Discrete contact

Alexander Vladimirovich Titenok¹ and Igor Alexandrovich Titenok²

¹ Bryansk State Agrarian University, 5 Sovetskaya str., Apt.21, Kokino, Vygonichsyy District, 243365, Russian Federation
E-mail: titenok@bk.ru

² ABB ltd, 2-1 Medynskay str, Apt. 398, Moscow, 117546, Russian Federation
E-mail: elproekt-it@yandex.ru

Abstract. On the basis of personal inventions and well-known experimental research the authors proved the characteristic of lubricant filling in the form of microscopic rounds as an antiwear and antifriction additive agent to improve toothed gearing quality. Trying to solve existing technical and economic contradiction, they proposed principally new construction of fixed members with higher kinematic pairs, that notably increased wearability of fixed members working surfaces. The discrete contact is proved in the work, so that there is no need to apply special technology to make new gear wheels. Theoretical basis of storability of system balanced condition on fixed members with higher kinematic pairs is elaborated. The main characteristics for the estimation of quality factors of reciprocating motion fixed member are defined: motion trajectory of the surface plate; ratio of recentering force to vertical load, i.e. rollback angle \( tg \); angle between resultant of forces and its normal projection in the contact points, i.e. meshing angle. In static and dynamic bench tests of the fixed members estimated characteristics were proved.

Introduction

Coefficient of performance (COP) is a quantitative indicator of technical efficiency and its value for toothed gearing is the most important evaluative factor. Tooth shape stability during operation influences the quality of gearing work. In the involute tooth transmission the peripheral surface of the wheel tip and fillet is more inclined to aging, and the maximum normal contact voltage is in the pitch pole. An involute tooth takes normal aging shape [1], stable at first and then having negative indicators associated with gear accuracy shift. There is a technical and economic contradiction. From a theoretical position, we have a high gearing COP at the form of a higher pair of kinematic elements. In operation this factor varies, which is accompanied by many negative manifestations. The article discusses one of the alternative ways to resolve mentioned contradictions by changing the working environment in gearing [2, 3] with the introduction of the concept “Discrete contact” that changes the structure and shape in friction process.

Rational base

Wide range and diverse combination of loads, rolling and sliding speeds, working temperatures, a variety of materials and processing methods lead to different character of gear damage and destruction.
Existing classification of tooth damage comes to the following factors: destruction under flexion and impact stress, tooth chipping (pitting); seizure; mechanical wear; plastic deformation of the tooth working surface; chemical wear.

Among these types of damage, only the first is less connected with the nature of lubricant. All other damage represent different types of wear. They are associated with the nature of lubricant, and their characteristics should be considered in the process of choosing lubricants.

The founder of the theory of hydrodynamic lubrication N.P. Petrov in the work "Friction in machines and its impact on the lubricant gave a description of the fluid friction importance between surfaces machine parts. Its essence is that the gap between sliding surfaces must have a wedge form. Lubricant should fill the gap and continuously arrive in the required quantity. Speed in relation to the movement of one of the surfaces should be enough to create internal pressure in the oil layer is created due to lubricant wedging. Lubricant should completely separate contacting parts.

The theory of the oil wedge proposed by N.P. Petrov is still actual, and hydrodynamic lubricant is implemented in run-in gears. In the interaction of two contacting surfaces with solid wear particles between them the latter, due to the specific properties and certain geometry can be involved in rotational movement \[4\]. And fluid elements also have the similar rotation. It is connected with simple shift (twist) and is due to kinetic energy of the fluid particles considered as small volumes. In 1956 M. Reiner called this phenomenon \[5\] the “teapot effect”. Simple shift vortex is not just fluid “sticking”, but its pressure on it surface due to kinetic energy of vortex rotation. Fluid swirling contributes to the surface irregularities flow. In the erosion process rough surfaces bumps get the optimum form which is rounded.

