PNEUMO-HYDRO-MECHANICAL CONTROL SYSTEM FOR AN AIRCRAFT SUPERSONIC INLET WITH MOBILE RAMP

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Abstract: *The paper studies a plan supersonic inlet with external compression and mobile panel and deals with its control system, based on the second oblique shock-wave positioning and its total pressure ratio recovery. Inlet's gas-dynamic conditioning and control criteria are determined. Based on overall total pressure recovery maximization, inlet's optimal geometry was determined, as well as inlet's main control law (consisting of mobile's panel position with respect to inlet's front Mach number) and its complementary control law. The author has established mobile panel's control system's mathematical model; the block diagram with transfer functions description, based on the above-mentioned model was also provided. Some simulations, concerning the system's stability and quality were performed; furthermore, some conclusions and comment concerning system's time behavior were issued.*

Keywords: *inlet, supersonic, Mach number, control law, angle, shock-wave, pressure, step input.*

1. INTRODUCTION

Aircraft engine inlet is one of the most important components, especially when it's about a supersonic aircraft. On supersonic military jets, the inlets are usually much more complex than on any other aircraft or airplane and use shock waves to slow down the air, together with movable internal parts (ramps, panels, vanes) to shape and control the flow; thus, the inlet is not a simply air duct, but an especially profiled canalization, meant to capture an appropriate air flow from the freestream and deliver it to the engine; the necessary airflow for engine's supply requires some special conditions, concerning the pressure and the velocity in front of engine's compressor (a moderate subsonic value, about Mach 0.4), so such a supersonic inlet will reduce the supersonic freestream to subsonic speed, and will provide an appropriate air mass flow rate to the engine.

Aircraft gas turbine engine requires a supply of uniform high total pressure recovery air for good performance and operation, thus the quality of the airflow in front of the engine will significantly affect its performance; it is well known that a loss of 1% from intake's total air pressure will lead to 0.5÷1.2 % lowering of engine's thrust [4,9], therefore, it is important to maximize the total pressure recovery in front of the engine. The total pressure recovery is defined as the ratio of the airflow's total pressure in front of the engine and the one in the freestream (in front of the inlet). Meanwhile, inlet's design should take into account the induced external drag, which affects aircraft's total drag, as well as the other aerodynamic performances, so inlet's shape and dimensions should be carefully chosen and designed in correlation to those of the aircraft.

The bigger the flight Mach number is, the more important the inlet is and the more difficult its design becomes.

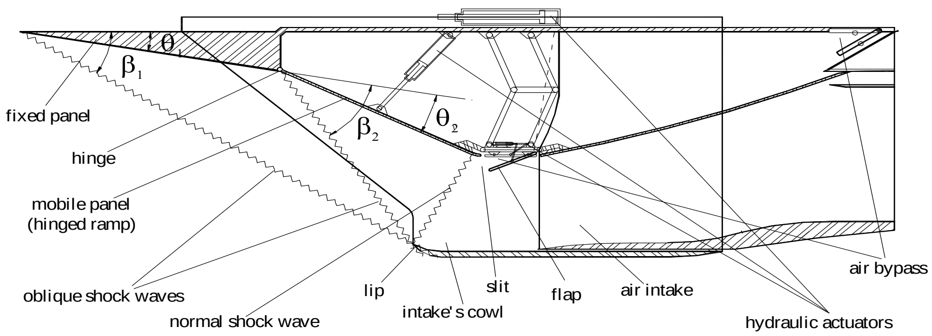


FIG. 1. Supersonic inlet with mobile panel "2+1"-type [12]

Because the inlet is so important to overall aircraft operation, it is usually designed and tested by the airframe company, not by the engine manufacturer; that is the reason because all engine manufacturers also employ aerodynamic engineers for inlet design.

An inlet, no matter its architecture, must operate efficiently over the entire flight envelope of the aircraft. At very low aircraft speeds, or when just sitting on the runway, free stream air is "sucked" into the engine by the compressor.

Meanwhile, at high speeds, an appropriate designed and manufactured inlet will allow the aircraft to maneuver at high angles of attack and sideslip, without disrupting the air flow to the compressor.

The paper is focused on a control possibility of a plan supersonic inlet with a mobile ramp, which operates as external compression inlet. Such an inlet is depicted in Fig. 1, similar to MiG-29's inlet, operating as "1+1" inlet for low supersonic flight Mach numbers and as "2+1" inlet for high supersonic Mach numbers.

