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METHOD FOR ESTIMATING THE STATIC FRICTION DEGREE IN THE SLIDE PAIR OF THE MINIATURISED ELECTROHYDRAULIC SERVOMECHANISM

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Abstract

One of the most important parameters specifying the usability of the miniaturised electrohydraulic servomechanism includes a static friction degree in its slide pairs, i.e. resistance of the slider's movement from rest after some time of its staying at rest under pressure. Therefore, at the stage of designing and construction of the electrohydraulic servomechanism, it is important to determine the greatest static friction degree, which may arise in the slider hydraulic pair of this device during its operation. The objective of this article is to present a method for estimating the maximum static friction values in the slide pair based on the extreme value theory. The operation and loading conditions of the slide pair of the electrohydraulic servomechanism for the unmanned aircraft control system were described. The procedure for estimating the maximum static friction degree in the slide pair with the use of the extreme and probabilistic grid was presented. The extreme and probabilistic grid structure was based on the Gumbel probability graph. The graphic presentation of results of the static friction experimental studies in the slide pair on the extreme and probabilistic grid was discussed. By using the graphics method, the empirical dependence of the static friction force in the slide pair on the working fluid pressure in the hydraulic drive (loading conditions) was determined. A practical example of estimating the maximum values of the static friction force that may occur in the slider hydraulic pair of the miniaturized electrohydraulic servomechanism is shown.

Keywords: *operation, hydraulic drive, electrohydraulic servomechanism, pressure, friction force*

1. Introduction

The most convenient drive type used for control and regulation of actuators of UAV is a hydraulic drive [1, 4, 6-8]. The tracking power element in the hydraulic drive, which is aimed at converting an electric input signal to a hydraulic output signal proportional to the input signal, includes an electrohydraulic servomechanism. One of the most important parameters specifying the usability of the electrohydraulic servomechanism includes a static friction degree in its slide pair, i.e. resistance of the slider movement from rest after some time of its staying at rest in the presence of the working fluid under pressure [4, 6, 9, 10]. The violation of the friction stability in the slide pair has adverse effects, among others, the work stability loss, and the lack of positioning accuracy, what causes the violation of working flow of the controlled actuator. Therefore, at the stage of designing the electrohydraulic servomechanism, it is important to determine the greatest value of the friction force, which may arise in the slide pair of this device during its operation within a specified period. It makes it possible to correctly select the electromagnetic control system of the servomechanism distributor slider.

In order to assess the reliability of highly reliable devices, the laboratory (station) tests, which provide extensive data on its accelerated degradation, are commonly carried out [1, 4, 7, 9, 10]. Laboratory tests are performed at different pressure values, flow rates, and contamination levels of the working fluid, i.e. different purity classes [2]. These tests can also be a source of information on a degree of friction forces in the electrohydraulic servomechanism slide pairs. The reliability of estimating the degrees of friction forces in the slide pair mainly depends on the used mathematical method of statistical processing of the information. The mathematical method of processing the laboratory test results is based on Bayesian inference or Monte Carlo method [3, 5, 11]. The main lack of such a concept is to base the analysis and predictions on the statistics of frequent events that are the events described by the distribution central zone. By using the compatibility tests, it is possible to verify a hypothesis of distribution, but only in its central zone. In addition, if the average values of a variable most often do not depend on the time interval or the number of periodically repeated observation, a probable level of the maximum value grows with the increase in the time interval of the number of observation. It generates a freely large error of estimating the parameter.

According to the author's opinion, the method based on asymptotic distribution of extreme values in the sample is a more objectified method for estimating the maximum friction force values in the slide pairs [3, 5]. This method uses an extreme and probabilistic grid based on Gumbel probability graph [3]. The friction force estimation in the servomechanism's slide pair based on distribution of their extreme values, inter alia, has an advantage over previous concepts that is the assessment independent on distribution hypotheses [3, 5].

2. Research object

The research object includes a slide pair of the miniaturised electrohydraulic servomechanism for the unmanned aircraft control system. The block diagram of the servomechanism is presented in Fig. 1.

