NEW DEVELOPMENTS OF ELECTRICALLY POWERED ELECTROHYDRAULIC AND ELECTROMECHANICAL ACTUATORS FOR THE MORE ELECTRIC AIRCRAFT

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Abstract

One of the common world tendencies of the aircraft building development is stepwise changing of the different airborne systems on the electrical power supply from the single power supply network.

Appreciable consumers of the electrical power supply on the aircraft are actuators of the aircraft control system. Conception of the electrical power supply of the A/C actuator systems from the single power supply network has the following purposes:

- decreasing of the weights and volumes indices of the actuator systems and A/C in the whole;

- decreasing of the time and cost of the A/C service;

- increasing efficiency of the actuators and decreasing a power consumption of the control system.

That tendency has stipulated creating in Moscow Aviation Institute on the "Servo drive systems for aerospace vehicles" department two directions in actuator system development. One of them consists in creating a new type of the self-contained hydraulic actuators, which have significant higher characteristics in comparing with the well-known self-contained actuators. Such actuators were named electrohydraulic actuators with combined regulation of speed of the output link. Second direction is the construction of the electromechanical actuators on principle of power miniactuator with rotational or linear motion of the output link.

Electrohydraulic actuators with combined regulation of speed of the output link

Hydraulic actuators due to their high dynamic characteristics, high level of reliability and safety are the main type of actuators for the primary control surfaces (ailerons, elevators and rudders). Let us briefly describe the situation in the sphere of aircraft hydraulic actuators.

The most common type of actuator which is used on the vast majority of aircrafts is a throttle actuator. In this type of actuator output speed is regulated by changing the resistance of the throttle. Actuators of this type have a high level of accuracy, stiffness and responsiveness. These performances are so high that they could provide not only trajectory control of any aircraft but also meet much higher requirements of controllability and stabilization improvement systems including aircrafts with unstable aerodynamic configuration. However, energy properties of throttle actuators are relatively low. Also on board the aircraft there are several (usually three) centralized hydraulic systems with adjustable pumps and constant high pressure to feed them. The use of electricity to power hydraulic actuator is provided by installing a hydraulic pump inside the actuator. That makes it possible not only to simplify the design of the pump but also, most importantly, to use more effective methods of controlling the speed of the output link: volume regulation with using a variable displacement pump or electric-powered regulation with using nonreversible fixed displacement pump.

The development of electrical industry and microprocessor technology has provided practical implementation of electromotor regulation of output speed in Electrohydrostatic

Actuators (EHA). These actuators are used to control the primary control surfaces on the latest serial aircrafts of various classes such as Airbus A380, A-400M, Gulfstrim G650, the Lockheed Martin F-35. In Electrohydrostatic actuator the velocity of the output link is regulated by changing the speed of the motor shaft and therefore by the performance of fixed displacement pump which is connected with the motor shaft. Reverse of the output link is carried out by changing the direction of shaft rotation. Energy losses in the hydraulic part of actuator are minimized with the use of this method of regulation. Energy properties of the electrical part, i.e. a brushless DC electric motor with the respective electronic control unit, are also quite high. As a result, Electrohydrostatic actuator has the greatest energy efficiency among all hydraulic actuators: its maximum theoretical efficiency is over 80%, the real efficiency exceeds the maximum efficiency of throttle actuators with variable displacement pump, which is installed in a centralized hydraulic system, by about 20%. High values of efficiency are achieved in a wider range of input loads. The power consumption of this actuator without input load in a neutral state is very low.

However, accuracy, stiffness and dynamic capabilities of Electrohydrostatic actuator are worse than these characteristics of a throttle actuator, and this gap is due to the way of speed control. Deadband and static stiffness of actuator are directly related with the gain of the pressure, but the last is many times greater when actuator has a throttle (servovalve) control than the electromotor. As a result, sensitivity and static stiffness of Electrohydrostatic actuator is significantly lower than of the throttle one. Dynamic stiffness of EHA is also 1.4 times less than of the throttle actuator: in EHA during the loading of the output link the pressure rises only in one of the two cylinder cavities, but in case of the throttle control the pressure changes in both cavities. Responsiveness and frequency characteristics of actuator also depend on the gain of the pressure, but in EHA they are additionally limited by rotor inertia of the motor and pump. For these reasons, the bandwidth of EHA is much narrower than that of the throttle actuator, especially in the area of small amplitudes (0.2 ... 2% of the maximum), which are typical for aircraft stabilization systems. As a result, EHA can be used in modes of trajectory control of the aircraft, but its use in onboard stabilization systems causes great difficulties [1].

