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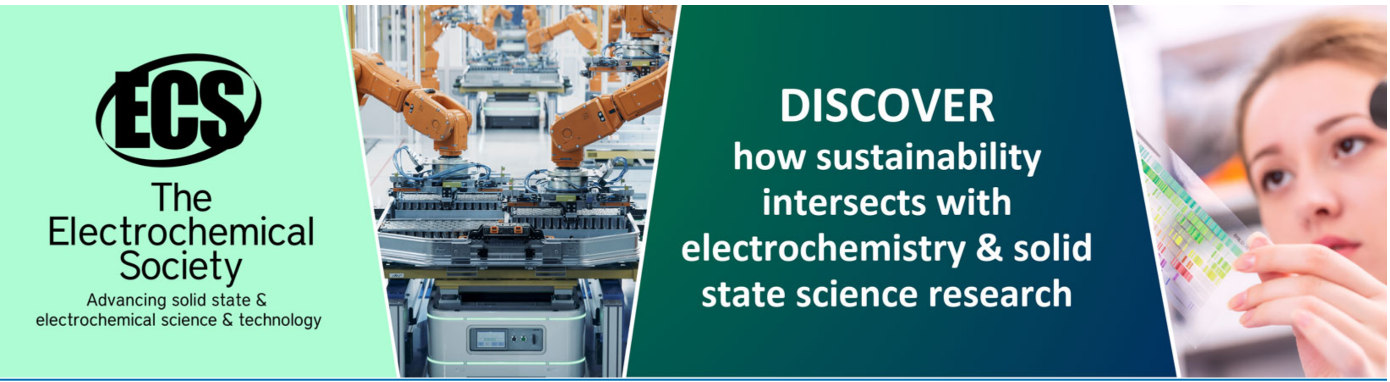

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Analysis of axial forces in harmonic drives of mining machines and heavy industrial equipment

V N Strelnikov[1] and M G Sukov[2]

[1]Belgorod State Technological University, 46, Kostyukova Street, Belgorod, 308012, Russia
[2] "Novokramatorsky Mashinostroitelny Zavod" Private Joint Stock Company, 5, Ordzhonikidze Street, Kramatorsk, Donetsk region, Ukraine

E-mail: viktor.strelnickov2017@yandex.ru

Abstract. Special features of arising axial forces in heavy-duty harmonic gear drives with the disk wave generator are described. As a result of research performed, it is found that kinematic pairs formed by the wave generator disks and the flexspline serve as a source of axial forces in heavy-duty harmonic gear drives. The disclosure of physics of the effects taking place in the elastic kinematic pairs: disk – flexspline, determination of nature of axial forces acting in the area of the wave generator under load, allows uprating of the performance data, lifting of load-carrying capacity restrictions and providing full development of heavy-duty harmonic gear drives. The force analysis of the results of the experimental research of axial forces in the heavy-duty harmonic gear drives with the disk wave generator, arising in kinematic pairs: disk – flexspline - has been carried out. Axial forces were measured employing the method of strain gauging of the flexsplines of the heavy-duty waveform gear reduction units tested under the laboratory and production-line conditions of heavy engineering, with the adjustable load conditions. Functional connection of axial forces values with the harmonic gear drives design features has been established, depending on the external loads.

1. Introduction

The main segment of the harmonic gear drive calling for special attention from the point of view of the loading capacity and service life is the flexspline that is permanently strained by the wave generator. Considering significant influence of such strains on the force processes occurring in the harmonic gear drive with the disk wave generator, we shall make assessment of the axial forces arising in the heavy-duty harmonic gear drives. The interaction of the wave generator and the flexspline is described in the papers [1, 2].

The torque is formed by the wave generator disks at the section of the flexible gear ring and transmitted by tangential forces distributed along the shell edge non-uniformly in consequence of the non-uniform strain of the gear ring. The flexspline transforms the wave generator rotation into the wave motion of the flexible gear ring, the rotational component of which is taken off by the shell and transferred through the splines to the driven shaft. The shell features the external load-free part of the flexspline that transmits the torque through the spline joint to the driven shaft. Strain capacity of the shell smooths the effect of peak loads when transmitting the torque, and equalizes distribution of forces in kinematic pairs [3, 4].