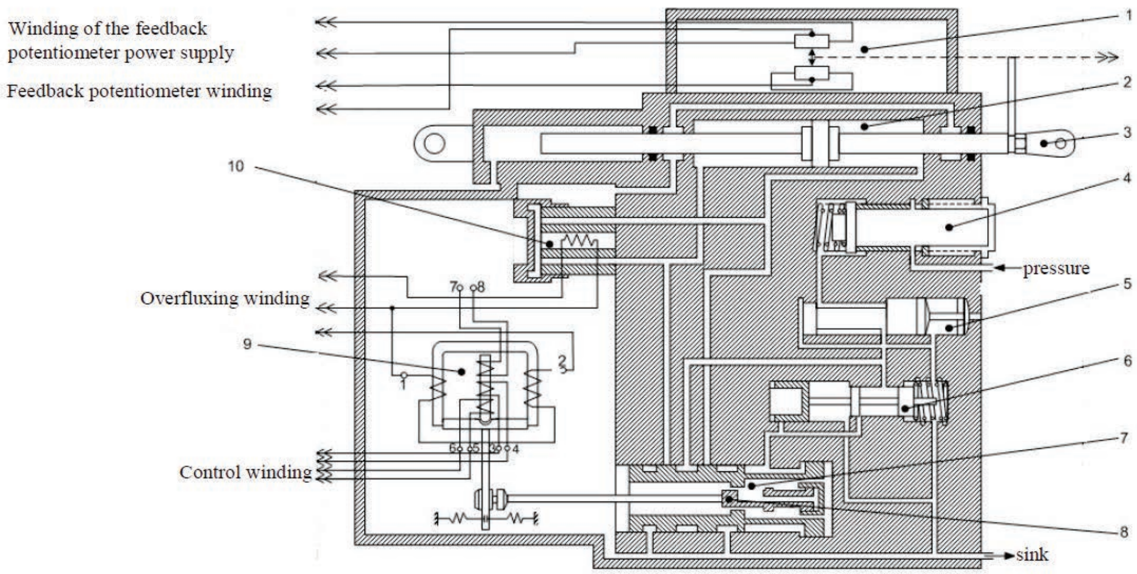

Fig. 1. Block diagram of the electrohydraulic servomechanism prototype: 1-feedback potentiometer; 2-power cylinder space; 3-actuator body; 4-filter; 5-high pressure reducing valve; 6-low pressure reducing valve; 7-the second level gain distributor slider; 8-the first level gain distributor slider; 9-polarised relay; 10-electromagnetic valve

The polarised relay (torque motor), mounted in the mechanism body, receives electric control signals of different values and polarisation from the autopilot system. Depending on these signals, a relay anchor moves with a suitable value to the left or right in relation to the neutral position. The anchor movement results in the first gain distributor slider, which controls the position of the second level gain distributor slider. The second level gain distributor slider adjusts the main working fluid flow rate to the appropriate cylinder chamber. With the use of the feedback potentiometer, an electric signal, proportional to the angle of deflection of elements used in the unmanned aircraft, is passed to the autopilot system.

The distribution of forces, flow rates, pressure, and the relative position of operating elements of the first and the second level gain of the electrohydraulic servomechanism for the slider neutral position were presented in Fig. 2, and for the cylinder piston to the right and to the left in Fig. 3.

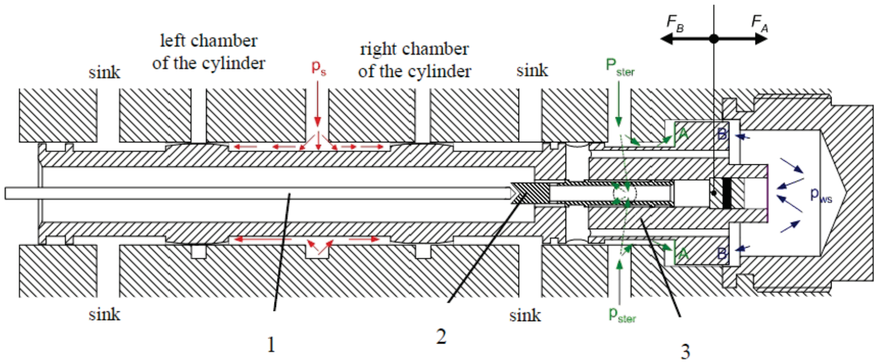

Fig. 2. The distribution of forces, flow rates, pressure and the relative position of operating elements electrohydraulic servomechanism for the slider neutral position 1 – relay pin, 2 – the first level gain slider; 3 – the second level gain slider

