Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 73 (2023), NO 2, 33 – 44

JUSTIFICATION OF THE CHOICE OF PARAMETERS FOR THE GEAR POWER SKIVING OPERATION BASED ON COMPUTER SIMULATION

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Abstract: The paper presents the results of modelling and investigation of the gear cutting process using the power skiving method. The investigations are based on the developed geometrical model of undeformed chips. The approach is based on the original method of forming an integral three-dimensional model on the basis of discrete cross-sections of tool tooth in their successive positions on the cutting path, taking into account the shape and size of the gap previously formed by this tooth. The formulae for calculating the cutting force and the forces acting on the work gear and tool are derived as a function of the angular position of the cutter. The dependence of this force on the angle of tool shaft setting and the angle of inclination of gear teeth is studied. The formulae take into account how the cutting intensity changes due to the peculiarities of the kinematics of power skiving technology and the influence of the actual geometric parameters of the tool on the cutting force. Based on the obtained dependencies, a methodology has been developed for the selection of the axial feed rate and spindle set angle to ensure a compromise between the required productivity and the accuracy of the gear profile.

KEYWORDS: undeformed chip, external gear, cutting force, power skiving process, simulation, machining error

1 Introduction

Recently, gear manufacturers have been increasingly using power skiving technology, which has been extended to internal and external cylindrical spur and helical gears of a wide range of modules due to a number of notable features. However the development of spur gears skiving requires the solution of a number of practical tasks. The realisation of these tasks means adapting the gear to be cut, to a particular machine tool by selecting the correct technological and design parameters, particular cutting conditions - cutting speed, feed rate, number of passes at a given depth of cut, and the choice of a cutter parameters and material.

One of these tasks is to determine the optimum helix angle of the tool or cutter shaft angle. This parameter determines the setting angle of the spindle of the power skiving machine and this affects the load distribution on the machine elements. Increasing this angle increases the productivity of the process and reduces the force of the axial feed motion. At the same time, the forces acting in the radial direction increase. Since the radial stiffness of the spindle arm is significantly less than its axial stiffness, there is a risk of elastic vibration and chattering of machine components. At the high cutting speeds and tool speeds typical of power skiving, high-frequency vibration of a tool has significant negative consequences and is unacceptable.

2 Literature review

The considerable interest shown by manufacturers in the gear power skiving, as fast, versatile and highly productive gear cutting process, has led to a great deal of research into

DOI: 10.2478/scjme-2023-0020, Print ISSN 0039-2472, On-line ISSN 2450-5471

improving the technology, machine tool design and construction, chip modelling, calculation of chip parameters, and cutting forces, as well as reducing energy consumption and increasing productivity in gear machining. An analysis of the known works in this area revelade the following.

In order to analyse the force load, it is necessary to have information about the chip parameters. The most common approach to solving the problem of chip modelling [1-4] and others is to consider only the movement of the cutter tooth as a combination of its movement along the feed and rotation with the tool. In this case, the cross section of the chip is defined as the difference between the previous and next tooth position. However, this approach does not reproduce the shape of the transition surface into which the tooth cuts. This surface is formed periodically for each cutting time of a given tooth within its contact with the gap, and the tooth enters this surface after the tool has moved a certain amount in the axial feed direction. It is the shape and dimensions of this transition surface that determine the actual shape of the chip, its volume and the actual cross-sectional parameters of the rake face of the tool tooth at any angular position of the cutter during its rotational movement**.**

The approach known as the plane section method for quantifying the engagement of a cutter with a workpiece [1] is also based on the same principles.

An original method for modelling undeformed chips is presented in [5]. The working surface of the internal gear, where the cutting takes place, is divided by a grid that maintains its constant position in the plane of the gear face. According to the cutting path calculations, successive variable tool tooth positions are superimposed on this grid, which is the basis for recreating the volumetric structure of the chip.

In the articles: [6, 7] used a simplified calculation of the cutting force in a power skiving gear. For example, in [6] the cutting force is represented by its components, the numerical values of which are determined by the coefficients obtained experimentally.

In [8] the kinematics of the gear power skiving process is miniserpreted. It considers the cutting process as if each tooth of the pinion shaped cutter performed cutting independently and separately from the cutter and had a movement close in trajectory to the hob cutter tooth. In this case, the gap in which the cutting take place is considered to be stationary. With this approach, the actual cutting parameters and cutting force will be inadequate to the actual values. A similar assumption is made in [9] where a method for calculating chip thickness in the power skiving is presented. Again, power skiving is assumed to be similar to gear hobbing, which is not true.

In [4, 6, 10, 11] the cutting force is only presented as a function of chip thickness only. While chip thickness is an important cutting parameter, it only determines the intensity of deformation of the stock when it is converted into chips. An additional and more complete cutting parameter is the chip cross section, which ultimately determines the cutting force. Therefore, this approach to calculating cutting force is limited and does not give a complete picture of this parameter.

A correct assessment of the kinematics is essential to analyse the oblique cutting and the actual angles that the tool reaches in the working position on the machine tool. The kinematics of the process involves determining the vectors of speed, feed, and the resulting cutting movement, since it is in relation to these vectors that the kinematic angles of the tool must be considered.

