гнучкого в'язкопружного поздовжнього рухомого паса визначені його динамічні характеристики під час поперечних коливань і досліджено вплив механічних властивостей матеріалу на ці характеристики.

Практична значимість. Запропонована методика дослідження поперечних коливань поздовжньо-рухомих гнучких пасів дозволяє визначити вплив на основні параметри динамічного процесу швидкості поздовжнього руху та в'язкопружних властивостей матеріалу. Отримані аналітичні залежності можуть бути базою для інженерних розрахунків вузлів і механізмів, складовими частинами яких є поздовжньо-рухомі гнучкі паси.

Ключові слова: *математична модель, хвильова теорія руху, в'язкопружність, поперечні коливання, пасова передача, методи збурень*

Цель. Создание вязкоупругой динамической модели гибкого продольно-подвижного ремня различных механизмов с учетом влияния механических свойств материала на его динамические характеристики в случае поперечных колебаний.

Методика. Методика исследования поперечных колебаний гибкого ремня базируется на асимптотических методах нелинейной механики и волновой теории движения.

Результаты. В работе для гибких вязкоупругих продольно-подвижных ремней получены аналитические зависимости для определения амплитуды и частоты поперечных колебаний. Проанализировано влияние вязких и упругих свойств материала ремня на его амплитудно-частотные характеристики.

Научная новизна. Заключается в том, что впервые аналитически на основании созданной динамической модели гибкого вязкоупругого продольно-подвижного ремня определены его динамические характеристики во время поперечных колебаний и исследовано влияние механических свойств материала на эти характеристики.

Практическая значимость. Предложенная методика исследования поперечных колебаний продольно-подвижных гибких ремней позволяет определить влияние на основные параметры динамического процесса скорости продольного движения и вязкоупругих свойств материала. Полученные аналитические зависимости могут быть базой для инженерных расчетов узлов и механизмов, составными частями которых являются продольно-подвижные гибкие ремни.

Ключевые слова: *математическая модель, волновая теория движения, вязкоупругость, поперечные колебания, ременная передача, методы возмущений*

Рекомендовано до публікації докт. техн. наук М. М. Семераком. Дата надходження рукопису 26.04.16.

UDC 621.914.5

M. M. Pidhaietskyi, Cand. Sc. (Tech.), Assoc. Prof., A. R. Aparakin

Kirovohrad National Technical University, Kropyvnytskyi, Ukraine, e-mail: anton.aparakin@gmail.com

DYNAMIC AND KINEMATIC SYNTHESIS OF THE CONTOUR GEAR HOBBING'S SYSTEM

М. М. Підгаєцький, канд. техн. наук, доц., А. Р. Апаракін

Кіровоградський національний технічний університет, м. Кропивницький, Україна, e-mail: anton.aparakin@gmail.com

ДИНАМІЧНИЙ ТА КІНЕМАТИЧНИЙ СИНТЕЗ СИСТЕМИ ЧЕРВ'ЯЧНО-КОНТУРНОГО ЗУБОФРЕЗЕРУВАННЯ

Purpose. Development of the finishing gear hobbing method based on the interaction of the change of the tool cutting edge and the machined surface.

Methodology. The study includes the method of abstraction based on gear hobbing as the interaction of the tool cutting edge with the machined surface. In turn, the properties of the interaction of the tool cutting edge and the machined surface are studied with the help of models under computer simulated conditions.

Findings. The specifications for the finishing gear hobbing method have been assigned. Possible variations of system of the tool cutting edge interaction with the machined surface were shown; the level of stability of the cutting process with specified variations of interaction was determined in terms of computer modeling. A dynamic model of the tool cutting edge interaction with the machined surface has been created. The model considers the nature (geometry) of the interaction, tension, damping and disturbance of technological system (self-adjustment – tool – component part). The directions to increase astatism of system were determined.

Originality. For the first time the gear hobbing modeling method was created which shows the research opportunities of the tool cutting edge interaction with the cutting surface including the machined surface under conditions of both their coincidence, and non-coincidence. For the first time the finishing gear hobbing process of involute surfaces was created in which the cutting surface does not match the determined involute surface and is set at an angle to it.

