{k_{xx}x_0}{(k_{RP}+k_{xR}+k_{zR})p_{R0}},\ k_{2p} = \frac{k_{PT}p_{i0}}{(k_{RP}+k_{PT})p_{p0}},$$

$$k_{2R} = \frac{k_{RP}p_{R0}}{(k_{RP}+k_{PT})p_{p0}},\ k_{2Q} = \frac{Q_{p0}}{(k_{RP}+k_{PT})p_{p0}},$$

$$T_y = \sqrt{\frac{m}{k_{r1}+k_{r2}}},\ 2\omega_0 T_y = \frac{\xi}{k_{r1}+k_{r2}},\ k_i = \frac{k_{Qi}p_{i0}}{Q_{i0}},$$

$$k_{yR} = \frac{S_R p_{R0}}{(k_{r1}+k_{r2})y_0},\ k_{yp} = \frac{S_P p_{p0}}{(k_{r1}+k_{r2})y_0},$$

$$\tau_i = \frac{\beta V_{i0}}{k_{PT}+k_{si}+k_{Qi}},\ k_{3p} = \frac{k_{PT}p_{p0}}{(k_{PT}+k_{si}+k_{Qi})p_{i0}},$$

$$k_{3y} = \frac{k_{sy}y_0}{(k_{PT}+k_{si}+k_{Qi})p_{i0}},\ k_{pn} = \frac{n_0}{Q_{p0}}\left(\frac{\partial Q_p}{\partial n}\right)_0 . \tag{38}$$

System's block diagram with transfer functions, based on the above-determined non-dimensional mathematical model, is presented in fig.2.

3.3. Simplified mathematical model

Some supplementary hypothesis, based on some practical observation, can be made. Thus, the fuel is a non-compressible fluid ($\beta = 0$), so $\tau_p = \tau_R = \tau_i = 0$; the inertial effects are very small, as well as the viscous friction, so the terms containing m and ξ are becoming null $(T_y = 0)$. Consequently, the equations (31)-(34) become

$$\overline{p_R} = k_{1p}\overline{p_p} - k_{1x}\overline{x} - k_{1y}(\tau_y s+1)\overline{y}\ , \tag{39}$$

$$\overline{p_p} = k_{2p}\overline{p_i} + k_{2R}\overline{p_R} + k_{2Q}\overline{Q_p}\ , \tag{40}$$

$$\overline{y} = k_{yR}\overline{p_R} - k_{yp}\overline{p_p}\ , \tag{41}$$

$$\overline{p_i} = k_{3p}\overline{p_p} - k_{3y}\overline{y}\ . \tag{42}$$

Furthermore, if the input signal u is considered as the reference signal forming parameter, from the equations (28) and (30) one can obtain the expression

$$\overline{x} = -k_{xd}\left(\overline{p_{d_{ref}}} - \overline{p_d}\right), \tag{43}$$

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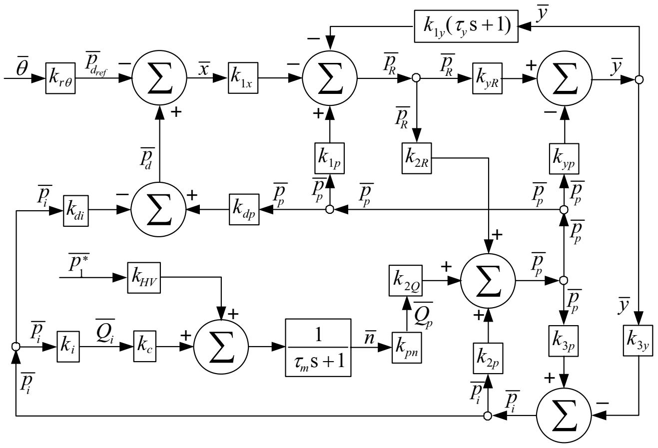

Fig.3. Controller's simplified block-diagram

where $\overline{p_{d_{ref}}}$ is the non-dimensional reference differential pressure, given by

$$\overline{p_{d_{ref}}} = \frac{k_\theta k_{rs} l_4}{S_m l_3 p_{d0}} \overline{\theta} = k_{r\theta} \overline{\theta} \,. \qquad (44)$$

Based on the new form of the mathematical model, the controller's simplified block diagram with transfer functions looks like the one in fig.3.