Meanwhile, the use of the system improving stability and controllability of the aircraft is now almost obligatory. Modern and future aircraft have unstable or low stable aerodynamic configuration. It allows to increase their maneuverability and to improve significantly their fuel efficiency. The first quality is important for a combat aircraft, while the latter is essential for a transport and passenger aircraft.

So, currently there are a two demanded methods to regulate the velocity of the output link of the aircraft hydraulic actuator. These methods virtually eliminate the advantages and disadvantages of each other. MAI employees were tasked to find a way to regulate the output speed uniting the advantages of these two methods and avoiding their disadvantages as well as to make its hardware implementation.

As a result of works that were carried out in MAI together with PMZ "Voskhod" and other industrial plants, a combined method to regulate the speed of hydraulic actuator output link was proposed, and a schematic solution of electrohydraulic actuator with combined regulation of the output speed (so-called EHA-CRS) was developed [2].

The method of combined regulation of the output speed is amplitude-dependent. It includes *predominantly throttle regulation* of actuator output link speed in the area of small input signals and *electromotor regulation* of actuator rod speed at medium and large amplitudes of control signals. The *predominantly throttle regulation* of output speed means that the spool valve regulation is the main one, but it may be supplemented by some fluid flow from the pump. Changing types of regulation occurs automatically and smoothly. [3]

Maximum sensitivity, stiffness and dynamic characteristics of the actuator for small input control signals (e.g. a few percent of the maximum value) are achieved due to the *predominantly throttle regulation*. Low energy efficiency in this case is not so important because in general it is a small value of the energy loss. Actuator passes to the electromotor regulation with increasing a magnitude of the input control signal. This type of regulation is characterized by high energy efficiency. The range of input control signals, for which *predominantly throttle regulation* is necessary, is determined by requirements for the aircraft stabilization system and typically is about 5...10% of the maximum control signal.

The principal scheme of the electro-hydraulic actuator with combined regulation, which was described previously, is shown in Fig.1.

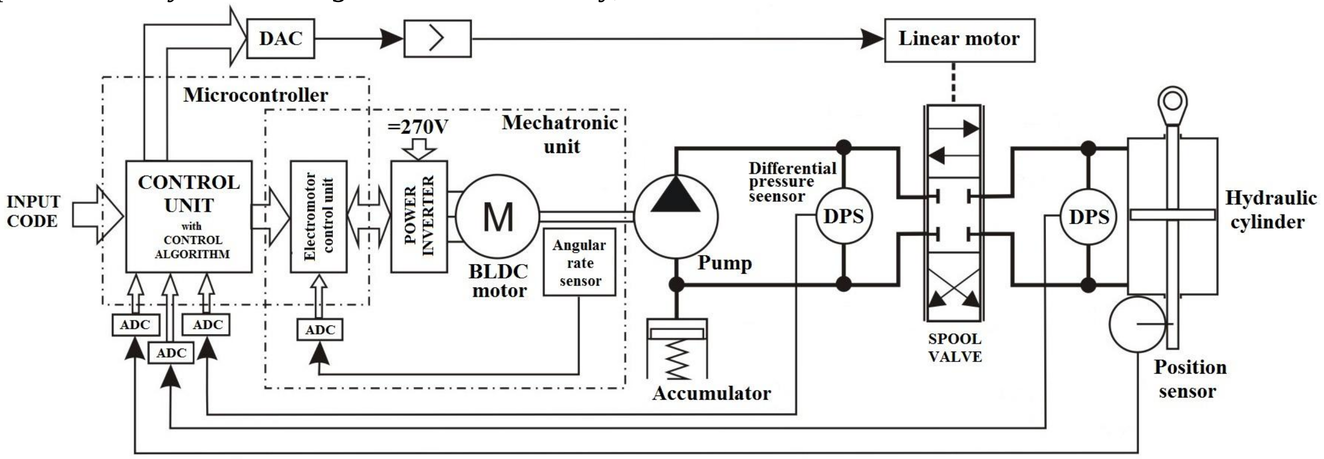

Fig. 1 Principal scheme of electrohydraulic actuator with combined regulation of output speed