Practical value. The astatism level of the single-mass conservative oscillatory system has been increased by changing the nature (geometry) of the interaction between the tool cutting edge and the machined surface that is adequate to the insertion of integrating links into the system. The scheme of gear hobbing based on the contour interaction of the tool cutting edge and the machined surface has been implemented.

Keywords: *dynamic model, cutting edge, astatism of the system, finishing gear hobbing*

Introduction. Traditional gear hobbing has limited reserves of efficiency increase that are determined by the limits of cutting and feeding speed, wearability of the tool and treatment quality. However, further increase in treatment efficiency is possible due to the change of cutting kinematics and application of new, rational cutting schemes with kinematic distribution of cuts.

Analysis of the recent research. A great amount of research on the traditional gear hobbing deals with the wear process including the durability of the milling cutter with superhard coating and the study of the effect of application of powder tool materials. The latest trend in the research is a computer modelling for studying finer-grained aspects of the method. These issues are investigated in the works of the Ukrainian scholars such as I. Hrytsai [1], as well as in the works of foreign scholars A. Antoniadis [2], B. Karpuschewski [3], G. Hyatt [4], S. Stein [5].

Unsolved aspects of the problem. All kinds of the above-mentioned research are aimed to improve or neutralise disadvantages of the existent scheme of the traditional gear hobbing. There are no attempts to change the scheme of formation, geometry of interaction of the tool cutting edge and the machined surface.

Objectives of the article. The methods of gear hobbing are quite energy consuming and cost-intensive because of considerable cutting force and they do not meet the demands of energy saving technologies. The article presents the attempt to create a technology of gear hobbing on radically other principles.

Presentation of the main research. There are certain requirements as to the system of contour gear hobbing which is synthesised:

- increase in accuracy of machining;
- decrease in energy consumption;
- increase in stability of the process.

The increase in accuracy can be achieved by the decrease in cutting force and as a result of elastic deformation. Chip cross sections which are cut in the course of operation can be the criterion to assess the cutting force [2]. The decrease in energy consumption can be also achieved by the decrease in cutting force.

The system of interaction between the cutting edge and machining surface is considered as the system of automatic control in order to determine its static and dynamic features.

At the stage of synthesis it is necessary to determine the criteria for the assessment of the method under consideration. The criteria for assessing the system of interaction between the cutting edge and the machining surface will be:

- variability of cutting force;
- nominal of cutting force;
- astatism of the system.

Determination of possible variants of the system of interaction between the cutting edge and machining surface. The formation of involute surface on the gear wheel has one common characteristic which is real surface tending to be geometric surface. The cutting edge of the tool can be tangent to the machining surface or to be normal as it is shown in Fig. 1.

Therefore, the formation of the surface requires geometric forming lines.

As we see in Fig. 1, *a*, traditional finishing gear hobbing is carried out in the way when two adjacent cutting edges of the tool tooth are located tangentially to the machining surface and the surface for cutting coincides with the machining surface.

On the basis of these statements we define the interaction between the cutting edge and machining surface:

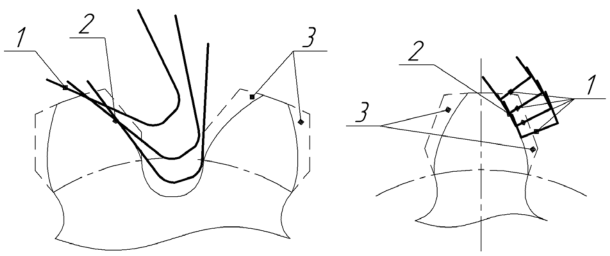
- profile interaction is the interaction when the cutting edge of the tool is tangent to the machining surface;
- contour interaction is the interaction when the cutting surface of the tool is located normally to the machining surface.

Dynamic synthesis. The level of stability of cutting processes can be determined under computer simulated conditions. The objective of modelling is to assess the state of the system when it gets astatism.

The astatism of the system as a property is when there is constant action (disturbance) the inaccuracy of the system is close to zero.