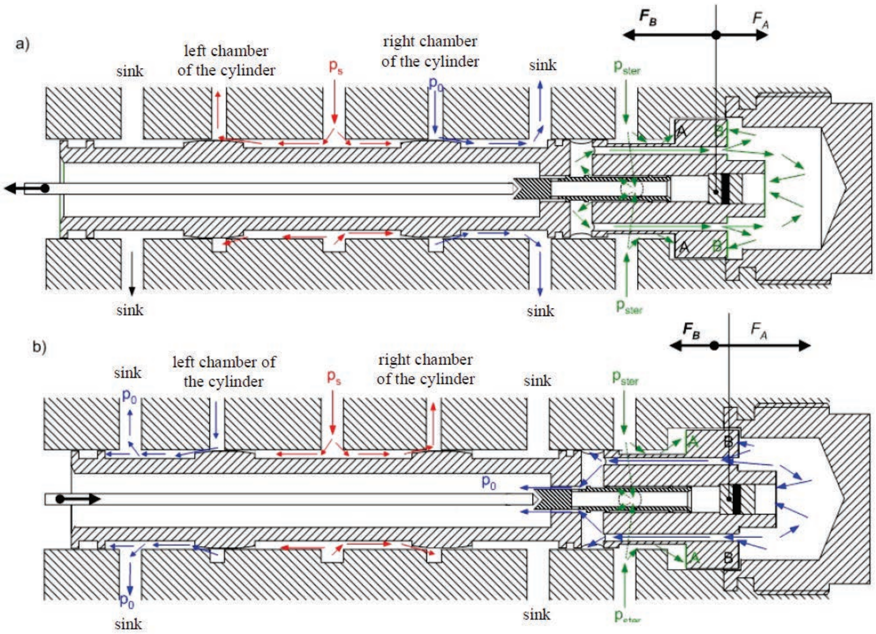

Fig. 3. The distribution of forces, flow rates, pressure, and the relative position of operating elements of the servomechanism actuator for: a) the cylinder piston movement to the right; b) the cylinder piston movement to the left

The importance of the functions performed by the slide pairs place high requirements for them in terms of accuracy, operation speed and stability. The slide pairs are required to provide smoothness of relative movements, depending on the friction size and stability between them. The basic property of working and loading conditions of elements of the slide pairs is the fact that the slider performs linear, periodic reciprocating motion in relation to the cylinder with small displacement, regardless of the level and stability of the working fluid pressure. The slide pairs are characterised by the following features:

– slider movement does not depend on the working fluid flow rate flowing to the slide pair,
– during the slider periodic rest, the constant working fluid flow through the clearances of the element pairs in relation to the cylinder occurs,
– relative sliding velocity of the slider in relation to the cylinder and its acceleration are

dependent on the control signal values,
- slider is not loaded on one side by the axial force from the working fluid pressure, because the fluid is distributed to the distribution channels in the sleeve,
- in case of the occurrence of pulsation of the working fluid pressure in the hydraulic drive, the slider does not perform vibration in the axial direction.

The slider of the electrohydraulic servomechanism slide pair (Fig. 2 and 3) are affected by the following forces: friction force between the slider and the sleeve, hydrodynamic force (radial force) resulting from the difference in the working fluid pressure in the slot between the slider and the sleeve, and axial force. In addition to the above forces, the slider may be affected by the friction force caused by the structural clearance of the slide pair of contaminants in the working fluid. As a result of these forces, there is certain resistance opposing the change of the slider position in relation to the cylinder.

The actual hydraulic pair slider is affected by the working fluid pressure in the slot (structural clearance). The friction forces between the slider and the sleeve primarily depend on the used minimum clearance in the slide pair, smoothness of the cooperating pair surfaces, the working fluid viscosity, the material type of the slider and the sleeve [8, 10].

In the slide pair characterised by the slider's absolute cylindricity and high quality of its surface, the slider's friction depends only on its movement velocity and the fluid viscosity. In case of incorrect geometry (conicity) of the slide pair's elements, the pressure distribution around the slider is asymmetric in relation to the longitudinal axis, as a result of which an unbalanced hydrodynamic (radial) force will occur. It results in the slide crossing in relation to the sleeve (pressing the slider against the sleeve), and at the same time, the occurrence of the increased friction in the slider-sleeve association. The frictional resistance resulted from the radial force depends primarily on the difference in pressure and correctness of the implemented geometric shapes of the slider and the sleeve [7, 8, 10].

