Increasing operation capacity for spherical bearing of indexing spatial mechanism under load

N V Zakharenkov¹, V E Konovalov¹, I N Kvasov¹ and Sh M Bigushev²
¹Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
²Gazpromneft-Yamal, 8b, 50-let Oktyabrya St., Tyumen 625000, Russia

Abstract. Indexing rotary mechanism is widely used in automatic machines. There are studies of such mechanism kinematics showing its effectiveness. The undertaken strength studies demonstrate the ability of the mechanism to operate under specified loads. Actual tests performed on prototypes exposed inoperativeness of the spherical bearing, namely jamming, under the load. The current work analyzes the failure of the spherical bearing. Factors affecting the jamming are determined as well. Such factors are forces at engagement and the friction forces at spherical surfaces contact. Structural provisions are proposed and considered to solve the issue of jamming and provide the mechanism normal operation.

Key words: rotary mechanism, gear mechanism, intermittent motion, orthogonal mechanism

1. Introduction

The paper considers a spherical bearing unit of an indexing spatial mechanism based on a bevel gear. The movement of the output member is indexing during constant movement of the input member. Such spatial mechanism structures are used, for instance, in advertising installations [1] and other application areas [2, 3]. The relevance of considering the challenges connected with improving advertising installations mechanism is caused by its wide spread [4, 5, 6, 7]. Study subject (Fig. 1) includes input and output members, as well as spherical bearing, to provide their mutual operation.

The research of indexing gear mechanism elements kinematics in rotating device drive unit [8] demonstrated its efficiency. The research of the strength issues regarding the mechanism showed the applicability of the chosen materials under the given loads. Field tests performed on the actual mechanism displayed a satisfactory operation of the kinematic pairs similar to the computer model [9]. However, at the torque transfer and forces emergence at engagement, the full-scale mechanism specimen operation was disrupted (complete shutdown with safety device triggering occurred) or it was accompanied by significant fluctuations and the movement of the links became erratic. The higher the loads imposed on the mechanism links were, the larger effects became. Visual observation of the study subject exposed the nature of the forces preventing the normal operation of the mechanism under load. However, since the bevel gear based spatial mechanism is complex in terms of kinematics, numerical simulation in SolidWorks environment was chosen for research. Examining similar models in the computer environment provides comprehensive information on the study subject [10].
The work is aimed at solving the issue of the indexing mechanism jamming under the load, as well as developing means to improve the performance of the spherical bearing under actual loads arising during operation.

2. Problem statement
Field tests performed on prototypes exposed inoperativeness of the spherical bearing, namely jamming, under the load. Therefore, the following objectives of the present research can be formulated:

- to analyze the reasons for the mechanism failure on a computer model;
- to determine the factors affecting or resulting in the normal operation failure;
- to search for a constructive solution eliminating the drawback of the existing design.

To calculate the loads, we applied the computer model that allowed us to obtain the system behaviour approximate evaluation by performing computational experiments [9]. Moreover, it is also necessary to define missing initial data used in calculations and required for future model research.

The input data are taken from the mechanism research [8] and summarized in table 1. Force distribution at engagement is shown in Fig. 2.

| Properties                                      | Value   |
|-------------------------------------------------|---------|
| Axial force acting at engagement $F_a$, N       | 200.5   |
| Radial force acting at engagement $F_r$, N       | 200.5   |
| Input/output member rotation frequency $\omega$, rad/s | 1.256   |

3. Theory

1. Analysis of the mechanism elements interaction
The interaction analysis can be performed on the stress values arising at the contact surfaces or on the values of the relative links displacements [10]. Information about the mechanism elements movement visualizes the interaction of the links during operation.
Bearing unit of the mechanism is a spherical bearing with a center pin, and it represents a higher 
kinematic pair of the 4th class with form constraint. Since it is a friction pair, the friction occurs at the 
contact line of the center pin and the sphere groove surface (the surface contact 2 in Fig. 2) as well as 
on the spherical surfaces 3.
Let us select idle and working strokes.
During idle stroke the driving disk rotates and no teeth engagement occurs. The output member 
securing in the current position is ensured by the surface contact at point 1. The sliding with no stress 
is registered on this surface. There is also no friction on surfaces 2 and 3. During operation on idle 
stroke, no forces from the mechanism elements interaction arise. The presence of the forces can be 
only due to the stress state resulting from the assembly.