Nonreversible fixed displacement pump and a spool valve (so-called *reversing valve*) are used in this actuator to regulate the speed of the hydraulic cylinder rod. Spool valve moves by the linear motor. Pump flow is changed by controlling the rotation speed of the DC motor. A spool valve works in proportional mode.

Embedded microcontroller performs continuous and synchronous regulation of the displacement of a reversing valve and speed of a motor shaft. Control algorithms are selected so that in the neutral state of the actuator, the electromotor shaft rotates with a minimum speed (about 1 ... 5% of the maximum) so the pump develops a slight pressure (about 5 MPa) that provides *predominantly throttle regulation*, which is achieved by small openings of windows in the spool valve. While the magnitude of the control signal is increasing, the motor speed also increases and windows are opens. So when the level of the input signal exceeds 6 ... 9% of its maximum value, the windows of the spool valve will be opened so hard that the change of their conductivity will not affect the actuator speed. Windows in a spool valve are selected so that in case of high magnitudes of the control signal the pressure losses on them are so small that the speed of the output link is regulated by the flow of liquid from the pump. Thus, the transition from *predominantly throttle regulation* to *electromotor regulation* is performed parametrically, gradually and smoothly, due to the developed control algorithm of electric motor and reverse valve. Differential pressure sensors installed in the actuator are used to correct its characteristics, to monitor the current state of the actuator and to configure the control unit.

Although the principal scheme and design of EHA-CRS are close to the scheme and design of EHA (they look different by using nonreversible pump and electrohydraulic servo valve (reverse valve)), the proposed actuator is a qualitatively new development of electrohydraulic actuators. It is achieved by using a special algorithm for parallel control of displacement of the reverse valve and the speed of electromotor.

Theoretical researches, which were confirmed by the tests of manufactured actuator, have shown that EHA-CRS has a high sensitivity that is comparable to the sensitivity of throttle actuators (positioning accuracy in a close-loop mode is at 0.1% from the maximum stroke of the output link). Dynamic stiffness and frequency characteristics are similar to those in high precision throttle actuators. This allows the use EHA-CRS in stabilization and stability systems for aircrafts with unstable aerodynamic configuration. Table 1 shows comparative data on the frequency characteristics of the various actuators.

Table 1

Spoiler EBHA, Airbus A-380, *Aout =2mm*					Electrohydraulic actuator with combined regulation of the output speed (designed by MAI, produced by PMZ "Voskhod", tested by "TSAGI")							
	Servocontrol mode		***EHA mode***		*Fload=0*				*Fload =5kN*		*Fload =15kN*	
					Aout =0.2mm		*Aout =2mm*		*Aout =2mm*		*Aout=2mm*	
f, Hz	Gain, dB	Phase, [°]	Gain, dB	Phase, [°]	Gain, dB	Phase, [°]	Gain, dB	Phase, [°]	Gain, dB	Phase, [°]	Gain, dB	Phase, [°]
0.5	-0.1	-12	-0.4	-16	-0.1	-11	-0.1	-9	-0.1	-6	-0.1	-10
1	-0.2	-21	-0.6	-33	-0.1	-18	-0.1	-18	-0.1	-15	-0.2	-20
2	-0.2	-43	-2.2	-62	-0.3	-50	-0.1	-40	-0.8	-25	-3	-35
4	-0.6	-90	-6.1	-135	-2	-90	-1	-75	-2.5	-45	-5.5	-65
8	-6	-164	-11	-168	-8	-140	-6	-120	-6	-90	-11	-100
15	-	-	-	-	-18	-180	-15	-160	-15	-170	-20	-180

Fig. 2 shows that due to the combined regulation this type of actuator has a unique feature among hydraulic actuators: its frequency characteristics are improving with reducing the amplitude of the harmonic signal from a few percent to fractions of a percent.