2. INLET ARCHITECTURE

The inlet in Fig. 1 consists of an air intake with a mobile cowl and a spike-shape body with two ramps (a fixed panel, mounted at θ_1-angle versus O*x*-axis and a hinged panel, having a variable θ_2 -angle), both cowl and mobile panel assisted by hydraulic actuators. During supersonic operating, the inlet has its own shock wave system, generated by the spike and by cowl's lip: one or two oblique shock-wave(s) due to spike's panels and a final normal shock wave attached to the cowl's lip.

The inlet is mounted below aircraft's wing; consequently, in supersonic flight, air speed in front of the air intake is less than the airspeed of the airplane, because of two shock waves: the first one is triggered by aircraft's nose (so it is a conical shock wave), the second one – by aircraft's wing.

The mobile panel could have three different positions, as follows: a) for subsonic flights it is completely retracted ($\theta_2 < 0$), offering to the intake the maximum air-breathing cross-section; b) for moderate supersonic flights, the mobile panel is on the fixed one's direction ($\theta_2 = 0$), extending it (the inlet operates as "1+1"); c) for high supersonic flights the mobile panel has variable position ($\theta_2 > 0$, as Fig. 1 shows), according to the air velocity in front of the inlet.

Inlet's slit, between the mobile panel and the flap, offers the possibility of air bleeding (or works as a by-pass), when the engine's air necessities are lower than the inlet's offer.

For an aircraft designed to reach a flight Mach number of 2.5, air velocity in front of this kind of inlet corresponds to a Mach number of 2.1, because of successive shock down of the air flow through the shock-waves triggered by aircraft's aerodynamic shape.

The air flow could be considered inviscid, with enough calculus accuracy, thus viscous effects and/or losses should be neglected. Inlet's shock wave system form and geometric parameters are depicted in Fig. 2.

Performance criterion for inlet's geometrical optimization is the maximum inlet efficiency, or else, maximum inlet total pressure loss co-efficient (pressure recovery) σ_i^*, given by

$$\sigma_i^* = \sigma_{osw1}^* \sigma_{osw2}^* \sigma_{nsw}^* \sigma_d^*, \tag{1}$$

where σ_{osw1}^*, σ_{osw2}^* are total pressure ratios for the oblique shock-waves, σ_{nsw}^* – total pressure ratio for the normal shock-wave and σ_d^* – total pressure ratio into intake's duct (assumed as constant, no matter the flight regime or the engine regime would be).

Algorithms of geometric optimization of external compression inlets, based on inlet's efficiency maximization, are presented in [10] and applied in [4, 15, 17]. This algorithm aims to determine optimum values of spike's angles θ_1 and θ_2, as well as an adimensional geometry of the inlet.

Terms in the right member of Eq. (1) are given by the aerodynamic and thermodynamic conditions of shock waves, using following equations:

- for the oblique shock waves

$$\sin^2\beta_k = \frac{1}{M_k^2} + \frac{\chi+1}{2}\frac{\sin\beta_k \cdot \sin\theta_k}{\cos(\beta_k\text{-}\theta_k)}, \tag{2}$$

$$M_{k_{av}}^2 = \frac{1}{\sin^2(\beta_k-\theta_k)}\frac{(\chi-1)M_k^2\sin^2\beta_k+2}{2\chi M_k^2\sin^2\beta_k-(\chi-1)}, \tag{3}$$

$$\sigma_{oswk}^* = \left[\frac{(\chi+1)M_k^2\sin^2\theta_k}{2+(\chi-1)M_k^2\sin^2\theta_k}\right]^{\frac{\chi}{\chi-1}}\left[\frac{\chi+1}{2\chi M_k^2\sin^2\theta_k-(\chi-1)}\right]^{\frac{1}{\chi-1}}, \tag{4}$$

where $k=\overline{1,2}$, M_k – Mach number before the shock-wave, $M_{k_{av}}$ – Mach number behind the shock-wave;

