Research of dynamic characteristics of the hybrid electrohydraulic aircraft actuator with combined speed control

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Abstract. The paper presents the results of mathematical modeling and experimental research of the dynamic characteristics of the prototype of aircraft hybrid electrohydraulic steering actuator with combined speed control. The mathematical modeling of dual-mode electrohydraulic actuator was performed in the MatLab Simulink and the experimental research was carried out at the control systems test-rig in Central Aerohydrodynamic Institute. The main goal of the experimental research was to determine the output characteristics of actuator, among them static (speed and mechanical) and dynamic (bode-diagrams, transients responses and dynamic stiffness) in the backup (autonomous) and main modes of its operation, including when the actuator was under load.

1. Introduction
Currently, in the technical literature is increasingly common term «More Electric Aircraft» (MEA) [1, 2]. Under this term, experts in the field of automatic control systems understand the aircraft, in which the total number of centralized hydraulic systems and pneumatic systems with their units is reduced and being replaced by power electrical systems and actuators with electric power supply.

From the point of view of the executive part of the integrated flight control system (IFCS) of the aircraft, this trend leads the necessity to develop and implement new types of steering actuators that are capable to get a power supply from the onboard aircraft power electrical system and have high dynamic characteristics, energy efficiency and a sufficient level of reliability and failure safety. Among the existing steering actuators that are used or planned to be used onboard of «more electric aircraft» for the primary control system, the following main types can be distinguished:

- EHA – Electro-Hydrostatic Actuator [1];
- Electrohydraulic actuators with combined speed control [3];
- EBHA – Electrical-Backup Hydraulic Actuator [4, 5, 6]), and dual-mode actuators with combined speed control [7, 8];
- EMA – Electro Mechanical Actuator [1].

As was shown by the review of the architecture IFCS of modern civil aircraft [1, 9, 10], the world's leading manufacturers of aircraft, including Airbus and Boeing, are seriously considering the opportunities of placing several heterogeneous actuators on one steering surface [1, 10, 11]. In
addition, actuators of the main control surfaces of the modern passenger aircraft Airbus A-380 are heterogeneous both in terms of the type of power supply and the type of regulating the speed of the output link [2, 5]. For example, each sections of rudder (rudder surface is split) are deflected by EBHA, and the elevators and ailerons (middle and inboard) are equipped with EHSV and EHA [5, 6].

The hybrid electrohydraulic actuator that was the object of research is a modification of electrohydraulic steering actuators with a backup source of hydraulic power supply [12], but it was made according to the original design [13], which allowed to significantly reducing the weight and dimensions of the hydraulic unit. This means that the research of the characteristics of this type of actuators is an urgent task.

### 2. Object of research and research methods

The object of the research, as was said before, was a prototype of a hybrid electrohydraulic steering actuator with combined speed control in a backup (autonomous) mode of its operation. Actuator was made according to the original design scheme [13]. The photography of investigated hybrid actuator with combined speed control on the test rig of flight control systems in a Central Aerohydrodynamic Institute [14] is shown in figure 1.

![Figure 1. Hybrid electrohydraulic actuator on the test rig of flight control systems in Central Aerohydrodynamic Institute.](image)

To analyze of the operation of a hybrid electrohydraulic actuator the detailed mathematical model was created in the special software MatLab Simulink. Mathematical model was made according to the modular scheme, and its general view is shown in figure 2.

The following factors were taken into account when the mathematical model was compiling:

- the hydraulic fluid is compressible: the module of volume elasticity (bulk module) depends on the fluid pressure and the set value of the air that contained in the fluid;
- the control object and the actuator rod have a mass: the effect of inertial load on the output characteristics of the actuator was taken into account;
- during the implementation of the ECU was takes into account the "digital part" with specified time delays and sampling of control signals;
- mathematical model of brushless DC motor was made with using of elements of the SimPowerSystems library;
- the mathematical model of the hydraulic cylinder takes into account the possible differential area of the piston;
- EHSV model takes into account the microgeometry of the valve spool.

