The study of slide-valve throttle orifice’s geometry influence on control surface actuator’s dynamical capabilities of maneuverable aircraft

A S Alekseenkov, V Y Obolenskiy, Y G Obolenskiy and S L Samsonovich
Moscow Aviation Institute (National Research University), 4, Volokolamskoe shosse, Moscow, 125993, Russia
E-mail: VYObolenskij@mai.ru

Abstract. The study of slide-valve throttle orifice’s geometry influence on required dynamical capabilities at the low angular deflection of maneuverable aircraft’s actuator has been carried out. To find the correlation dependences of slide-valve throttle control area opening to its transfer, the six configurational forms of fluid flow throttle regulation orifices were considered, the geometrical dependences were obtained and mathematical model were designed. The Bode plots of control surface actuator at six different geometrical forms of orifices have been achieved. Main findings of slide-valve orifice influence on the actuator dynamical sensitivity have been stated. The obtained results have a theoretical benefit for the designers of aircraft control systems and actuators.

1. Introduction
As is well known, in the transfer to unstable maneuverable aircraft layout, the control actuator’s dynamical sensitivity is of fundamental importance, in other words, actuator’s capability to process at input signal of low and ultra-low amplitude.

In the first flight of Russian fighter Su-27 in unstable layout, the test pilot V. S. Iliushin paid attention to the appearance of self-sustained oscillation that appreciably complicated the piloting [1]. In Central Aero Hydrodynamic Institute, the intensive studies were conducted and they allowed defining the reason of oscillation’s appearance (M. A. Kluev, B. S. Manuykan, S. V. Konstantinov [2]). The researches led to replacement of the traditional structural arrangement of mechanical control system “first-stage actuator—booster” to fly-by-wire actuator with electrical feedback. Moreover, the analyses revealed the permissible oscillation restrictions of pitch angle and aircraft measured overload in point of apparent stability and controllability view (V. P. Evdokimov, V. I. Kobzev, V. A. Syrovatskiy [3]).

The methods to define required limits of Bode plot at low and ultra-low amplitude input signal have been designed in works [2, 4]. The surface actuators of aircraft’s unstable layout must satisfy these limits. However, the search of technical means, that are able to ensure required restriction, did not take place. That is why the research of technical solutions that are able to ensure Bode plot required restriction is an actual problem.
2. Problem definition

Nowadays, the electrohydraulic actuators of throttle regulation are used in the fly-by-wire control systems that assures the artificial stability of unsteady maneuverable aircraft layout. This way provides the best weight and overall dimension characteristics.

The foremost purpose of this article is the research of methods to obtain the required dynamic characteristics due to orifice profiling of electrohydraulic amplifier of throttle regulations actuator.

The main control unit of this actuator’s is a slide-valve hydraulic distributor that is represented as throttle control part. It regulates the control flow incoming to the chambers of hydro cylinder under operation of electrohydraulic control signal

\[ Q_{slv} = \mu A_0(x_{slv}) \left( \frac{2 \rho}{\rho} \right)^{1/2} (p_{in} - p_f \text{sign} x_{slv})^{1/2}, \]  

(1)

\( Q_{slv} \)—control flow through slide-valve hydraulic distributor; \( \mu \)—control flow coefficient; \( A_0(x_{slv}) \)—orifice area of slide-valve hydraulic distributor in the slide-valve transfer; \( \rho \)—fluid density; \( p_{in} \)—input pressure; \( p_f \)—pressure of external load.

Thus, the control flow (1) depends on throttle orifice profile area, which in turn, depends on the value of slide-valve travel \( x_{slv} \).

When we take into consideration the flow rate characteristic, which is represented by the functional dependence of control flow to slide-valve travel \( Q = f(x_{slv}) \) or control current \( Q = f(I_c) \) in the field of low and ultra-low input signals, then usually the notion of “lap” \( (\Delta) \) is used: initial offset of slide-valve relatively to the operating orifices shell.

![Figure 1. The influence of “lap” on the flow rate characteristic.](image)

At the figure 1, the flow rate characteristics are shown. The qualitative changes of flow rate depending on “lap” value are illustrated [5]. The presence of overlapped valve leads to the appearing of “dead zone” that has a bad influence on the actuator’s dynamical sensitivity. The underlapped valve determines the initial duct of working fluid and the presence of hydro-mechanical forces deteriorate the actuator’s stability in the field of low and ultra-low input...
signals, so they provoke no stationary of fluid flow—“divagation” of slide-valve and output rod of actuator.

The transition to the two-stage design of electrohydraulic amplifier and short travel slide-valve $x_{\text{slv}}^{\max} \approx 1 \div 1.5$ mm leads to the barest necessity to increase requirement of slide-valve execution quality. Consequently, the slide-valve “closing” value must be practically lacking.

