Experimental research of dynamic characteristics of electro-backup hydraulic actuator at the load test-rig of flight control systems

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Abstract. The trend in aircraft systems development to overall electrification includes electrification of flight control actuation system. Generally, there’re two main technologies of «electrical» actuation, which use the power of on-board electrical system to move the aerodynamic surfaces. These technologies are electro-hydrostatic (EHA) and electromechanical (EMA) actuation systems. This paper describes the results of the dynamic testing of electro-backup hydraulic actuator (EBHA), which is one of the possible solutions for actuation systems of the next-generation flying vehicles.

1. Introduction

Primary flight control actuators are one of critically important elements of the airplane integrated flight control system (IFCS) with a high level of the flight automation [1, 2]. It is due to the fact, that the actuator reliability and the quality of its functioning determine the level of the flight safety in many aspects. Strict requirements to the fault-safety of the actuation control and the capability to operate under such a low amplitude of control signals as 1% of maximum range are imposed. That’s why an experimental improvement of flight control actuators and systems is the «must» step during the development of flight control systems, as it allows to safely ensure correct functioning of the system in the complete operational range.

An experimental testing of actuators has the purpose to identify any weakness in the actuator design or its control system, or to prove the absence of any weakness. The objectives of the tests can be varied on different stages of the actuator life cycle: it can be the obtaining of some research data (research tests) in order to develop an accurate mathematical model of the actuator, a preliminary assessment of design decisions, the qualification for test flight, an actuation system formal qualification, a device acceptance etc.

Also it is necessary for the test-rig to have the capability to simulate external conditions for the tested actuator, which greatly influence its performance. That is environmental effects (temperature, humidity etc.), and external forces applied to the actuator output shaft/rod, which is more important from the viewpoint of control system dynamics.

The researched electro-backup hydraulic actuator (EBHA) was tested at the department of flight dynamics and control systems of Central AeroHydrodynamic Institute at the specialized test-rig for actuators and actuation systems.

The main purposes of such test-rig are in the area of dynamics and fault-safety of such systems under relevant external conditions, and it’s used during research tests and tests for the first test flight.
approval. The test-rig was used during the development of such airplanes as Su-27, Su-35, MiG-29, «Buran» shuttle, «Ansat» helicopter, others [3].

2. Object of research and test bench description
The object of the research was a prototype of an electro-backup hydraulic steering actuator that was developed by MAI and manufactured at the factory «Gidrotekhnika» (Pavlovo, Nizhny Novgorod obl.). The photography of investigated EBHA at the MAI test bench is shown in figure 1.

The main feature of the EBHA is the ability to operate in normal mode as an electrohydraulic servovalve actuator which is powered by centralized hydraulic system, and in backup mode actuator operates as a electrohydraulic actuator with combined speed control which is powered by the electrical system.

Figure 1. The researched EBHA.

To provide dynamic tests of the EBHA prototype under load at TsAGI test bench a specialized test-rig was used, the main device of which is a hydraulic loader with a maximum developed force $F_L=50$ kN. The photography of such installation is shown in figure 2.

The loader consists of a special hydraulic cylinder, flow and force control system. The bandwidth of the loader is wide up to 40 Hz. It is an important characteristic that provides to perform frequency tests of actuators to determine their dynamic stiffness with frequencies exceeding the flutter frequency (up to 30 Hz). It allows to ensure the oscillations stability of an elastic structure of the A/C in the event of this effect in flight.

The force from the loader is transmitted on the tested EBHA through a rotating lever, which is fixed in supports. The mobility of such installation is provided by hinged supports at the attachment points of both the loader and the tested actuator.
Figure 2. The load test bench for the EBHA.

The hydraulic system of the test bench provides the power supply of the loader and actuator under test. The hydraulic system contains both industrial pumps which have increased service life with the maximum working pressure up to 350 bar and airborne ones with the maximum working pressure up to 280 bar. The maximum flow rate in hydraulic lines for the loaders is up to 300 liters/min and 200 liters/min for tested hydraulic actuators.

3. The methodology of the experiment and the results of research
According the experimental research, the following static and dynamic characteristics (including under the load) of EBHA in each operating modes were determined:

- step responses;
- mechanical characteristic;
- frequency response;
- dynamic stiffness.

Step responses were obtained when the actuator was loaded by assist and counteractive force. The direction of force action in the experiment was such that when the actuator’s rod was retracted, the force was counteractive to the movement, and when the rod was extended the force helped to move.

A constant force with different values and step by 5 kN was applied to the actuator’s rod to determine the mechanical characteristic. A step control signal with value of ±25 mm was applied to the actuator’s control unit. The signal from the actuator’s feedback sensor was registered. For each value of the applied force, the maximum speed values were determined. The obtained mechanical characteristic of tested EBHA for each operation modes is presented in figure 3.