Violation of the surface layer structure in the friction process leads to the formation of wear particles which are deformed in a specific way. Becoming spherical or cylindrical, these masses have rotational moving. The rotational movement mechanism is typical for fragments of destruction.

In the study of ball bearings using a scanning electronic microscope the tiny spherical particles were found infatigue cracks; similar particles were found on the ferrograph glass. We know about the phenomenon spontaneous rolling caused by sliding friction: in some modes there were microspheres that rolled grooves like bearing tracks. Coefficient of friction sharply diminished. In such cases, the geometric shape of rolling elements tends to ideal. The value of the mechanism of spontaneous rolling increases when the contact points become smaller and relative surface bearing capacity becomes higher due to the big factor of strength \[6, 7\].

It was established experimentally that if the size of wear particles (of any shape) does not exceed 5 microns, then they, having a larger developed surface, adsorb the products of oil oxidation, that can reduce the intensity of parts wearing. The particles probably intensify heat transfer between friction surfaces. Small particles serve as antiwear and anti-friction additives, preventing direct contact between sliding surfaces.

All this applies to particles less than 5 microns. Large particles are harmful. Spherical metallic particles appear in rolling and sliding systems as a result of different processes. The formation of spherical wear particles with wear resistant boride coatings on contact surfaces is explained by the aggregation of the smallest wear products and by the reflow of secondary structures consisting mainly of boron oxides and other compounds in the amorphous state.

The elementary composition of spherical wear particles showed that they contain of 47% carbon, 34% oxygen, 8.7% iron, 8.2% boron, 1.6% sulfur. Since the temperature of boron oxide melting is 450 C, we can suppose the appearance of spherical wear particles under more severe test conditions. It is characteristic that such relatively high temperatures occur only in the volumes of no more than a few micrometers.

A model in which spherical particles are secondary correspond to the experimental data. The particles obtained in the experiment do not exceed 5 microns, but the particle size can significantly vary depending on friction conditions and material properties (2.5 to 16 microns). It is assumed that spherical particle appear when the proportion between oscillation amplitudes and spherical
circumference particles is equal to 1 (according to different data this ratio ranges from 0.2 to 2.4). On practice spherical particles are very rare in tribosystems with unidirectional motion.

The quality level of gearing rises when the lubricant is supplied with spherical particles of not more than 5 microns [2, 3], that allows to realize the contact mechanism of adjacent surfaces of complex shape using rolling elements. In the process of gearing microspheres will move to the pitch point. This phenomenon provides the effect discovered by Schulz [1] for wheels with natural wear teeth.

The second positive effect of innovation is that the lubricant microspheres fill the depressions of asperities in the working surfaces of the teeth. Thus, the specific surface load is redistributed and contact voltage is reduced.

The technological aspect of innovation is the following: spherical microparticles can be produced by the method used in powder metallurgy: by spraying the melt in inert gases [8]. What should be the size of particles? Intensity of movement over the body surface and the wear of this surface from the pressure of particles depend on their forms [9, 10]. According to foreign studies [11, 12] after reaching a critical particle size metal wear almost does not depend on their size (particles ranging in size from 0 to 70 microns are analyzed). With changing the size of wear particles from 75 to 250 microns the wear rate of steel samples at the beginning gradually decreases and then when resizing particles from 250 to 500 microns remains unchanged. Maximum wear is observed at a particle size of about 40 micron or, in another similar study, at a particle size of 600 microns. D.N. Garkunov [13] cites data on the impact of small abrasive particles on wear in the case when the lubricant contains these particles. At different times and independently on each other such data was obtained by the researchers (Nikiforov O.A., Vinogradov G.V., Wenzel S.V. and Wenzel E.S., Barabash M.L., Korogodsky M.V., Bortnik G.I., Shpenkov G.P.).

The similar effect is possible on macro level.

