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PNEUMATIC ANTI-STALL AUTOMATIC SYSTEM FOR A JET ENGINE COMPRESSOR

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Abstract: *The paper deals with a pneumatic system for the engine's compressor's anti-stall valve's automatic opening, in order to keep the compressor's operating enough far from the stall line. The authors have chosen an automatic opening system based on a pneumatic actuator and a pneumatic command system; starting from the non-linear motion equation, one has determined the linearized, adimensionalised mathematical model, as well as its simplified form. Based on it one has determined the block-diagram with transfer functions and one also has performed some studies concerning system's stability and quality. Results could be used for similar systems' studying, as well as for further studies of embedded engine control systems*

Keywords: *compressor, stall, control, command pressure, air flow rate.*

1. INTRODUCTION

Jet engines for aircraft are built in a wide range of types, with respect to their thrust, constructive solutions and dimensions; no matter the solution were, they are equipped with compressors (centrifuge or axial).

The compressor is one of the most important engine's parts, which is responsible for the air pressure raise before the engine's combustor. Its pressure ratio, defined as $\pi_c^* = \frac{p_2^*}{p_1^*}$, depends on the total pressure values behind and before it, p_2^* and p_1^*,.

However, the more important its task is and the bigger its pressure ratio is, the more sensitive the compressor is. Its sensitivity is represented by the possibility of stall operating, when the air flow rate through the compressor isn't co-related to the air necessities of the engine's combustor, especially during engine's transient (dynamical) operating regimes.

Obviously, in order to keep the compressor in the stable operational range, one has to assure the permanent correlation between the combustor's necessary air flow rate and the effective delivered compressor air flow rate, as well as the correlation with the injected fuel flow rate; that means that compressor's working line is enough far from the stall-line.

Stall is caused by the air flow stream's critical attack angle override, followed by stream's detachment and flow's spectrum alteration. In order to prevent it, an air valve is mounted on the compressor's crankcase, which role is to evacuate the excessive air, readjusting the air speed in the front of the compressor's blades.

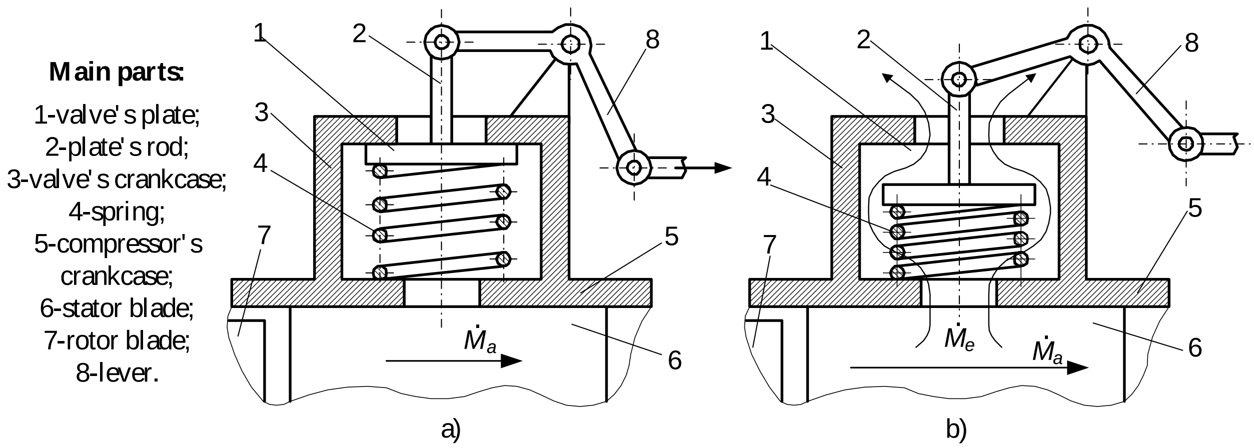


Fig. 1. Anti-stall valve

Compressor's stall is very difficult to be modeled, but some authors have explained it (see [10] and [11]) and have proposed some prevention methods, such as stator blades position adjustment and/or exhaust valves using. Blades position adjustment systems are described in [2], [13] and [14], while anti-stall valves using are described in [14] and [15].

