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INVESTIGATION OF THE INFLUENCE OF STRUCTURAL AND ADJUSTING PARAMETERS OF A QUADRUPLE-ORIFICES ELECTROHYDRAULIC AMPLIFIER ON THE STATIC CHARACTERISTICS OF ROCKET PACK STEERING ACTUATOR

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Abstract

The article considered the results of researches of influence of constructional and adjusting parameters of the quadruple-orifices electrohydraulic amplifier on static characteristics of the steering actuator of the rocket pack. The studies are carried out using static analysis methods, including methods for calculating the static characteristics of an autonomous single-stage steering actuator with a quadruple-orifices electrohydraulic amplifier with negative overlapping of throttling windows of rectangular shape by spool plungers. As a result of research it is shown that the steering actuator does not have static stability. It is shown that the slope of the speed characteristic of the steering actuator is exerted by the dimensionless parameter of the local thickness of the incoming liner wall (the driven axis of the three-gear pump). Consequently, with the help of the variation of this parameter, it is possible to adjust the slope angle of the speed characteristic of the steering actuator, i.e., its gain factor. The design solutions of the steering actuator are proposed, which allow improving their output characteristics and facilitating adjustment

Keywords

Structural and adjusting parameters, electrohydraulic amplifier, steering actuator, static characteristics

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Introduction. The function of the executive bodies of the thrust vector control systems (TVCS) of liquid-propellant rocket engines (LRE) of ballistic missiles, spacecraft and their accelerating blocks (AB) is performed by autonomous single-stage analog electrohydraulic steering actuators (SA), which include an electric pump unit, electrohydraulic amplifier (EHA) and power hydraulic cylinder [1].

The four-throttle EHA SA (Fig. 1) consists of an electromechanical control unit (CU) and two simple three-way spool valves (SV) [2–4], each of which includes a spool plug and sleeve. Through sleeves are provided with through radial rectangular openings that form, together with the slide valve, rectangular throttle windows.

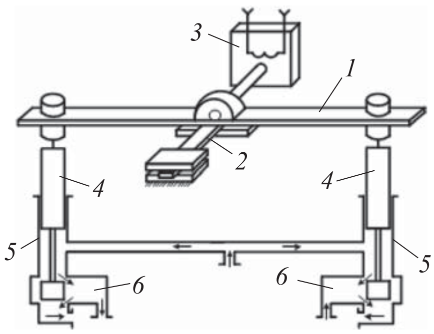

Fig. 1. Design of a four-throttle EHA: *1* is rocker arm; *2* is flat load spring; *3* is electromechanical converter, type of polarized relay; *4* is spool plug; *5* is sleeve (pump axis); *6* is EHA working cavity

The main structural feature of the EHA SA is the placement of spool plungers in the hollow rotating axes of three-gear pumps, which play the role of sleeve spool SV. Studies of the working processes of the EHA spool SV_s showed that this solution positively affects the functioning of the SA, since the dry friction between the spool and the sleeve is almost completely replaced by viscous [5]. Simultaneously stationary component of hydrodynamic force, acting on the spool plungers, significantly decreases due to changes in the angles of the outflow of flows in the throttle windows and changes in their conductivity compared with SV_s with stationary sleeves. In addition, it was found that the flow angles in the throttle windows and their flow rates are affected by such complex dimensionless parameters as the ratio of the linear speed of circular motion of the middle surface of the liner V_g to the average flow rate in the window V_o, as well as the ratio of the local wall thickness of the sleeve in the area of the throttle window δ_g to the width of the throttle window b.

Statement of the problem. The objective of the research was to find ways of parametric optimization of SA. Important parameters for optimization are the slope of its speed characteristic and the current of start motion of piston. Therefore, the aim of the research was to search for parameters that most significantly affect these characteristics.

The studies were carried out by means of a static analysis, including methods for calculating static (speed and force) characteristics [6]. For computational experiments, mathematical models of the static modes of operation of the SA with a four-throttle EHA were used, providing an error in calculating the static characteristics of not more than ± 2 % in a wide range of temperatures and power supply voltages of the SA [7].