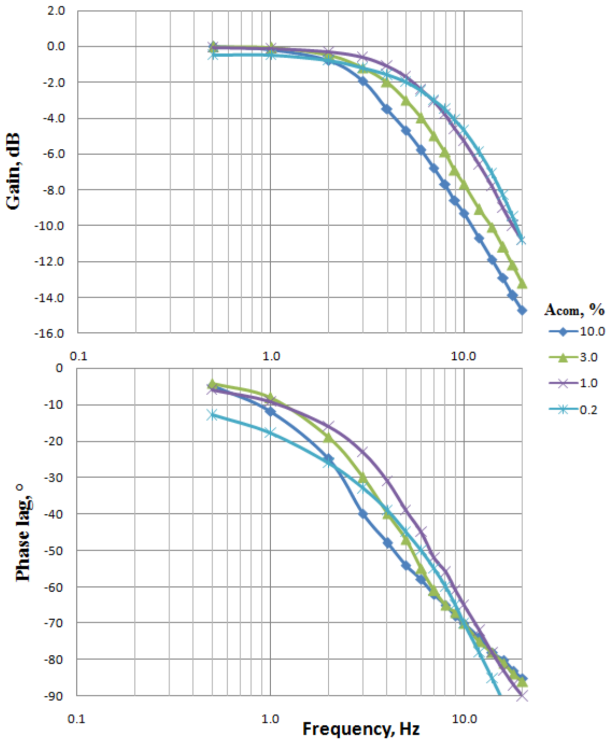

Fig. 2 Theoretical frequency characteristics of electro-hydraulic actuator with combined regulation for small magnitudes of command signal

At the same time these actuators retain high power characteristics that are typical for actuators with electromotor regulation of output speed. In the neutral state actuators with combined regulation retain a small rotation speed of the electromotor shaft, but the power consumption of the actuator in this state remains at a low level. EHA-CRS has features of adaptability to the load that reduces the power consumption of the control system during the flight and increases the life of the actuator.

Is necessary to note, that in EHA-CRS requirements for the electromotor and pump are significantly reduced in comparison with the electrohydrostatic actuator. For actuators with combined regulation of output speed reversibility of a pump and electromotor and high sensitivity of the electromotor are not required. The level of friction and leakage in the pump does not affect, in general, the sensitivity of the actuator.

Moscow Aviation Institute in collaboration with aviation manufacturers has developed several different versions of EHA-CRS in the power range of 0.8...4.2 kW which were tested or will be tested later.

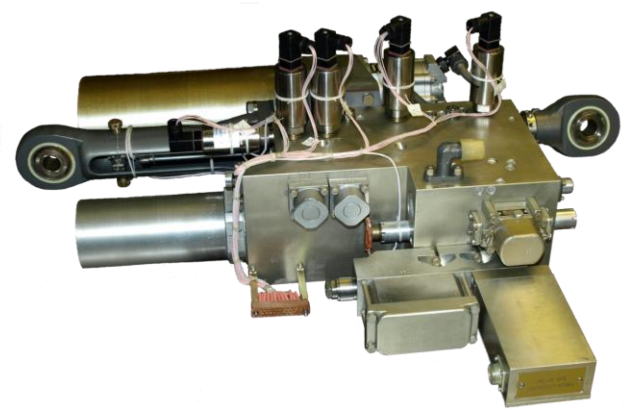

Fig. 3 Prototype of a hybrid electro-hydraulic actuator with combined regulation of output speed

Hybrid electrohydraulic steering actuator is presented in Figure 3 and 4. That actuator combined a classic throttle actuator which is powered by a centralized hydraulic system and EHA-CRS powered by electrical system in one construction. In this case these two actuators work alternately using the single hydraulic cylinder. That allows avoiding additional weight of the actuator system on the aircraft. This actuator is a part of a high-reliable control system with different redundancy. The structure of a hybrid actuator takes into account a fact of preservation of a part of centralized hydraulic systems on modern "more electric" transport and passenger aircrafts.