Computer modelling will be carried out on the basis of cutting schemes shown in Fig. 2.

In order to simplify the process, the traditional finishing gear hobbing is changed by the modelling in the conditions of turning operation (Fig. 2, *a*), which meets the requirements of the profile interaction taking into account that the machining surface coincides with the surface of cutting. In its turn, the contour interaction in the process of contour gear hobbing is modelled by turning of straight turning tool (Fig. 2, *b*). The adequacy of the cutting processes for the created models is achieved by the analogue interaction between the cutting edge and the machining surface.



a *b*

Fig. 1. Possible interaction of cutting edge of the tool placed tangent to the machining surface (a), placed normally to the machining surface (b):

1 – cutting edge of the tool; 2 – machining involute profile; 3 – machining allowance

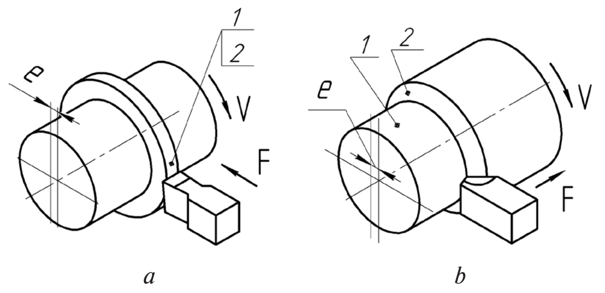


Fig. 2. Cutting schemes for computer modelling:

a – profile interaction while cutting on turning machine; b – contour interaction while turning by straight turning tool on the turning machine: 1 – machining surface; 2 – surface of cutting; e – eccentricity; F – feed; V – cutting speed

The reproduction of disturbance which is similar to the disturbance that appears when the teeth of the milling cutter penetrate is achieved by the eccentric position *e*. In this case the rate of production tolerance z_i has running value which approaches the conditions of turning to the conditions of gear hobbing.

The modelled system of vibrations is single-mass (Fig. 3), and consists of the carriage and the tool with the mass *m*, its stiffness *c* and the damper λ (friction between the bed plate and the carriage).

Let disturbed vibrations of the technological system be defined by the operation of cutting force W_{P_y}, and the work of damping the vibrations W_d.

The amplitude of vibrations of machining allowance is described by the formula and is adequate to the amplitude of vibrations of the system influenced by the cutting force P_y

$$y = a \cdot \cos \omega t,$$

where *a* is an amplitude of vibrations; ω is frequency; *t* is time.

Work of W_{P_y} to cut machining allowance and stimulation of vibrations is created by the linear value X_{in}

$$W_{P_y} = X_{in} = P_y \cdot t = \int_0^t P_y(t)\,dt,$$

where P_y is cutting force; *t* is time.

Therefore, the fluctuations of cutting force P_y will lead to damaging operation of elastic deformations *We* of the technological system which is to be neutralised by the known ways, for example introducing integrating link into the system or creation of its conventional operation.

Let us have some conditionality

$$W_e = X_{out};$$
$$X_{in} = P_y \cdot \cos \omega t.$$

Taking into account conditionality, the equation of operation of tension movements W_e becomes the equation that characterises the integrated link, i. e.

$$W_e = X_{out} = k\int_0^t P_y \cdot \cos\omega(t)\,dt. \qquad (1)$$

According to formula (1) it is necessary to consider the results of computer modelling influence of the geometry of cutting process on the level of astatism of the system under consideration, and to determine the amount of necessary damping operation W_d which can neutralise partially or fully the damaging operation of elastic deformations of the technological system W_e.

The operation value of damping forces W_d can be defined by the formula

$$W_d = W_{P_y} - W_e = \int_0^t \left(P_y(t) - kP_y \cdot \cos\omega(t)\right)dt. \qquad (2)$$

Let us build mathematical model of the cutting process.

Real value of machining allowance z_i is defined by the formula

$$z_i = z_0 + y, \qquad (3)$$

where *y* is the amplitude of machining allowance vibrations.