![Figure 2. Force distribution acting at engagement and the friction surface: 1 - plane on plane; 2 - cylinder on plane; 3 - sphere on sphere.](image)

During working stroke, at teeth engagement and before sliding surfaces contact at point 1, the force 
from the driving disk transfers to the output member. During the interaction of the teeth surfaces, the 
forces acting in engagement arise, i.e. circumferential, axial and radial ones. At the same time contact 
pressure arises on the surfaces of the spherical bearing. The cylindrical surface of the center pin rolls 
over the plane and it can be assumed that there is no sliding. The right (in the figure) hemisphere slides 
along the concave spherical surface. It follows that the most dangerous sliding friction is that of 
spherical surfaces under load resulting in shape deviation of the right hemisphere caused by the wear.

2. **Optimal design of a spherical bearing**
Spherical bearing is the means for axial securing of the driving disk on the shaft. No other ways of 
securing are provided. As noted, this leads to significant forces on the friction surfaces. There are 
other design options possible in which one can avoid the wear of the spherical surface. For instance, 
one can provide an axial securing of the driving disk on the shaft with a pin. 
Improved efficiency can be achieved by eliminating the surfaces for increased sliding friction. The 
optimal variant to completely eliminate the sliding of the spherical surfaces [14] in working stroke can 
be to modify the hemisphere structure by creating a flattened spot as shown in Fig. 3.
4. Experimental results

Fig. 4 demonstrates the mechanism cutaway with the plane parallel to the center pin axis for two design variants of the spherical bearing: with and without modification. At the contact of spherical surfaces, force $F_s$ arises, that acts in the plane of force $F_p$ effect.

The diagrams shown in Fig. 5 and Fig. 6 demonstrate the changes in force values over time. The time scale is shown in the range 0.5…2.5 s, i.e. on working stroke.

- **Figure 3.** Flatted driving disk.

- **Figure 4.** The diagram of force distribution on working stroke on the spherical bearing: without modification (left), with flattened spot (right).

- **Figure 5.** Force at the contact of the center pin and the sphere groove surface: 1 - original model, 2 - improved flatted model.
5. Results discussion

Let us consider the results of modeling and the diagram of forces distribution (Fig. 4) for forces arising at working stroke. The displacement of the parts within the backlashes required by the design is clearly visible. In this case, the forces emerge on the contacting surfaces of the teeth (the normal force acting at the engagement $F_n$) [11], spherical surfaces $F_s$ and the contact surface of the center pin and the sphere $F_p$ groove. With such forces distribution, it is evident that the working surfaces of the spherical bearing are those where forces $F_s$ and $F_p$ appear. If force $F_s$ is projected on the axis parallel to that of force $F_p$ action, the reaction of the forces is clearly seen.

Therefore, due to the axial force acting at engagement, the driving disk displaces and the load is created on one hemisphere. On the other hand, the opposing force arises from the center pin, and this force acts on the other hemisphere. This phenomenon is similar to brake shoes operation. Left (in the figure) hemisphere and the center pin act as shoes. To avoid such interaction in the existing design is impossible due to constant form constraint.

Spherical bearing surface allows the load on the engagement to be lessened. However, to increase the mechanism lifespan, force closure should be eliminated on the sliding surface by modifying the shape. Otherwise the lifespan of these materials will be short as shown in work [14].

To analyze the diagrams (Fig. 5), the mean value for the forces at the contact of the center pin and the groove is more than 4% at sphere modification, but absolute values go beyond by 27%. As clearly

Figure 6. Normal force at teeth engagement: 1 – original model, 2 – improved flatted model.