- for the normal shock-wave

$$M_{av}^2 = \frac{(\chi-1)M_k^2+2}{2\chi M_k^2-(\chi-1)}, \tag{5}$$

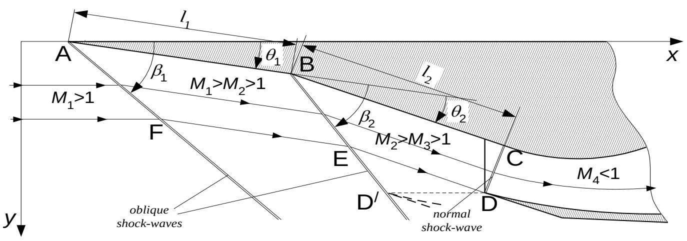


FIG. 2. Supersonic inlet "2+1"-type geometry

$$\sigma_{nsw}^* = \left[\frac{(\chi+1)M_k^2}{2+(\chi-1)M_k^2}\right]^{\frac{\chi}{\chi-1}}\left[\frac{\chi+1}{2\chi M_k^2-(\chi-1)}\right]^{\frac{1}{\chi-1}}, \tag{6}$$

where M_k – Mach number before the normal shock-wave, M_{av} – Mach number behind the normal shock-wave, χ – air's adiabatic exponent.

First inlet configuration design issue is the determination of the spike's angles values, starting from the nominal Mach number value in front of the inlet. For a flight Mach number in front of the inlet $M_1 = 2.1$ one can apply the algorithm, in order to obtain the maximization of σ_i^*. One has obtained (as presented in [17]) for a fixed geometry inlet, the results: $\theta_{1_{opt}} = 11.14^\circ$, $\theta_{2_{opt}} = 12.22^\circ$, $l_1 = 0.8849$, $l_2 = 0.7624$ and the coordinates of the characteristic points as A (0,0); B (0.874; 0.142); C (1.569; 0.454); D (1.324; 1), as Fig. 2 shows.

For different M_1 Mach numbers, $M_1^{/} < M_{1_{nom}}$, but fixed inlet geometry, both external oblique shock-waves are depleting, so angles β_1 and β_2 in Fig. 2 are growing, which means that pressure recovery coefficient σ_i^* and flow coefficient C_D are modifying too. While σ_i^* can be calculated with above-mentioned formulas ((1), (4) and (6)), C_D is represented by the ratio of inlet's effective air-breathing area $A_H / A_{1^{/}}$, which is exactly the co-ordinate y_F in Fig. 2.

3. INLET CONTROL LAWS

3.1. Mobile ramp motion law. Operation of an inlet with fixed geometry architecture means a lot of losses from air flow rate's point of view, especially for low or medium Mach numbers, when flow coefficient C_D is far from the maximum value 1 and it could lead to buzz behavior of the inlet, especially when the engine's regime decreases. In order to grow the C_D-value, an appropriate solution is to keep the second oblique shock-wave tangent (attached) to the cowl's lip, by progressively growing the second spike angle θ_2, by rotating the mobile panel about its hinge. The condition of attaching the shock-wave is to keep constant the β_2 – angle, which means that one has to find the value of θ_2 which generates such an angle, with respect to the Mach number in front of the inlet; consequently, one has to solve the implicit equation

$$\sin^2\beta_2 = \frac{1}{M_2^2} + \frac{\chi+1}{2}\frac{\sin\beta_2 \cdot \sin\theta_2}{\cos(\beta_2\text{-}\theta_2)}, \tag{7}$$

where β_2 is the constant angle value, given by the position of points B and D in Fig. 2, θ_2 – equation's argument, M_2 – Mach number behind the first oblique shock-wave and before the second oblique shock-wave, which is given by the value of Mach number in front of the inlet and the spike's first angle θ_1. Eventually, one obtains a dependence $\theta_2 = \theta_2(M_1)$, as shown in Fig. 3, curve I, which is a possible motion law for the mobile panel and a theoretical control law for the inlet.

The curve in Fig. 3, determined in [17], is a bit non-linear and can be described as:

$$\theta_2(M_1) = 40.07 \cdot M_1^3 - 265.397 \cdot M_1^2 + 603.895 \cdot M_1 - 456.623 \left[{}^\circ\right]. \tag{8}$$

Aerodynamics studies have proved that small values for spike angles (under 4^{o}) didn't generate appropriate oblique shock-waves [9, 11], so, in order to avoid the shock wave's detaching, the variation domain of θ_2 should begin at values bigger than $M_1^{//} = 1.8$, which correspond to a minimum value $(\theta_2)_{\min} = 4.2^\circ$, so the aspect of the control law should be as the curve II in Fig. 3 shows [17].