During the experiments, the influence of the following parameters on the static characteristics of the SA was studied:

– relative coefficient of elasticity of a flat spring CU EHA $\overline{K}_{mp}$, determined as $\overline{K}_{mp} = K_{mp} / K_{mp}^N$, where K_{mp} is coefficient of elasticity of a flat spring; K_{mp}^N is nominal value of coefficient of elasticity of flat spring;

– relative initial opening of drain throttle windows $\overline{X}_{z0}$, determined as $\overline{X}_{z0} = X_{z0} / X_{z0}^N$, where X_{z0} is initial opening of drain throttle windows; X_{z0}^N is nominal value of the initial opening of the drain throttle windows;

– the relative width of the throttle holes in the spool sleeve $\overline{b}$ for the fixed initial areas of the throttle windows, defined as $\overline{b} = b / b^N$, where b is the width of the throttle holes in the spool sleeve, b^N is nominal value of the width of the throttle holes in the spool sleeve;

– the relative local wall thickness of the spool sleeve in the area of the throttle hole $\overline{\delta}_g$, defined as $\overline{\delta}_g = \delta_g / \delta_g^N$, where δ_g is the local wall thickness of the spool sleeve in the zone of the throttle hole; δ_g^N is nominal local wall thickness of the spool sleeve in the area of the throttle hole.

Description of research. During the research, the influence of the indicated chracteristics on the following static characteristics of the SA was determined:

– speed characteristic of the SA $V_p = f(i_k)$ under the against load on the rod 1000 N, where V_p is the speed of movement of the SA piston, i_k is the command current;

– force characteristic of the SM $F_p = f(i_k)$, where F_p is the force developed by the piston rod SA;

– dependence of the hydraulic force F_g, acting on the spool plungers on the movement of the spool plunger X_z with an opposing load on the rod of 1000 N and when the piston is completely inhibited $F_g = f(X_z)$.

Results of computational experiments and analysis of the influence of parameters. The influence of the relative coefficient of elasticity of the flat spring of the EHA control unit $\overline{K}_{mp}$ on the static characteristics of the SA is illustrated in Fig. 2, which presents the results of computational experiments conducted by varying the specified characteristic.

Analysis of the influence of the parameters $\overline{K}_{mp}$. As follows from the graphs (Fig. 2, *a*), the variation of the parameter $\overline{K}_{mp}$ leads to a simultaneous shift of the speed characteristic along the i_k axis and a change in the angle of inclination $\overline{K}_{mp}$ to this axis, while a decrease leads to a decrease in the current of start motion of piston, of the SA, which is accompanied by an increase in the angle of inclination of the speed characteristic, and an increase leads to an increase in the

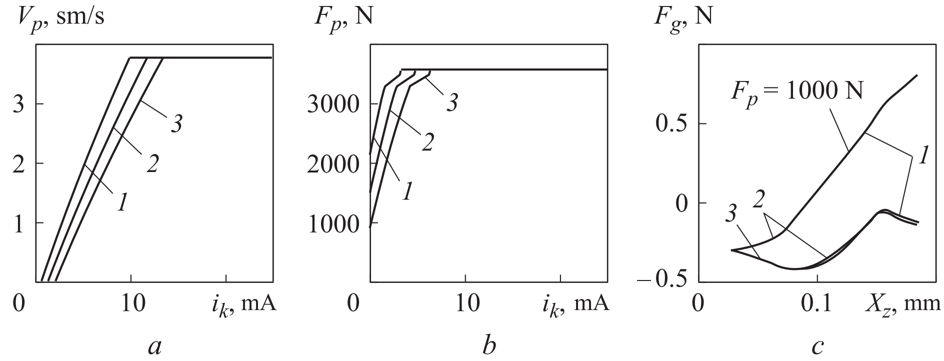

Fig. 2. Influence $\overline{K}_{mp}$ on the static characteristics SA:

a is the influence $\overline{K}_{mp}$ on $V_p = f(i_k)$; *b* is the influence $\overline{K}_{mp}$ on $F_p = f(i_k)$; *c* is the influence $\overline{K}_{mp}$ on $F_g = f(X_z)$, $\overline{K}_{mp} = 0.666$ (curve *1*); 1.000 (curve *2*); 1.333 (curve *3*)

current of start motion of piston, which is accompanied by a decrease in the slope of the speed characteristic, i.e., to the opposite effect. In Fig. 2, *b* it can be seen that the variation of the parameter K_{mp} leads to an almost parallel shift in the power characteristics of the SA along the i_k axis. Having examined the dependency graphs $F_g = f(X_z)$, presented in Fig. 2, *c*, it can be seen that the variation of the characteristic has practically no effect on the values of the hydraulic force under the opposing load on the SA 1000 N rod. And from the dependency graphs $F_g = f(X_z)$ with a braked piston, it follows that the characteristics leave the origin. This means that the SA does not have static stability, and spool plungers of SA, in the presence of the smallest command signal, fall into a certain equilibrium state, shifted relative to the origin by a certain distance. In this case, an increase in the parameter $\overline{K}_{mp}$ decreases this shift.