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2. Statement of the problem

When transmitting high torques, low stiffness of the flexspline determines considerable in value strains, approximating it to a certain shape of helicoidal tapered surface [5]. The asymmetrical distribution of normal load on the wave generator disks surfaces deflects them relative to the surfaces of motion through an angle γ. At running-in the disks with the misaligned axes relative to the axis of the strained flexspline over its internal surface the disks are "screwed" into the flexspline, while moving the wave generator along the axis by the value of the axial end clearance, taking up of which is accompanied by the axial load impact on the support bearing [6].

The present paper is aimed at determining a dependence of the axial forces arising in the harmonic gear drive with the disk wave generator on the used materials of the friction pairs and the transmitted torque.

3. Materials and methods

The research of axial forces arising in the heavy-duty harmonic gear drives with the disk wave generator was conducted experimentally, employing the method of strain gauging the flexible spline shell. Vz-1120A waveform gear reduction unit of MGR5500×7500 ore-pulverizing mill relining drive and Vz-1120B waveform gear reduction unit of MP–600AC mobile mixer tilting drive were used as a subject of research. The experimental research was carried out on the universal test stand, with the open force loop, shown in Figure 1. The stand included the following items: thyristor unit, powder brake, multiplying gear, two electric motors with tachometer generators and the reduction unit under testing. Loading torque M_2 on the output shaft of the reduction unit under testing was provided by TEP 4500-U1 powder brake through the multiplying gear with gear ratio U_{M} = 0,03322.

Axial forces arise in kinematic pairs formed by the disks of the wave generator with the flexspline. The wave generator design does not provide rigorous parallelism of the disks axes with the common axis of the harmonic drive. Misalignment of axes of the wave generator disks forms the imitation of the friction screw pair with the fine pitch of the screw: generator – flexspline. Rotation of the drive shaft initiates helical motions of the generator which is «screwed» into the flexspline with axial force P, proportional to loading torque M_2.

Stand tests of Vz-1120A waveform gear reduction unit of MGR 5500×7500 ore-pulverizing mill have demonstrated that during operation of the reduction unit under load fatigue failure of M16 bolts fixing axial displacement of the flexspline takes place. Bronze journal of the wave generator axial motion restraining has also failed. Causes of axial forces development in the harmonic drive were not clear that generated a need for the present research [7].

4. Results and discussion

Axial forces arising in the heavy-duty harmonic gear drives with the disk wave generators were determined by strain gauging of the flexspline shell at different loading modes of the harmonic drives operation and summarized in table 1. For friction kinematic pairs comprising the wave generator disks and the flexspline, different materials were used for manufacturing ring spacers installed between the disks and the flexspline i.e., steel and bronze. Following the results of the flexspline shell strain gauging, the flexspline axial force-vs-loading torque curves for the waveform reduction gear units of MP–600AC mobile mixer tilting drive and relining drive of MGR 5500×7500 ore-pulverizing mill were constructed, Figure 2.

The axial forces initiated by the helical motion of the wave generator within the axial end clearances of the waveform reduction gear unit are taken by the flexspline. In the serial waveform reduction gear units axial forces are low and practically do not affect their operation. Depending on the design features of the heavy-duty waveform reduction gear unitaxial forces can reach sufficiently high values, whereby causing failure of the parts and units restricting the flexspline and the wave generator movement in the mutually antithetic axial directions.

