Experimental estimation of efficiency and kinematic accuracy of a spherical roller transmission

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Experimental estimation of efficiency and kinematic accuracy of a spherical roller transmission

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Abstract. Spherical roller transmissions with double-row pinions provide high reduction ratios in drives with a compact and lightweight design. The transmissions can be used as mechanical modules in kinematic chains of robots and manipulators. The pinion has two rows of coaxially arranged rollers and, when in operation, performs a regular precession. The paper examines the characteristics of an experimental model of a speed reducer with a spherical roller transmission with a reduction ratio of 44. The arrangement of the test rig as well as the test instruments and methods are described. The results of experimental study determining the efficiency of a spherical roller transmission depending on the torque being transmitted and the rotational speed of the drive shaft are presented. It has been found that the mean efficiency of the speed reducer is within the range of 0.7 ... 0.8 and its maximum value is 0.81, which corresponds to the efficiency of worm gears with similar characteristics. The theoretical calculations for determining the efficiency, which were obtained in previous studies, have been confirmed; the value of the reduced friction coefficient has been calculated. The constancy of the efficiency and the reduction ratio of the experimental model of the speed reducer and the factors influencing this constancy have been investigated.

1. Introduction

Mechanical transmissions with high reduction ratios are used in drives of aerospace equipment, robots and manipulators, pipe valves, etc. When designing a low-speed drive, a set of cylindrical and bevel gears connected in cascade can be used; other types of gears that can achieve high reduction ratios in one stage can be employed as well. The second option is more promising, since the cascade connection of gears leads to larger dimensions and greater weight of the drive as well as an increase in backlash; the rigidity, accuracy and reliability of the system are reduced. Due to the use of compact coaxial transmissions providing high reduction ratios in one stage, the actuator is brought closer to the engine, the weight and dimensions of the drive are reduced. To achieve these goals, various types of mechanisms are used, and cycloidal pin planetary gears are the most promising ones [1]. High reduction ratios can be achieved in schemes of transmissions with double-row pinions. However, as slip increases, efficiency tends to decrease; the pinion mounted on the drive shaft with eccentricity needs to be balanced.

Spherical mechanisms are compact in size, provide additional kinematic capabilities [2, 3] and are used to produce transmission mechanisms. Due to the use of rolling elements instead of teeth, sliding is replaced with rolling, which results in increased efficiency. Spherical transmissions with centers of mass (axes) of rolling bodies not fixed on the pinion [4] are characterized by excessive noise, wear and potential jamming. Motion transmission in precessional (nutation) transmissions is based on the phenomenon of regular precession [5–7]. These transmissions meet specified requirements in many respects and can be regarded as spherical mechanisms, since trajectories of the pinion points lie on spherical surfaces. A spherical roller transmission (SRT) with a pinion with two rows of rollers mounted coaxially [8] can produce reduction ratios in the range of 16 ... 200 and has a number of advantages, such as improved balance and higher load capacity.

This paper examines experimentally a model of the developed SRT in order to determine the instantaneous and mean efficiency of SRT as well as the constancy of the instantaneous reduction ratio depending on the rotational speed of shafts and the transmitted torque.

2. Object, instrumentation and methods used for SRT testing

In this study, an experimental model of a speed reducer with a double-row pinion SRT and with graphite grease applied during assembly was chosen as the test object. One row of SRT rollers interacts with a periodic closed groove formed by outer cams mounted in the housing; the second row of rollers interacts with a groove made on the inner cam connected to the driven shaft. In contrast to available gear transmission mechanisms, the load capacity is increased due to a larger number of parallel power flows. All the rollers of the row are simultaneously in contact with the outer cams, and about half of them are in contact with the inner cam. Sliding in the transmission is partially replaced by rolling, since rollers have the ability to rotate around their axes being in contact with grooves. The center of mass of the pinion is located on the transmission axis and coincides with the fixed point of spherical motion, which improves the balance of the mechanism and reduces the starting torque. The reducer has a reduction ratio of $i_{12}^{(3)} = -44$, which is determined by the number of periods of grooves formed by outer cams – $Z_2 = 11$, by inner cams – $Z_3 = 15$ and the number of the rollers of the outer row n_{s3} and the inner row n_{s2}, which are one more than the numbers of periods of the corresponding grooves. The maximum diameter of the reducer housing is 82 mm.

