Teeth interference in harmonic drives intended for heavy engineering

V. N. Strelnikov¹, M. G. Sukov²

¹ Belgorod State Technological University 46, Kostyukova Str., Belgorod, 308012, Russia.
² Novokramatorsky Mashinostroitelnny Zavod Private Joint Stock Company, 5, Ordzhonikidze Str., Kramatorsk, Donetsk reg., Ukraine.
E-mail: viktor.strelnickov2017@yandex.ru

Abstract
Based on geometric studies and force analysis of a heavy harmonic gearing and through application of the elasticity theory methods, motions of the deformed gearing from the theoretically preset positioning have been ascertained. A fundamental design feature of the heavy harmonic drive consists in a disk wave generator which permits to provide additional deformations of the flexible gear due to incomplete contact between the disks and the flexible wheel. The scale factor along with the small tooth module between 1.5 and 2 mm of the wave-type reducers and heavy loads imposed on the flexible gear increase its deformations and intensify formation of interference between the teeth. The above circumstances drastically reduce load-carrying capacities of the harmonic drives and actually restrict them due to the carrying capacity of a flexible bearing. The results obtained provide both qualitative and quantitative characteristics of the teeth interference depending on the wave generator swivel angle \( \phi \) at various values of the transmitted torque between 0 and \( 5 \cdot 10^5 \) kNm.

1. Introduction
During designing and operation of large-size harmonic gear drives with an extensive contact zone, it is necessary to take into consideration a relative position of the teeth in engagement and especially at boundary points where several key parameters take on critical values. The deformation of the flexible gear exerts negative impact on the relative position of flexible and rigid gears, causing the teeth deflection from the preset conditions of their positioning that decreases main operational characteristics of the harmonic gear drive. Thus, energy losses and specific teeth loads in harmonic gear drive rise along with teeth wear-out and also the conditions for teeth interference, binding and slipping are created. The interaction of deformed flexible and rigid gear teeth is not governed by general theory of gear systems and has crucially different nature which requires individual consideration of this quite complex scientific challenge. This paper defines the correlations of the gaps in the most dangerous teeth engagement-disengagement zones and geometrical, power and design factors of the large-size harmonic gear drive.
2. Statement of the problem

Geometric, kinematic and force parameters of a gearing greatly influence the teeth wear-out, power losses and load-carrying capacity of the harmonic drive. Relative speeds of the teeth increase from the poles towards the periphery. In contrast to rigid gears, a tooth deference in internal gearing of the harmonic drive equals two, i.e., with the 40 to 55-percent concurrent contact between gear sets (depending on the torque being transmitted and on the wedging effect being available) the mentioned tooth difference induces high power losses, tooth interference and tooth jamming. Wave reducers of such leading companies as “HASEG”, “Harmonic Drive Systems”, “USM”, etc. are designed to transmit up to 30-kHm torques and equipped with the cam-type wave generator provided with the flexible ball bearing. Due to the contact all around the cam and the flexible gear, the effects of loads causing its deformation may be restricted and the tooth strength to interference increased. However, a general solution of the tooth interference task suitable for heavy harmonic drives has not been found [1, 2].

Deformations of the flexible wheel cause the tooth interference [3, 4]. To eliminate it, a gear rim width may be decreased, addendum modifications applied, teeth with wide valleys and, sometimes, a 30-degree basic rack used. In the wave reducers made at “NKMZ” PJSC, a disc wave generator is used to form a flexible gear in the contact area with its curvature being decreased along free sections. The tooth module between 1.5 and 2 mm, gear rings of 100 to 120 mm in width and heavy loads $M_2 = 5 \cdot 10^5$ Nm induce the tooth interference. At the points of the tooth engagement into and disengagement from mesh, interference of the 2nd rank teeth reaches its maximum values. The influence of a scale factor under heavy loads causes the tooth overshot- quite a new effect. Interference of the teeth in heavy harmonic drives is associated with the scale factor and may not be eliminated in a usual way. Solving such tasks entails development of the new designs based on theoretical and experimental studies, production experience and servicing of the heavy wave gear reducers.

3. Materials and methods

Tooth deformations are mainly measured with the strain gages, make it difficult to secure them on fine teeth of the harmonic drives. Therefore, a pair of parallel slots is made in the rigid gear while a pair of adjacent teeth is removed. The slots may be either through or blind ones across the gear width. Said slots are made on both faces of the gear rim so that its middle portion will remain intact. According to the researches, deep through slots may drastically reduce rigidity of the gear. Thus, as shown in the reported works, middle portions of the teeth are not removed.

Blind slots reduce rigidity of the selected tooth elements thus, distorting its strained and deformed condition and bringing noticeable errors into the force characteristics of a gearing. As to lessening of the gear rigidity, then, under experimental conditions, thickness of the rigid gear rim is not specified. Therefore, the statements made earlier may not be grounded. The available procedures do not consider the effect of the adopted model on the results of measurements thus it turns out to be impossible to determine deformation in the middle portion of a tooth. This distorts the nature of the force distribution in a gearing of the harmonic drive. Real evaluation of the load distribution between the teeth is required for determining the contact patch, minimizing the widths of gear rims and optimizing geometry of the gearing based on conditions of the tooth interference absence and maximum load-carrying capacity.

Optimization of the load-carrying element geometries is impossible without evaluation of their interaction character [5-7]. Study of interference, kinematic and force aspects of the gearing and parametric dependence of the axial forces on the effecting factors is of a paramount importance in terms of augmentation of the heavy harmonic drive load-carrying capacity.