4. System's quality

As figures 2 and 3 show, the system has two inputs: throttle's position - or engine's operating regime - (given by θ-angle) and the aircraft flight regime (given by the inlet inner pressure p_1^*). So, the system should operate in case of changing which affects 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 VK-1F jet engine, presented in [10]), by analyzing its step response (system's response for step input for one or for both above-mentioned parameters). As output, one has considered the differential pressure $\overline{p_d}$, the engine speed $\overline{n}$ (which is the most important controlled parameter for a jet engine) and the actuator's rod displacement $\overline{y}$ (same as the profiled needle's).

Output parameters' behavior is presented by the graphics in fig. 4; the situation in fig. 4.a has as input the engine's regime (step throttle's repositioning) for a constant flight regime; in the mean time, the situation in fig. 4.b has as input the flight regime (hypothetical step climbing or diving), for a constant engine's regime (step throttle's constant position). System's behavior for both input parameters step input is depicted in fig. 5.a).

One has also studied the system's behavior for two different engine's models [8],[10]: a stable-one (which has a stabile pump-engine connection, its main co-efficient being $k_c k_{pn} < 1$, situation in fig. 5.a) and a non-stable-one (which has an unstable pump-engine connection and $k_c k_{pn} > 1$, see fig. 5.b).

5. Conclusions

The non-dimensional mathematical model, with its co-efficient forms, was used to simulate the system's time behavior for different regimes and different operating conditions.

Concerning the system's step response for throttle's step input, one can observe that all the output parameters are 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, being

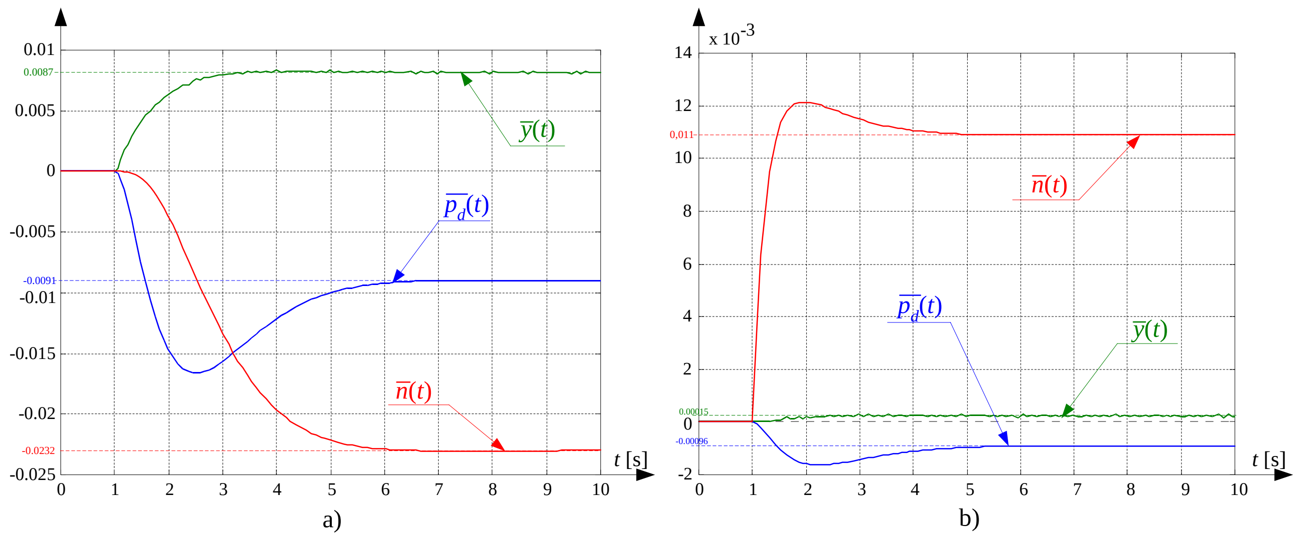

Fig.4. System's step response a) step input for $\overline{\theta}$ and $\overline{p_1^*} = 0$; b) step input for $\overline{p_1^*}$ and $\overline{\theta} = 0$.