A typical view of the vectors system is reflected in [1, 5], where the cutting motion (V_c) is represented as the geometric sum of the speed vector and the tool vector. However, the resulting cutting motion should be considered as the vector sum of the feed vector and the tool speed vector. Deviations in these directions will lead to incorrect estimates of the geometric parameters of the tool, such as the true rake angle and cutting force.

Bruno Vargas [4] considers the influence of kinematic angles on cutting forces, but only gives a qualitative assessment of this influence, without deriving the corresponding formulae.

In the same work, there is a provision reference to the specific cutting force. It is known that the cutting force can be represented by the product of the specific force and the cross-sectional area of the cut. In cutting theory, this force is a function of the chip cutting ratio and it can vary within a single cut depending on the chip thickness. This is noted in the paper, but no recommendations are given on how to quantify this effect.

2. Research results

To solve this problem, it is necessary to develop a power model of the cutting process in a gear skiving process.

2.1 Parameters of the layers to be cut

Based on the basic principles of cutting theory, the calculation of the cutting force requires data on the parameters of the layers to be cut and the intensity of plastic deformation during cutting [12, 13]. Therefore, the first step is necessary to create a geometric three-dimensional model of undeformed chips.

To solve this problem, we used an original approach developed for gear hobbing [14]. It consists of representing the continuous cutting process as a sequence of discrete movements taking into account the angular and linear displacements of the hob tooth and the workpiece, in accordance with the kinematics of a hobbing process**.** In each position of the cutter tooth, movement traces are reproduced in its current position and in the positions that this tooth occupied in the previous axial and rotary feed positions. In a skiving operation, unlike hobbing, the cutter tooth continues to cut in the same working gap when the cutter is moved not by the axial feed f_a - but by a distance equal to $f_a \cdot i$, where "*i"* is the gear ratio in the tool/work mesh.

By superimposing these traces, their intersection with the face of the tool tooth in its current axial feed and angular positions relative to the work gear is found. This makes it possible to accurately reproduce the actual shape and dimensions of the transition surface formed in previous cutting positions and to determine the true shape and dimensions of the chip cross section and calculate of its parameters - the area, width and thickness of the cut for each of the blades.

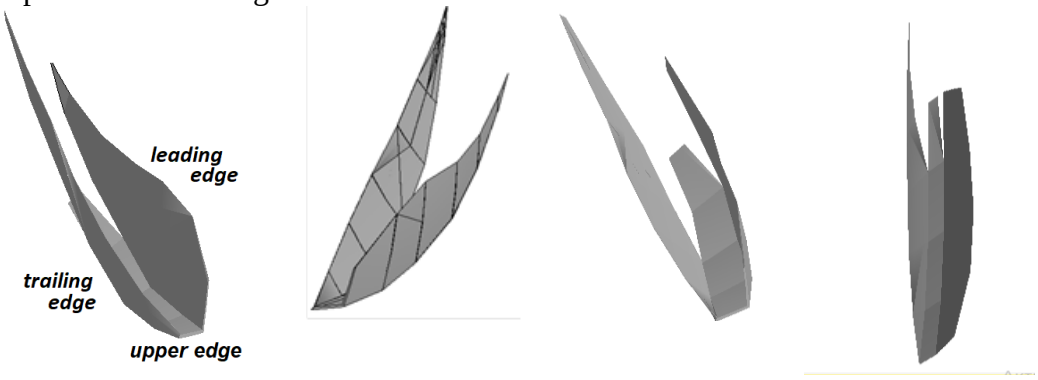
This also makes it possible to identify the operation of these blades and their involvement in cutting and shaping of a gear tooth. A complete *3D* model of an undeformed chip is created from successive cross-sections taken at successive cutting positions (Fig. 1)

In accordance with the problem formulated, the effect of a spindle angle set on the parameters of cuts was studied at the values of the cutter helix angle ω of 20^0, 25^0 and 30^0; for spur gears, this angle is equal to the angle of crossed axis of a tool spindle and the gear to be cut.

Initial data: external involute spur gear; module m = 2.5 mm; number of gear teeth Z_g = 33, number of cutter teeth Z_t = 24; axial feed f_a = 0.75 mm/rev; depth of cut is equal to whole tooth height; material of cutter inserts - hard titanium-tantalum alloy; cutting speed - 190 m/min.cutter outer diameter D_{a_h} = 66 mm; gear width 22 mm.

The following definitions are used. Contact ratio is the ratio of the arc of action in the plane of rotation of the gear (face plane of gear) to the circular pitch, i.e. the ratio of the length of action to the base pitch. It is equal the average number of teeth in contact, in our case 1.38.