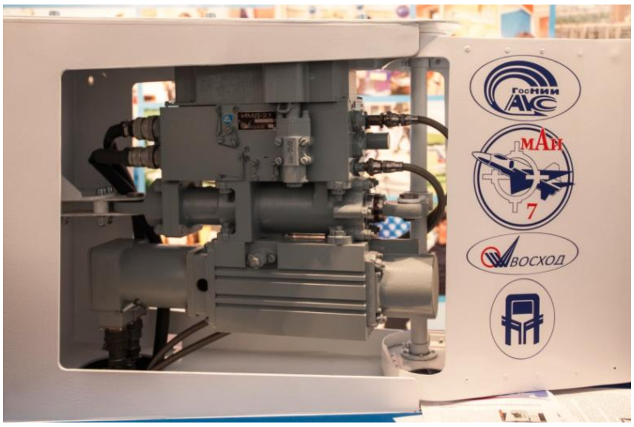

Fig. 4 Demonstrator of a hybrid electro-hydraulic actuator with combined regulation of output speed

Electromechanical miniactuators

When developing new electromechanical actuators main attention is focused on reduction of weight and dimensions.

Achieving this goal is carried out in 3 ways:

- Optimization of weight and dimensions;
- Using modern element base;
- Searching for ideal solutions.

The essence of these directions is in the following. Given that the drive systems have the greatest mass and dimensions of power supply sources and actuators, optimization of weight and size parameters was conducted:

- Through analysis and selection of primary and secondary sources of energy by the type of energy used and development of energy supply schemes ;
- By calculating the optimum power consumption of the engine and selecting the gear ratio;
- By choosing the type of engine and power transmission;
- Through construction of the gear actuator with the minimized outer diameter.

When analyzing and selecting the power supply to the drive system the following items were considered: the operating system drive, patterns of energy consumption and the distance between the energy source and the actuator drive, which significantly affects the mass indices [4].

As a result, the overall established trend of construction of drive systems with a centralized source of power is the use of actuators, which are a special case and combined hydrostatic drives, which use hydraulic transmission as torque and speed converters of the electric motor.

Comparisons of the primary sources of autonomous driving systems with limited working time suggest that the best specific energy indicators have solid gas generators and batteries.

Regarding the construction of the redundant drive system, in order to improve the reliability in addition to the use of electric and hydraulic networks it is advisable to use a centralized and independent power source.

An important design factor is the choice of electromechanical drive motor speed and the type of mechanical transmission. It is known that increasing the engine speed reduces its dimensions and weight, but it is necessary to increase the gear ratio to achieve the required actuator output parameters. And, as a consequence, dimensions and weight can be increased depending on the type of mechanical transmission.

The ratios of different volumes of the engine and mechanical gears to the maximum magnitude of the developed torque gear ratios are shown in fig.5.

Using the ratio of the volume of the mechanism to the maximum time to develop these mechanisms can be considered independently on the magnitude of the transmitted torque.

The graphs in fig.5 show that the total volume of the engine with manual transmission or cylindrical planetary gear increases with the number. Thus there are optimum values of the gear ratios at which this volume is minimal.

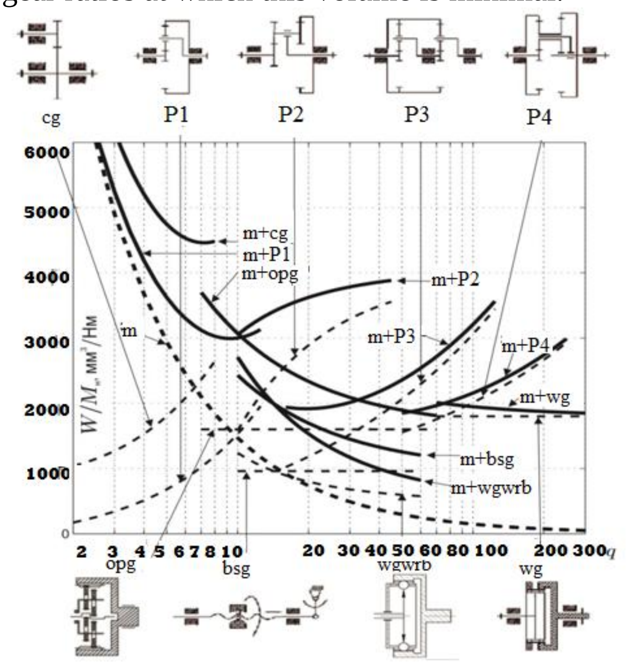

Fig. 5 Dependencies of different volumes of gear ratios. Cp-cylindrical gear, P1-P4-planetary gears, opg-orbital planetary gear, bsg-ball-screw gear, wgwrb-wave gear with rolling bodies, wg- wave gear

