Research results of planetary roller screw transmission for high-precision mechanisms

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Abstract. In the article experimental survey results of planetary roller screw drive for usage in high precision parallel structure mechanisms for space application are considered. The drive was developed in Academician M.F. Reshetnev Information Satellite System. Roller screw is perspective type of precision linear drives which excels in several characteristics extensively used in modern time ball screws. Ground tests conducting methodology, tests scheme of the developed roller screw are described. Key parameters of analyzed precision linear drive such as: transmission accuracy, repeatability, axial stiffness and operating lifetime are presented.

1. Introduction
In communication spacecraft (SC), to ensure high signal quality, the use of mechanisms is required that are capable of fine-tuning the spatial position of the spacecraft structural elements according to six degrees of freedom.

There are many approaches and directions in solving this problem, but the most relevant to modern requirements is the use of multi-degree control devices (CD) [1−5], built on the basis of high-precision linear drives. Linear drives, which are part of the CD, must have high accuracy and rigidity, simple and technological design, low weight and overall dimensions, high reliability and the possibility of operation in outer space. One of the most important components of the mechanical part of the drive is a linear transmission, which ensures the conversion of the rotational motion of the motor shaft into the translational motion of the output link.

Having regard to the studies carried out by V.V. Kozyrev [6], D.V. Bushenin [7, 8], D.S. Blinov [9], A. Baccar [10], S.A. Velinsky [11, 12] and M.H. Jones [11, 12], the most promising type of linear transmission is planetary roller screw transmission (PRST).

The purpose of the work is to consider the results of experimental studies of PRST for use as part of high-precision mechanisms of the parallel structure of space applications.

2. Design of planetary roller screw drive with split nut
As a result of development work at JSC “ISS”, a PRST was designed and manufactured with a split nut (figure 1), consisting of screw 1 (12 mm in diameter), split nut 2, threaded rollers 3, synchronizing gears 4, separators 5, spring rings 6 and an adjusting distance washer 7. The PRST with a split nut due to the many contact points, the possibility of selecting clearances
and due to preload in the engagement of the thread of the rollers, screw and nut has a high axial stiffness, less kinematic error and absence of play compared to a conventional threaded pair.

![Figure 1](image1.png)

**Figure 1.** Construction (a) and photo (b) PRST.

### 3. Methodology and results of functional tests of a planetary roller screw drive with a split nut

Experimental studies were carried out according to the program and test procedure developed with the participation of the authors, in order to verify the parameters of the PRST: under normal conditions; when exposed to low and high temperatures (± 70 °C); after exposure to mechanical vibrational loads (corresponding to the loads that occur when the spacecraft is launched into orbit); and also after confirmation of the required resource (100,000 cycles in the range of ± 25 mm).

Checking the error of positioning the PRST was carried out according to the scheme according to figure 2.

![Figure 2](image2.png)

**Figure 2.** Scheme for determining the positioning error and repeatability of PRST: 1 - PRST nut; 2 - screw PRST; 3 - interferometer; 4 - technological plate; 5 - corner reflector; 6 - stock; 7 - bracket; 8 - technological drive.

The nut PRST 1 using the technological drive 8 was reported axial displacement equal to theoretical $x_n$, with a pitch of 1 mm in the range from 0 to 50 mm. The results obtained when checking the kinematic error are summarized in table 1.

| Operating factors                  | Kinematic error, not more than, mm |
|------------------------------------|-----------------------------------|
| Normal conditions                  | ±0.002                            |
| Exposure to low and high temperature | ±0.003                           |
| Mechanical stress                  | ±0.003                            |
| Guaranteed life                    | ±0.003                            |

The screw was gradually loaded by force $F$ to a load of 100 N in a positive direction and gradually unloaded to 0 N. Then, loading was repeated in a negative direction. The results obtained when checking axial stiffness are summarized in table 2.
Table 2. PRST axial stiffness test results.

| Operating factors                  | Axial stiffness, min, N/m | Axial stiffness, max, N/m |
|------------------------------------|----------------------------|--------------------------|
| Normal conditions                  | $1 \cdot 10^7$            | $7 \cdot 10^7$           |
| Exposure to low and high temperature | $1 \cdot 10^7$           | $9 \cdot 10^7$           |
| Mechanical stress                  | $1 \cdot 10^7$            | $8 \cdot 10^7$           |
| Guaranteed life                    | $1 \cdot 10^7$            | $5 \cdot 10^7$           |

Repeatability was checked at nine points evenly spaced along the threaded portion of the PRST screw. Using the technological drive, the PRST nut was given movement commands in the following sequence: $0 \text{ mm} \rightarrow 4 \text{ mm} \rightarrow 0 \text{ mm}$. The movements in the presented cycle were performed four times. At a point of $4 \text{ mm}$, the actual position of the PRST nut $L_1...L_4$ was checked. Among the values $L_1...L_4$, the maximum and minimum values of the displacement $L_{\text{max}}$ and $L_{\text{min}}$ were determined. The calculation of the repeatability $\pm t$ was performed according to the formula $t = (L_{\text{max}} - L_{\text{min}})/2$. The results obtained when checking the repeatability are summarized in table 3.