Cutting force is connected with real value of tolerance z_i

$$P_y = C_{P_y} \cdot z_i \cdot F^v \cdot V^n.$$

Taking into account conditionally small influence of the parameters C_{p_y}, S^v, V^n this law can be linearized

$$P_y = K_p \cdot z_i, \qquad (4)$$

where K_p is the coefficient of linearization

$$K_p = C_{P_y} \cdot F^v \cdot V^n.$$

Separate equation of technological system deformations which corresponds to the forced vibrations as a result of variable machining allowance *z*

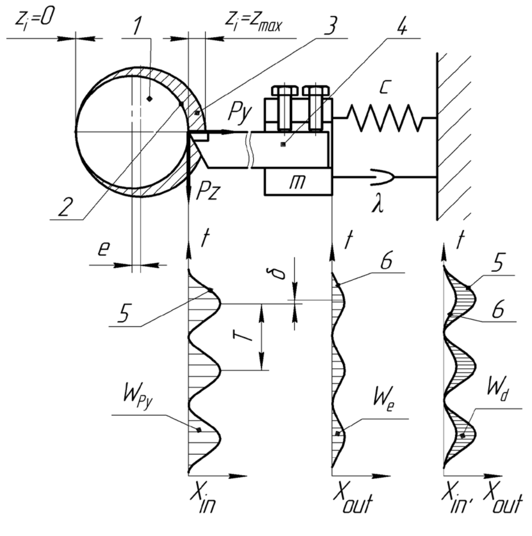


Fig. 3. Dynamic model of the process:

1 – the workpiece with eccentricity; 2 – machining surface; 3 – surface of cutting; 4 – technological system; 5 – graph of fluctuations caused by variable machining allowance z_i; 6 – graph of elastic deformations of the technological system; c – coefficient of system stiffness; λ – coefficient of damping; P_z, P_y – cutting forces; z_i – machining allowance; T – vibration frequency; δ – retardation value of vibrations; W_{P_y} – work of cutting force; W_e – work of elastic deformations of the technological system; W_d – work of the system directed at damping the vibrations; X_{in}, X_{out} – value of input and output vibrations; t - time

$$m\frac{d^2y}{dt^2}+\lambda\frac{dy}{dt}+c=Py. \quad (5)$$

The equation system (3...5) is a mathematical model of the cutting process in the closed technological system with the single degree of freedom. Changing the intermediate variables the system becomes the equation

$$m\frac{d^2y}{dt^2}+\lambda\frac{dy}{dt}+c=K_p\cdot z_i,$$

which in standard form is the following

$$T_1^2s^2y+T_2sy+y=K_1\cdot z_i, \quad (6)$$

where $T_1^2=m/c+K_p$; $T_2=\lambda/c+K_p$ are system time constants; $K_1=K_p/c+K_p$ is a transmission ratio.

As the equation (6) connects input value (variability of allowance) with output value (system deformation) we can get a corresponding transfer function which reflects the change of tension deformation while changing tolerance value

$$W_2(s)=\frac{Y(s)}{z_i(s)}=\frac{K_1}{T_1^2s^2+T_2s+1}.$$

In order to get other transfer functions of the system we should consider the mathematical model again. To get a transfer function which reflects the dependence of the cutting force constituent on the given depth of cutting it is necessary to put y from equation (3) and z_i from equation (4) to (5). After the changes we get the equation in standard form and considering Laplace images obtain

$$W_2(s)=\frac{Py(s)}{z_i(s)}=\frac{K_2}{T_1^2s^2+T_2s+1},$$

where $K_2=cK_p/(c+K_p)$ is transfer ratio.

Oscillograms and elastic deformation values of the system on a given cutting schemes were obtained using the application software "Modelling technological hereditarities" developed by Prof. Petrakov Yu. V. The interface and initial data for modelling are shown in Fig. 4.

The results of modelling are shown in the form of response surface in Fig. 5.