The wave gear with rolling elements and the ball screw with a lever mechanism have the smallest dimensions. In this case, the volume of wave transmission with rolling elements decreases with increasing transmission gear ratio.

However, a large gear ratio for a given torque can be realized in wave transmission with the rolling elements due to a larger diameter and a small length, or due to large length and small diameter. Aircraft actuators must fit into the small midsection of the wing, stabilizer or flaps cargo compartments, i.e. they should have the limited outer diameter. The results show that the outer diameter of the wave transmission rolling elements has a minimum value, which depends on the maximum load torque gear ratio and the number of rows of rolling elements. Dependencies of the outside diameter for a given load torque depending on the gear ratio and the number of rows of rolling elements are shown in fig.6.

These features of wave transmission with rolling elements caused two-stage construction of the gear. Output stage is built with the optimal gear ratio and provides the required torque, while the intermediate step complements the required gear ratio and implements the desired speed.

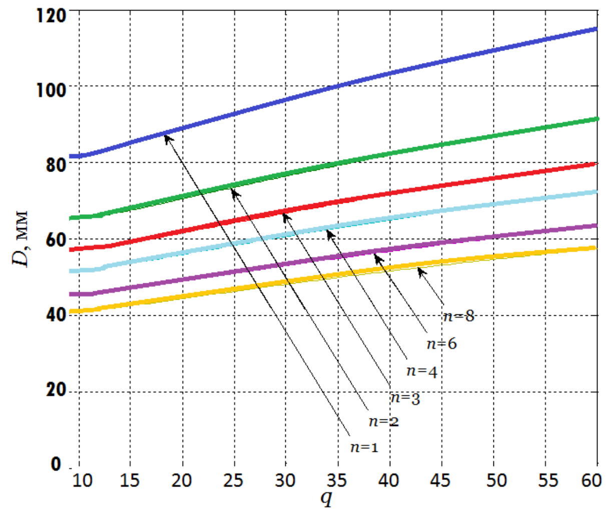

Fig. 6 Dependencies of the outside diameter for a given load torque depending on the gear ratio and the number of rows of rolling elements

Several features of wave transmission with rolling elements were identified.

Wave transmission includes 3 main elements inside, which are waveformer, separator and circular spline. The separator can be the output link with fixed circular spline, and the circular spline can be the output link when the separator is fixed. In this case the arrangement of the machines can be different, and it is not necessary to center the circular spline, because it is based on bearing balls or rollers arranged evenly around the perimeter.

Furthermore, if the waveformeris designed as a set of disks located on eccentric bushings with extra degree of mobility, it reduces the moment of inertia of the actuator in dozens of times.

Such actuators which include frameless motor and wave transmission are called power miniactuators and have a set of properties which were identified.

The set of identified properties of drives containing frameless motor and wave transmission with rollers led to the creation of great moments in the small size which gave the name to these drives - power miniactuators [5].

Mathematical models of the wave transmission and power miniactuators were developed. There have been developed methods of calculating the basic parameters, providing the required dynamic characteristics at a given outside diameter.

The concept is implemented in the samples of power miniactuators with rotational and linear motion [6].

When developing the linear motion actuator, there was used wave transmission deployed along the longitudinal axis of the drive or it can be used a ball screw and retainer. It is shown in fig.7.