The test rig (figure 1) operation is based on the open power flow method. The reducer is placed in the kinematic chain of the rig between the torque sensor and the rotational speed sensor.

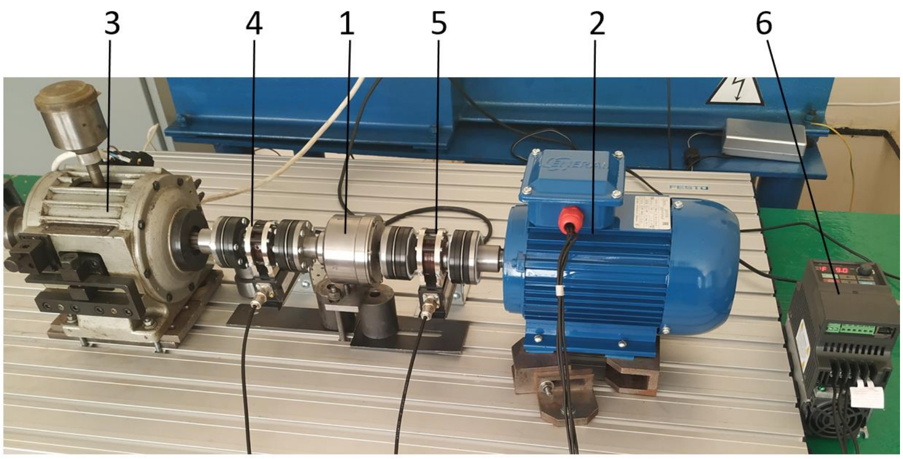

Figure 1. Test rig arrangement: 1 - speed reducer; 2 - asynchronous electric motor; 3 - powder brake; 4, 5 - torque sensor and rotational speed sensor; 6 - frequency converter.

Torque measurement is based on deformation of strain gauge elements and determination of the magnitude of unbalance of the strain gauge bridge circuit. Rotational speed measurement involves recording pulses by means of the infrared detector on the rotor, which are generated from the infrared emitter mounted on the stator.

A number of well-known methods were used in the design of the experiment [9]. Instantaneous efficiency was calculated as the ratio of the powers on the input and output shafts

$$\eta = \frac{T_2 \cdot n_2}{T_1 \cdot n_1}, \tag{1}$$

where T_1, T_2 are torques on the drive and driven shafts, respectively; n_1 and n_2 are rotational speeds of the drive and driven shafts, respectively.

The kinematic accuracy of SRT is characterized by the error of the actual instantaneous reduction ratio (its deviation from its nominal value). It was defined as the difference between the nominal $i_{12}^{(3)}$ and real values.

$$\Delta i = \left| i_{12}^{(3)} \right| - \left| \frac{n_1}{n_2} \right|. \tag{2}$$

To perform spectral analysis based on the discrete Fourier transform, the data were centered. For instantaneous efficiency, the centered values were determined according to the formula

$$F\eta_j = \eta_m - \frac{1}{N_r} \cdot \sum_{j=1}^{N_r} \eta_j . \tag{3}$$

where N_r is the number of measurements made during one revolution of the driven shaft, η_m is the mean value of the efficiency during a specified time interval.

Fourier coefficients were calculated according to the following formulas:

$$C_{1k} = \frac{2}{N_r} \cdot \sum_{j=1}^{N_r} F\eta_j \cdot \cos\left(\frac{2 \cdot \pi \cdot k \cdot j}{N_r}\right); \; C_{2k} = \frac{2}{N_r} \cdot \sum_{j=1}^{N_r} F\eta_j \cdot \sin\left(\frac{2 \cdot \pi \cdot k \cdot j}{N_r}\right), \tag{4}$$

where $j = 1 \ldots N_r$, $k = 1 \ldots N_r/2$, since the maximum number of spectral components cannot be greater than half of the measurements.