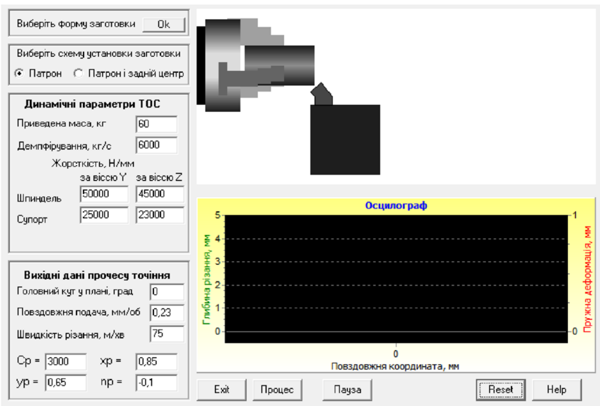


Fig. 4. Interface software

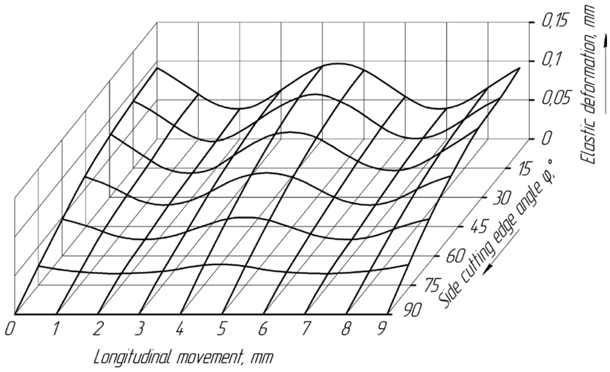


Fig. 5. Results of computer modelling

As we see from the response surface (Fig. 5), the profile interaction reveals itself as a typical conservative oscillatory static link with transfer function

$$W(p)=\frac{k}{1+T^2p^2}.$$

In its turn, under contour interaction the order of astatism of the system increases due to the changes of character (geometry) of interaction between cutting edge and machining surface which is adequate to the introduction of an integrating link into the system with transfer function

$$W(p)=\frac{k}{p}.$$

It is necessary to consider the functional link as a result of interaction between the input and output signals, in other words, to consider it in the form of operation which is performed by input value and reaction of output value. As it is known that the work is always defined by the integral, them it will be reasonable to consider the system as a system with integrating link.

Realization of the scheme of gear hobbing on the basis of contour interaction between the cutting edge and machining surface. Contour gear hobbing is the method of finishing gear hobbing in which the cutting edge of the tool tooth is located normally to the machining involute surface and is the continuation of the radius of curvature and the surface of cutting does not coincide with the machining surface [6].

The essence of contour gear hobbing is that it is applied as the method of finishing treatment of involute profiles of teeth with formed bottom land. In this case the tool operates with one cutting edged which is located on helical curve with a pitch equal to the pitch of cutting wheel according to the arc of the basic circle and is defined by the formula

$$P=\pi\cdot m\cdot\cos\alpha,$$

where m is a module of cutting wheel; α is the gearing angle.

Contour gear hobbing is realized under the condition that the form-building cutting edge of the tool is located on continuation of radius of curvature of nominal involute profile of the teeth of machining gear in such a way that its initial point delineates the conditioned involute profile of tooth in the way of form-building (Fig. 6, *b*). It is difficult to show graphically the process of form-building involute surface by the initial point of the cutting edge while modelling in the conditions of rotary motion. That is why an adequate scheme of replacement of rotary motion of generation for the rectilinear motion of generation should be worked out.

Cinematically, the process of cutting teeth while contour gear hobbing, should be considered as gearing of a worm and a worm-wheel. The rotary motion of a contour gear cutter and machining gear are connected and defined by the relation of number of cuttings to the number of teeth of the machining gear. At one rotation of the single flute cutter the machining wheel should rotate at one tooth

$$i = \frac{k}{z},$$

where k is the number of starts of the contour gear hob; z is the number of teeth of cutting gear.

While treating by worm-contour cutters the shaft of tool-holding spindle of machine tool is located at the angle θ to the long axis of the machining tooth which is calculated by the formula

$$\theta = 90^\circ - \omega,$$

where ω is the tip angle of the helical line of the cutter, degrees.

