Analysis of load distribution unevenness in ball screw with a separator

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Abstract. The work is devoted to the actual problem of liner electromechanical actuator designing. The object of study is a ball screw with a separator, the presence of which in the design provides increased reliability and causes a lower manufacturing cost due to the absence of a nut with an internal thread. A calculated solid model of a ball screw with a separator is compiled, its stress-strain states are determined. The coefficient of the load distribution unevenness over the turns of the gears is determined for a different ratio of the diameter of the ball and the width of the bridge of the separator. The axial stiffness of the transmission is determined.

1. Introduction
The development of aircraft control systems electromechanical actuators is a promising direction in the development of technology. Currently, hydraulic engines of linear action are used in the control systems of aircraft. Their replacement with electromechanical actuator, consisting of electric motors and screw gear, would increase maintainability, as well as reduce the cost of maintenance of such control systems [1,2]. At the same time, the developed linear electrometrical actuators must provide high similar to the hydraulic ones shown reliability [3].

The ball screw [4], in which the nut is made in the form of a separator with cylindrical holes located along a helical line, and a cylindrical sleeve, is known. The location of each ball in a separate slot eliminates the possibility of crushing balls during movement under shock load, which leads to an increase in the reliability of this transmission. And the absence of a nut with a female thread and a recirculation channel in the design causes a low manufacturing cost of the transmission. Issues related to determining the carrying capacity and stiffness of a ball screw with a separator are considered for the first time and requires a separate new research.

2. Formulation of the problem
The main tasks are determination of the distribution of contact stresses and strains along the turns of a ball screw with a separator in order to determine the coefficient of load distribution unevenness on the turns of a screw, determination of the axial stiffness of a ball screw with a separator and formulation of recommendations on the ball screw with a separator transmissions design.
3. **Compilation of calculation models and analysis of results**

It is known [5] that the load in ballscrews with recirculation of rolling elements is distributed unevenly between the turns of the screw, in addition, in [6], the nature of the load distribution is shown to vary depending on the magnitude of the contact deformations that arise and the gaps in the transmission. Also in [6], the upper and lower limits of the load distribution curve between the turns of ball-screw gears with recirculation of rolling elements were determined.

To calculate stress-strain states, a simplified transmission model (figure 1) was compiled which was a screw mechanism with multi-pair gearing, having one degree of mobility and taking into account the basic design parameters of the transmission, such as: helix pitch, ball diameter, contact angle, helix angle and the separator bridge width.

![Figure 1. Simplified multi-pair gear mechanism: 1 – movable link, 2 – fixed link.](image)

Figure 1 shows the following design parameters: \( p \) - helix pitch, \( d_b \) - diameter of the ball, \( r_s \) - radius of the thread profile of the screw, \( h_s \) - width of the separator bridge, \( \alpha \) - angle of pressure, \( \psi \) - helix angle, \( F \) - axial load force acting on the movable link.

In accordance with the simplified model, a solid-state 3D model was developed in the SolidWorks environment and using the software package of finite element analysis SolidWorks COSMOS, contact stresses were determined at the contact points of the movable (loaded) and fixed link.

The voltage at the point of contact is related to the contact force by the following relationship [7]:

\[
\sigma_i = \frac{2}{3} K F_i^{\frac{1}{3}}
\]
where, \( \sigma_i \) – contact stress at the \( i \)-th point of view, \( F_i \) – contact force at the \( i \)-th point of view, \( K \) – coefficient corresponding to the properties of materials and the radii of curvature of the contacting surfaces.

As a result of stress analysis at the contact points, contact forces were determined from the condition:

\[
F = \sum_{i=1}^{z \cdot n} F_i \cdot \cos \alpha \cdot \cos \psi
\]

where, \( z \) is the number of contact points in one turn, \( n \) is the number of turns.

The ratio of the sum of the contact forces \( F_i \) in the \( j \)-th turn \( F_j \) to the axial load \( F \) characterizes the fraction of the axial load perceived by the \( j \)-th turn. Figure 2 shows the curves of the load distribution over the turns, constructed for different ratios of the diameter of the ball and the width of the jumper of the separator.

![Figure 2: Curves of the load distribution over the turns in a ball screw transmission with a separator for different sizes of separator bridge.](image)

From figure 2, it can be seen that the unevenness of the load distribution increases with increasing size of the separator bridge, and in the absence of a bridge the curve of the distribution of forces over the turns lies in the range established in [6], which confirms the correctness of the selected calculation model. Since the coefficient of unevenness of the load distribution is determined as the ratio of the average value of the contact force to the maximum, then, as can be seen from figure 2, with an increase in the size of the separator bridge, the coefficient of unevenness decreases. The unevenness coefficient affects the required number of rolling bodies necessary to provide the desired load capacity of the transmission. In this case, the smaller the coefficient of unevenness, the more rolling elements will be needed for this and, consequently, the mass-dimensional transmission parameters will increase. Thus, it is advisable to design ballscsrews with a separator with the smallest possible jumper size. Its size should be determined from the strength conditions for each particular structure individually.

Then, to obtain accurate results and determine the axial stiffness of a particular design, a 3D model of ball-wine transmission with a separator, shown in figure 3a, was created.
The developed design has the following design parameters: \( d_b = 2 \text{ mm}, \ p = 5 \text{ mm}, \ n = 6, \ n = 54, \) and \( h_s = 1.3 \text{ mm}, \) Young's modulus \( E = 2.2 \times 10^5 \text{ MPa}. \) The stress-strain states of a ball screw with a separator, shown in figure 3b correspond to the initial conditions under which the nut is fixed, and the axial force \( F \) acts on the screw protected from rotation. screw from the value of the axial force at the same structural parameters are presented in figure 4.

**Figure 3.** Ball screw transmission:

a) 3D model of a ball screw transmission with a separator, b) stress-strain state of the ball screw with a separator.

**Figure 4.** Ball screw transmission characteristics: a) curve of the load distribution in the turns, b) the dependence of axial deformation on the magnitude of the axial load force.
From figure 4f it follows that the results of modeling the stress-strain state of a ball screw transmission with a separator coincide with the results of modeling a simplified model (see figure 2). Figure 4b shows that the axial stiffness of a ball screw transmission with a separator increases with increasing axial load, which coincides with the results of a study of the axial stiffness of a ball screw transmission with recirculation of rolling elements presented in [6,8].

4. Conclusions
An analysis of the stress-strain state of a ball screw transmission with a separator indicates that the nature of the uneven distribution of load in the transmission depends on the ratio of the diameter of the ball to the width of the separator bridge.

It is shown that in order to increase the uniformity of load distribution, it is necessary to design the transmission in such a way that the separator jumper width is minimal. It was established that an increase in axial stiffness with an increase in axial load, which is characteristic of ball screw gears, is also characteristic of ball screw gears with a separator.

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