In this paper the authors have studied an anti-stall valve's pneumatic command system.

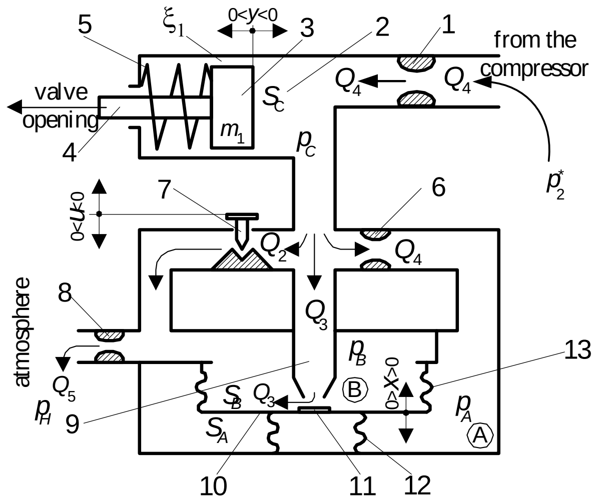
2. COMMAND SYSTEM PRESENTATION

Anti-stall valve (see fig.1) operates by evacuating a small air mass flow (no more than 3 % of the total compressor's air mass flow $\dot{M}_a$) from jet engine's compressor towards the atmosphere, in order to avoid the stall. Valve's command systems are various, from the simplest version (consisting of a valve with spring) to the most complex, equipped by pneumatic, hydraulic, electric or combined actuators and sensors.

Figure 2 presents a pneumatic system consisting of a single active chamber actuator, a nozzle-flap distributor and a two sylphons pressure sensor.

Main input signal is the pressure captured from the last or from an intermediate "*k*" compressor stage (p_2^* or p_k^*); this pressure signal is converted into command pressure signal p_C, by using the nozzle-flap distributor, as well as the pressure sensor chambers A and B. The command pressure signal generates the actuator's rod displacement *y*, which is the output signal. The command system's rod (4) in fig. 2 should be connected properly to the lever (8) in fig. 1, in order to assure valve's opening when the input pressure p_2^* reaches a certain value. The command pressure value would be presetted by the opening of the variable drossel (7).

One can observe that the command system's air supplying is realized by the controlled compressor and no other active fluid is involved.



System parts: 1, 6, 8-drossels; 2-pneumatic actuator; 3-actuator's piston; 4-actuator's rod; 5-actuator's spring; 7-adjusting bolt; 9-nozzle; 10-plateau; 11-flap; 12, 13-silphon.

Fig. 2. Valve's opening command system

3. SYSTEM 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, as well as for simulations.

3.1. Non-linear mathematical model.

System's non-linear motion equations are the following:

a) air mass flow equations:

$$Q_1 = \mu_{d1} \frac{\pi d_1^2}{4} \sqrt{\frac{2}{\rho}} \sqrt{p_2^* - p_C} \,, \tag{1}$$

$$Q_2 = \mu_7 b_7 (u_s - u) \sqrt{\frac{2}{\rho}} \sqrt{p_C - p_H} \,, \tag{2}$$

$$Q_3 = \mu_3 b_3 (x_s - x) \sqrt{\frac{2}{\rho}} \sqrt{p_C - p_B} \,, \tag{3}$$

$$Q_4 = \mu_{d6} \frac{\pi d_6^2}{4} \sqrt{\frac{2}{\rho}} \sqrt{p_C - p_A} \,, \tag{4}$$

$$Q_5 = \mu_{d8} \frac{\pi d_8^2}{4} \sqrt{\frac{2}{\rho}} \sqrt{p_B - p_H} \,, \tag{5}$$

b) nozzle-flap distributor equations:

$$V_A = V_{A0} + S_A x \,, \tag{6}$$

$$V_B = V_{B0} - S_B x \,, \tag{7}$$

$$Q_2 + Q_3 - Q_5 = \frac{\mathrm{d}V_B}{\mathrm{d}t} + \beta V_{B0} \frac{\mathrm{d}p_B}{\mathrm{d}t} \,, \tag{8}$$