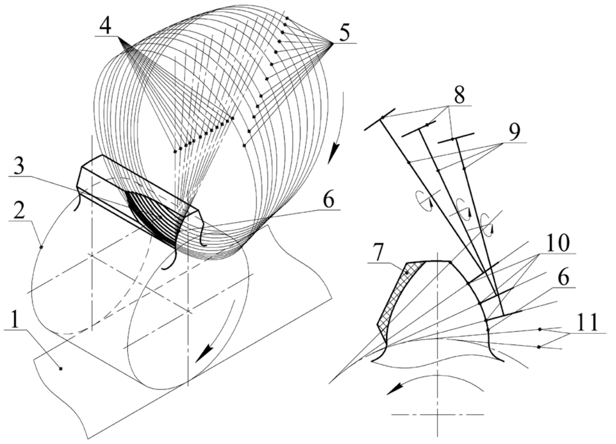


Fig. 6. Generation of involute profile with contour gear hobbing:

a – scheme of movement of the point of cutting edge which delineates the machining involute surface in the conditions of replacement of rotary motion of generation for rectilinear; b – diametric cross-section of the movement scheme; 1 – plane tangential to the main cylinder; 2 – main cylinder of the machining tooth wheel; 3 – machining surface; 4 – set of axis that form the plane of diametric cross-section; 5 – set of circles, repeating the trajectory of the initial point of the form-building cutting edge of the tool; 6 – nominal involute tooth profile; 7 – allowance for finishing machining; 8 – form-building cutting edges of the tool; 9 – tool; 10 – initial points of the form-building cutting edge of the tool; 11 – continuation of radius of curvature of involute profile

The treatment of gears is carried out by the set of worm-contour cutters which consist of two pieces (with the front flanks of the cutters being located horizontally-opposed). The treatment is done in two passes.

During the first pass with in-plane movement, for example, downward one of the worm-contour cutters from the set operates and right or left profiles on all teeth are machined.

After the pass “from top downwards” is finished the tool spindle will be located in the second position and another cutter starts operating which treats the opposite profiles with the movement of cutter support “from the bottom upwards”. The direction of rotation of the workpiece in the process of treating opposite profiles is opposite to the direction of rotation during the first pass and analogical to the cutter.

The implementation of the suggested treating method is possible on the existent gear-hobbing machines with NC.

Kinematic synthesis. According to the research results of the cutting force while gear hobbing [2] it was found that cutting forces which appear on every cutting flank of the gear tooth can be calculated on the basis of the material cross-section. In this case most important is to determine intersections of cuts of the several teeth. The cutting speed and feeding make very little impact on the thickness of cuts and arc length of the cuts in the process of gear hobbing. They are determined by geometric parameters of the cutter and the machining gear in most cases.

There are well-known methods of research of surface cross-sections in the process of gear hobbing described in works [1, 2]. The methods allow determining the exact geometry of certain cuts skimmed by the tooth of the hob cutter in various generating positions of the tooth and in radial intersecting surfaces by the trajectory of tooth movement of the hob cutter. But the above-mentioned methods have certain disadvantages which are:

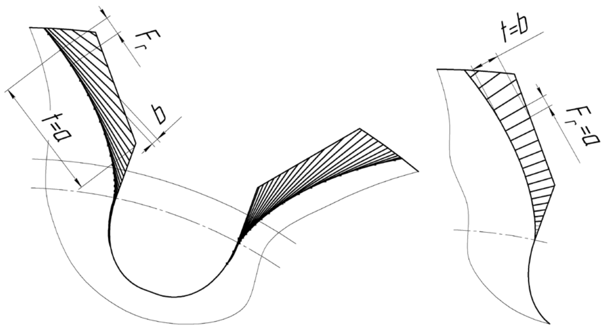
- complexity of regeneration;
- unexpected items for the research of finishing gear hobbing.

Therefore, for this research it is sufficient to consider distribution of surfaces of single cuts while generating the workpiece of infinitesimal thickness on generating rack-type tool and the determination of intersections and the surface of single cuts at every generating position.