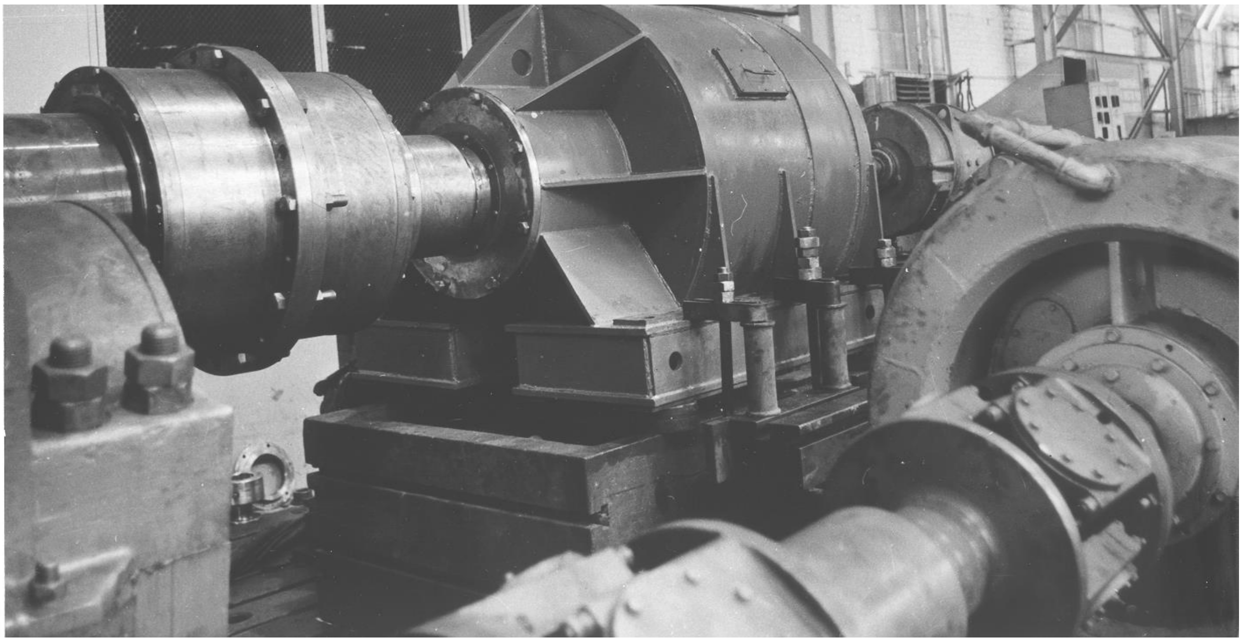

Figure 1. Ore-pulverizing mill harmonic gear drive stand tests

Table 1. Flexspline axial force $P{\cdot}10^{3}$ H-vs-loading torque $M_2{\cdot}10^{5}$ Nm curve on the output shaft of the harmonic gear drive depend on wave generator disks different angle position

Mobile mixer MP–600AC turning harmonic gear drive						
Loading torque M2 ·105 Nm		1.0	2.0	3.0	4.0	5.0
Disks angle γ, degree	Ring spacer material	Values of axial force on flexspline, P·103H				
1.5	Bronze	0.33	1.89	3.78	5.94	7.43
	Steel	1.21	4.18	7.60	9.54	11.21
3.0	Bronze	0.50	2.36	4.54	6.66	8.20
	Steel	1.43	4.67	8.38	10.26	11.83
4.5	Bronze	0.66	2.80	5.30	7.38	8.93
	Steel	1.65	5.10	9.16	10.98	12.46
6.0	Bronze	0.82	3.26	6.06	8.10	9.71
	Steel	1.87	5.58	9.94	11.70	13.11
7.5	Bronze	0.98	3.71	6.82	8.83	10.51
	Steel	2.09	6.07	10.72	12.43	13.69
Ore-pulverizing mill MGR 5500×7500 relining harmonic gear drive						
1.5	Bronze	0.41	2.12	4.16	6.30	7.86
	Steel	1.32	4.41	7.99	9.90	11.56
3.0	Bronze	0.58	2.59	4.92	7.03	8.60
	Steel	1.54	4.86	8.77	10.62	12.14
4.5	Bronze	0.74	3.00	5.68	7.74	9.36
	Steel	1.76	5.34	9.55	11.35	12.77
6.0	Bronze	0.90	3.48	6.44	8.46	10.17
	Steel	1.98	5.82	10.33	12.06	13.40
7.5	Bronze	1.10	3.95	7.21	9.18	10.83
	Steel	2.21	6.33	11.12	12.78	14.00