The effect of the relative initial opening of the drain throttle windows $\overline{X}_{z0}$ on the static characteristics of the SA is shown in Fig. 3, which shows the results of computational experiments conducted by varying the specified characteristic.

Analysis of the influence of the parameters $\overline{X}_{z0}$. As follows from the graphs (Fig. 3, *a*), the variation of the parameter $\overline{X}_{z0}$ leads to an almost parallel shift of the SA speed characteristic along the i_k axis without changing its angle of inclination to the i_k axis, with a decrease $\overline{X}_{z0}$ leading to an increase in the current of start motion of piston of the SA, and an increase $\overline{X}_{z0}$ to its decrease. In Fig. 3, *b* it can be seen that a decrease in the parameter $\overline{X}_{z0}$ leads to the appearance of a dead zone of the power characteristic, and an increase in the parameter $\overline{X}_{z0}$ leads to a steeper increase in the developed SA force.

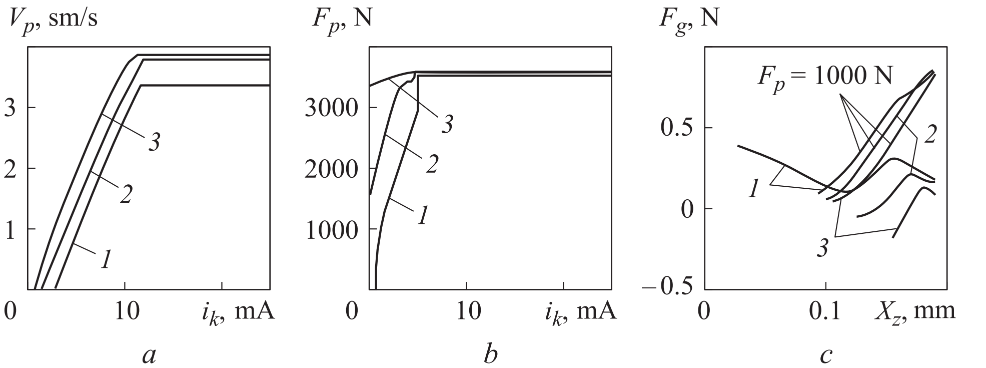

Fig. 3. Influence $\overline{X}_{z0}$ on the static characteristic:
a is the influence $\overline{X}_{z0}$ on $V_p = f\left(i_k\right)$; *b* is the influence $\overline{X}_{z0}$ on $F_p = f\left(i_k\right)$; *c* is the influence $\overline{X}_{z0}$ on $F_g = f\left(X_z\right)$; $\overline{X}_{z0} = 0.875$ (curve *1*); 1.000 (curve *2*); 1.125 (curve *3*)

Having examined the dependency graphs $F_g = f\left(X_z\right)$, it can be seen that an increase in the parameter $\overline{X}_{z0}$ with an opposing load on the SA 1000 N rod leads to an increase in the modulus of the negative hydraulic force acting on the spool plungers, and a decrease in the parameter $\overline{X}_{z0}$ leads to a decrease in the values of this force modulo. From the dependency graphs $F_g = f\left(X_z\right)$ with a braked piston, it follows that with a decrease in the parameter $\overline{X}_{z0}$, the stall depth of the spool plungers increases.

The influence of the relative width of the throttle holes in the liner $\overline{b}$ at fixed initial areas of the throttle windows on the static characteristics of the SA is shown in Fig. 4, which presents the results of computational experiments conducted by varying the specified characteristic.