As a result of the fluid flow, effect on side surfaces of the slider's working edge and the pressure decrease on these edges in the slider-sleeve pair, the axial hydrodynamic force is created. This force increases the axial resistance when the slider moves in the sleeve. The axial force value depends on the radial clearance and the pressure value.

3. Method for estimating the static friction degree in the slide pair based on the extreme value theory

The starting point of the method is a theory that is as follows: It is possible to estimate the impact of the static friction resulting from operational factors on the miniaturised electrohydraulic servomechanism based on asymptotic distribution of extreme values within the sample. The operational factors may include the slider's hold time at rest with a given value of pressure and the degree of the working fluid contamination. It was based on the probability graph offered by Gumbel [3]. In order to create a graphic presentation of the probability of the occurrence of the highest values of friction forces in the electrohydraulic servomechanism slide pair, the author modified the Gumbel graph. The modified probability graph for creating the extreme and probabilistic characteristics of the slider's friction force (force of moving from rest) in the slide pair was presented in Fig. 5. On the lower horizontal axis, the reduced variable values $y = \alpha(x + \beta)$ [3, 5]. The assigned P probabilities, resulting from a distribution function of the Gumbel distribution, were applied above on the horizontal axis: $P = \Psi(y) = \exp(-e^{-y})$ [3, 5]. In this article, according to Gumbel, $P = \frac{n}{N+1}$ was adopted as an expected value of the cumulative frequency of n positional statistics for *N* sample size. On the upper horizontal axis, there are the periods of a time series calculated on the basis of the following relationship: $T = \frac{1}{1-P}$.

In order to estimate the static friction force value in the electrohydraulic servomechanism slide pair, the laboratory test results are used. The tests should be carried out with the assumed concentration and size distribution of contaminants in the working fluid according to NAS 1638 standard [2] and at the working fluid temperature of 25°+5°C, at a given pressure value in the hydraulic drive and the slider's hold time at rest. The tests should be conducted at three or more pressure values and while maintaining all other test conditions unchanged. The static friction values in the servomechanism slide pair should be recorded under unchanged test conditions within the minimum of 15 cycles of its operation [3, 5].

In order to determine the static force degree (slider force of moving from rest) in the electrohydraulic servomechanism slide pair, by using the extreme value theory, it is important to:

1) Organise the highest values of the slider force of moving from rest, recorded under unchanged conditions of testing the slide pair in 15 working cycles, in the order of the obtained results. The ordering number is assigned to each value, from the first lowest to the last highest one.
2) Calculate the frequency Ψ (cumulative probability of occurrence) for each highest value for the friction force obtained in one experiment:

$$\Psi(n) = \frac{n}{N+1}, \tag{1}$$

where:
n – ordering number of values,
N – number of values;

3) Calculate average values of the friction force $\overline{F}$ and S standard deviation:

$$\overline{F} = \frac{\sum_{N=1}^{n=N} F_n}{N}, \; S = \sqrt{\frac{\sum_{n=1}^{n=N} \left(F_n - \overline{F}\right)^2}{N-1}}, \tag{2}$$

4) Determine the control limits. The control limits should be placed in parallel to the theoretical line (approximation line of observation values) on the section (0.15-0.85)Ψ(n). If not less than 60% of all the observation reaches the control limits, they should maintain on a theoretical line within the range of $\Delta \approx \pm 0.895S$ [3, 5].
5) Determine the approximation line of the friction force value:

$$F = u + \frac{1}{a} y, \tag{3}$$

where:
$u = \overline{F} - y_n \frac{1}{a}$,
$\frac{1}{a} = \frac{S}{\sigma_n}$ – a measure of the distribution dispersion,
y_n – a mean value of the reduced variable presented in Tab. 1 [3],
σ_n – an average deviation of the reduced variable presented in Tab. 1 [3].

6) Apply the approximation line of observation values and control limits on the modified probability graph article (Fig. 5). If the points corresponding to the observation values reach the area bounded by the control limits, the observation values are homogeneous.
7) On the basis of the determined approximation line (”balancing”), it is possible to specify the empirical dependence of the slider force of moving from rest in the slide pair of the electrohydraulic servomechanism on loading conditions. The empirical dependence of the slider force of moving from rest (friction force) on the working fluid pressure, with sufficient accuracy for engineering purposes, can be presented in the following form:

$$F_{\max} = m \cdot \lg p + n\,, \tag{4}$$

where:

p – the working fluid pressure,

m and n – constant coefficients, the values of which can be determined by the method of selected points, arithmetic means or least squares.