Centreline - a straight line which acts as the axis of symmetry for the central tooth gap and divides the meshing zone into left (input) and right (output) parts. In this study, the meshing zone is divided into 13 successive angular positions, designated -6, -5,...0, +1, +2,...+6, with the zero position coinciding with the centre line.



a b c d

Fig. 1 3D model of an undeformed chip in a one-pass full heist machining
d - top view of a chip

Fig. 2 shows the results of determining the parameters of the cuts. The following conclusions can be drawn from the data obtained. In stationary cutting, the current cutter tooth starts cutting in a separate gap not in its first angular positions, but in the entry area close to the centre line. As the cutter tooth continues to move, the parameters of the cuts on all three edges increase rapidly. The largest part of the allowance is cut by the top edge, and the smallest part - by the leading edge. This blade starts to cut earlier than the others from zero thickness, which means that at this moment in time the material is not being cut – is being crushed in the flute. Such conditions lead to increased wear of the tooth in this area, which is located on the leading edge close the cutting tooth fillet. Considering that the cutting depth of this edge is less than that of other edges, heat flows of high intensity are generated in this area. These two factors will lead to increased wear on the leading edges at this point. Similar conditions will be experienced by the trailing edge, but in the area closer to the centre of the tooth height. It can therefore be said that these areas, together with the corners of the teeth, where there is increased friction due to unfree cutting, will be the areas of maximum wear (Fig. 3).

2.2 Force

According to the basic rules of cutting theory, the shearing force P_τ is a function of the shearing cross-sectional area S_τ (mm^2) and the ultimate shear strength, i.e. $P_\tau = [\tau] \cdot S_\tau$.

From the shear force, we can proceed to the cutting force component P_o, which coincides with the direction of the cutting speed and is called the main component of the cutting force. In our case, the direction of the P_o force coincides with the feed vector. Its value is equal to $P_o = P_\tau \cdot \cos\Phi$.

The shear area S_τ is related to the chip cross-sectional area S by the following relationship - $S_\tau = \frac{S}{\sin\Phi}$, where Φ - is the shear angle.

The intensity of shear deformations is characterized by a chip thickness ratio ξ, which is a function of the face angle of the cutting edge γ and the shear angle Φ:

$$\xi = ctg\Phi \cdot \cos\gamma + \sin\gamma \ . \quad (1)$$

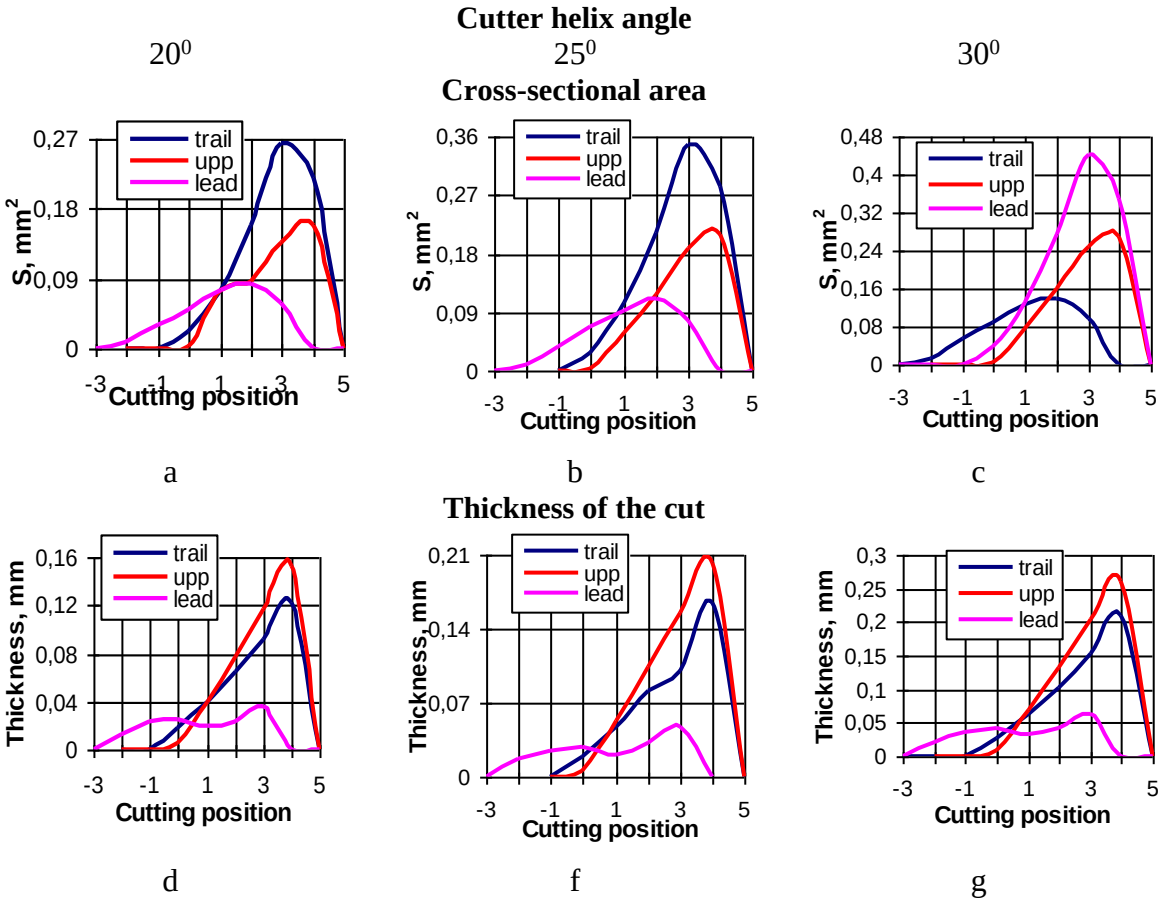


Fig. 2 Cross-sectional area (a-c) and cut thickness (d-g) at different cutter tooth/shaft set angle