On the other hand, in “Encyclopedia Maschinostroeniya” v. IV-2 [6] work was dedicated to hydraulic actuators and N.S. Gamynin [7], D.N. Popov [8, 9], M. Gion [10], E. Luis and X. Stern [11], paper’s, that’s became practically the classic school-book, the questions about influence of the slide-valve “lap” value on control flow characteristics in the field of low and ultra-low input signal amplitude were not considered. In addition, there was no mention of the influence of control orifice form. In these entire works, only the rectangular form of control orifice was examined.

In articles [4, 13], the detailed discussion of actuator rate characteristics requirement ensuring in the case of given amplifier coefficient $k_{vx}$ in the field of low amplitude signals was realized. Nevertheless, they did not observe the influence of slide-valve orifice form.

The authors recommended using the set of throttle orifices in the form of perforated vents series to own linear rate characteristics in the field of low input signals. This set should be disposed all along spiral line on the surface of shell with the realization of underlapped value

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Figure 2. The scheme of orifices’ location: $d$—the diameter of throttle orifice; $\varepsilon$—the pitch of orifice’s locations; $x_m$—the maximal slide-valve travel from hydraulic neutral; $N$—the total quantity of throttle orifices; $O_1, O_2, \ldots, O_n$—the center of orifices’ position; $M$—spiral line reamer of orifices’ position; $K, L$—the positions of slide-valve cut-off ports; $S^\circ$—the “lap” of slide-valve cut-off ports.

Figure 3. The scheme of three-stage control actuator SPM-6: 1—distribution unit; 2—linear variable differentials transformers of CAS ram; 3—filter; 4—control valve; 5—shutoff valve; 6—control unit; 7—distributor; 8—servo amplifier; 9—throttle; 10—nozzle; 11—solenoid valve; 12—gate; 13—correction sensors; 14—correction valve; 15—correction rod; 16—ram; 17—master control valve; 18—CAS Ram; 20–22—filters; 24—linear variable differentials transformers of piston; 25—piston rod.
of slide-valve edge (figure 2). The minimal diameter value of vent could not be less than 0.65 mm [12], the width of equivalent rectangular orifice will come to \( b = d \geq 0.65 \) mm.

The authors [12] recommended choosing the diameter of throttle vents in the range of 0.65 mm \( \leq d \leq 0.9 \) mm, considering that the best value is \( d = 0.8 \) mm. Such technology made a good showing in the three-stage electrohydraulic amplifier of SPM-6, SPM-6B, SPM-6P actuators (figure 3). This type of actuators had a power slide-valves, that moved by the control pistons of actuator and had a sufficient movement \( x_{\text{max}} = 4.5 \div 6 \) mm, thus, the perforated openings could be displaced.

![Figure 4](image)

**Figure 4.** The scheme of two stage control actuator RPD-14: 1—servo amplifier; 2—dual stage electro-hydraulic servo valves; 3—quad fault detection sensors; 4—filter; 5—non-return valve; 6—shutoff valve; 7—bypass and damping valve; 8—piston rod; 9—linear variable differentials transformers of piston.

In two-stage electrohydraulic amplifier, the control slide-valves are not mechanically connected and have a comparative short stroke \( x_{\text{max}}^{\text{slv}} = 1 \div 1.5 \) mm, on which the perforated vents could not be practically displaced (figure 4). That is why the influence of geometrical form of throttle orifice on control actuator dynamical sensitivity was studied.

3. The research and results

The researches have shown that geometrical forms of throttle orifices have a great influence on the dynamical sensitivity of electrohydraulic throttle regulation actuators. The six configurational forms of fluid flow throttle regulation orifices were considered:

1) rectangular form;

2) round form;

3) form of ellipse;

4) triangular form (the throttle vent area changing along slide-valve transfer from the peak of triangular);

5) triangular form (the throttle vent area changing along slide-valve transfer from the base of triangular);

6) rhombus form.

The main research guideline is an equality of all throttle vent areas along all configurations

\[
A_0^{\text{rect}} = A_0^{\text{round}} = A_0^{\text{ellipse}} = A_0^{\text{trian (from the peak)}} = A_0^{\text{trian (from the peak)}} = A_0^{\text{hombus}}.
\]

On this purpose, the geometrical dependences were obtained and the mathematical models in MATLAB/Simulink.
**Table 1.** The orifices forms and flow rate characteristics.