$$S_B p_B - S_A p_A - (S_B - S_A) p_S = k_s x \,, \tag{9}$$

c) pneumatic actuator equations:

$$Q_1 - Q_2 - Q_3 - Q_4 = \frac{\mathrm{d}V_C}{\mathrm{d}t} + \beta V_{C0} \frac{\mathrm{d}p_C}{\mathrm{d}t} \,, \tag{10}$$

$$Q_4 = \frac{\mathrm{d}V_A}{\mathrm{d}t} + \beta V_{A0} \frac{\mathrm{d}p_A}{\mathrm{d}t} \,, \tag{11}$$

$$V_C = V_{C0} + S_C y \,, \tag{12}$$

$$m_1 \frac{\mathrm{d}^2 y}{\mathrm{d}t^2} + \xi \frac{\mathrm{d}y}{\mathrm{d}t} + k_{el} y = S_C p_C \,, \tag{13}$$

where d_1, d_3, d_6, d_8 – drossels' diameters; b_7 – variable drossel (7) width; μ_{d1}, μ_{d6}, μ_{d3}, μ_{d8}, μ_7 – mass flow co-efficient; p_A, p_B – silphon chambers pressure; V_C, V_A, V_B – chambers volumes; m_1 – piston and rod mass; ξ – friction co-efficient; k_{el} – spring (5) elastic constant; k_s – silphons' elastic constant; S_A, S_B – plateau (10) surfaces areas; S_C – actuator's piston area.

The above determined non-linear equation system (equations (1) to (13)) is difficult to be used for further studies, so it can be brought to a linear form, using the small perturbation method, considering formally any variable or parameter X as

$$X = X_0 + \Delta X \,, \tag{14}$$

where X_0 – steady state regime's value, ΔX – parameter's deviation and $\overline{X} = \frac{\Delta X}{X_0}$ the non-dimensional deviation.

3.2 Linearized mathematical model

In order to determine a linearized form for the above equation system, one has to identify the main parameters. The adjusting bolt displacement u (performed during the ground testing period), has no relevance for the system dynamic behavior, so it should be excluded.

Expressing each one of the main parameters as in eq. (14) and introducing them into the equation system, after eliminating the terms containing the steady state regime, one obtains the system's linear form, as follows:

$$\Delta Q_1 = k_{1p2} \cdot \Delta p_2^* - k_{1C} \cdot \Delta p_C \,, \tag{15}$$

$$\Delta Q_2 = k_{2C} \Delta p_C - k_{2B} \Delta p_B - k_{2u} \Delta u \,, \tag{16}$$

$$\Delta Q_3 = k_{3C} \Delta p_C - k_{3B} \Delta p_B - k_{3x} \Delta x \,, \tag{17}$$

$$\Delta Q_4 = k_{4C} \cdot \Delta p_C - k_{4A} \cdot \Delta p_A \,, \tag{18}$$

$$\Delta Q_5 = k_{5B} \cdot \Delta p_B - k_{5H} \cdot \Delta p_H , \tag{19}$$

$$\Delta V_A = S_A \cdot \Delta x , \tag{20}$$

$$\Delta V_B = S_B \cdot \Delta x , \tag{21}$$

$$\Delta Q_2 + \Delta Q_3 - \Delta Q_5 = \frac{\mathrm{d}}{\mathrm{d}t}\Delta V_B + \beta V_{B0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta p_B , \tag{22}$$

$$S_B \cdot \Delta p_B - S_A \cdot \Delta p_A = k_s \cdot \Delta x , \tag{23}$$

$$\Delta Q_1 - \Delta Q_2 - \Delta Q_3 - \Delta Q_4 = \frac{\mathrm{d}}{\mathrm{d}t}\Delta V_C + \beta V_{C0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta p_C , \tag{24}$$

$$\Delta Q_4 = \frac{\mathrm{d}}{\mathrm{d}t}\Delta V_A + \beta V_{A0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta p_A , \tag{25}$$