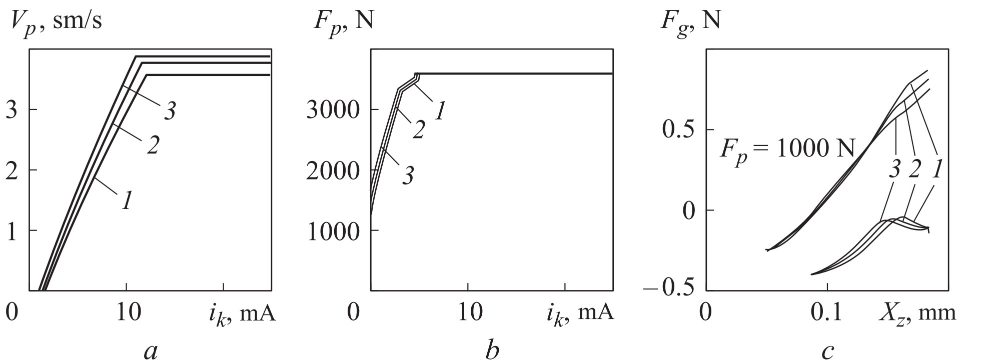

Fig. 4. Influence $\overline{b}$ on the static characteristics *P*:
a is the influence $\overline{b}$ on $V_p = f\left(i_k\right)$; *b* is the influence $\overline{b}$ on $F_p = f\left(i_k\right)$; *c* is the influence $\overline{b}$ on $F_g = f\left(X_z\right)$; $\overline{b}$ = 0.952 (curve *1*); 1.000 (curve *2*); 1.047 (curve *3*)

Analysis of the influence of the parameter $\overline{b}$. As seen in Fig. 4, *a*, the variation of the parameter $\overline{b}$ leads to a simultaneous shift of the speed characteristic along the i_k axis and a change in the angle of its inclination to this axis, while a decrease $\overline{b}$ leads to an increase in the current of start motion of piston of the SA, which is accompanied by a decrease in the angle of inclination of the speed characteristic, and an increase $\overline{b}$ leads to a decrease in the current of start motion of piston, which is accompanied by an increase in the slope of the speed characteristic, i.e., leads to the opposite effect. From the graphs (Fig. 2, *b*) it follows that the variation of the parameter $\overline{b}$ leads to an insignificant parallel displacement of the force characteristic of the SA along the i_k axis. From the dependency graphs $F_g = f(X_z)$ it follows that with an opposing load on the SA 1000 N rod, the influence of the parameter $\overline{b}$ on the hydraulic force is insignificant, and with a braked piston, a decrease in the parameter $\overline{b}$ leads to an increase in the modulus of the negative hydraulic force acting on the spool plungers, and an increase in the parameter $\overline{b}$ leads to a decrease in absolute value of this force.

The influence of the relative local liner wall thickness in the area of the throttle hole $\overline{\delta}_g$ on the static characteristics of the SA is shown in Fig. 5, which presents the results of computational experiments conducted by varying the specified characteristic.

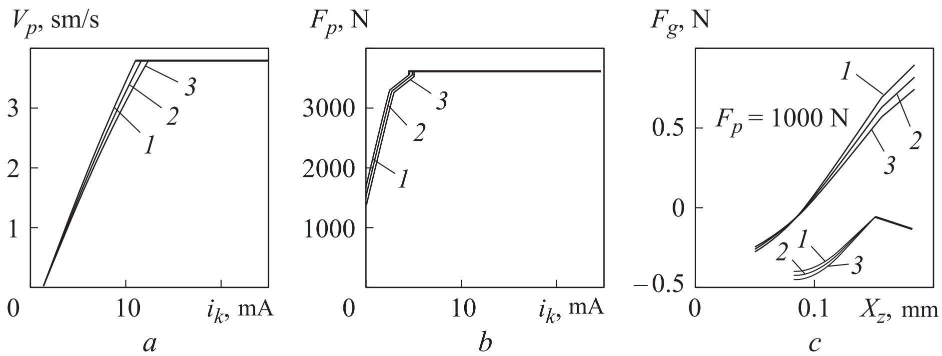

Fig. 5. Influence $\overline{\delta}_g$ on the static characteristics SA:
a is the influence $\overline{\delta}_g$ on $V_p = f(i_k)$; *b* is the influence $\overline{\delta}_g$ on $F_p = f(i_k)$; *c* is the influence $\overline{\delta}_g$ on $F_g = f(X_z)$; $\overline{\delta}_g = 0.666$ (curve *1*); 1.000 (curve *2*); 1.333 (curve *3*)

Analysis of the influence of the parameter $\overline{\delta}_g$. As seen in Fig. 5, *a*, the variation of the parameter $\overline{\delta}_g$ leads exclusively to a change in the angle of inclination of the speed characteristic to the axis i_k, while a decrease $\overline{\delta}_g$ leads to a decrease in the angle of inclination of the speed characteristic, and an increase $\overline{\delta}_g$ leads to the opposite effect. From Fig. 5, *b* that the variation of the parameter $\overline{\delta}_g$ leads to an insignificant parallel displacement of the force parameter of the SA along the axis i_k. The dependency graphs $F_g = f\left(X_z\right)$ (Fig. 5, *b*) we can see that with an opposing load on the SA 1000 N rod, a decrease in the parameter $\overline{\delta}_g$ leads to an increase in absolute value of the negative hydraulic force acting on the spool plungers, and an increase in the parameter $\overline{\delta}_g$ leads to a decrease in the absolute value of this force, while the parameter $\overline{\delta}_g$ affects the hydraulic force when the piston is inhibited similar to the effect with an opposing load on the SA rod 1000 N.