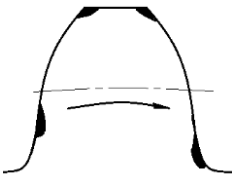


Fig. 3 Predicted areas of maximum cutter tooth wear

If a face angle is equal to 0 then $\xi = ctg\varphi = \frac{\cos\Phi}{\sin\Phi}$. Based the abow relationship, we obtain the following expression for the main component of the cutting force P_o:

$$P_o = P_\tau \cdot \cos\Phi = [\tau] \cdot S_\tau = [\tau] \cdot S \cdot \frac{\cos\Phi}{\sin\Phi}\ , \qquad (2)$$

which is:

$$P_o = [\tau] \cdot S \cdot \xi\ . \qquad (3)$$

Contrary to the Western school of cutting theory, the value of chip thickness ratio ξ is assumed to be equal to the coefficient of the chip thickening, i.e., its value is greater than one. The chip thickness ratio as a function of cut thickness for a given workpiece material can be calculated using the DEFORM-2D [15].

3 Results and discussion

3.1 How the kinematics of the power skiving process affect the cutting force

Power skiving is the process of continuously generation a gears profile. As such, it has the following features: the cut is multi-teeth, multi-blade and oblique. This means that all three edges of each tooth - the side edges and the top edge - are involved in the cut, and a number of teeth are engaged in the szmt time with the gap being cut over the entire overlap angle. During cutting, the rake face of the tooth is at an angle to the cutting speed vector equal to the angle of inclination of the cutter teeth ω and perpendicular to the axial feed vector.

Let's take a closer look at these features that affect the cutting force. Due to the fact that the cutting speed vector forms an angle ω, with the rake face of the cutter tooth, the actual (kinematic) face angle at the top edge changes, and its value can be determined with sufficient accuracy from the following relationship: $\gamma_K = \gamma_0 \cdot \cos\omega$. An increase in the actual rake angle leads to a change in the chip sliding vector and a decrease in the friction between the chip and the tooth face, which is equivalent to a decrease in the intensity of chip deposition and cutting force. However, this change in friction is not significant for the upper blades, as the tooth axis forms an angle close to 90^0 with the direction of rotation.

Consider the figure 4 below, which shows a kinematic diagram of the power skiving process. The resultant or total cutting speed V_{cut} in this process is the geometric sum of the vectors of feed V_f and tool speed V_{tool}. At the axial feed rates typical of this process (0.1 - 0.5mm/rev), the direction of the V_{cut} and V_{tool} vectors is almost identical.

The analysis of the kinematic angles in this direction is shown in Fig. 5. The figure shows the position of the leading and trailing blades of a cutter tooth relative to the cutting speed. The leading blade produces a positive face angle and a negative clearance angle, and the trailing blade produces a negative face angle and positive clearance angle.

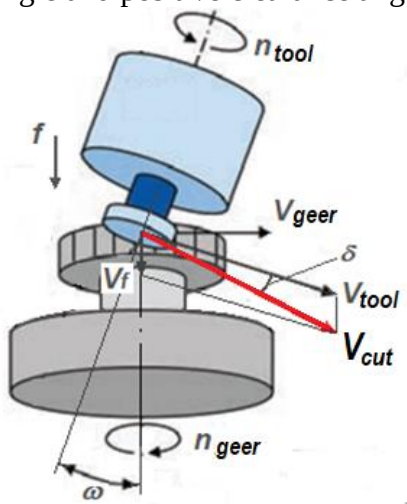
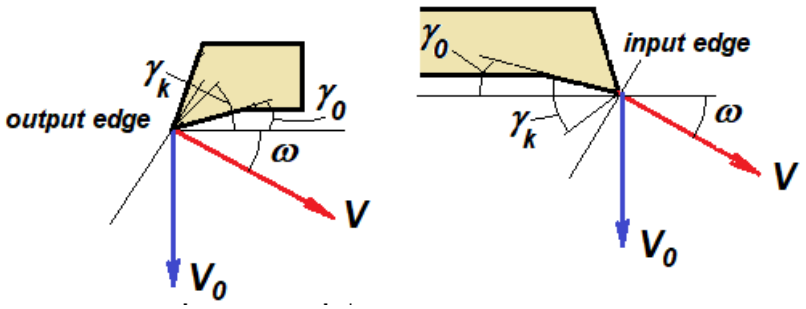


Fig. 4 The kinematic diagram of the Power skiving process

In this figure, V_0 is the direction that the speed would have in a rectangular cut, V is the vector of the actual speed, relative to which the kinematic angles on the blades γ_k, are determined, their values being: for the input blade $\gamma_k = \gamma_0 + \omega$, on the output blade $\gamma_k = (-\gamma_0 - \omega)$; at $\gamma_0 = 0$ $\gamma_k = \pm\omega$.