Amplitude-frequency and phase-frequency response characteristics of EBHA were made for a closed control loop. Frequency response characteristics for each actuator's modes were made in the operating frequency range of 0.1÷20 Hz under the action of external loads of 10, 20 and 30 kN.
Figure 3. Mechanical characteristics of the tested EBHA.

The dynamic stiffness is determined according to the expression (1). It is a complex dependence that shows the value of actuator’s movement under load which has different values of magnitude and frequency.

\[ C(\omega) = F(j\omega)/X_p(j\omega) \]  

(1)

Also, the dynamic stiffness can be defined as the dependence of the reaction force of the actuator, which occurs when the rod is moved by the force (the deviation of the rod from a control position) under the influence of an external force, on the magnitude of rod displacement. The second definition, although, is more complex, but corresponds by characteristics that are defined by the experimental. In experimental characteristics the input effects are a movement of actuator’s rod, and the output hydraulic force of actuator (equal to external force of the loader). The characteristic was determined with the parameters that are specified in table 1. The values of the actuator’s parameters that were obtained from the dynamic stiffness characteristics are given in table 2.

Table 1. Parameters of a loading force.

| The mode of operation of actuator | \( F_{\text{const}}\), kN | \( F_{\text{var}} \), kN | \% \( F_{\text{max}} \) | \( f \), Hz |
|----------------------------------|-----------------|-----------------|-----------------|-------|
| Main                            | 15              | 5               | \( \sim 10 \)   | \( 0,1…40 \) |
| Backup                          | 15              | 5               | \( \sim 10 \)   | \( 0,1…40 \) |

Table 2. The results of dynamic stiffness research of EBHA.

| The mode of operation of actuator: | Main | Backup |
|-----------------------------------|------|--------|
| Static stiffness, kN/mm           | \( \sim 100 \) | \( \sim 192,8 \) |
| The amplitude of the load on actuator’s rod, kN | 5 | 5 |
| Minimum stiffness, kN/mm          | 47   | 79,4   |
| Frequency of minimum stiffness, Hz | 16   | 12     |
| Initial phase, deg.               | +6,0 | -1     |
| Minimum phase, deg.               | -13  | -26,7  |
| Transition frequency (\( \phi=0 \)), Hz | \( \sim 5,5 \) | \( \sim 9,5 \) |
| Maximum phase, deg.               | +19  | +14    |
4. Conclusions

According to the complex experimental research of electro-backup hydraulic actuator (EBHA) at the load test-rig of flight control systems, the following results were obtained:

1. The sensitivity of actuator is more than 0.2 mm (0.5% of $A_{\text{max}}$), respectively, the actuator has no a rod’s displacement when input signals are less than the specified value;
2. The maximum force of actuator is near 48 kN;
3. The maximum actuator’s speed is near 155 mm/s to retraction and 176 mm/s to extension in the main mode. Actuator has different speeds of movement to retraction and to extension;
4. The maximum speed of the actuator rod’s movement without load in the backup mode is 25 mm/s. The assisting force leads to a significant increase of the maximum speed;
5. In the main mode a bandwidth is more than 10 Hz for input control signals less than 10% of $A_{\text{max}}$. For input signals more than 10% of $A_{\text{max}}$ the bandwidth is near 6÷8 Hz. The bandwidth is depending on the value of the output load;
6. In the backup mode a bandwidth is near 2÷3 Hz for input control signals less than 5% of $A_{\text{max}}$. For input signals more than 5% of $A_{\text{max}}$ the bandwidth is near 1÷2 Hz. There are practically no nonlinear distortions and resonance peaks in the operating frequency band;
7. The static stiffness in the main mode is near 190 kN/mm, and the minimum stiffness exceeds the maximum actuator force by more than 1.5 times.
8. The static stiffness in the backup mode does not exceed 100 kN/mm, and the minimum stiffness approximately corresponds to the maximum actuator’s force.
9. The transition frequency for the main mode is lower than the minimum stiffness implementation frequency and is near 9 Hz;
10. The transition frequency for the backup mode is lower than the minimum stiffness implementation frequency and is near 5÷6 Hz;
11. Up to the transition frequency, actuator works as a closed-loop steering actuator, and at higher frequencies actuator works as a damper: the output movement of actuator is ahead the input signal in phase.

According to the results of tests of EBHA in Central Aerohydrodynamic Institute it was found that this type of actuator can be used for the primary flight control system of promising civil aircraft which will be made by a “more electric” concept. This type of actuator provides the required level of flight safety due to the selected design scheme and heterogeneity of power supply channels and required dynamic performances.
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