Steering actuator based on a ball screw with a separator

R R Abdulin¹, V V Bolshakov¹, V A Podshibnev¹,² and S I Samsonovich¹,²

¹Joint Stock Company “Avionica”, Moscow, Russian Federation, 127055
²Moscow Aviation Institute, Moscow, Russian Federation, 125993

E-mail: bolshakov.blumey@gmail.com, samsonovich40@mail.ru

Abstract. This paper considers the issue of improving the reliability of an electromechanical actuator in which the possibility of ball screw jamming has been excluded. For this purpose, an analysis of design solutions which allows to increase the reliability of an electromechanical ball screw linear actuator was carried out, design of ball screw with a separator was developed and patented, experimental studies of an actuator prototype with ball screw with a separator were carried out. The proposed constructive solution of ball screw, in which the nut is made without an internal thread, significantly simplifies the design and manufacturing technology. For experimental determination of static and dynamic characteristics of the actuator containing ball screw with a separator a mathematical model has been designed and a prototype similar to the electromechanical actuator with ball screw with ball recirculation has been made. The experiments showed that compared actuators have practically same static and dynamic characteristics, but the efficiency of the ball screw with a separator is lower than that of ball screw with ball recirculation, the reasons for the decrease and ways to increase efficiency in ball screw with a separator are considered.

1. Introduction
The general trend in the aircraft drive systems development is the application of electromechanical actuators (EMA), instead of widespread hydromechanical systems. This is due to the fact that replacing the central onboard hydraulic system with electrical cables can significantly reduce the total weight and the cost of its maintenance [1,2,3]. For example, on Lockheed F-35, a complete replacement of the central hydraulic system with an electric system made it possible to reduce the weight of the control system by 300 kg [4], also the transition to electricity with EMAs nearly eliminates the periodic maintenance of the aircraft that is necessary in the presence of a hydraulic pipes [5].

The prevailing opinion about the low reliability of ball screw due to the theoretically possible ball jamming is the main constraint for the use of EMA in aircraft drive systems [2], despite the fact that jamming of these gears is not described in the specialized technical literature. Work on the design of a ball screw actuator, in which jamming is excluded, is being carried out both abroad [6,7,8] and in Russia [9,10], since the problem of increasing reliability is always relevant.

This paper is devoted to one of the methods to solve this problem.

2. Elimination methods of ball screw EMA jamming
Improving the reliability of ball screw EMA is currently achieved through the use of additional devices, called anti-jamming or redundant. As such devices, a double ball screw and a differential...
mechanism [6] or a single screw with several nuts that are driven by separate motors [7] are used, there are also solutions with additional locking devices that, when jammed, free the output rod from connection with a screw for free movement of a functioning backup EMA [8].

In such constructs [6, 7, 8] of ball screw EMAs, the use of anti-jamming devices leads to a significant complication of the design and, accordingly, the actuator cost.

Considering that jamming in ball screw can be caused by deformation of the screw, nut, or balls jamming during recirculation along closed paths and ball return channel, an actuator design with a transmission that converts rotational motion into translational, for which the indicated causes of jamming are excluded, is proposed. Jamming causes exclusion is achieved by placing rolling elements (balls or rollers) in the separator nests, which also simplifies the manufacturing technology and gear cost [9, 10].

Figure 1 shows the design of the actuator with such transmission. In this construct, rotating screw is the input link of the ball screw and the nut is the output link. The design feature is that the nut performs the function of a piston, made multi-piece, consisting of a housing having a smooth cylindrical inner surface and a separator with sockets located along a screw line with a step equal to the pitch of the screw. The separator and the housing are coaxially and rigidly interconnected at the ends of the separator so that the rolling elements are constantly in contact with the surfaces of the flank of screw thread, the inner smooth cylindrical surface of the nut housing and the surfaces of the separator sockets. Both rollers and balls may be used as rolling bodies. Using rollers allows to increase the load capacity of the transmission.

As a result, the proposed ball screw design, in which the nut is made without an internal screw thread, greatly simplifies the manufacturing technology and transmission cost. However, it should be noted that the placement of the rolling bodies in the separator nests leads, firstly, to an increase in the length of the nut with the same number of rolling bodies relative to the ball screw with ball recirculation along closed paths, and secondly, to an increase in friction losses between the rolling bodies and a separator.

3. Comparative analysis of EMA characteristics with various types of ball screw

For comparative analysis, experimental studies of two EMAs that differ only in the design of ball screw were carried out: the first actuator contains ball screw of the Swiss company Eichenberger Gewinde, built according to the classical construct with ball recirculation, the second actuator contains a ball screw with a separator, developed by JSC «Avionika» together with the staff of the Moscow
Aviation Institute and manufactured by JSC «Michurinsky Zavod «Progress». The screw pitch, the number of thread starts, the diameter and the number of balls for both ball screws are the same, they have the same gear ratio.

Experimental studies of positioning accuracy and frequency response (FR) were carried out at the test stand for checking EMA positional accuracy (figure 2).

![Figure 2. Test stand for checking EMA positional accuracy: 1 – EMA, 2 – base, 3 – extension, 4 – end measure, 5 – indicator.](image)

To check the accuracy of positioning, the EMA output rod is set to the neutral position corresponding to 25 mm by the control signal. Between the end surface of the extension and the indicator on a special support, end measure equal to 25 mm is setting. The end measures used have respective lengths of 10, 25, 40 and 50 mm. Then the end measure is removed and a control signal is supply on the EMA corresponding to the required position of the rod 10, 40 and 50 mm.