$$V_C = S_C \cdot \Delta y , \tag{26}$$

$$m_1\frac{\mathrm{d}^2}{\mathrm{d}t^2}\Delta y + \xi\frac{\mathrm{d}}{\mathrm{d}t}\Delta y + k_{el}\Delta y = S_C\Delta p_C , \tag{27}$$

where the used annotations are:

$$k_{1p2} = \left(\frac{\partial Q_1}{\partial p_2^*}\right)_0 = \frac{\mu_{d1}\pi d_1^2\sqrt{2}}{8\sqrt{\rho\left(p_{2_0}^* - p_{C_0}\right)}} = \left(\frac{\partial Q_1}{\partial p_C}\right)_0 = k_{1C}$$

$$k_{2u} = \left(\frac{\partial Q_2}{\partial u}\right)_0 = \mu_7 b_7\sqrt{\frac{2}{\rho}}\sqrt{\left(p_{C_0} - p_{B_0}\right)};$$

$$k_{3x} = \left(\frac{\partial Q_3}{\partial x}\right)_0 = \mu_3\pi d_3\sqrt{\frac{2}{\rho\left(p_{C_0} - p_{A_0}\right)}};$$

$$k_{2C} = \left(\frac{\partial Q_2}{\partial p_C}\right)_0 = \frac{\mu_7 b_7\left(u_s - u_0\right)\sqrt{2}}{2\sqrt{\rho\left(p_{C_0} - p_{B_0}\right)}} = \left(\frac{\partial Q_2}{\partial p_B}\right)_0 = k_{2B};\ k_{3C} = \left(\frac{\partial Q_3}{\partial p_C}\right)_0 = \frac{\mu_3\pi d_3\left(x_s - x_0\right)\sqrt{2}}{2\sqrt{\rho\left(p_{C_0} - p_{B_0}\right)}} = \left(\frac{\partial Q_3}{\partial p_B}\right)_0 = k_{3B};$$

$$k_{4C} = \left(\frac{\partial Q_4}{\partial p_C}\right)_0 = \frac{\mu_{d6}\pi d_6^2\sqrt{2}}{8\sqrt{\rho\left(p_{C_0} - p_{A_0}\right)}} = \left(\frac{\partial Q_4}{\partial p_A}\right)_0 = k_{4A};\ k_{5B} = \left(\frac{\partial Q_5}{\partial p_B}\right)_0 = \frac{\mu_{d8}\pi d_8^2\sqrt{2}}{8\sqrt{\rho\left(p_{B_0} - p_{H_0}\right)}} = \left(\frac{\partial Q_5}{\partial p_H}\right)_0 = k_{5H} . \tag{28}$$

3.3 Non-dimensional linearized model

Using some appropriate chosen amplifying terms, the above-presented linearized mathematical model can be transformed in a non-dimensional one; after applying the Laplace transformation, one obtains the system's linear non-dimensional mathematical model, as follows:

$$K_{p2}\overline{p}_2^* + K_B\overline{p}_B + K_A\overline{p}_A + K_{uC}\overline{u} + K_{xC}\overline{x} - \tau_C s\overline{y} = \left(\tau_{yC}s + 1\right)\overline{y} , \tag{29}$$

$$K_{CB}\overline{p}_C + K_H\overline{p}_H - K_{uB}\overline{u} - K_{xB}\left(\tau_x s + 1\right)\overline{x} = \left(\tau_B s + 1\right)\overline{p}_B , \tag{30}$$

$$K_{CA}\overline{p}_C - \tau_x s\overline{x} = \left(\tau_A s + 1\right)\overline{p}_A , \tag{31}$$

$$\overline{x} = K_{Bx}\overline{p}_B - K_{Ax}\overline{p}_A , \tag{32}$$

$$\left(T_y^2 s^2 + T_\xi s + 1\right)\overline{y} = K_{yC}\overline{p}_C , \tag{33}$$