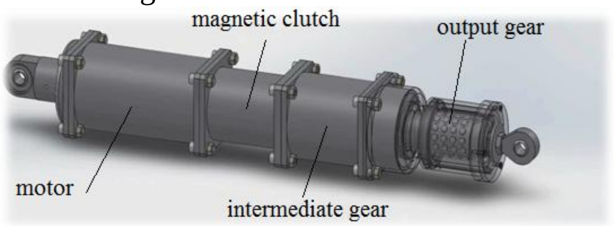

Fig. 7 Linear motion power miniactuator

Placing the balls in the retainer causes the exception of closed recirculating ball tracks and thereby it allows to avoid jamming of transmission paths and abrasion of balls and to prevent the balls from crumpling.

Power mini actuators with rotary motion can be constructed as a loop and placed along or parallel to the axis of rotation of the adjustment. It allows to have more free volume in the wing or fuselage. It is shown in fig.8.

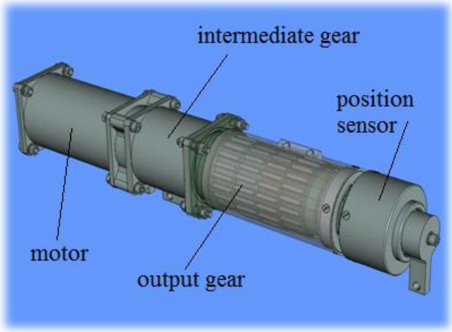

Fig. 8 Rotary motion power miniactuator

The outer diameter of designed actuators is 80 mm. The mechatronic unit for actuators was designed and manufactured by JSC "Polytech".

Electromechanical power units were designed and developed together with "Corporation aviation equipment" and manufactured at "Michurinsky instrument making plant". The actuator is designed to control the maneuverable aircraft cargo compartment flaps.

The main feature in the construction of power miniactuator units is in blocks of output and intermediate gear stages and motor, wherein the input block units are linked with output stages through the intermediate stage by the synchronizing shaft. The design allows to place the gear units along the cargo compartment flaps. The outer diameter of units is equal to 60 mm. It is shown in fig.9.

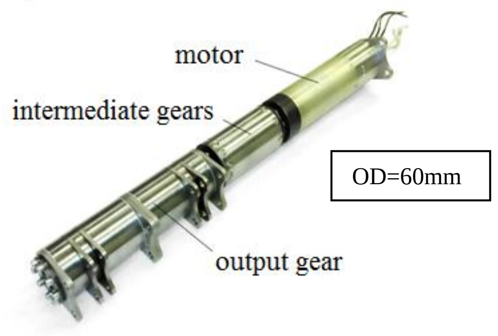

Fig. 9 Actuator for aircraft cargo compartment flaps

The electromechanical power unit for aerodynamic surfaces was designed and manufactured by JSC "Metallpark" and tested at RAC "MiG".

The actuator has a mechatronic unit produced by «KEB» firm. It is shown in fig.10.

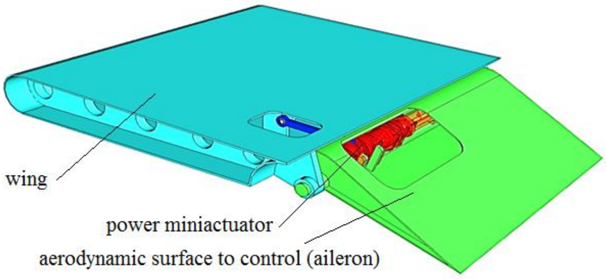

Fig. 10 Power unit for aerodynamic surfaces

The actuator is designed for redundant systems with summing moments. The actuator has an outer diameter equal to 80 mm.

Placing the actuator along the rotation axis of the aerodynamic control surface can improve aerodynamic characteristics of the wing due to exclusion of fairings for using other actuator types with linear action, as well as free volume occupied by linear actuators in the wing.

The conducted tests are demonstrate that dynamic characteristics of the electromechanical power miniactuators are similar to the characteristics of existing actuators. It is shown in fig.11 and fig.12.

