Comparative analysis of linear electromechanical steering drives with an autonomous hydraulic drive

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Abstract. The work is devoted to the topical problem of choosing a scheme of a linear electromechanical drive, developed as an alternative to an autonomous electro-hydraulic drive. Mass characteristics of the main functional elements of the actuators: electric motors and ball screws are considered. Synchronous motors and a collector motors were considered in this work as an electric motor. Ball-screw transmissions with separator and ball-screw transmissions with recirculation of balls were considered in this work as a ball-screw transmission. Comparison was made according to functional, technological and economic criteria of two schemes for construction of linear electromechanical drives: with intermediate mechanical transmission based on a collector motor and based on a permanent magnet synchronous motor without an intermediate mechanical transmission. The comparison showed that the scheme with an intermediate mechanical transmission has better mass characteristics compared to the scheme without an intermediate mechanical transmission with similar dynamic characteristics. The presented comparison results can be useful in solving the problem of choosing schemes for newly developed electric electromechanical steering drives.

1. Introduction

The actual tasks facing the developers of the drive systems of aircraft (AC), especially the steering drives, are the reduction of their weight and overall dimensions, cost reduction, and simplification of operation.

A significant simplification of operation can be achieved by replacing existing autonomous hydraulic drives with electromechanical drives (EMD), which do not require frequent routine maintenance to check the leakage of the working fluid.

The solution to the problem of reducing the mass-dimensional indicators and cost determines the use of new approaches that allow to implement the required functions of the actuator through the use of other physical principles of operation, new design solutions based on known principles of operation, as well as the transfer of a number of functions to logical electronic devices.

In this work, for linear EMD, motors with permanent magnets made of rare earth materials (Samarium–Cobalt, Neodymium–Iron–Boron) are considered as electric motors, namely: DC collector motors with independent excitation from permanent magnets and brushless motors with winding commutation by an electronic control unit.
As ball-screw transmissions (BST) are considered, which differ in the placement of balls: in one case, along a closed track, in the other, with the placement of each ball in a separate seat of the separator.

The electric motor and ball screws are considered in different layouts, depending on their location and relationship. The rotor of the electric motor can be connected to the rotary link of the ball screw (screw or nut) through an intermediate mechanical transmission or directly, without an intermediate transmission.

For comparison of EMD, the parameters of an autonomous hydraulic drive with a power of 1.5 kW, which consists of: a DC collector drive motor with independent excitation; fixed displacement axial plunger pump; compensating and pressing device (accumulator); an electromechanical transducer with a translational slide valve pair; hydraulic cylinder and an inductive feedback sensor mechanically connected to the hydraulic cylinder rod were taken as reference parameters.

2. Formulation of the problem
The purpose of this work is a comparative analysis and selection of an electric motor and a ball screw for a linear electromechanical steering actuator according to their technical capabilities, mass-dimensional indicators, layout with and without an intermediate gear, technological and economic parameters.

3. Comparative analysis of BST
The fundamental difference between ball screws transmissions lies in the design of the nuts. In ball screws with recirculation of balls, the nut contains an internal helical track and a channel for recirculation (return) of balls along a closed track, including two or more turns. In a ball screw with a separator, the nut is a cylindrical sleeve with a smooth inner surface, with which the balls are in contact, located along a helical line in the separator seats, while the separator is rigidly or with the possibility of relative rotation connected to the sleeve [1].

Such design features of the nut with a separator determine its simpler manufacture, and in mass production with the manufacture of separator nests according to a conductor or according to a control program on a programmed machine, a significant cost reduction.

![Figure 1. Dependences of the BST mass with a stroke \( x = 30 \text{ mm} \) on the axial force.](image)

The use of ball screws with a separator in the electromechanical steering drive provides increased reliability of this drive, since it eliminates the possibility of gear jamming caused by possible deformation of the ball or nut profile under shock loads.
With regard to weight and dimensions, the nut with a cage has a greater length with the same number of balls due to the presence of bulkheads. In addition, the mass-dimensional parameters are influenced by the uneven distribution of the load on the turns of the ball screw, the results of the study of which are given in works [2, 3].

When comparing the mass-dimensional indicators of the ball screw assembly, it should be noted that the mass of the screw is significantly greater than the mass of the nut, especially at large working strokes.

The calculated dependences BST masses $m_{BST}$ with a stroke $x = 30$ mm on the maximum axial force $F$ are shown in figure 1.

4. Comparative analysis of electric motors

The analysis was carried out under the assumption that when using permanent magnets, the magnetic induction in the air gap and the current linear load in the collector and synchronous motors are the same. The assumptions are valid provided that the magnets with the same characteristics are used in both types of motors and the dimensions of the rotor position sensor in the synchronous motor correspond to the dimensions of the collector in the DC collector motor. The dependence of the mass of the collector motors on the rated torque is built according to the method [4]. The same dependence for synchronous motors with permanent magnets is built according to the procedure [5] (see figure 2). The graphs are constructed with magnetic induction in the air gap $B = 0.7$ [T] and linear current load $A = 19500$ [A/m].