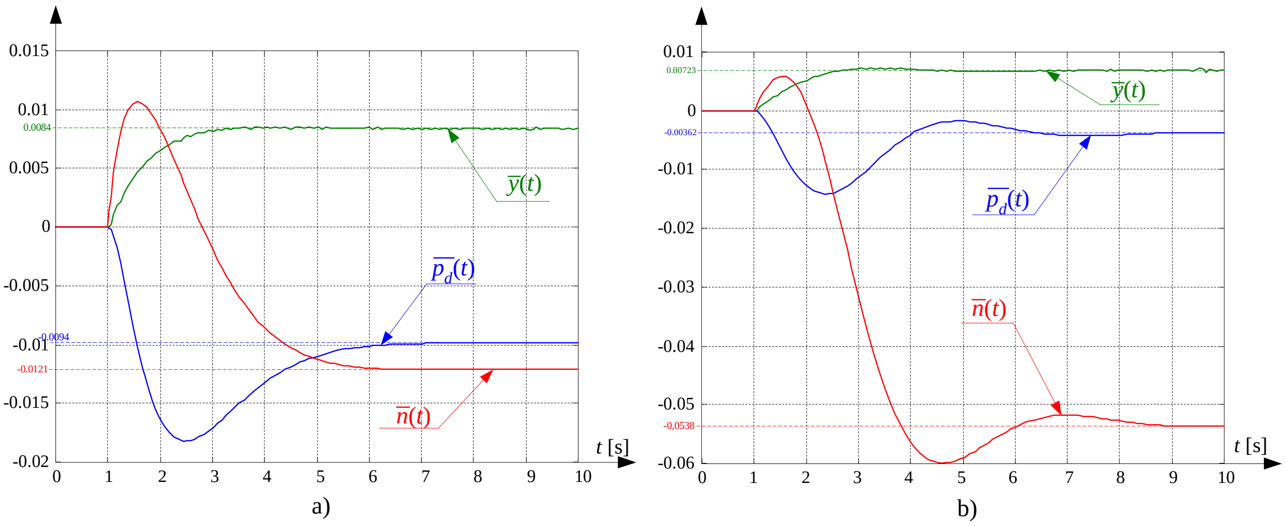

Fig.5. Comparative step response between a) stabile fuel pump-engine connection $k_c k_{pn} < 1$ and b) unstable fuel pump-engine connection $k_c k_{pn} > 1$.

fewer than 2.5% for each output parameter. The differential pressure and engine's speed static errors are negative, so in order to reach the engine's speed desired value, the throttle must be supplementary displaced (pushed).

When the throttle is immobile, for a step input of $\overline{p_1^*}$ (the flight regime) system's behavior is similar (see fig.4.b), but the static errors' level is lower, being around 0.1% for $\overline{p_d}$ and for $\overline{y}$, but higher for $\overline{n}$ (around 1.1%, which mean ten times than the others). When both of the input parameters have step variations, the effects are overlapping, so system's behavior is the one in fig. 5.a).

System's stability is different, for different analyzed output parameters: $\overline{y}$ has a non-periodic stability, no matter the situation is, but $\overline{p_d}$ and $\overline{n}$ have initial stabilization values overriding. Meanwhile, curves in fig. 4.a), 4.b) and 5.a) are showing that engine's operating regime has a bigger influence than the flight regime above the controller's behavior.

Curves in fig. 5.b) are showing a periodical stability for a controller assisting a non-stable connection engine-fuel pump, so the controller has reached its limits and must be improved by constructive means, if the non-periodic stability is compulsory.

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