In addition, the frictional forces on the leading and trailing blades are reversed: the frictional force on the trailing blade acts in the opposite direction to the rotation of the cutter, while the friction force on the leading blade is in the same direction. These changes result in an increase in the cutting force on the trailing blade and a decrease in the cutting force on the leading blade.



a b

Fig. 5 Kinematic front angles on the blades

From the equation (1), the actual chip thickness ratio will differ from the nominal ξ_0:

$$\xi_{act} = \frac{\xi_0 - \sin(\pm\gamma_K)}{\cos\gamma_K}, \tag{4}$$

where is the kinematic angle $\gamma_k = \pm\omega$.

According to the expression (4), the deposition intensity due to changes in the actual angles will increase on the input blades ($\gamma < 0$), and decrease on the output blades ($\gamma > 0$). The change in deposition intensity due to changes in the angles on the blades can be seen in Fig. 6.

Using the results of the determiation of the cutting parameters, the dependence of the chip thickness ratio on the thickness of the cuts [15] and the dependencies (3) and (4), Fig. 7(a-c) - Fig. 7 (d-g) show graphs of the R_o force on the blades in single tooth gap cutting and the total cutting force, taking into account the kinematic angles on the cutter blades.

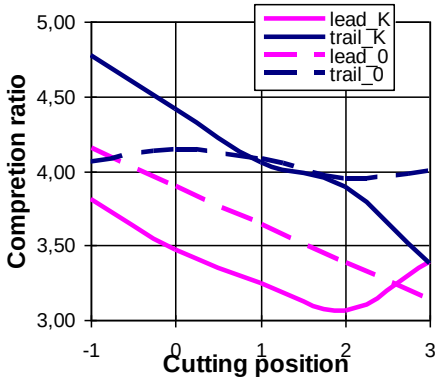


Fig. 6 Changes in chip deformation intensity due to changes in face angle at the side blades at $\omega = 20^0$

The total force is the result of the simultaneous operation of several cutter teeth; the number of ich is equal to the contact ratio, i.e. 3.18. As can be seen from the data obtained, the total force is harmonic with a certain frequency. For our initial data, the spindle speed is 916.8 rpm, so the frequency of the cutting force is a multiple of the number of cutter teeth Z_c and is 366 Hz.

The total cutting forces at helix angles $\omega = 20^0$, 25^0 and 30^0 have the following parameters, respectively: mean force value 392N, 825N, and 1030N; amplitude: 235N, 483N and 485N.

To determine the tangential (rotational) forces acting on the outside diameters of the tool and gear, consider the diagram in Fig. 8.

The force P_o that we use in these studies is a component of the total cutting force, also known as chipping force R. The magnitude of the cutting force depends not only on the shear rate but

also on the frictional forces. Therefore, in our calculations, we need to take into account the frictional forces acting on the rake face of the teeth. When cutting with a sharpened tool, the frictional forces on the back face are negligible and can be ignored.