For each k-th harmonic, the amplitude was determined as follows

$$A_k = \sqrt{C_{1k}^2 + C_{2k}^2} . \tag{5}$$

Similar calculations were performed for the reduction ratio deviation Δi.

3. Test results and their analysis

The values of the mean efficiency at different torques on the driven shaft and different rotational speeds are given in table 1.

Table 1. Results of experimental study of SRT efficiency.

T_2, N·m	η_m	T_2, N·m	η_m	T_2, N·m	η_m	T_2, N·m	η_m	T_2, N·m	η_m
$n_1 = 500$ min^{-1}		$n_1 = 750$ min^{-1}		$n_1 = 1000$ min^{-1}		$n_1 = 1250$ min^{-1}		$n_1 = 1500$ min^{-1}	
3	0.689	3	0.678	3	0.745	3	0.687	2	0.669
5	0.708	5	0.713	5	0.79	6	0.726	5	0.732
8	0.725	8	0.735	8	0.8	8	0.741	10	0.749
12	0.724	12	0.735	10	0.81	10	0.744	12	0.676
-	-	-	-	12	0.775	-	-	-	-

Note: the table shows the mean values of rotational speeds n_1 and torques T_2

Figure 2 shows the results of studies with addition of fifth-order polynomial trendlines.

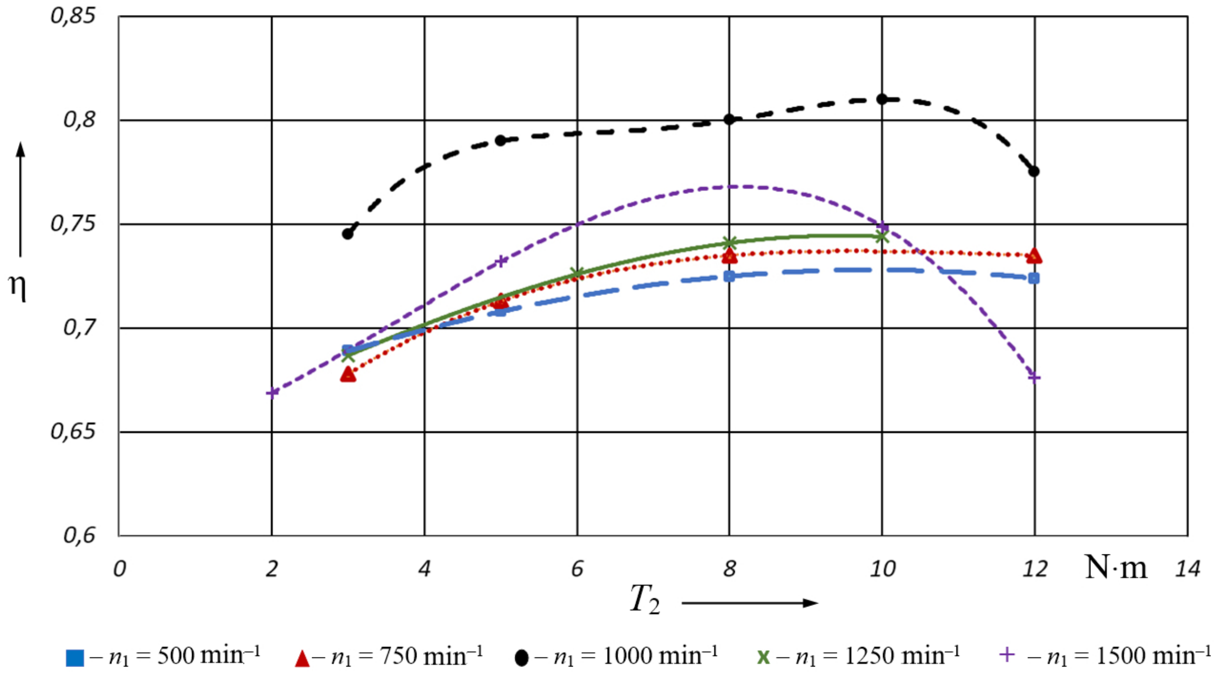

Figure 2. Graphs of SRT efficiency change

As the load increases, the efficiency of the transmission increases as well reaching a certain maximum. Then a decrease is observed, which indicates the existence of optimal values of the transmitted torque according to the criterion of maximum efficiency. Besides, there is an optimal rotational speed; a decrease or increase in its values leads to higher power losses. The graph in figure 3 shows the change in the instantaneous efficiency during one revolution of the driven shaft for T_2 = 10 N·m and n_1 = 1000 min^{-1}.