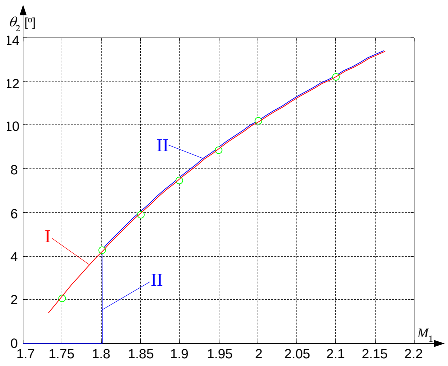


FIG. 3. Inlet's control law (mobile panel's angle versus Mach number in front of the inlet) [17]

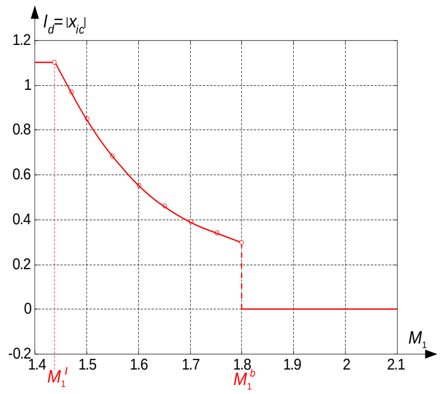


FIG. 4. Intake's cowl displacement (inlet's complementary control law) [17]

Consequently, the inlet operates as "1+1" external compression device until the airspeed in front reaches a Mach number $M_1 = 1.8$, because the fixed panel and the mobile one are building a single-flare spike $\theta_2 = 0^\circ$; for a Mach number $M_1 = 1.8$ the mobile panel moves sudden at $(\theta_2)_{\min} = 4.2^\circ$, then, over this limit, the inlet behaves like a "2+1" external compression device, but with the second oblique shock-wave tangent to its cowl lip, until the nominal flight Mach number value $(M_1)_{\text{nom}} = 2.1$ is reached, as determined in [17]. Inlet's flow rate characteristics is improved.

3.2. Intake's cowl displacement (complementary law). Inlet's behavior may be also improved for the "1+1" operation, from the flow rate characteristics point of view. Thus, in order to assure the maximum value of the flow coefficient C_D, the oblique shock-wave should be tangent to the cowl's lip, no matter the Mach number in front of the inlet.

Since the spike has a fixed single flare, the only adjustment possibility remains intake's cowl displacement; therefore, a complementary law can be issued, which is intake's cowl positioning x_{ic} with respect to the Mach number in front of the inlet M_1.

According to Eq. (2) and as Fig. 2 shows, the oblique shock-wave's angle β_1 is given by the spike's angle θ_1 and the Mach number M_1, while D-point's co-ordinates are fixed. Intake cowl's displacement should reduce till cancellation of the distance between the cowl's lip and the oblique shock-wave, which means that D-point's new position must be D$^/$; therefore, one has to determine the complementary law as:

$$x_{ic}(M_1) = x_{D'}(M_1) - x_D = \frac{1}{\text{tg}\beta_1(\theta_1, M_1)} - 1.324 \,. \tag{9}$$

From the intake's position point of view, when the Mach number in front of the inlet decreases, the cowl must be extended, so its extension should be equal to $|x_{ic}|$.

The complementary law for the intake's cowl displacement is graphically represented in Fig. 4; it has three important zones: a) the first zone, for subsonic and low supersonic airspeeds ($M_1 < M_1^/ = 1.438$), when the cowl is completely extended, b) the second (nonlinear) zone, between $M_1^/ = 1.438$ and $M_1^b = 1.8$ airspeeds.

Respectively c) the third high supersonic airspeeds zone ($M_1 > M_1^b$), when the cowl is completely retracted. When the Mach number M_1 becomes equal to M_1^b, the cowl must be sudden retracted.

4. AUTOMATIC CONTROL SYSTEM'S MODEL

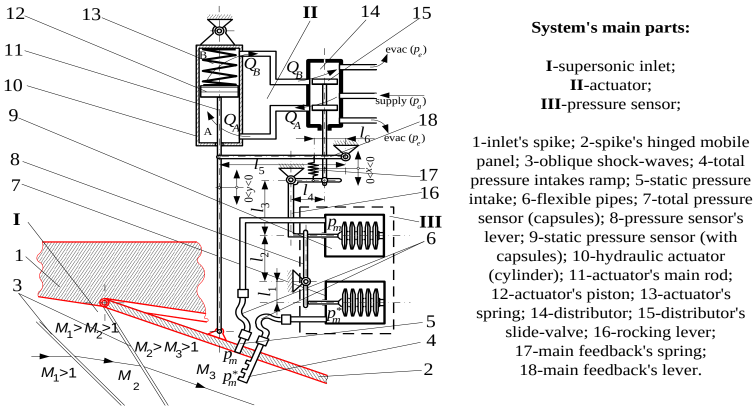


FIG. 5. Supersonic inlet's automatic control system's architecture [17]