Figure 2. The structure of mathematical model of a hybrid electrohydraulic actuator. In the figure the following designations are introduced: ECU - electronic control unit, ISHPS - internal source of hydraulic power supply (it includes a mathematical model of the electric motor and pump), EHSV – electrohydraulic servo valve.

Mathematical model allows defining a static and dynamic characteristic of hybrid electrohydraulic actuator. Mathematical model also allows investigating actuator work when it is powered by the external (centralized) hydraulic system, and from the internal source of hydraulic energy. Switching of modes of actuator operations is carried out by a command signal in ECU.

3. The results of research
The results of mathematical modeling of step response of hybrid electrohydraulic actuator are shown in figures 3 and 4. Input control signals was corresponded to amplitudes of movement of a piston rod on 2 mm and 35 mm (35 mm is a full stroke). Figure 3 shows the characteristics of actuator in autonomous working mode, and figure 4 shows the characteristics of actuator in the main mode of its operation (powered by an external hydraulic system). Figures 3 and 4 also show the experimental characteristics of actuator.

Figure 3. The comparison of the results of mathematical modeling and experimental testing. The displacement of actuator rod is 2 and 35 mm, respectively. Actuator worked in autonomous mode.
Figure 4. The comparison of the results of mathematical modeling and experimental testing. The displacement of actuator rod is 2 and 35 mm, respectively. Actuator worked in main mode.

As can be seen from figures, the model and experimental characteristics have a high convergence between them. A slight discrepancy was observed when the actuator worked at low amplitudes of control signals in the autonomous mode of its operation. According to the authors, this is due to the configuration of the control unit of the brushless BC motor which could not be completely implemented in the mathematical model because the control algorithms in BDC-motor are closed and hidden.

Diagrams of logarithmic amplitude and phase frequency characteristics (frequency response diagrams) of the actuator are shown in figures 5(a,b). Figure 5a shows the frequency response of the actuator when it operates in autonomous mode with the implementation of the combined speed control, figure 5b shows the frequency response characteristics when it operates in the main mode. The characteristics were determined for the piston rod displacement amplitudes of 1, 2 and 5 mm.

Figure 5. Frequency response of actuator in main mode.
As it can be seen from the figures, when actuator worked in main mode, it had a fairly wide bandwidth (more than 10 Hz). In this case, in the autonomous mode of operation the power of actuator's backup hydraulic supply source was limited and high dynamic characteristics were provided only in the region of low amplitudes of control signals (due to the implementation of combined speed control).

In general, according to the results of the experimental research, it can be noted that the obtained dynamic characteristics of hybrid actuator were correspond to the laid requirements. At the same time, the dynamic capabilities of actuator were partly overstated during its operation in the main mode and can be reduced in a future.

4. Conclusions

As a result of research, a highly detailed mathematical model of the hybrid electrohydraulic steering drive was compiled. Mathematical model allows to study its operation in main mode (when hybrid actuator is powered from the external (centralized) hydraulic system) and in a backup (autonomous) mode when it is powered from the aircraft power electrical system. Mathematical model allows researching the different methods and strategies of controlling the speed of the output link.

Mathematical model was confirmed on the results of an experimental research in terms of the dynamics of the control elements and the characteristics of sensors and showed a high convergence with the experimental characteristics. On the basis of the refined mathematical model, the ways of improving of actuator dynamic characteristics were considered and the influence of control settings on the output characteristics was detected.

The developed mathematical model can be recommended for a detailed study of hybrid electrohydraulic actuators that will be implemented according to the scheme given in [15], as well as in the educational process that is conducted at the 702 department of MAI. Also it can be useful for specialists in the field of actuators technology.

According to the results of tests in Central Aerohydrodynamic Institute hybrid actuator can be used for the primary control system of perspective civil aircrafts those will be realized with "more electric" concept. Actuator provides the required level of flight safety due to the selected design scheme and heterogeneity of power supply channels and has satisfactory dynamic characteristics.

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