The group of authors [14…18] worked up and analyzed a series of mechanisms with higher pair of kinematic elements for reciprocating motion of machine actuating device and diminishing of vibratory action influence on a person and environment using the example of grain combine cutter.

Vibratory action is classified according to the following criteria: the way of impact on a person – general and local; source of origination – transport (in machine movement), transport and technological (in combination of movement and technological process, e.g. in scything and thrashing with self-propelled combine, in tranch excavation etc.) and technological (in fixed machines, e.g. pump units); vibration frequency – underfrequency (less than 22.6 hz), midfrrequency (22.6-90 hz), radio frequency (more than 90 hz); spectrum type – narrow-band and broad-band; active time – constant and temporary; the latter is divided into modulate in time, dashed and impulsive.

Vibratory norms are defined for three directions normal to each other in orthogonal coordinate system. In general vibration measuring and estimation it’s necessary to remember that x-axis runs from a person’s back to his breast, y-axis – from the right shoulder to the left, z-axis – vertically along the body. In local vibration measurement it’s necessary to know that z-axis runs along the hand tool, and x and y-axes are perpendicular to z-axis.

There are separate norms for transport vibratory movement (category 1), transport and technological (category 2) and technological (category 3); besides the norms for the category 3 are divided into subcategories: 3a – for vibratory movement on permanent facilities working places; 3b – on working places in storage area, mechanical rooms without machines causing vibration; 3c – in rooms for intellectual workers.

In cases of vibration excess allowed for a person it should be decreased. Vibration influences a worker through such objects as machines, constructions and transport facilities with vibration source (electric motors, explosion engines, machine tool stations etc.). So, protective measures should embrace all the elements of the system “vibration source-object-person”.

If the object is under vibration of periodic forces, they should be diminished in vibration source. In this case balance quality of swiveling parts, working accuracy and surface condition of mating parts should be increased, interbalancing mechanisms should be applied, force that influences a shaking detail and rate speed should be decreased, machine rotors loads should be equally divided, work-cycle
time should be raised. There is an active method to stimulate vibration in the contrary direction with fundamental oscillations in the construction in order to effectively resist them. Such vibration damping is possible when there is only one fixed or dominant frequency and with strict regard to phase opposition. Besides, vibratory movement influences machine life cycle, especially when voltage is close to endurance strength. Then high level of vibration accelerates the limit number of cycles, and fatigue stress can appear in a machine too soon.

Thus, the task to elaborate the table balance is actual.

Here is specification for such a mechanism:

· Quantity of motion (mv) of equivalent mass of equilibrator and reaper machine cutter must be equal.
· Kinematic characteristics of equilibrator and reaper machine cutter must be ambidextral.
· Equilibrator drag force must not notably differ from force of rolling friction.

This specification can be realized with positive results of mechanism updating on the fixed members with higher kinematic pairs.

In this regard there are following tasks:

· To analyze the possibility of material system balanced condition rigidity on the fixed members with higher kinematic pairs.
· To elaborate fundamental constructive bearing project where sliding motion is replaced with rolling in order to notably diminish abrasive wear and power waste on friction.
· To define the main characteristics for the estimation of quality factors of reciprocating motion fixed member.
· To elaborate a device that guarantee stable work of a fixed member no matter how the friction angle changes in the sliding contact surfaces.
· To suggest the fixed member for equilibrator of inertial forces and reaper machine cutter weight.

Here are the following gradual results:

Summary 1:

· there is a constructive bearing project of reciprocating motion fixed members with higher kinematic pairs where sliding motion is replaced with external surfaces rolling on internal ones;
· there found the main characteristics for the estimation of fixed member quality factors: motion trajectory of the surface plate; ratio of recentering force to vertical load, i.e. rollback angle $\tan \theta$; angle between resultant of forces and its normal projection in the contact points, i.e. meshing angle;
· there got theoretical characteristics, and four special cases of influence of fixed member parameters to its characteristics; each special case can be used depending on fixed member application and its exploitation conditions.