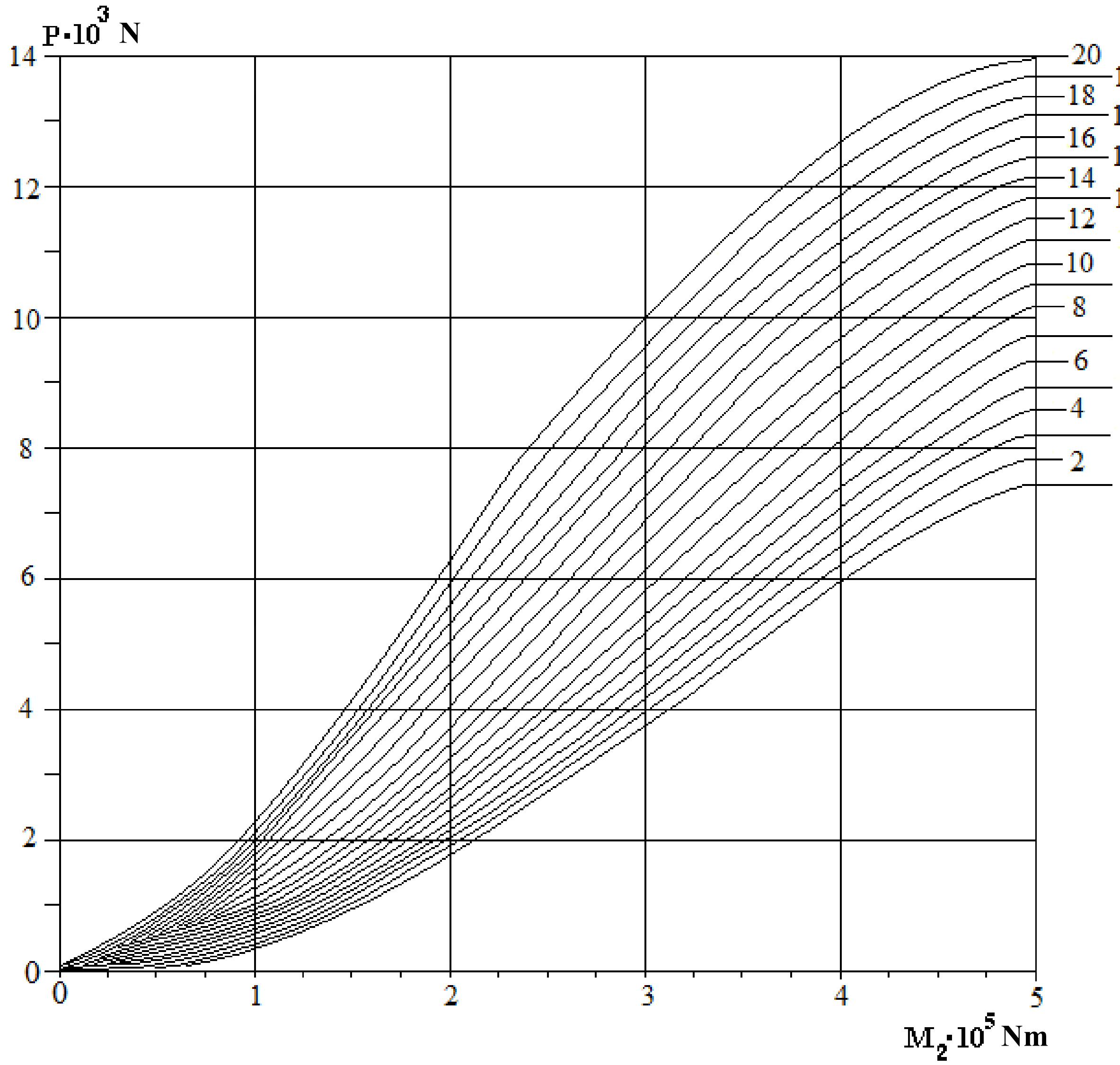

Figure 2. Curve of axial force ***P*** acting on the flexible gear against loading torque M_2 of mixer tilting drive: 1, 3, 5, 7, 9 - with bronze ring spacer; 11, 13, 15, 17, 19 – with steel ring spacer; mill drive: 2, 4, 6, 8, 10 – with bronze ring spacer; 12, 14, 16, 18, 20 – with steel ring spacer.

As the research has shown, the axial force on the flexspline is some function of loading torque M_2. It is monodirectional - always stretching and does not depend on the direction of the wave generator rotation. The excitation of axial forces in the harmonic gear drive is connected with the flexspline strain and method of the wave generator installation: either «floating» or in bearing supports as well as wave generator disks support design that influences their axes misalignment with the harmonic gear drive axis parallelism.

With the loading torque $M_2 = 10^5$ Nm, the axial stretching force on the flexspline of the mixer reduction gear unit with the bronze ring spacer and disks angle $\gamma = 1.5^\circ$ makes $P_{k_б} = 0.33 \cdot 10^3$ N; and the same with the steel one is $P_{k_c} = 1.21 \cdot 10^3$ N. With the same loading $M_2 = 10^5$ Nm and disks angle increasing to $\gamma = 7.5^\circ$ the axial force on the flexspline with the bronze ring spacer makes $P_{k_б} = 0.98 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 2.09 \cdot 10^3$ N.

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With the same loading torque $M_2 = 10^5$ Nm, the axial stretching force on the flexspline of the mill harmonic gear drive with the bronze ring spacer and disks angle $\gamma = 1.5^\circ$ makes $P_{k_б} = 0.41 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 1.32 \cdot 10^3$ N. Keeping the loading $M_2 = 10^5$ Nm and disks angle increasing to $\gamma = 7.5^\circ$ the axial force on the flexspline with the bronze ring spacer makes $P_{k_б} = 1.1 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 2.22 \cdot 10^3$ N.