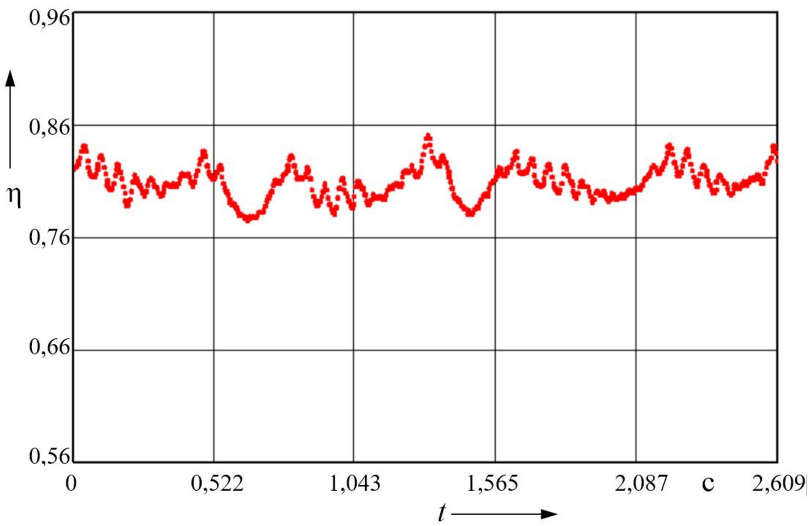

Figure 3. Measurements characterizing change in instantaneous SRT efficiency.

When the geometric parameters of SRT, the reduced coefficient of friction between the rollers and grooves f = 0.02 and the coefficient of friction in the bearings of the pinion f_b = 0.003 were substituted into the theoretically obtained SRT model, developed to determine the mean efficiency [10], the calculated efficiency was η = 0.762, which corresponds to the values obtained during the experiments.

However, the efficiency in the theoretical model does not depend on the load and rotational speeds of the shafts. The coefficient f is reduced and takes into account sliding and rolling.

From the spectrum in figure 4 we can see that the sixth harmonic has the highest amplitude, which corresponds to half the number of rollers in the inner row ($n_{s2} = 12$). Thus, the constancy of the efficiency of the transmission under study is affected by uneven spacing between the rollers in the inner row. The forty-first harmonic is an indication of the influence of inaccuracies in manufacture of the drive shaft with the pinion on the eccentric and mounting errors.