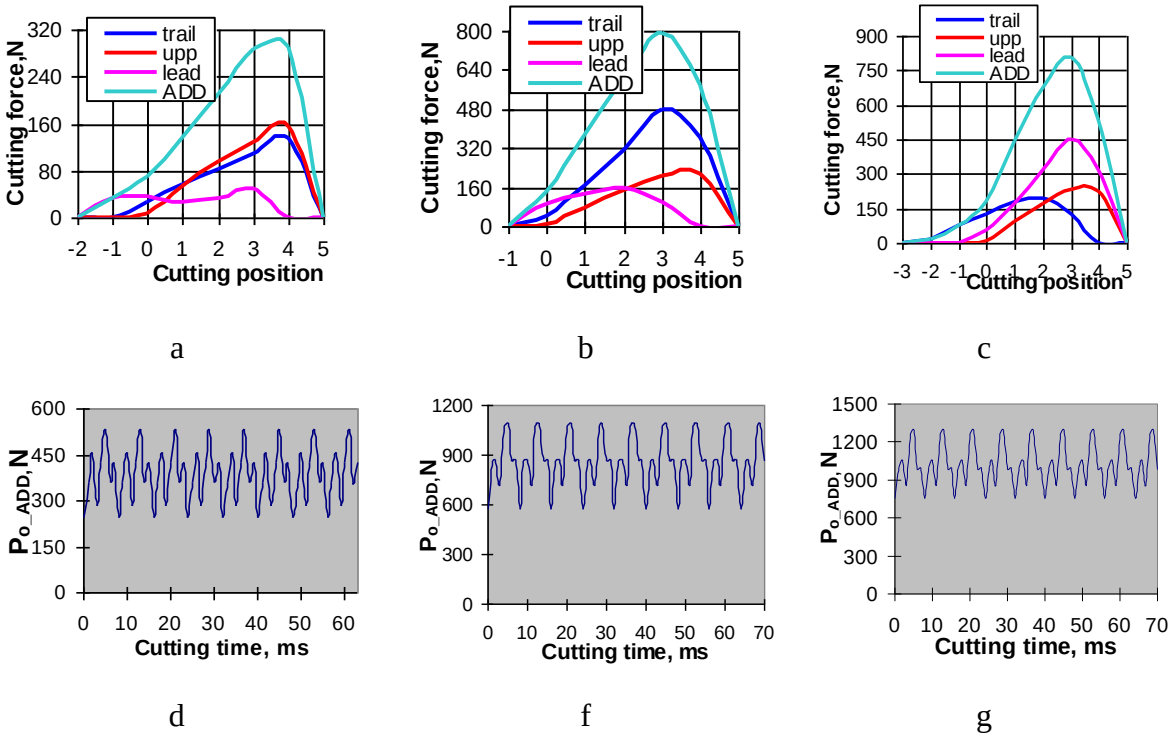


Fig. 7 Cutting force P_o on the blades as a function of the angle of rotation in successive angular positions of the cutter and a total force in oblique cutting (a –c); total cutting forces in continuous gear machining (d – g) a, d: ω = 200 ; b, f: ω = 250; c, g: ω = 300

Figure 8, shows a diagram of these forces on the blades of a single cutter tooth in a certain intermediate angular position of this tooth relative to the gear. The direction of the frictional forces F is opposite to the direction of chip flow along the face near the top, leading and trailing edges. From this diagram, we can derive a relationship for calculating the tangential forces P_z acting on the cutting tool ($P_{z\,tool}$) on the outside diameter and generating a torque on its axis:

$$P_z = (F_{lead} - F_{trai}) \cdot \cos\omega + F_{upp} \cdot \cos\varphi_{i_t} + P_{o_ADD} \cdot \sin\omega$$
$$= (P_{o_lead} - P_{o_trai}) \cdot \mu \cdot \cos\omega + P_{o_upp} \cdot \mu \cdot \cos\varphi_{i_t} + P_{o_ADD} \cdot \sin\omega \quad (5)$$

where F_i – frictional forces at the tooth face near the corresponding blades.

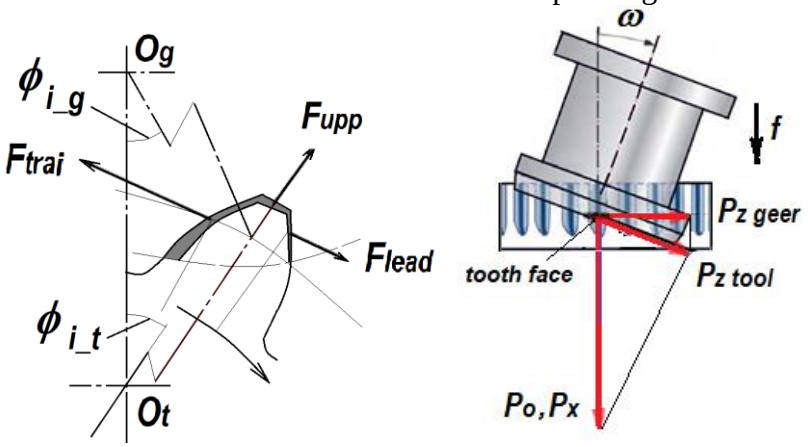


Fig. 8. Forces acting on the face of the tooth on its edges (a) and diagram of the forces acting on the tool and gear

This and the following dependencies take into account the variation in the forces on the blades as a function of their kinematic angle, and the force P_o on the blades is denoted by the index P.

In accordance with dependence (5), the graphs of changes in the circular force on the blades and the total value of this force on the tooth for different shaft set angles ω are shown in Fig. 9. As can be seen, as the set angle increases, the negative component of the circular force acting in the counter-rotation direction of the cutter decreases, while its absolute value increases: from 75 N and 148 N (force range at $\omega = 20^0$ and $\omega = 25^0$) to 396 N at $\omega = 30^0$.

From the graphs of the total forces, it can de seen that at angles $\omega = 20^0$, 25^0 and 30^0, the average values of the forces and their range are equal, respectively: 27 N and 80N; 138N and 38 N; and 256N and 370N.