Summary 2:

· amplitude of oscillation of a fixed member with higher kinematic pairs can be notably increased with the help of locking mechanisms that will take tangential forces, if meshing angle exceeds friction angle;
· in locking mechanisms installation there is small sliding motion, if $2 < R/r \leq 3$; if $1.5 \leq R/r < 2$,
· sliding motion notably increases approaching to 1.5;
· for the variant $R/r = 1.5$ angular amplitude must be limited to 20 deg.

The results of theoretical analysis let us formulate the conclusion: we suggest constructions of reciprocating motion fixed members with higher kinematic pairs and elaborated calculation procedure of the main geometric, kinematic and force parameters; spheres of possible using are proposed; general calculation procedure of contact and strength voltage is elaborated.

Summary 3:

· the results of restoring force theoretical characteristics are proved with the statistic experiments on the testing bench;
· either derived and experimental curves have nonlinear behavior of restoring force;
• in the experiment restoring force curve turned out to be lower than theoretical one because of friction forces in the elements of the system;
• while dynamic experiments of vibration on the testing bench we got oscillating amplitude changing curves of charge depending on frequency and amplitude of exciting force for two variants of nonlinear system;
• maximum oscillating amplitude of the system depends on amplitude of exciting force, at the same time in kinematic amplitudes 10 mm and 7 mm there happens “the reset” of the amplitudes in the superresonance zone, with the amplitude 4 mm it doesn’t reach “the reset” point because of notable friction in the system;
• the experiments let us reliably prove, that charge behavior on the fixed members with higher kinematic pairs with forced motion does not contradict the general oscillation theory of nonlinear systems;
• in the bench tests of the fixed member full-scale specimen the restoring force characteristics almost coincided with the design numbers.

Summary 4:
• if reaping machine cutter is not equilibrated, then in reciprocal motion the whole reaping machine vibrates;
• vibration amplitude depends on the ratio of natural frequency to forced frequency, and if this ratio is close to 1, the amplitude may theoretically increase infinitely;
• equilibrator stopping excludes vibration of reaping machine cutter.

Finally, the following points are proved:
• Theoretical basis of startability of system balanced condition on fixed members with higher kinematic pairs is elaborated.
• There proposed principally new construction of fixed members with higher kinematic pairs, in which sliding motion is replaced with rolling of buckled cylindric surfaces on concave surfaces, that notably increased wearability of fixed members working surfaces.
• The main characteristics for the estimation of quality factors of reciprocating motion fixed member are defined: motion trajectory of the surface plate; ratio of recentering force to vertical load, i.e. rollback angle $\tan$; angle between resultant of forces and its normal projection in the contact points, i.e. meshing angle.
• Fundamental project and analysis technique of tangential forces locking elements are elaborated. It is a device that guarantee stable work of a fixed member no matter how the friction angle changes.
• The elements of construction of the fixed members with higher kinematic pairs and strength calculation procedure are proposed.
• In static and dynamic bench tests of the fixed members estimated characteristics were proved.
• The construction of a fixed member with higher kinematic pairs for equilibrator of inertial forces and reaper machine cutter weight is elaborated.

Despite positive results of work, such fixed members are of limited utility because of its design features, so, the device was updated.

The fixed member of reciprocal motion with higher kinematic pairs having baseboard and surface plate with concave surfaces and put between them fixed members with convex surfaces on the flanks differs from the ones examined before in the fact that contact working surfaces of the baseboard, surface plate and fixed member are made with unevenness, that can be either teeth of any form, or convex-concave congruent form, or convex-concave tooth form (application for an invention N 2017142218/20(073019) from 04.12.2017). In this project we analyze the possibilities of “discrete contact” realization in toothed gearing of reciprocal motion.

In some technical spheres they use suspension tackings with bearing supports with higher kinematic pairs so that their wearing capacity is notably higher than that of sliding supports.
Suspension tackings with such bearing supports are positive-acting for more than 20 years. But these bearing supports are too big and heavy that’s why they are not so actively used in technics.