Also, in figure 2 the parameters of motors of various manufacturers, known from catalogs [6–10], are shown.

![Figure 2. Dependences of the mass of electric motors on the rated torque.](image)

A comparison of the calculated dependences and parameters of the manufactured motors shows that for the initial assessment of the motors mass at the stage of selecting the parameters of the functional elements of the drive, it is possible to use the theoretical dependences shown in figure 2. The spread of values relative to the calculated dependences is due to the parameters of the magnets used, the design and technological features of specific motors.
Also, from the analysis of figure 2, it follows that the mass of the synchronous motor is less than the mass of the collector motor in the entire range of rated torque considered. At the same time, as a rule, synchronous motors have a larger diameter and a shorter length compared to collector motors. It should be noted that the use of synchronous brushless motors as part of the actuators of unmanned aerial vehicles (UAVs) does not require special sealed enclosures, which expands the scope of their use in a wider range of air densities.

5. Placement of the electric motor and BST in the steering drive actuators

The choice of the electric motor and BST placement in actuator depends on the volume allocated for it in the UAV. Linear EMD is used when the overall dimensions of the electric motor and mechanical transmission along the longitudinal axis do not allow the actuator to be placed coaxially with the axis of rotation of the steering surface. In this case, the output rod of the mechanical transmission of translational action, creating a force, is located so that through a certain shoulder, located perpendicular to the axis of rotation of the steering surface, creates a torque.

At the same time, the electric motor can be placed coaxially, perpendicular, parallel or at an angle to the longitudinal axis of the BST.

As a result, all possible results of the layout of the motor with the BST can be represented in the form of two schemes: the first scheme coaxially, without intermediate mechanical transmission, the second scheme with intermediate gear whose scheme depends on the location of the axis of the motor relative to the axis of ball screw.

As an example, a functional and structural diagram of an electromechanical drive based on a collector motor and BST located in parallel and connected to each other by cylindrical gears is shown in figure 3(a). An example of a scheme based on a synchronous motor and a BST with a separator located coaxially is shown in figure 3(b).

![Functional and constructive schemes](image)

**Figure 3.** Functional and constructive schemes: (a) functional and constructive scheme of an EMD based on a collector electric motor and a BST; (b) functional and constructive scheme of an EMD on a BST with a separator and a brushless electric motor.

In figure 3 are designated: $A$—actuator, $AB$—accumulator battery, $DCU$—drive control unit, $PG$—pulse generator, $EM$—electric motor, $FBS$—feedback sensor, $BST$—ball screw transmission, $RPS$—rotor position sensor, $U_p$—power voltage, $U_c$—control voltage, $U_{EM}$—voltage on the electric motor, $U_{P FBS}$—power voltage of the FBS, $U_{FBS}$—signal from the FBS, $F$—load force on the output rod, $V$—output rod speed, $U_{P RPS}$—supply voltage of the PRS, $U_{RPS}$—signal from the RPS.
6. Weight comparison analysis of EMDs

The mass of the EMD $m_{EMD}$ consists of the masses of the BST $m_{BST}$, the electric motor $m_{EM}$, the gearbox $m_G$, the corpus elements of the $m_C$, the mass of the DCU $m_{DCU}$:

$$m_{EMD} = 1.2 \cdot (m_{EM} + m_G + m_{DCU} + m_C + m_{BST}).$$

Given that the output parameters of the compared drives are the same, their masses can be expressed in terms of the maximum force at the output translational rod of the BST. The greater this force is, the greater the mass of the drive.

In the original autonomous hydraulic drive, the maximum force on the rod is 15700 N. For such a force, as follows from figure 1, the mass of BST with a separator and a screw diameter of 32 mm is twice as large as the mass of BST with recirculating balls and a screw diameter of 25 mm. The mass of the electric motor is expressed in terms of the maximum torque on the motor rotor $M_{EM}$

$$M_{EM} = \frac{M_{BST}}{\eta_{BST} q_G} = \frac{F \cdot p}{2\pi \cdot 1000 \cdot \eta_{BST} \cdot \eta_G \cdot q_G},$$

where $M_{BST}$—moment on the BST [Nm], $F$—force on the BST [N], $q_G$—gear ratio of the gearbox, $\eta_G$—efficiency of the gearbox, $\eta_{BST}$—efficiency of the BST (0.9 for BST with ball recirculation; 0.7—for BST with separator), $p$—pitch of the screw line of the ball screw [mm].