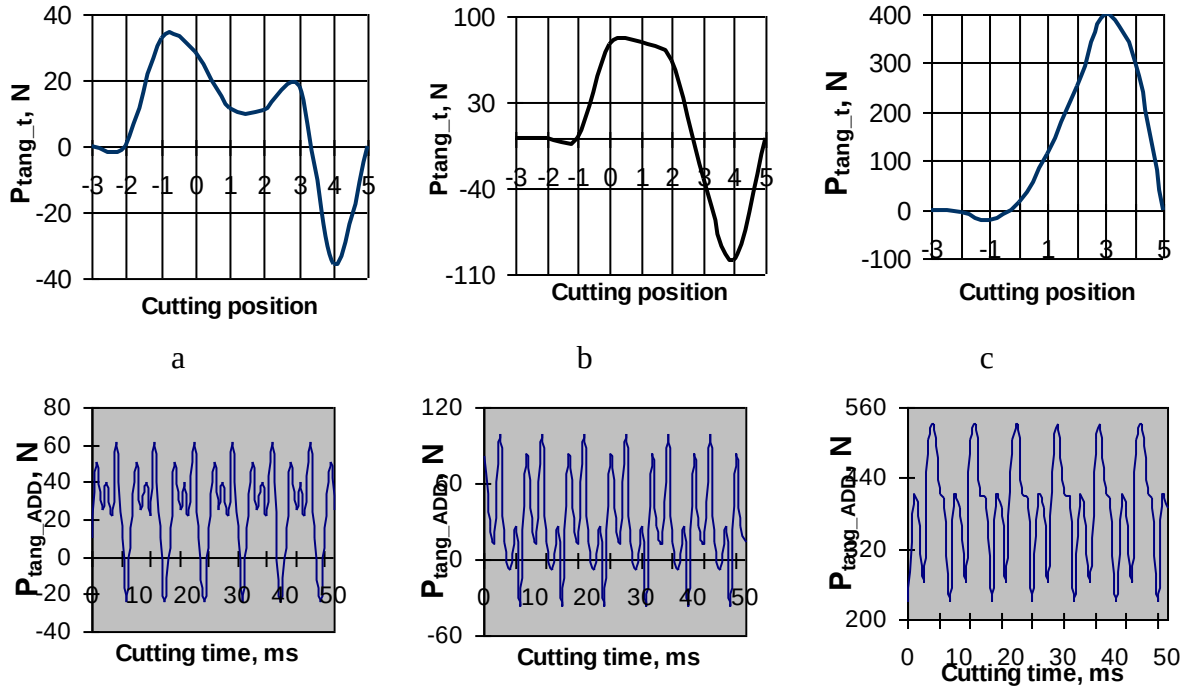


Fig. 9. Tangential (circular) forces acting a cutter in single-tooth cutting (a-c) and multi tooth cutting (d-g), a, d: ω = 20^0 ; b, f: ω = 25^0; c, g: ω = 30^0

Dependencies for calculation the tangential forces $P_{z\,gear}$, acting on the gear are as follows:

$$P_{z_gear} = F_{lead} \cdot \cos(\varphi_{i_gear} + \varphi_{i_tool}) - F_{head} \cdot \cos(\varphi_{i_gear} + \varphi_{i_tool}) - \\ - F_{tral} \cdot \cos(\varphi_{i_gear} + \varphi_{i_tool}) = = \left[F_{lead} - \left(F_{upp} + F_{trai}\right)\right] \cdot \cos(\varphi_{i_gear} + \varphi_{i_tool}) \quad (6)$$

that is

$$P_{z_gear} = \left[P_{o_lead} - \left(P_{o_upp} + P_{o_trai}\right)\right] \cdot \mu \cdot \cos(\varphi_{i_gear} + \varphi_{i_tool}), \quad (7)$$

where φ_{i_gear}, φ_{i_tool} – are, respectively - the angles of the *i-th* position of the tooth gap and the tool tooth in their discrete successive angular positions.

Fig. 10 show graphs of these forces for single tooth cutting (7) and their total values for multi-tooth cutting. From the formula (7) and graphs (fig. 10 (a-c)), it can be seen that, at a certain part of the cutting path, the force on the working gear acts in the direction opposite to its rotation, whereas as the angle of the cutter setting increases, the force increases in the direction of its rotation. This explains why both its average value and range (double amplitude) decrease: from and at $\omega = 20^0$ …to and at $\omega = 30^0$.