Tab. 1. The mean value and average deviation of the variable reduced correspondingly to N

N	***y_n***	***σ_n***	***N***	***y_n***	***σ_n***
10	0.4952	0.9497	18	0.5181	1.0411
11	0.4996	0.9676	19	0.5220	1.0566
12	0.5035	0.9833	20	0.52355	1.06283
13	0.5070	0.9972	21	0.5252	1.0696
14	0.5100	1.0095	22	0.5268	1.0754
15	0.5128	1.02057	23	0.5283	1.0811
16	0.5157	1.0316	24	0.5296	1.0864
17	0.5282	1.0493	25	0.53086	1.09145

5. Example of estimating the static friction degree in the slide pair

The results of the laboratory tests under simulated operational loading conditions of the slide pair of the miniaturised electrohydraulic servomechanism, in terms of values related to forces needed for moving (budging) the servomechanism slider for given pressure and its statistics, were presented in Tab. 2. The values of the force needed for moving (budging) the servomechanism slider were recorded after 5 minutes of its staying at rest under pressure. The research was conducted with the working fluid purity not exceeding the 4-th class according to NAS 1638 standard.

Tab. 2. Data from laboratory tests of the slide pair of the miniaturised electrohydraulic servomechanism

Ordering Number	Pressure	Force required to move the slider	Cumulative probability of the occurrence of *Ψ(n)*	$F_n - \overline{F_0}$	$(F_n - \overline{F_0})^2$
-	MPa	N	-	-	-
1	5	6.2	0.063	22.25	495.063
2	5	6.2	0.125	22.25	495.063
3	5	6.2	0.188	22.25	495.063
4	10	16.0	0.250	12.45	155.0
5	10	16.0	0.313	12.45	155.0
6	10	16.1	0.375	12.35	152.523
7	15	28.1	0.438	0.35	0.1225
8	15	28.1	0.500	0.35	0.1225
9	15	28.1	0.563	0.35	0.1225
10	20	35.3	0.625	6.85	46.923
11	20	35.3	0.688	6.85	46.923
12	20	35.3	0.750	6.85	46.923
13	25	56.5	0.813	28.05	786.803
14	25	56.5	0.875	28.05	786.803
15	25	56.5	0.938	28.05	786.803
		$\sum F_{\max} = 426.7$			$\sum\left(F_n - \overline{F_0}\right)^2 = 4449.26$

The average value of the force needed to move the slider $\overline{F}$ and S standard deviation are $\overline{F} = 28.45$ and S = 17.827. Control limits are as follows: $\Delta \approx \pm 0.895S = \pm 15.955$. Based on

Tab. 1, for N=15, it is possible to read the reduced variable values: σ_n = 1.02057 and y_n = 0.5128. The dispersion measure of distribution is: $\frac{1}{a}=\frac{S}{\sigma_n}=\frac{17.827}{1.02057}=17.47$

$$\text{and } u=\overline{F}-y_n\frac{1}{a}=28.45-0.5128\cdot 17.47=18.491.$$

The approximation line of the force value needed for moving the slider in the servomechanism slide pair of one of a series of research, carried out under the same research conditions, has the following form: $F=u+\frac{1}{a}y=18.491+17.47y$.

The data from the research, the approximation line of values related to the slider force of moving from rest in the slide pair and control limits were applied on the extreme and probabilistic grid presented in Fig. 5. Fig. 5 shows the graph of values related to the slider force of moving from rest in the slide pair of the servomechanism operating in the working fluid with the purity of not more than the 4-th class according to NAS 1638 standard after 5 minutes of the slider's staying at rest under the pressure up to 25 MPa.

The graph in Fig. 5 shows that the points corresponding to the measurement results are arranged with slight scattering along the straight line (observation values are homogeneous) and are within the area restricted by control limits. The distribution of values related to the slider force of moving from rest in the servomechanism slide pair is a straight line adjusted to measurement points. For any value of the slider force of moving from rest in the slide pair, it is possible to read its assigned P probability (from the axis of cumulative frequency) of the occurrence of a value less or equal to the maximum value. The obtained graph shows that the value related to the slider force of moving from rest in the slide pair under given loading conditions should be less or equal to 60 N with the probability equal to 0.9. On the basis of the determined “balancing” line (Fig. 5) from the relationship (4), it is possible to specify the empirical dependence of the slider force of moving from rest in the slide pair of the miniaturised electrohydraulic servomechanism on the working fluid pressure. Based on constant coefficients in the relationship (4), a method of selected points was determined. By using data from Tab. 2 and Fig. 5, the pressure extreme values were assigned to the corresponding slider extreme forces of moving from rest.