4.1. Control system's architecture. The automatic control system is depicted in Fig. 5. It consists of a mobile panel (of the inlet's spike) with pressure intakes, a pressure sensor (with two capsules, one for the total pressure, the other for the static pressure) and a hydraulic actuator with a slide-valve distributor and a rigid feedback. System's main parts are identified in Fig. 3. Pressure intakes are positioned so as they measure the average total pressure p_m^*, a well as the average static pressure p_m behind the second oblique shock-wave. Pressures ratio φ_w, from aerodynamic and thermodynamic points of view, is a function of the Mach number behind the second shock wave M_3, as follows:

$$\varphi_w = \frac{p_m^*}{p_m} = \left(1 + \frac{\chi - 1}{2} M_3^2\right)^{\frac{\chi}{\chi - 1}}. \tag{10}$$

Inlet's control law, with respect to the flight regime, as determined in [14], has a form depending on the Mach number in front of the inlet M_1. Thus, Mach number(s) behind the shock-wave(s) (M_2 and/or M_3) are depending themselves on M_1. One may affirm that the pressure ratio behind the oblique shock-wave(s) should be preserved, which involves the panel repositioning with respect to the Mach number.

The inlet operates both as "1+1" and as "2+1" external compression device; for low values of Mach number M_1, the mobile panel is kept on its initial position (as an extension of the fixed panel of the inlet); after $M_1 = 1.8$ the mobile panel will be positioned with respect to the flight Mach number. To modify the Mach number means to modify the pressure balance, as well as pressure's ratio; when the mobile panel is repositioned, pressure ratio should be restored, in order to assure the same position of the second oblique shock-wave. Positioning law (8) is a non-linear one, but it could be linearised, accepting a mobile panel positioning error and, obviously, a better correlation with the complementary control law (which means the inlet cowl's displacement).

4.2. Control system's mathematical model. Non-linear mathematical model consists of each part's motion equation, but its form is impossible to be used for further studies. Based on the small perturbation hypothesis one can linearize these equations and, after appropriate transformation, they can be brought to an adimensional simplified form. This algorithm, completed with the Laplace transformation applying, is described in [16] and also applied in [2, 13, 14, 15]; in this particular case one obtains for each part as follows:

$$k_{mt}\,\overline{p_m^*} - k_m\,\overline{p_m} - k_r\,\overline{y} = \overline{x}, \tag{11}$$

$$k_x\overline{x}-\tau_y s\overline{y}=\left(\tau_{Ap}s+1\right)\left(\overline{p_A}-\overline{p_B}\right)\approx\left(\overline{p_A}-\overline{p_B}\right), \tag{12}$$

$$\overline{y}=k_y\left(\overline{p_A}-\overline{p_B}\right), \tag{13}$$

where the coefficients involved in the equations are determined in [17].

System's transfer functions can be obtained based an the above-presented equations and have similar forms, as follows:

$$H_{mt}(s)=\frac{k_x k_y k_{mt}}{\left(k_y\tau_y s+k_r\right)}\overline{p_m^*},\ H_m(s)=-\frac{k_x k_y k_m}{\left(k_y\tau_y s+k_r\right)}\overline{p_m}. \tag{14}$$

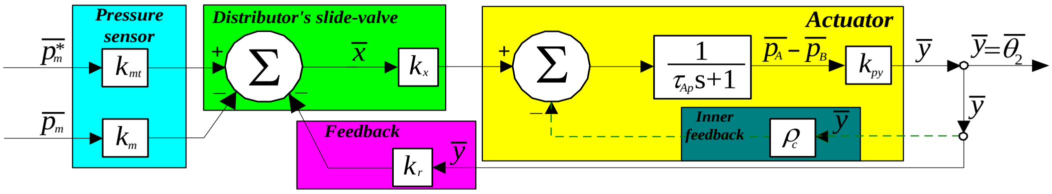


FIG. 6. System's simplified block diagram with transfer functions

System's block diagram with transfer functions is presented in Fig. 6; one should observe that the system has an outer rigid feedback, but its actuator may have its own inner feedback [16], in order to improve system's quality.