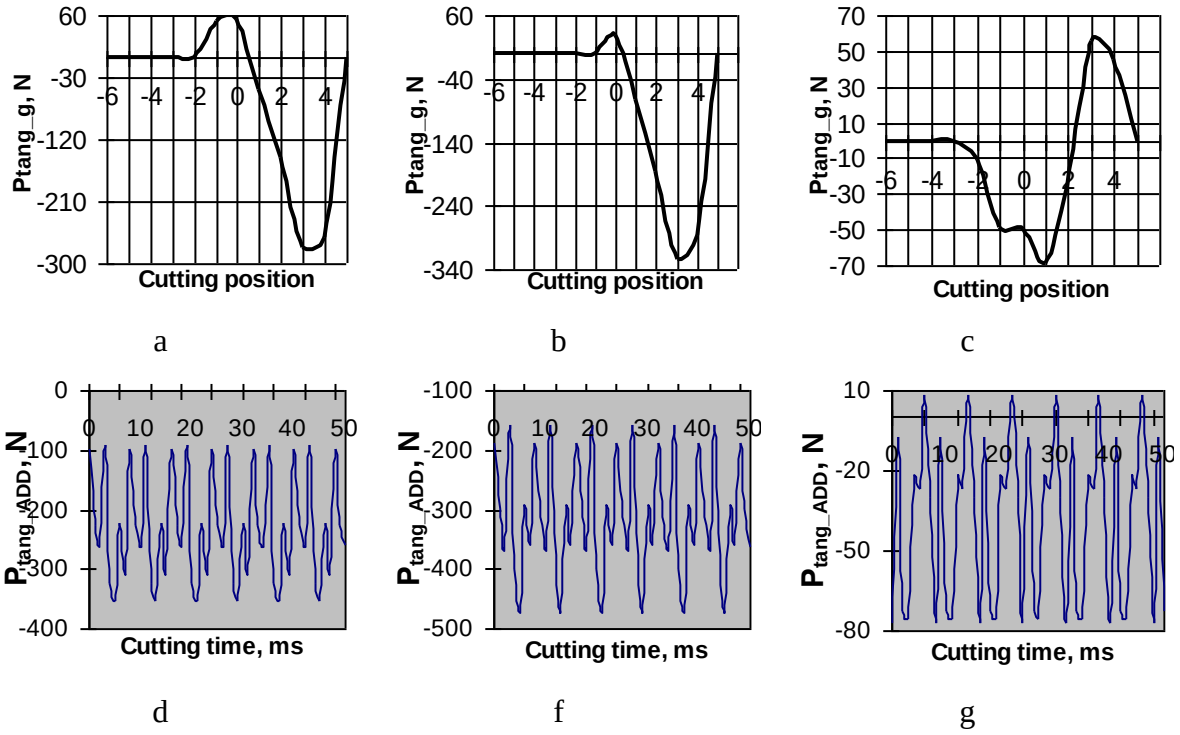


Fig. 10. Tangential (circular) forces acting a gear in single-tooth cutting (a-c) and multi tooth cutting (d-g) a, d: ω = 20^0 ; b, f: ω = 25^0; c, g: ω = 30^0

3.2 Use of the developed methodology

On the basis on the above studies, the following main results can be presented, which can be taken into account in practical activities.

When changing the angle of inclination of the tool teeth and the angle of a tool spindle setting and when moving from an angle of $\omega = 20^0$ до $\omega = 30^0$, the circular force acting on the cutter axis and its amplitude change the most - their values increase by 8-10 times and 3 times, respectively. At the same time, the force acting on the gear decreases significantly, both in terms of the average value (decrease by 6-8 times) and in terms of the range (decrease by 1.5-2.5 times).

The harmonic components of these forces act as an external disturbance to the machine's elastic system. The frequency of this perturbation (366 Hz) means that if components with natural frequencies equal to or close to this frequency are present in this system, intense elastic vibrations and chatter will occur in the machine. These vibrations are low frequency vibrations that carry significant energy, so the chatter they cause will be intense.

Consider how these forces affect the deformation of the tool spindle. Let's apply the force to the axes of the spindle coordinate system. If we apply oppositing forces to the cutter axis, equal in magnitude to the circular force on the cutter, we get a radial force and a pair of forces that create a torque on this axis. The maximum torque at a set angle of 30^0 will be 17.2 Nm. If the torsional stiffness of the machine tool spindle is, for example, 6.5 kNm/g, this torque will produce an angular error on the cutter axis of $2{,}7 \cdot 10^{-3}$ rad, which corresponds to an error in the gear sircular pitch of 65 microns.

Such an error is one of the the kinematic errors that cause fluctuations in the gear ratio when such a gear operates in the gearbox, i.e., speed instability at the gearbox output. Another negative consequence of such an error is an increase in the noise level of a gearbox.

To avoid such errors, multiple passes cutting are used in practice. Based on the methodology developed here, it is possible to determine the optimum number of such passes to ensure a given accuracy of gear machining. For example, if three passes are used, the angular error can be reduced by a factor of 2.6 to 2.75, i.e. the error in the sircular pitch will be equal to 25 microns. The fact that the reduction in error is slower than the reduction in the number of cuts decreases, so the shear intensity and chip thickness ratio, i.e., the cutting force, increase slightly.

On the other hand, increasing the number of passes increases the machining time. Consider how the machining time t_m changes. With a tool spindle set angle of 30^0, the cutting path increases by 66 mm due to the distance required for tool penetration and runout, and the total cutting length is 132 mm. The time t_m will then be 30 seconds if the gear cut in one pass, and 90 seconds if it is cut in three passes. The loss of 1 minute in the production of a batch of gears can be quite significant, especially in mass production. For example, if the batch of gears consist of 60 parts, then cutting in three passes will increase the machining time by one hour.

Increase the spindle angle setting also has a negatively affects the height of the micron irregularities on the formed tooth surface. For example, at an angle of $\omega = 20^0$, the height of micron irregularities on the side surface of the cut tooth is 7.3 microns, and at an angle of $\omega = 30^0$ - 9 microns.

Conclusion

1. A comprehensive methodology for modelling the gear cutting process using power skiving method has been developed. The methodology includes modelling an undeformed chip and calculating its parameters, calculating the forces acting in the system and the deformations they cause. The forces are represented in the form of harmonic oscillations for single tooth and multi-tooth (total) cutting.

2. The methodology is developed at the level of individual teeth and blades of a cup cutter and allows you to analyse the cutting performance of each of them and identify areas of maximum tool wear.

3. The effect of tool spindle setting angles and the inclination of the cutter teeth on the cutting forces and the height of micro-irregularities in the gear tooth profile was investigated. It was found that an increase in this angle resulted in a large increase in the cutting force and circular force acting on the cutter and tool spindle. At the same time, the circular force and torque acting on the work gear and machine table are significantly reduced. Increasing the setup angle also worsens the roughness of the resulting tooth surfaces.

4. The methodology developed makes it possible to establish process conditions that guarantee a given accuracy by selecting the number of passes, the range of axial feed or the inclination of the cutter teeth, which are compromised by the criteria of machining accuracy, tooth surface roughness, and loss of machining time

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