The key scientific goals of the research are as follows:

- Determination of the tooth interference origin in a harmonic drive.
- Determination of the tooth interference size depending on the gearing parameters and applied loads for various phases of the tooth equipment.
- Elaboration of recommendations as to forming design parameters which exclude origin of the interference and the tooth overshot in heavy harmonic drives.
4. Discussion of results
Clearances at the places of the teeth engagement and disengagement constitute the main prerequisite to elimination of the tooth interference. Many works deal with the study of interference between the teeth. The results of some of such works were used during evaluation of clearances between the teeth in the wave reducers of the MP–600AC 600-ton Torpedo Car tilting drive and the MGR 5500×7500 160-cub.m, 200-ton capacity Ore Crusher relining drive.

In Fig. 1 negative clearances at the teeth tips of the flexible and rigid gears under load shift towards the side of the teeth disengagement. Under load \( M_2 = 5 \cdot 10^5 \text{Nm} \), interference of the flexible gear teeth tips along the front and rear faces of the flexible gear provided for Torpedo Car tilting drive reaches \( J_{aq1} \cong J_{aq2} = -0.2 \text{ mm} \). For the harmonic gearing of the Ore crusher lining drive, clearances at the teeth tips of the flexible gear along the front face \( J_{aq1} = -0.3 \text{ mm} \) while along the rear face \( J_{aq2} = -0.26 \text{ mm} \) under load \( M_2 = 5 \cdot 10^5 \text{Nm} \) (Fig. 2).

Figure 1. Clearances at teeth points along the front and rear faces of the MP–600AC Torpedo Car under load \( M_2 = 5 \cdot 10^5 \text{Nm} \): 1, 2 – flexible gear; 3 – rigid gear

In the harmonic drives of the MP–600AC Torpedo Car tilting drive and the MGR 5500×7500 Ore Crusher relining drive, clearances at the teeth tips of the flexible and rigid gears \( j_{aq} \) and \( j_{ab} \) slightly differ from each other in the absence of a load \( (M_2 = 0) \). In this case negative clearances are observed in the
neighborhood of the wave generator longer axis within 15° at the places of the teeth engagement and disengagement. Negative clearances are shifted towards the teeth disengagement side. Maximum values of interference between the teeth tip in unloaded harmonic drives of the MP–600AC Torpedo Car and MGR5500×75000 re Cruiser are comparable and make up 0.06 mm and 0.08 mm respectively.

Figure 2. Clearances at teeth points along the front and rear faces of the MGR 5500×7500 Ore crusher at load $M_2 = 5 \cdot 10^5$ Nm 1, 2 – flexible gear; 3 – rigid gear

Augmentation of interference along the rear face at the teeth engagement within $40^\circ \leq \phi \leq 60^\circ$ results from distortion of the flexible gear shape and position under load. Traces of the intensive tooth wear-out may be observed nearby gear faces. Such phenomenon is caused by deviation of the flexible gear teeth from straight line through the gear rim width relatively the teeth of a rigid gear under load and also by the taper-shaped deformation of the flexible gear. As a result, a clearance at the teeth tips of the flexible gear along its front and rear faces in case of the teeth engagement and disengagement will be of limiting values. The start of the tooth overshot may be caused by the condition under which absolute value of the negative clearance between the teeth tips at the engagement $|\Delta|\leq\text{exceeds the total thickness}$
of \( S_a^F \) of the flexible gear and \( S_a^R \) of the rigid gear along chords of their tips, \(|\Delta| > (S_a^F + S_a^R)\). Modification of the flexible gear teeth is illustrated in Figure 3.

**Figure 3.** Flexible gear of the MGR 5500x7500 Ore crusher wave reducer with modified teeth. Tooth thickness is lessened and teeth are made tapered through the height

5. Conclusion
Ranges and sizes of the teeth interference in loaded and unloaded engagements and conditions of the tooth overshoot in heavy harmonic gearings designed according to established practices and applied in metallurgical and ore and mining equipment made at “NKMZ” PJSC have been determined. It has been ascertained that interference reaches maximum values at the tooth tips under load, in the neighborhood of the flexible gear rim faces and at the teeth engagement/ disengagement points.

It has been found that the available procedures for analyzing and designing the heavy harmonic drives seem to be unsuitable. Wave reducers developed for heavy machines, designed according to well-known procedures and made at “NKMZ” PJSC usually stopped down even under minor loads and a part of the reducers turned out to be jammed after assembling. The analysis of heavy wave reducers has demonstrated the following:

- A scale factor is not represented in the available design procedures.
- Design and development works have been usually carried out according to the well-known recommendations that satisfy conditions of the small-sized harmonic drives.
- Design and functional features of the parts and assemblies of the heavy harmonic drives have not been taken into account.
- Wave reducers usually turned out to be jammed through interference of the second-rank teeth caused by the flexible gear deformations.
- Well-known procedures for elimination of interference in harmonic drives do not consider design features and scale factors upon designing and manufacture of the heavy wave reducers.

Based on the researches already conducted and with the aim of optimizing and increasing load-carrying capacities of the heavy harmonic drives in view, it is recommended to:

- reduce the contact patch up to 30…35 deg. on each side from the longer axis of the wave generator;
- accept the module \( m \) within \( 4 \leq m \leq 2 \, \text{mm} \) for transmission of \( 6 \times 10^5 \leq M_2 \leq 10^6 \, \text{Nm} \) torques since with module \( m \) values being lesser, insurmountable interference in a gearing may occur due to considerable deformations of the flexible gear resulting from the above load torques. In addition, by increasing module over 4 mm within the same load limits, negative effect of the scale factor will increase;
- eliminate interference areas in a gearing by special tooth modification both on the flexible and rigid gears based on theoretical and experimental procedures.

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