with the annotations

$$k_{AB} = k_{2B} + k_{3B};\ k_{BC} = k_{2C} + k_{3C};$$

$$k_{CA} = k_{1C} + k_{2C} + k_{3C} + k_{4C};$$

$$k_B = k_{5B} + k_{2B} + k_{3B};\ K_{p2} = \frac{k_{1p2}p_{20}^*}{k_{CA}p_{C0}};$$

$$K_B = \frac{k_{AB}p_{B0}}{k_{CA}p_{C0}};\ K_A = \frac{k_{4A}p_{A0}}{k_{CA}p_{C0}};$$

$$K_{uC} = \frac{k_{2u}u_0}{k_{CA}p_{C0}};\ K_{xC} = \frac{k_{3x}x_0}{k_{CA}p_{C0}};$$

$$\tau_{CA} = \frac{\beta V_{C0}}{k_{CA}};\ \tau_{yC} = \frac{S_C y_0}{k_{CA}p_{C0}};$$

$$\tau_B = \frac{\beta V_{B0}}{k_B};\quad \tau_x = \frac{S_B}{k_{3x}};\quad K_{xB} = \frac{k_{3x}x_0}{k_B p_{B0}};$$

$$K_H = \frac{k_{5H}p_{H0}}{k_B p_{B0}};\quad T_y^2 = \frac{m_1}{k_{el}};\quad T_\xi = \frac{\xi}{k_{el}};$$

$$K_{CB} = \frac{k_{BC}p_{C0}}{k_B p_{B0}};\ K_{Bx} = \frac{S_B p_{B0}}{k_s x_0};$$

$$K_{Ax} = \frac{S_A p_{A0}}{k_s x_0};\ K_{yC} = \frac{S_C p_{C0}}{k_{el}y_0} . \tag{34}$$

3.4. Simplified mathematical model

One can make some simplifications to the above-determined model, based on several experimental observations and determinations:

a) piston+rod mass is very small, so inertial effects could be neglected; consequently, the term $T_y^2 = \frac{m_1}{k_{el}}$ in equation (33) becomes null;

b) viscous friction is insignificant, so the friction co-efficient ξ depends almost only on the mechanical friction;

c) if the p_2^*-pressure is enough high, the flow through the drossels (1), (6), (7) and (8) in fig.2 is critical, so pressures p_A and p_B become proportional to their supplying pressure, which is p_C. Consequently, the terms τ_A and τ_B, depending on the compressibility co-efficient β are becoming null;

d) for small values of (10)-plateau's areas and for small value of the (3)-drossel's diameter, the time constant $\tau_x = \dfrac{S_B}{k_{3x}} = \dfrac{\sqrt{2}S_B\mu_3\pi d_3}{\sqrt{\rho\left(p_{C_0} - p_{A_0}\right)}}$ can be considered as null;

e) if the flight regime (airspeed and altitude) remains the same, the pressure p_H is constant, so $\overline{p}_H = 0$ and the terms containing it dissapears.

Consequently, the simplified mathematical model is

$$K_{p2}\overline{p}_2^* + K_B\overline{p}_B + K_A\overline{p}_A + K_{xC}\overline{x} - \tau_C s\overline{y} = \left(\tau_{yC}s + 1\right)\overline{y}, \tag{35}$$

$$K_{CB}\overline{p}_C + K_H\overline{p}_H - K_{xB}\overline{x} = \overline{p}_B, \tag{36}$$

$$K_{CA}\overline{p}_C = \overline{p}_A, \tag{37}$$

$$\overline{x} = K_{Bx}\overline{p}_B - K_{Ax}\overline{p}_A, \tag{38}$$

$$\left(T_\xi s + 1\right)\overline{y} = K_{yC}\overline{p}_C. \tag{39}$$

Based on it, one can build the system's block diagram with transfer functions, which lays in fig.3, as well as the system's transfer functions:

- with respect to the supply pressure

$$H_p(s) = \frac{\overline{y}(s)}{\overline{p}_2^*(s)} = \frac{K_{yC}K_{p2}}{\tau_{CA}T_\xi s^2 + \left[(1-K_D)T_\xi - K_{yC}\tau_{Cy} + \tau_{CA}\right]s + (1-K_D)};(40)$$