| No. | The forms of fluid flow throttle regulation orifices | Flow rate characteristics |
|-----|----------------------------------------------------|---------------------------|
| 1   | ![Rectangular form](image1.png)                    | ![Rectangular form](image2.png) |
| 2   | ![Round form](image3.png)                          | ![Round form](image4.png)    |
| 3   | ![Form of Ellipse](image5.png)                      | ![Form of Ellipse](image6.png) |
| No. | The forms of fluid flow throttle regulation orifices | Flow rate characteristics |
|-----|--------------------------------------------------|---------------------------|
| 4   | ![Diagram](image1.png)                           | ![Graph](image2.png)      |
| 5   | ![Diagram](image3.png)                           | ![Graph](image4.png)      |
| 6   | ![Diagram](image5.png)                           | ![Graph](image6.png)      |
combines environment were designed. These models allowed to find the correlation dependences of slide-valve throttle control area opening to its transfer $A_b = f(x_{slv})$. These findings and dependences are shown in table 1, $a, b, r, h$ are geometrical parameters, $x_{slv}$ is a value of slide-valve travel, $S_Q(x_{slv})$ is an area depending on value of slide-valve travel, $S_Q(\text{max})$ is a maximal area of throttle vent.

The issue was realized in mathematical environment Matlab/Simulink. The models of studied actuator were designed with following functional dependences of control flow through hydraulic throttle (2)–(5)

$$Q_{slv1} = G_{in+}(x_{slv})\sqrt{|p_{sup} - p_1| \text{sign}(p_{sup} - p_1) - G_{out+}(x_{slv})\sqrt{|p_1 - p_{ret}| \text{sign}(p_1 - p_{ret})},$$

$$Q_{slv2} = G_{out-}(x_{slv})\sqrt{|p_2 - p_{ret}| \text{sign}(p_2 - p_{ret}) - G_{in-}(x_{slv})\sqrt{|p_{sup} - p_2| \text{sign}(p_{sup} - p_2)},$$

$$\dot{p}_1 = \frac{E_h(p_1)}{V_h}[Q_{slv1} - A_{sg}\dot{x}_{sg} - k_l(p_1 - p_2)],$$

$$\dot{p}_2 = -\frac{E_h(p_2)}{V_h}[Q_{slv2} - A_{sg}\dot{x}_{sg} - k_l(p_1 - p_2)],$$

where $G_{in+}(x_{slv})$, $G_{out+}(x_{slv})$, $G_{in-}(x_{slv})$, $G_{out-}(x_{slv})$ are described by table data with linear interpolation; $p_{sup}$—supply pressure; $p_1, p_2$—pressures incomes to road chambers; $p_{ret}$—return pressure; $E_h$—viscoelastic fluid coefficient; $V_h$—volume of fluid into rod chamber; $A_r$—area of road; $x_r$—steering gear movement; $k_l$—pressure loss coefficient.

At the figure 5, the principle control circuit of slide-valve is represented. If the slide-valve moves to the right, control flow $Q_{slv1}$ comes to the left hydro cylinder chamber through slide valve conductivity $G_{in+}(x_{slv})$, on the static characteristics it is the area of positive values of fluid flow characteristics and motion of slide-valve. The extrusion of fluid in the right part of chamber is going through conductivity $G_{out+}(x_{slv})$, which corresponds the static characteristics the field of negative values of fluid flow characteristics and motion of slide-valve. When the slide-valve moves to the left, this process description is identical to the conductivity $G_{in-}(x_{slv})$, $G_{out+}(x_{slv})$.

As the result, we have an opportunity to study the influence of slide-valve orifice form micro geometry on the dynamical sensitivity of electrohydraulic throttle regulation’s actuators.

![Figure 5](image_url)

**Figure 5.** The functional scheme of slide-valve.

The studies of control surface actuator dynamic characteristics were realized for amplitude of input signal $A_{in} = \pm 0.1^\circ \pm 2^\circ$ with $0.1^\circ$ degree spacing and for input frequency $f_{in} = 0.1 \pm 10$ Hz with the variable spacing depending on input signal frequency range. This type of input signals is present at the precision control tasks, such as air refueling operation and collocated control. On these modes, the pilot has to operate control stick energetically in the field of low and ultra-low input signals amplitude. The most interesting results are for the amplitudes $\pm 0.143^\circ$ and $\pm 0.286^\circ$ in the view of slide-valve movement dependency on dynamical sensibility characteristics.
Figure 6. The Bode plot characteristic for the amplitude of input signal corresponds to control surface deflection angle $A_{in} = \pm 0.143^\circ$.

Figure 7. The Bode plot characteristic for the amplitude of input signal corresponds to control surface deflection angle $A_{in} = \pm 0.286^\circ$.

As may be seen from the figures 6 and 7, the rectangular orifice has the best dynamical sensibility characteristics, whereas the form of ellipse has slightly worse characteristics in comparison with rectangular.
4. Conclusion

The form of slide-valve throttle orifice in consequence of its area changing along the opening has a considerable influence on the dynamical sensibility of control surface actuator.

The rectangular orifice has achieved the best characteristics, such as linear dependence of rate characteristic, the minimal phase delay and amplitude distortions.

For the completeness of the profiling orifice definition, it is necessary to study the hydrodynamical force influence on the slide-valve working properties.

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