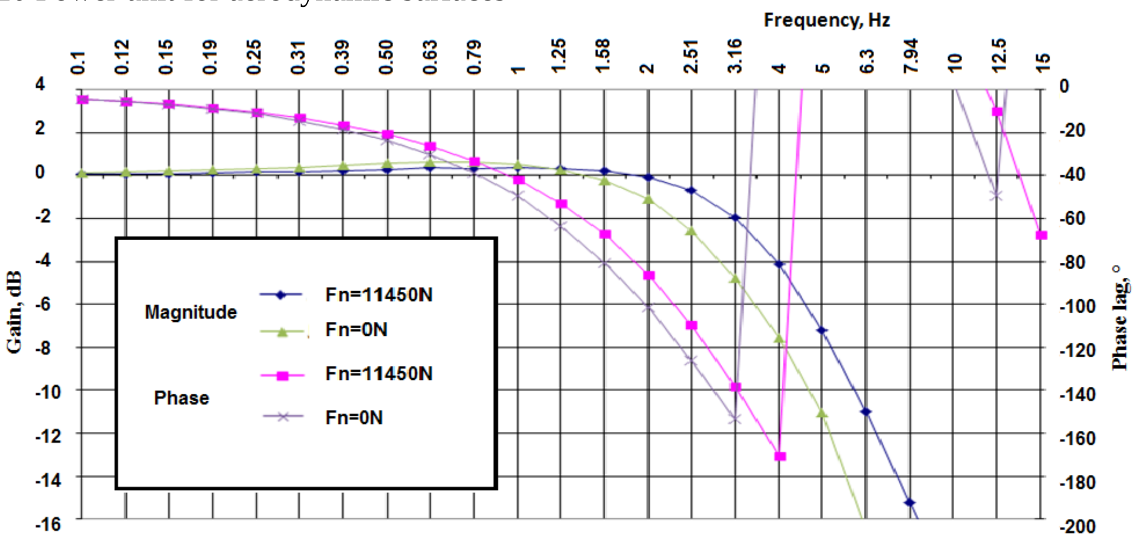

Fig. 12 Bode response graphs of power unit for aerodynamic surfaces

Fig. 11 General view of the stand

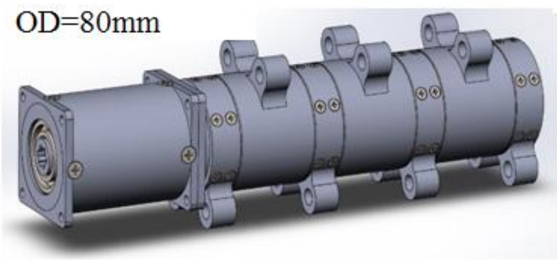

Fig. 13 Modular design in power miniactuator units

More work is being conducted on creation of electromechanical power actuator units in modular design. Unified modules allow to collect the intermediate and output drive gear stage with different specifications for systems of various applications. It is shown in fig.13.

1st intermediate gear	2nd intermediate gear	Summary gear ratio
		11
	6	66
	8	88

	10	110
	20	220
6	6	396
6	8	528
6	10	660
8	8	704
8	10	880
10	10	1100
6	20	1320
8	20	1760
10	20	2200
20	20	4400

Summary

Thus at the department "Servo drive systems for aerospace vehicles" there were developed hydraulic and electromechanical actuators that can be used in more electric aircraft with a unified electric power supply network.

The use of hybrid and electrohydraulic actuators with combined regulation of the output speed (EHA-CRS) is prospectively in the future. EHA-CRS has great characteristics in comparing with the well-known self-contained actuators. Frequency characteristics and dynamic stiffness are similar to those characteristics in throttle actuators. This allows to use electrohydraulic actuators with combined regulation of the output speed in stabilization systems for aircrafts with unstable aerodynamic configuration.

According to the authors, the throttle actuator inside the hybrid actuator will be powered by a local hydraulic system and become a part of the emergency control system turning on after a total failure of the electrical system on the passenger aircraft. Applying the EHA-CRS in the hybrid actuator provides a high quality of control and stabilization of the aircraft using any of energy channels.

As for electromechanical power miniactuators, their schematics and design solutions allow to obtain dynamic performances similar with hydraulic actuators. Developing schemes of the electromechanical power miniactuators can work in multiplex systems, with speed or torque summing, ensuring energy recuperation.

Rotary motion actuators provide required torques. Actuators have small dimentions, which allow to place them in a controlled aerodynamic surface along (or parallel) to the axis of rotation.

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