- with respect to the flight altitude

$$H_H(s) = \frac{\overline{y}(s)}{\overline{p}_H(s)} = \frac{K_{yC}K_H\left(K_B + \dfrac{K_{xC}}{1+K_{xB}}\right)\left(T_\xi s + 1\right)}{\tau_{CA}T_\xi s^2 + \left[(1-K_D)T_\xi - K_{yC}\tau_{Cy} + \tau_{CA}\right]s + (1-K_D)}$$

where one has used the annotation

$$K_D = K_B K_{CB} + K_A K_{CA} - \frac{K_{CB} - K_{xA}\left(K_B K_{xB} - K_{xC}\right)}{1 + K_{xB}}. \tag{42}$$

System's transfer functions, (40) and (41),

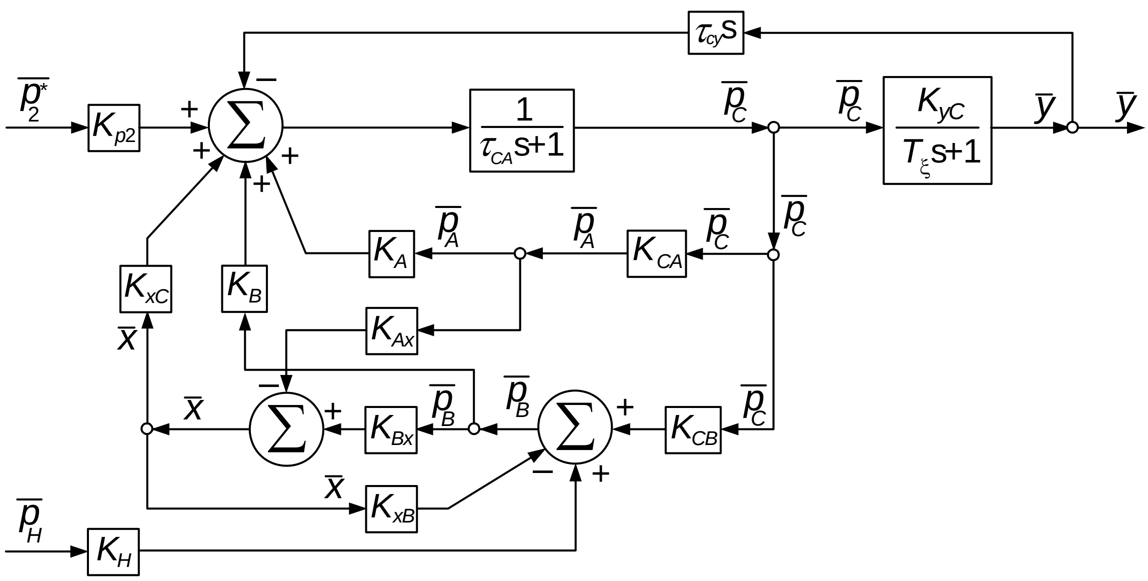


Fig. 3. Block diagram with transfer functions

have simplified forms; their characteristic polynomial is of second order.

4. SYSTEM'S STABILITY

According to algebraic Routh-Hurwitz criteria, system's stability is assured if the characteristic polynomial's co-efficient are strictly positive.

One can observe that, as long as τ_{CA} and T_{ξ} are time constants and are strictly positives, the first polynomial co-efficient $\tau_{CA}T_{\xi}$ is always a positive one; although, the other co-efficient must be analyzed.