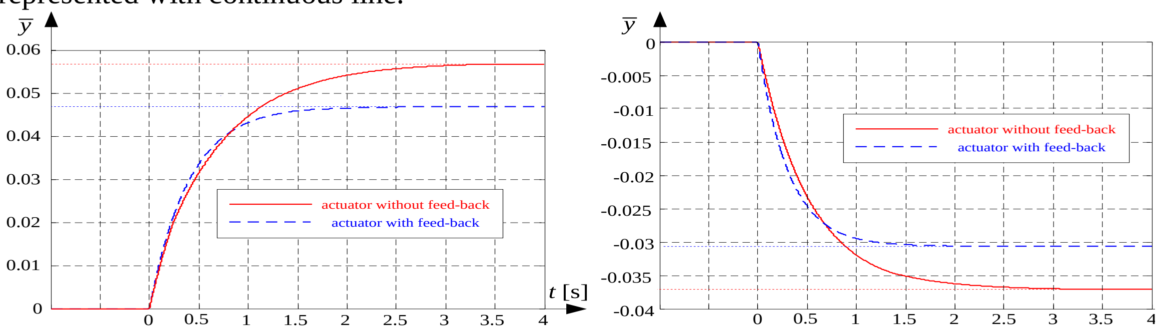
5. ABOUT SYSTEM'S STABILITY AND QUALITY

Since transfer functions expressions are first order, as far as one chooses appropriate values for the system's geometric parameters, the above-studied system should be always a stabile one. The conditions of stability ($k_y\tau_y$ and k_r to have the same sign, in this case strictly positive) are identically fulfilled if one chooses the values of the pressure sensor's lever arms as

$$l_1=\frac{S_a p_{m0}^2 l_4}{p_{m0}^*\left(l_3k_{r2}-l_3k_{r1}+S_a p_{m0}\right)},\ l_2=\frac{S_a p_{m0}^2\left(S_a p_{m0}-l_3k_{r1}\right)}{p_{m0}^* l_4 k_{r2}\left(l_3k_{r2}-l_3k_{r1}+S_a p_{m0}\right)}, \tag{15}$$

which are depending on: capsules' surface area S_a, rocking lever arms length l_3, l_4, capsules' elastic constants k_{r1}, k_{r2}, steady state regime's values for pressures p_{m0}^*, p_{m0}.

In order to evaluate system's quality some simulations were performed, regarding system's output $\overline{y}$ behavior as time response, considering both situations of step inputs: a) step input of $\overline{p}_m^*$ and constant $\overline{p}_m$, respectively b) step input of $\overline{p}_m$ and constant $\overline{p}_m^*$. Results are graphically presented in Fig. 7 a) and b), for both of the studied situations; the curves are represented with continuous line.



a) step input for $\overline{p}_m^*$ and constant $p_m\left(\overline{p}_m=0\right)$ b) step input for $\overline{p}_m$ and constant $p_m^*\left(\overline{p}_m^*=0\right)$

FIG. 7. System's step response

For system's behavior improvement, a rigid feedback between the actuator and the distributor may be used; obviously, the presence of this feedback modifies system's mathematical model and transfer function (both new values of the time constant and of the gain are becoming smaller). System's new behavior was represented in Fig. 7 with dashed line.

CONCLUSIONS

The paper studied a plan supersonic inlet with mobile ramp, as controlled object; an automatic control system was described and mathematically modeled. As controlled parameter the system has the mobile panel's position and as control parameter one has chosen the pressure ratio through the second oblique shock-wave (which is proportional to the flow's Mach number behind this shock). Control system most important element is the pressure transducer, which should realize both the sensing task, as well as the comparing with the preset pressure ratio value, imposed by the lever's arm's length choice. For the complementary law, similar control systems may be used (as in [13, 14]).

If the system uses an actuator without inner feedback, the results for both of studied cases show that the system has appropriate stabilization time (around 3.2 seconds for both of cases a) and b)); meanwhile, it has static errors (5.5% positive for $\overline{p}_m^*$-step input and -3.7% negative for $\overline{p}_m$-step input). Using an actuator with inner feedback (by its rod displacement, as studied in [16]), system's step response was improved, but not essentially.

Thus, the stabilization times were reduced (from 3.2 seconds to $2.0 \div 2.5$ seconds), which means that the intensity of the command signal was diminished; meanwhile, system's static error were also reduced: from 5.5% to 4.7 % for $\overline{p}_m^*$-step input, respectively from -3.7% to -3.1 % for $\overline{p}_m$-step input.

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