Discussion of research results. As a result of the studies, it was found that SA with a four-throttle EHA does not have static stability, and one of the goals of optimizing SA is to increase its stability. An analysis of the effect on the static characteristics of the SA of variations of the studied parameters shows thatit is possible to increase the static stability of the SA by increasing the relative coefficient of elasticity of the flat spring of the EHA control unit while increasing the relative width of the throttle holes in the sleeve with fixed initial areas of the throttle windows. However, the initial laboratory testing of the SA showed that in this case, to ensure the static characteristics of the SA, the displacement of the spool plungers is significantly reduced. And this value becomes comparable with the value of the oscillations of the spool plungers under the influence of vibration, shock and linear accelerations, which makes the SA practically uncontrollable.

In addition, it was found that the variation of the parameter $\overline{\delta}_g$ leads exclusively to a change in the angle of inclination of the speed characteristic to the axis i_k. Therefore, by varying this parameter, it is possible to adjust the angle of inclination of the speed characteristic of the SA, i.e., its gain.

For the practical implementation of the research result, new structural and technical solutions of the SA have been proposed, consisting in the fact that the rotating sleeves of the EHA spool plungers in the area of the throttle holes contain grooves [8] (Fig. 6, *a*) or annular grooves [9] (Fig. 6, *b*), reducing the local wall thickness of the rotating sleeves. As a result, their effect on flows in the throttle windows is weakened, contributing to an increase in the hydraulic force acting on the spool plungers, due to which the inclination angle of the speed characteristic of the SA decreases.

The indicated structural and technical solutions were introduced into the production process of steering actuators installed in marching engines of upper stages of type D and DM [10].

The introduction of these solutions into production fully confirmed the research results and made it possible to significantly facilitate the adjustment of the SA in the manufacturer's workshop.

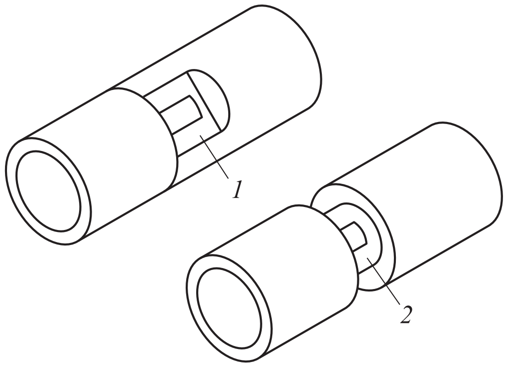

Fig. 6. Structural and technical solution of sleeves:
1 is groove (patent RU 2240260 C2);
2 is annular groove (patent RU 2293687 C2)

Conclusion. As a result of the studies, the following main results were obtained:

– SA with a four-throttle EHA does not have static stability;

– the variation of the following characteristics has the greatest influence on the inclination angle of the SA speed characteristic;

– relative local thickness of the liner wall in the area of the throttle hole; moreover, the influence of the relative local thickness of the liner wall in the area of the throttle hole on the slope of the speed characteristic of the SA is exceptional. By varying this parameter, you can adjust the angle of inclination of the speed characteristic of the SA, that is, change its gain;

– the relative width of the throttle openings in the liner with fixed initial areas of the throttle windows;

– relative coefficient of elasticity of a flat spring of an EHA control unit;

– it was found that the magnitude of the current of start motion of piston SA is most affected by variations of the following characteristics;

– the relative coefficient of elasticity of the flat spring of the EHA control unit;

– the relative initial opening of the drain throttle windows.

Summary. To control the slope of the speed characteristic of the SA, structural and technical solutions of the SA are proposed, namely, that the rotating sleeves of the EHA spool plungers (axis of the driven gears of the three-gear pump) in the area of the throttle openings contain either grooves or annular grooves that reduce the local wall thickness of the rotating sleeves, as a result of which their effect on flows in the throttle windows is weakened, contributing to an increase in the hydraulic force acting on the spool plungers, thanks to which the slope of the speed characteristic of the SA is reduced.

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