The third co-efficient, $1-K_D$, should also be a positive one. So,

$$1-K_B K_{CB}-K_A K_{CA}+ \\ +\frac{K_{CB}-K_{xA}\left(K_B K_{xB}-K_{xC}\right)}{1+K_{xB}}>0\,, \qquad (43)$$

which leads to

$$d_6^2 > a\times d_8^2+b\,, \qquad (44)$$

where the used annotations are

$$a=\left[\mu_7 b_7 S_C\left(p_{C0}-p_{A0}\right)^2 y_0 Q_{10}- \\ -\mu_{d6}\pi S_A\left(p_{C0}-p_{B0}\right)^2 x_0 Q_{60}\right]: \\ : S_C{}^2 x_0\left(\mu_7 b_7 u_0-\frac{\pi}{4}\mu_{d1}d_1^2\sqrt{p_{H0}}\right)^2;$$

$$b=\frac{x_0 y_0\left(\mu_7 b_7 x_0-\frac{\pi}{4}\mu_{d6}S_A\sqrt{p_{H_0}}\right)}{\pi S_A\left(p_{C0}-p_{B0}\right)^2 x_0}\times \\ \times\left[k_{el}S_C-S_B{}^2 x_0\left(\mu_7 b_7 u_0-\frac{\pi}{4}\mu_{d1}d_1^2\sqrt{p_{H0}}\right)^2\right. \\ \left.+\left(p_{C0}-p_{A0}\right)^2\sqrt{\frac{2}{\rho}}y_0 Q_{10}\right]. \qquad (45)$$

The above-determined relation (44) may be graphically expressed as a domain of stability into a co-ordinates system $\left(d_6, d_8\right)$, as fig. 4.a shows. As far as these two drossel diameters are strictly positive, the diagram is relevant only in the positive side of its axis. It results a stability domain, as well as an instability domain on the diagram's surface. An observation may occur, concerning the (8)-drossel absence, when the drossel (8) should have a minimum value $\left(d_6\right)_{\min}$ in order to keep the system's stability.

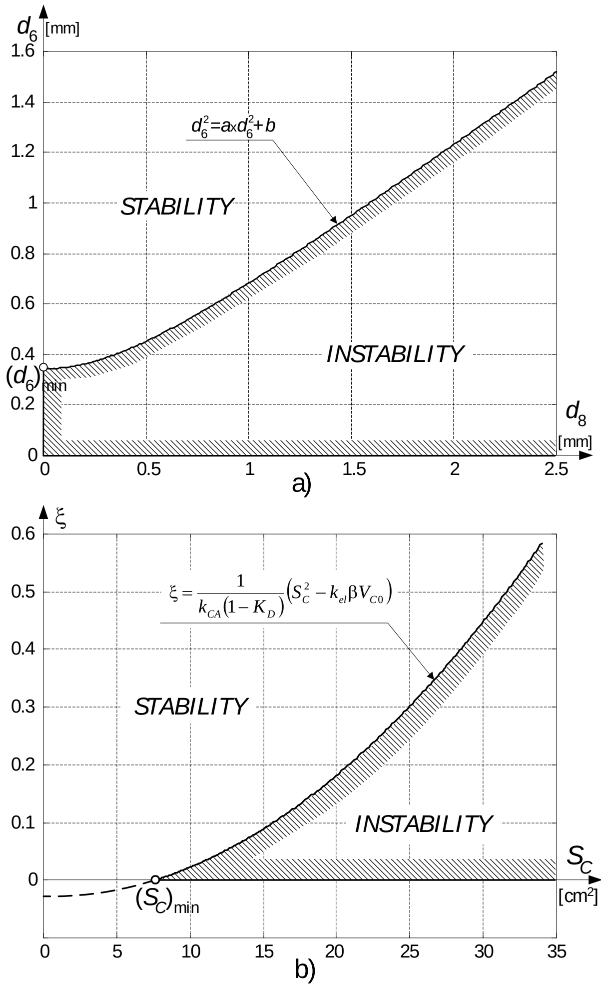


Fig. 4. System's stability conditions

The second characteristic polynomial's co-efficient must be also positive

$$\left(1-K_D\right)T_{\xi}-K_{yC}\tau_{Cy}+\tau_{CA}>0\,. \qquad (46)$$

Time constants τ_{CA} and τ_{Cy} are strictly positive, as well as the term $K_{yC}=\dfrac{S_C p_{C0}}{k_{el}y_0}$, determined by strictly positive factors. Moreover, one considers the first stability condition as fulfilled, meaning $1-K_D>0$, so condition (46) becomes $T_{\xi}>\dfrac{K_{yC}\tau_{Cy}-\tau_{CA}}{1-K_D}$.