Figure 7 shows the displacement of the driving disk under the axial forces, acting at engagement along the shaft axis for two variants of spherical bearing.

Figure 7. Displacement of the driving disk under the axial forces: initial position (left); not flatted spherical bearing (centre); flatted spherical bearing (right).
seen from the diagrams, the force increases at each subsequent tooth engaging on the driving disk without the sphere modification. The diagrams for modified sphere demonstrate less pronounced maximums, indicating a smoother mechanism operation. Similarly, it is seen from the diagrams (Fig. 6), that the teeth engage more smoothly without the flattened spot.

The comparison of the displacement value due to Fig. 7 shows, that the additional flattened spot has no effect on the driving disk displacement.

6. Conclusions
As a result of the work carried out:
- the question was solved as regards eliminating the indexing mechanism jamming under the load;
- the structure was developed improving normal operation of the spherical bearing under the existing loads arising during operation.

The undertaken analysis of the mechanism elements interaction due to computer model justifies the phenomenon of the mechanism jamming occurring in field tests. Factors affecting the normal operation is the interaction pattern for the surfaces of the sphere and the center pin under the forces at engagement similar to the brake mechanism.

The constructive solution eliminating the drawback of the existing design was found. The difference in two designs operation can be explained as less smooth operation of the mechanism with the modified bearing.

The further research can be aimed at considering the synthesis in the indexing mechanisms based on the bevel gear [15] with due regard for the operational peculiarities of the spherical bearing under the load.

References

[1] Ju V Buchakov, V P Dobrovolskij and A A Kulakov 2004 Experimental study of the disc-sprocket rotation mechanism performance of the advertising installation Dynamics Proc. Int. Conf. (Omsk: Omsk State Technical University) 1 428-32
[2] Ji S, Zhao J and Zhang Y 2015 An application of geodesics to the calculation of the rib-thickness of globoidal cam mechanisms Mechanism and Machine Theory 87 163-76
[3] A M Goanta and P Dumitrache 2017 IOP Conf. Ser.: Mater. Sci. Eng. 227 012049
[4] Advertising installation. Patent Russia 18792, IPC G09F 11/02 No. 2001108114/20, 30.01.2001, 2001
[5] T Guilan, F Haibo and Z Weiyi 1999 A new method of torque compensation for high speed indexing cam mechanisms ASME Journal of Mechanical Design 121 319-23
[6] H Zhaoa, Y Caob and P Guoc 2011 Dynamics Simulation of Parallel Indexing Cam Mechanism Based on Rigid-flexible Coupled Modelling Advanced Materials Research 156-157 172-76
[7] J F Hsieh 2014 Design and analysis of indexing cam mechanism with parallel axes Mech. Mach. Theory 81 155–65
[8] N V Zakharenkov and I N Kvasov 2018 J. Phys.: Conf. Ser. 1050 012100
[9] F Xu, N Nu and W He 2009 Modeling and Simulation of Globoidal Indexing Cam Mechanism Based on CATIA and ADAMS Journal of Mechanical Transmission 33 42-3
[10] R Cioar 2016 IOP Conf. Ser.: Mater. Sci. Eng. 161 012032
[11] Li Cheng et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 274 012103
[12] F Zheng, L Hua, X Han, B Li and D Chen 2016 Synthesis of Indexing Mechanisms with Non-circular Gears and Machine Theory 105 108-28
[13] L Li, X Feng, Z Zhang, X Han and Y Song 2010 3D Modeling and Simulation of a New Type of Globoidal Indexing Cam Mechanism. Applied Mechanics and Materials 26-28 931-5
[14] N V Zakharenkov and I N Kvasov 2018 J. Phys.: Conf. Ser. 998 012042
[15] I Talpasanu and P A Simionescu 2012 Kinematic Analysis of Epicyclic Bevel Gear Trains With Matroid Method Journal of Mechanical Design 134 114501