The proposed bearing support with higher kinematic pairs, that works in compression and has the advantages of a suspension tacking, is not so high and has several times less mass. Besides, as it became clear in the process of working on the project, its band of performance is much wider than that one of the suspension tacking.

V.V. Shultz [1] took into consideration the form of toothed gearing normal aging. In his opinion mathematical theory of moving matching joints wear-out should be based on experimental research of microscopic behavior of a wearable contact. During the research on gears teeth wear-out the rational theoretical teeth profile was found: wear-optimized convex-concave form, that is in fact the form of twice involute gear. A range of other interesting technical solutions were found taking account of natural aging form.

This toothed gear is called twice involute because the gear teeth have ordinary involute spirals, and the wheel teeth have concave spirals outlined in normal section on rack trochoid or its equidistant. It was technically proved that teeth surface form in energetic optimum is tolerant to wearing.

In fact this suggestion is a curved flank of wearable involute tooth fillet and point taken from the pitch point, i.e. these wheels are ‘worn out’ involute gearing. Wearing is an inevitable result of gearing use. Starting with running-in phase wearing leads to progressive loss of kinematic and strength characteristics of involute spur gear and to the loss of only strength characteristics of helical gear. It is known that in the wearing process working surface involute takes form similar to cycloid outlined profile.

As a result of running-in wear toothed gearing must tend to keep kinematic characteristics and to level off strength ones. That’s why it must: be helical gear; have convex and concave teeth profiles in cross-sectional view; be initially point-tracked with almost linear contact, at the same time line of contact must be parallel to axis of instantaneous rotation; be out of poles, at the same time this effect must be little as well as the meshing angle $\alpha$; have as long dimple spherical radius as possible.

Special demands: through the influence to generating surfaces that make moving incongruent zone to let rule the form and development of contact patch for better tooth load-sharing and forming profile crossing. Idea of dividing kinematic and strength functions, that breaks profiles conjunction using at the time spiral characteristics, allows to construct these profiles taking into consideration not only contact resistance, but better hydrodynamics and wearing qualities.

Here not only surfaces forms conformance in the contact point is important, but also conformance of a form and relative motion. It means that nonworking points of engaging teeth must have such traces of relative motion, that would stimulate tight lubricating oil wedge appearance.

As it is obvious that only gearings out of poles are meant, the traces of all the teeth points of one wheel (e.g. with convex profile) will be enlarged epicycoid. Therefore its doubled concave profile must be either of the closest trochoid or of rack trochoid. Such profiles will slowly move apart in relative motion.

Line of contact is a geometrical place of contact points in fixed coordinate system. The data of a problem to find energetically optimal line of contact is in a curve that corresponds to the least friction forces work and maximal COP of toothed gearing with permanent gearing ratio (this is in fact an attempt to solve the task of L. Eiler). Such curves correspond to involute and cycloid gearing. They were found from geometro-kinematic considerations without taking into consideration the energy of gearing process.

Continuity of these curves do not reflect snap-back action from one-pair contact to two-pair contact, when all gearing parameters change in steps. Therefore involute wheels profiles wearing notably deform the line of contact. Cycloid line of contact is less deformed because it is closer to optimal form. It is proved by the well-known facts of gearing profile deformation.

Gear wheels made with account for natural wear form are more technologically problematical than now dominating wheels with involute profiles. That is why the discrete contact proved in the work,
moving the loading material to the gearing pole in the gearing process, imitate natural wear in involute gearing, that there is no need to apply special technology to make new gear wheels.

Summary
Small particles (up to 5 microns) introduced into the lubricant as an additive to improve the quality of toothed gear serve as an antiwear and antifriction additive. Larger particles are harmful. This can be taken as a recommendation to the selection of parameters for spherical filler particles.

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