Considering (28), (32) and (42) annotations one obtains for (46) the expression

$$\xi > \frac{1}{k_{CA}(1-K_D)}\left(S_C^2 - k_{el}\beta V_{C0}\right), \qquad (47)$$

which represents the second stability condition of the system; it could be graphically expressed as fig. 4.b) shows, which offers the possibility to choose the surface area of the actuator's piston S_C with respect to the friction co-efficient ξ. The same diagram shows a minimum piston area S_C-value, when piston motion would occur, hypothetically, frictionless.

For usual friction $\xi-$values, actuator's piston area should be chosen in the range of $(30 \div 50)$ cm^2.

Stability studies may be extended, in order to determine the periodic/aperiodic stability domains; one has to verify the characteristic polynomial's discriminant sign as well as its roots locus.

5. SYSTEM'S QUALITY

Based on the block diagram in fig. 3, one has performed a simulation, concerning system's step response, for a constant flight regime. One has simulated a step input of $\overline{p}_2^*$, for two different situations, involving two $\xi-$values and one has evaluate system's time response, depicted in fig. 5.

In both of the above-mentioned situations the system is a stable-one. When the friction co-efficient's value is small, system's stability is periodic-type, with an initial 10% override and a response time around 1.2 seconds, while when the friction grows, the stability becomes aperiodic and the response time increases too.

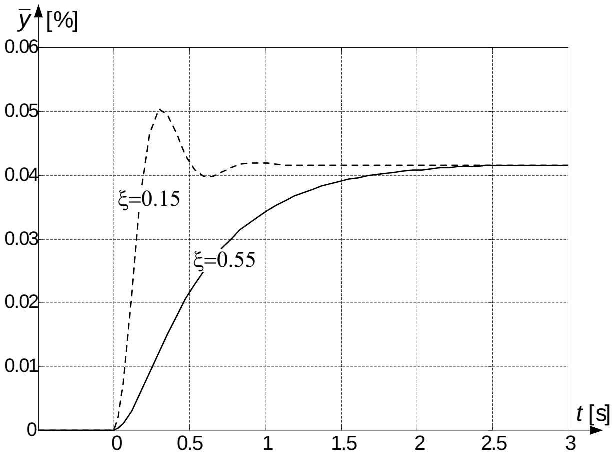


Fig. 5. System's quality

6. CONCLUSIONS

The studied pneumatic anti-stall valve's opening system is a second order control system, as its transfer function shows.

Because of its working fluid (air) compressibility, this kind of systems are less precisely, but very effective for a wide range of compressors. Compressibility factor β is found in many mathematical model co-efficient expressions (see (28)-expressions) and has an important influence above system's behavior.

Based on the simplified linearized mathematical model the authors have studied the stability of the system and, subsequently, have determined two graphic stability conditions, involving relations between constructive and functional parameters, which may be used by engine designers during the pre-design phases.

One has also performed a simulation, concerning system's quality, estimated through system's step response, for a step input of the main system parameter, $\overline{p}_2^*$. The conclusion is that system's behavior depends on the friction co-efficient values, which means that it depends on the materials combination used for the actuator's manufacturing.

If the friction co-efficient is very low, even if the system is stable and its time response is small, its stability is periodically type, which is unacceptable from the compressor's operating point of view, because anti-stall valve's periodic opening induces itself an unstable flow through the compressor, acting contrary to its main objective.

If the friction co-efficient is enough high, system's stability becomes aperiodic, which is acceptable, even if the stabilization time increases (from 1.2 seconds to 2.5 seconds), which means that the system becomes slower. Consequently, a very important aspect of the system design is the choice of manufacturing materials, especially concerning the friction co-efficient between actuator's piston and cylinder materials.

The study is useful for aerospace students, engineers and professionals and may be extended for similar systems' analysis, as well as for further studies concerning axial compressors control systems, or embedded jet engine control systems.

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