| Parameter            | The EMD based on a collector electric motor and a BST | The EMD on a BST with a separator and a brushless electric motor |
|----------------------|------------------------------------------------------|------------------------------------------------------------------|
| screw line pitch, mm | 5                                                   | 8                                                                |
| efficiency of the BST| 0.9                                                 | 0.7                                                              |
| gear ratio           | 6                                                   | —                                                                |
| efficiency of the gearbox | 0.9                                             | —                                                                |
| $m_{BST}$, kg        | 0.5                                                 | 1.1                                                              |
| $M_{EM}$, kg         | 2.57                                                | 20                                                               |
| $m_{EM}$, kg         | 3                                                   | 10                                                               |
| $m_G$, kg            | 0.6                                                 | —                                                                |
| actuator mass, kg    | 5.5                                                 | 13                                                               |
| $m_{DCU}$, kg        | less than 0.65                                      | less than 0.65                                                   |
| $m_{EMD}$, kg        | 6.15                                                | 13.65                                                            |

The more the gear ratio of the gearbox, and a smaller screw line pitch, the smaller the value of developed torque, and hence less weight of the motor. The considered electromechanical drives have the following mass characteristics, shown in table 1. The purpose of this work is a comparative analysis and selection of an electric motor and a ball screw for a linear electromechanical steering actuator according to their technical capabilities, mass-dimensional indicators, layout with and without an intermediate gear, technological and economic parameters.

7. Comparison analysis of EMD dynamic characteristics

To analyze EMD static and dynamic characteristics in Simulink is developed the nonlinear mathematical model of the EMD on the basis of collector DC motor and BST with the intermediate gear shown in figure 4, and the model of the EMD based on a ball screw transmission with the separator and torque synchronous motor shown in figure 5.
Figure 4. Mathematical model of EMD based on DC motor and ball screw transmission with intermediate gear.

Figure 5. Mathematical model of EMD based on synchronous motor and ball-screw transmission with separator.

The mathematical model includes the following basic structural blocks: a regulator, a power electronics unit, an electric motor, a mechanics unit, feedback sensors, and an external load unit.

Table 2 shows the simulation results.

| Parameter                          | Original autonomous hydraulic drive | EMD based on DC motor and ball screw with intermediate gear | EMD based on synchronous motor and ball screw with separator |
|-----------------------------------|-------------------------------------|-----------------------------------------------------------|----------------------------------------------------------|
| bandwidth, amplitude 4 mm        | 16 Hz                               | 10 Hz                                                     | exceeds 10 Hz                                            |
| phase margin                      | 87°                                 | 135°                                                      | exceeds 135°                                             |

The analysis of tables 1 and 2 shows that an EMD based on synchronous motor and ball screw with separator has better dynamic characteristics and, at the same time, a greater mass.

8. Evaluation of the manufacturing cost of the considered actuators
The cost of manufacturing actuators is determined by the total cost of purchased products, labor intensity of manufacturing component parts, assembly and preparation of production.

The cost of purchased electric motors is largely determined by the technical capabilities and experience of the manufacturer of this type of electric motor, as well as the volume of the manufactured batch. When comparing motors in terms of relative cost, both types of motors
contain permanent magnets made of the same material, and the difference lies in the cost of the collector in a DC motor and the rotor position sensor used to control a synchronous motor.

In addition, the actuators with a DC motor includes an intermediate gearbox, and the actuators with a synchronous motor includes a special additional electronic unit for switching windings.

However, high precision servo drives use complex feedback control algorithms, regardless of the motor type. Thus, regardless of the type of functional-constructive scheme according to figure 3, in order to ensure the specified control algorithms in the EMD, an electronic unit is required in which the necessary drive control laws will be implemented. The EMD electronics unit with a DC motor, in general, differs in a smaller number of power elements of the circuit, which allows reducing the total cost of the electronics unit by no more than 10%.

At the same time, the presence of an intermediate gearbox in an EMD with a DC motor increases the cost of the drive by approximately the same amount.

9. Conclusions
Comparative analysis of linear EMDs, containing electric motors and ball screws, shows that such actuators have better performance characteristics with similar functional, technological and economic characteristics in comparison with an autonomous hydraulic actuator in the considered range of developed forces, which indicates the possibility of their interchangeability.

It is shown that the weight of electric motors in the considered EMDs is significantly greater than the mass of ball screws and the total weight is determined by the mass of the electric motor. Simultaneously, the cost of the electric motor should be determined together with the cost of the control unit.

Comparison of the layouts of the considered EMDs indicates that actuators with an electric motor and a ball screw connected by an intermediate mechanical transmission have better mass characteristics in comparison with an EMDs without an intermediate gear.

At the same time, actuators in which electric motor and ball screw are located coaxially without an intermediate gear have increased reliability, better dynamic characteristics, manufacturability and ease of manufacture.

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