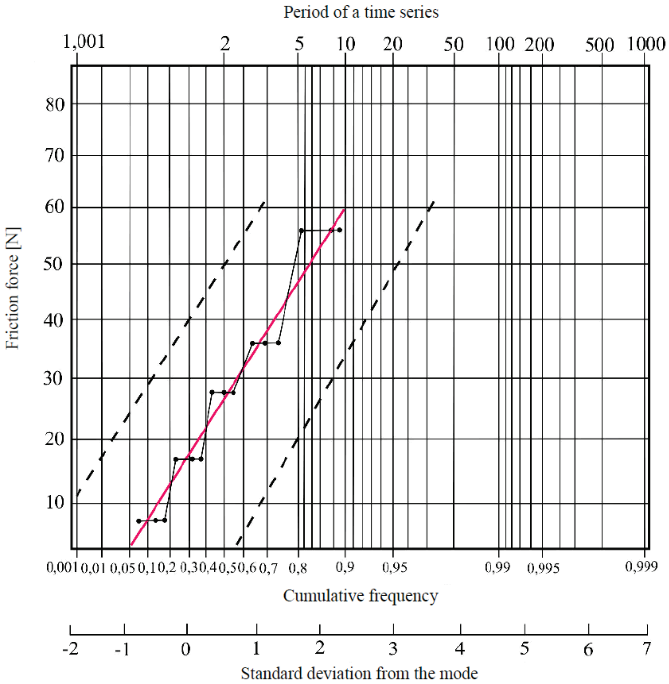

Fig. 5. Graphic presentation of the values related to the slider force of moving from rest in the electrohydraulic servomechanism slide pair under given loading conditions

For the scope of working pressure from 5 MPa to 25 MPa, the slider forces of moving from rest are respectively 6.2 N and 56.5 N. In case of the relationship (4), the extreme values of pressure and the slider maximum force of moving from rest were substituted:

$$\begin{cases} 6.2 = m \cdot \lg 5 + n, \\ 56.5 = m \cdot \lg 25 + n \end{cases}$$

and m = 71.96 and n = -44.10 constant coefficients were determined.

The empirical dependence of the slider force of moving from rest in the slide pair on the working fluid pressure within the range from 5 MPa to 25 MPa has the following form:

$$F_{\max} = 71.96 \cdot \lg p - 44.10 . \tag{5}$$

The empirical dependence (5) allows estimating the maximum slider force of moving from rest in the slide pair for any operation pressure. For example, at the pressure of 9 MPa, the maximum slider's force of moving from rest is 24.6 N, 40.5 N at 15 MPa, and 51.0 N at 21 MPa.

6. Conclusion

The presented method uses a statistical extreme value theory for processing information of laboratory tests. It involves a graphic presentation of results of the static friction experimental studies in the slide pair of the electrohydraulic servomechanism on the extreme and probabilistic grid, and performance of the appropriate extrapolation. The extreme and probabilistic grid structure was based on the Gumbel probability graph. Points on the extreme and probabilistic grid corresponding to the measurement results of the slider movement force in the slide pair are arranged along the straight line. It is a basic condition for correctness and accuracy of the presented method.

The graphic presentation of the static friction value allows determining the empirical dependence of the slider force of moving from rest in the slide pair of the electrohydraulic servomechanism on the working fluid pressure in the hydraulic drive (loading conditions). The empirical dependence allows estimating the maximum value of the slider's force of moving from rest in the slide pair for any pressure of the servomechanism operation.

The demonstrated method allows, with sufficient accuracy for engineering purposes, to estimate the maximum value of the static friction force, which may occur in the slider hydraulic pair of this device during its operation, and also to estimate the electrohydraulic servomechanism durability within a specified period for different conditions of its operation. It is important to consider the occurrence of the static friction value, which excesses the value in the presented method, in the slide pair, as the end of the slide pair durability.

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