With the loading torque M2 = $2 \cdot 10^5$ Nm and disks angle $\gamma = 1.5^\circ$, the axial stretching force on the flexspline of the mixer gear unit with the bronze ring spacer makes $P_{k_б} = 1.89 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 4.18 \cdot 10^3$ N. With the disks angle increasing to $\gamma = 7.5^\circ$, the axial force on the flexspline with the bronze ring spacer for the mixer gear unit makes $P_{м_б} = 3.71 \cdot 10^3$ N; and with the steel one is $P_{м_c} = 6.06 \cdot 10^3$ N.

With the same loading torque $M_2 = 2 \cdot 10^5$ Nm and disks angle $\gamma = 1.5^\circ$, the axial stretching force on the flexspline of the mill gear unit with the bronze ring spacer makes $P_{k_б} = 2.12 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 4.41 \cdot 10^3$ N. The same loading torque and with the disks angle increasing to $\gamma = 7.5^\circ$, the axial force on the flexspline with the bronze ring spacer for the mill gear unit makes $P_{м_б} = 3.95 \cdot 10^3$ N; and with the steel one is $P_{м_c} = 6.33 \cdot 10^3$ N.

Load increasing leads to harmonic drive axial forces increasing. With the loading torqu $M_2 = 5 \cdot 10^5$ Nm and disks angle $\gamma = 1.5^\circ$, the axial stretching force on the flexspline of the mixer gear unit with the bronze ring spacer makes $P_{k_б} = 7.43 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 11.21 \cdot 10^3$ N. With the disks angle increasing to $\gamma = 7.5^\circ$, the axial force on the flexspline with the bronze ring spacer for the mixer gear unit makes $P_{м_б} = 10.51 \cdot 10^3$ N; and with the steel one is $P_{м_c} = 13.69 \cdot 10^3$ N.

With the loading torque $M_2 = 5 \cdot 10^5$ Nm and disks angle $\gamma = 1.5^\circ$, the axial stretching force on the flexspline of the mill gear unit with the bronze ring spacer makes $P_{k_б} = 7.86 \cdot 10^3$ N; and with the steel one is $P_{k_c} = 11.56 \cdot 10^3$ N. The same loading torque and with the disks angle increasing to $\gamma = 7.5^\circ$, the axial force on the flexspline with the bronze ring spacer for the mill gear unit makes $P_{м_б} = 10.83 \cdot 10^3$ N; and with the steel one is $P_{м_c} = 14.00 \cdot 10^3$ N.

In the harmonic gear of MGR 5500×7500 ore-pulverizing mill drive the axial forces are higher than the same in the waveform reduction gear unit of MP – 600AC mobile mixer tilting drive. For loading torques $M_2 = 10^5 \div 5 \cdot 10^5$ Nm, disks angles $\gamma = 1.5 \div 7.5^\circ$ and bronze ring spacer the axial force on the flexspline of the ore-pulverizing mill exceeds similar force of the mobile mixer reduction gear unit by $5 \div 6$ %. In case of steel ring spacer, the axial force on the flexspline of the ore-pulverizing mill exceeds similar force of the mobile mixer reduction gear unit by $3 \div 4$ %. Higher axial forces on the flexspline of the ore-pulverizing mill reduction gear unit as compared with the same of the mobile mixer tilting drive reduction gear unit are conditioned by the relationship of the geometrical dimensions because of different gear ratios. With the same loading torques M_2 on the reduction gear units under consideration, power transferred by the mill reduction gear unit is by 28% higher than the same transferred by the mixer reduction gear unit.

5. Conclusion

The results obtained make it possible to refine the force analysis and strength calculation of the waveform reduction gear units with the disk wave generator and to work out the following recommendations on reducing axial forces in the heavy-duty harmonic gear drives built into power drives of the heavy-duty machines:

- To eliminate «floating» installation of the wave generator and secure it in rigid supports;
- To supply forced lubrication to the zone of gearing and contact of disks with the flexspline, to eliminate "spinning" of the disks relative to the wave generator axis;
- To eliminate axial plays on the wave generator and on the flexspline;
- To install the bronze ring spacer between the disks and the flexspline;
- To provide lubricants with high antifriction properties

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