Output rod stroke determined by the equation: $X = L + \Delta$,

where $X$ – output rod stroke, $L$ – end measure length, $\Delta$ – indicator data relative to the zero position.

Table 1 shows the results of the average values of four repeated measurements, which indicate the identity of the EMA positional accuracy.

| End measure length, mm | 10 | 25 | 40 | 50 |
|------------------------|----|----|----|----|
| Output rod stroke of the EMA with Ball screw with ball recirculation, mm | 9.90 | 25 | 40.07 | 50.13 |
| Output rod stroke of the EMA with ball screw with separator, mm | 9.90 | 25 | 40.15 | 50.06 |

The study of frequency responses was carried out with the amplitude of the output rod stroke of 2 mm, 1 mm, 0.25 mm. The experimental results are shown in figure 3.
The obtained FRs indicate that they are almost identical for both EMAs. This is due to the fact that the presence of the separator led, on the one hand, to a friction increase between balls and separator along the diameter line, and on the other hand, to an increase of the transmission stiffness. Increased friction reduces efficiency when the actuator is in static mode, but stiffness increase compensates this friction in dynamic mode.

To estimate the efficiency of ball screw with a separator, a mathematical model of the force interactions of the balls with contact surfaces has been designed. The force interactions are shown in figure 4.
Relation of the efficiency on transmission parameters is obtained:

\[ \eta = \frac{\tan \psi}{\tan \psi + (\cos \psi + \tan(\psi + \rho) \cdot \sin \psi) \cdot \left( \frac{f_1}{\cos \alpha} + f_2 + f_3 \cdot \tan \alpha \right) } \]

where \( \psi \) – helix angle, \( f_1 \) – friction coefficient between ball and screw, \( \rho \) – angle of friction between the direction of the applied force and the perpendicular to the helical curve at the contact point, \( f_2 \) – friction coefficient between ball and separator, \( f_3 \) – coefficient of rolling friction between ball and housing, \( \alpha \) – contact angle.

The differences in efficiency depend on the friction coefficient between ball and separator \( f_2 \), which depends on the nature of the contact between the balls and the walls of the separator nests, which may be diametral or single-point.

In the manufactured prototype, the contact between the balls and the walls of the separator nests occurs along the diameter lines of the balls. The experimental studies of the efficiency were carried out at the EMA loading stand (figure 5).

![Figure 5. Loading stand: 1 – actuator prototype; 2 – gearbox \((q = 3)\); 3, 4 – brackets 1 and 2 respectively; 5 – freights.](image)

Determination of efficiency \( \eta \) consists in calculating the ratio of output power \( W_{\text{out}} \) to input \( W_{\text{in}} \): \[ \eta = \frac{W_{\text{out}}}{W_{\text{in}}} \]

The output power was determined as the product of the output rod speed with applied load: \( W_{\text{out}} = V \cdot F \). Speed was determined as the ratio of the output rod stroke from one uttermost position to another to the movement time (tests were carried out with a uttermost stroke of 50 mm), and as a load, freights of 0, 10.7 and 20 kg were used, and taking into account the test stand gear ratio \( q = 3 \) forces of 0, 315, 588 N were applied upon the output rod.
The tests were carried out by alternately setting each freight on first bracket while output rod movement from 0 mm to 50 mm. Then the freight was transferred to the second bracket, and the output rod was moving from 50 to 0 mm.

The power consumption was determined by simultaneously measuring the current and voltage on the electric motor for the same period of time.

As a result, the following efficiency values of EMAs with different types of ball screw were obtained:

Average efficiency of the electromechanical actuator with ball screw with ball recirculation is equal to 49.5.

Average efficiency of the electromechanical actuator with ball screw with separator is equal to 29.325.

We draw attention to the fact that experimental efficiency values were obtained taking into account electrical losses in power electronics and motor, as well as mechanical losses in motor and transmission.

4. Conclusions
As a result of comparing various methods of eliminating possible jamming in ball screw EMA from the point of design complexity and simplicity of implementation, it is shown that the easiest and cheapest way to eliminate jamming in ball screw is to place rolling bodies (balls or rollers) in the separator nests. A comparison analysis of EMAs comprising ball screw with a separator and ball recirculation having the same screws and number of balls indicates that both actuators have the same kinematic, load and frequency response characteristics, however, ball screw with a separator has lower efficiency compared to ball screw with ball recirculation.

References
[1] Halyutin S 2016 Electric plane: past, present, future Aviapanorama 6 42-51
[2] Bandurin N V, Shiryaev D V, Obolenskiy Yu G and Polkovnikov V A 2011 Comparative analysis of steering drives of a maneuverable plane according to energy criteria Izvestiya TulGU Technical science 5(1) 267-90
[3] Hussain Y, Burrow S, Henson L & Keogh P 2018 A review of techniques to mitigate jamming in electromechanical actuators for safety critical applications International Journal of Prognostics and Health Management 9(9) 1-11
[4] Voronovich S, Kargopoltsev V and Kutahov V 2009 “Completely electric plane” current status and prospects Aviapanorama 14-7
[5] Edited by Samsonovich S L 2016 Electromechanical mini-actuators for a more electrified aircraft (Moscow aviation institute press)
[6] Griman D H and Jonnes T L 1992 Pat. application No. 07738763 US
[7] Teske D R, Senasack H E and Wilkins M 1987 Pat. application No. 06791692 US
[8] Gonzaber-Tabas E C, Lopez F A, Lopez E M, Olazabal A J 2015 Pat. Application No. 14601695 US
[9] Samsonovich S L and Konstantinov S A 2005 Pat. application No. 2265147 RU
[10] Samsonovich S L et al. 2018 Pat. application No. 2017104322 RU