Table 3. PRST repeatability test results.

| Operating factors                  | Repeatability, min, mm | Repeatability, max, mm |
|------------------------------------|------------------------|------------------------|
| Normal conditions                  | $\pm 0.0001$           | $\pm 0.0004$           |
| Exposure to low and high temperature | $\pm 0.0001$           | $\pm 0.0005$           |
| Mechanical stress                  | $\pm 0.0001$           | $\pm 0.0004$           |
| Guaranteed life                    | $\pm 0.0001$           | $\pm 0.0005$           |

As a result of the experimental studies, a PRST was obtained with the summary characteristics presented in table 4.

Table 4. Characteristics of PRST.

| Parameter                              | The minimum value of the parameter | The maximum value of the parameter |
|----------------------------------------|------------------------------------|------------------------------------|
| Kinematic error, mm                    | $\pm 0.002$                        | $\pm 0.003$                        |
| Axial stiffness, N/m                   | $1 \cdot 10^7$                     | $1.9 \cdot 10^7$                   |
| Repeatability, mm                      | $\pm 0.0001$                       | $\pm 0.0008$                       |
| Operating temperature range, °C        |                                    | $\pm 70$                           |
| Resource, cycles, not less             |                                    | 100 000                            |

The experimental studies of the designed and manufactured at ISS JSC PRST with a split nut showed that, according to their technical characteristics, this gear is at the level of world analogues [13], and, therefore, multi-stage parallel kinematics drives can be built on its basis, allowing adjust the relative position of the telecommunication spacecraft design elements with high accuracy. In addition, using the experience gained in the design, manufacture and testing of the PRST considered in the article, it is possible to create a number of standard sizes of similar mechanisms that can be used not only at ISS, but also at other enterprises of the Russian space industry.
4. Conclusion
Significant increase of satellite structural components size leads to appearance of features of their relative position fine adjustment that is a result of separated masses and linking structural elements site separation. All structural components are affected by different space factors, including temperature impact which leads to changing of satellite structure optimal geometric disposition as a result of deformations. In order to provide fine adjustment six-degree-of-freedom adjustment devices, based on precision linear actuators, are used.

Linear actuators, which are used for adjustment device, must have high precision and stiffness, ordinary structure, low mass and dimensions, high reliability and possibility of space application. Linear drive is vital component of mechanical part of linear actuator. It is responsible for electric motor rotary motion to linear motion of output shaft transmission.

Planetary roller screw is the most perspective linear drive type. In the linear actuator, based on this drive, it is possible to reach axial displacement of nut relatively to screw equal 0.001…0.002 mm with minimal backlash.

As a result of the development work a planetary roller screw with separated nut was developed and produced by ISS-Reshetnev Company. The roller screw consists of screw (diameter is 12 mm), separated nut, threaded rollers, synchronizing gears, retainers, C-rings and distance washer. The drive has high axial stiffness, minimal backlash and low transmission error in comparison with ordinary screw-nut gear due to plurality of contact points, possibility of backlash elimination, preload in the thread mesh of rollers, screw and nut.

Experimental survey is carried out in accordance with tests program and methodology developed by authors with the object of planetary roller screw parameters control in normal conditions, under high and low temperature impact (±70°C), after vibration load impact (in accordance with loads arising in process of a satellite launch) and after life test (100 000 cycles). During the tests technical characteristics listed below was defined: transmission accuracy (no more than ±0.003 mm), repeatability (no more than ±0.0008 mm), axial stiffness (better than 1·10⁷ H/m).

Experimental survey of planetary roller screw with separated nut developed and produced in Academician M.F. Reshetnev Information Satellite Systems demonstrates that the drive is on the one level with world analogs taking into account its technical characteristics. As a result, relative position fine adjustment of telecommunication satellite structural components can be reached by means of multy-degree-of-freedom mechanisms based on developed roller screw. Moreover, it is possible to create range of roller screw drives for Russia space branch using background which is got during the process of design, producing and tests.

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