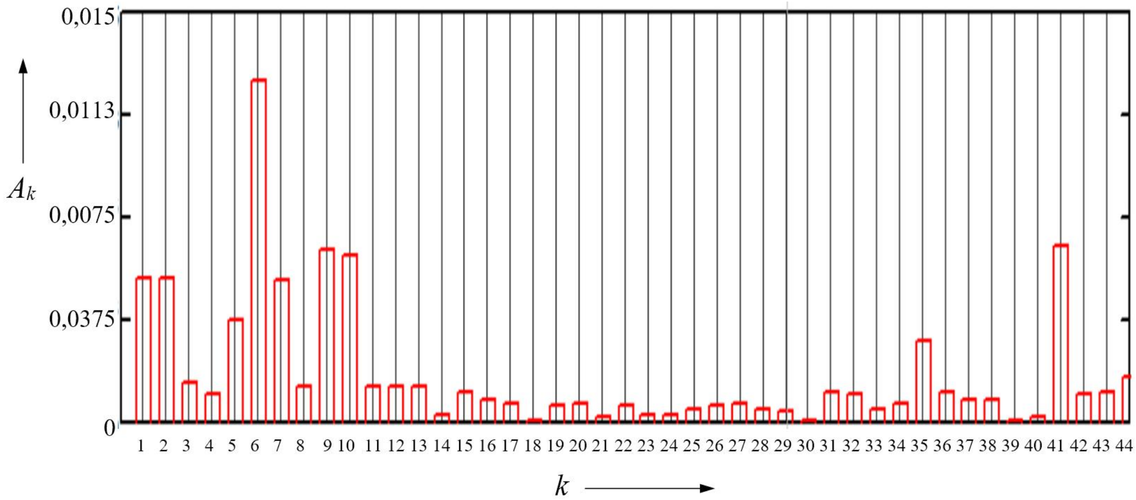

Figure 4. Data spectrum of instantaneous efficiency measurement for SRT experimental model.

The kinematic error (constancy of the reduction ratio) is most affected by the low-frequency components of the spectrum, which indicates the presence of errors in the manufacture of the driven shaft and driven cam and their incorrect mounting (figure 5).

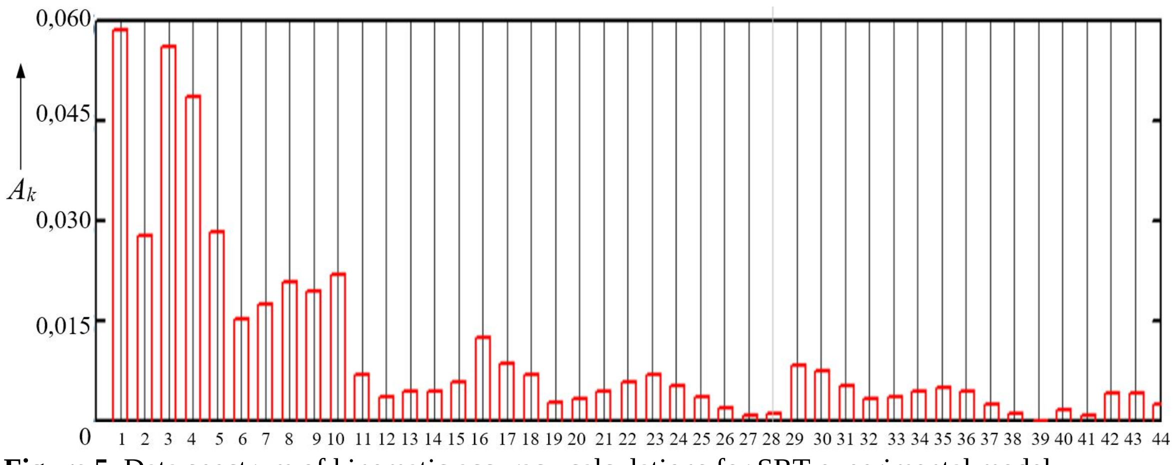

Figure 5. Data spectrum of kinematic accuracy calculations for SRT experimental model.

The error in the instantaneous reduction ratio can be considered insignificant, since its maximum values do not exceed 0.14% of the nominal value, while the instantaneous efficiency deviations from the mean values are within the range of 1.6 ... 1.8%.

4. Conclusions

The results of tests of experimental models of speed reducers and motor-reducers with SRT: theoretical calculations for estimating the mean efficiency have been confirmed, a mean efficiency of

0.7 ... 0.8 has been achieved with a reduction ratio of 44, which corresponds to the efficiency of worm gears with similar reduction ratios. The optimal rotational speeds of the shafts and the transmitted torque have been determined according to the criterion of minimum power losses in the engagement.

The results of the experimental data processing have demonstrated that the constancy of the efficiency of the transmission under study is most affected by uneven spacing between the rollers of the inner row as well as inaccuracies in the manufacture of the drive shaft and mounting errors. The kinematic error (the reduction ratio stability) of the experimental model of the transmission is mainly influenced by the error in the manufacture of the driven shaft and its incorrect mounting.

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