The term generating position was introduced as an analogy of the rotary motion of the hob cutter taking into consideration its complex kinematics as the formation of every gear gap on the workpiece is done by cutting the tooth of the cutter into the gap of the workpiece. The necessary condition to determine the numerical value of intersections of cuts is the cutter tooth entrance into the gap which was formed at the previous generating positions.

The research is done under graphic computer simulated conditions. One intertooth gap is machined for conventional gear hobbing and one involute profile is machined for contour gear hobbing. The required original values are fixed according to Fig. 7.

Input parameters of the research are presented in Tables 1...4.



a *b*

Fig. 7. Output parameters of the research:

a – machining of intertooth gap by the method of conventional gear hobbing; b – machining of one involute profile by the method of contour gear hobbing; F_r *– a rotary feed; t – the depth of cutting; a – the width of cuts; b – the thickness of cuts*

Table 1

Cutting modes

Name	Notation	Unit measure	Numerical value
Conventional gear hobbing			
Kinematic rotary feed	F_r	mm/tooth	2.826
Contour gear hobbing			
Kinematic rotary feed	F_r	mm/tooth	1.709

Table 2

Parameters of workpiece

Name	Notation	Unit measure	Numerical value
Number of teeth of a workpiece	z_w	pieces	9
Module	*m*	mm	9
Tolerance for the thickness of tooth	ΔS	mm	2

Table 3

Parameters of hob cutter

Name	Notation	Unit measure	Numerical value
Number of teeth of a cutter	z_c	pieces	14
Module	*m*	mm	9
Number of starts	*k*	–	1
Axial pitch*	P_o	mm	28.274

* see GOST 9324-80 for other sizes of profile of teeth in normal section

Table 4

Parameters of contour hob cutter

Name	Notation	Unit measure	Numerical value
Number of teeth of a cutter	$z_ф$	pieces	20
Number of starts	*k*	–	1
Axial pitch	P_o	mm	28.274

The formula for calculation of cutting force is

$$P = C_p \cdot t \cdot F^{0.75} \cdot V^n,$$

where C_p is const which takes into account the properties of the machining material; *t* is depth of cutting, mm; *F* is rotary feed, mm/rev of the workpiece; V^n is velocity of cutting, m/minute.

If we ignore the influence of the properties of the machining material and the influence of cutting speed, taking into consideration modeling of treatment of similar workpieces under equal cutting speed we may derive the coefficient of cutting force

$$K_p = t \cdot F^{0.75}.$$

The calculated values of the coefficient of cutting force are presented in the form of graph in Fig. 8, *d*, by substituting the value of cutting depth and rotary feed.

Under profile interaction the involute profile is formed as enveloping curve of consecutive positions of teeth of the gear hob while generation. This scheme of generation of geometry is characterized by a considerable cutting width which is proved in Fig. 8, *a*.

Under contour interaction the involute profile is formed as enveloping curve of consecutive positions of material particles (top of cutting edge) of teeth of contour gear hob while generation. The suggested scheme of generation of geometry considerably decreases cutting width (Fig. 8, *a*) but increases cutting thickness as it is shown in Fig. 8, *b*.

As it is seen in graph Fig. 8, *c*, cross-sections of cuts are distributed according to two side cutting edges of the tooth of the gear hob. From proposition $\varphi = 34°$ the side edges operate simultaneously. It is also seen that input edge cuts larger surfaces of cross-sections cuts rather than input edge; the edges are loaded unequally.

Analyzing modeling data of the traditional worm finishing gear hobbing and worm contour gear hobbing we may conclude that the decrease in a cutting thickness under constant area of cutting influences the cutting force less than increase in a cutting width. With less depth the thickness of cutting can appear so small that its influence on cutting force increases considerably. Cutting of micro-thicknesses is connected with the sharp increase in specific force and energy consumption. Decrease in cutting thickness increases the specific force by 2...4 times. In the conditions of usual cutting the least specific forces are provided by the scheme of contour interaction.

The analysis of schemes of cutting allowance and the interaction of cutting edge with machining surface

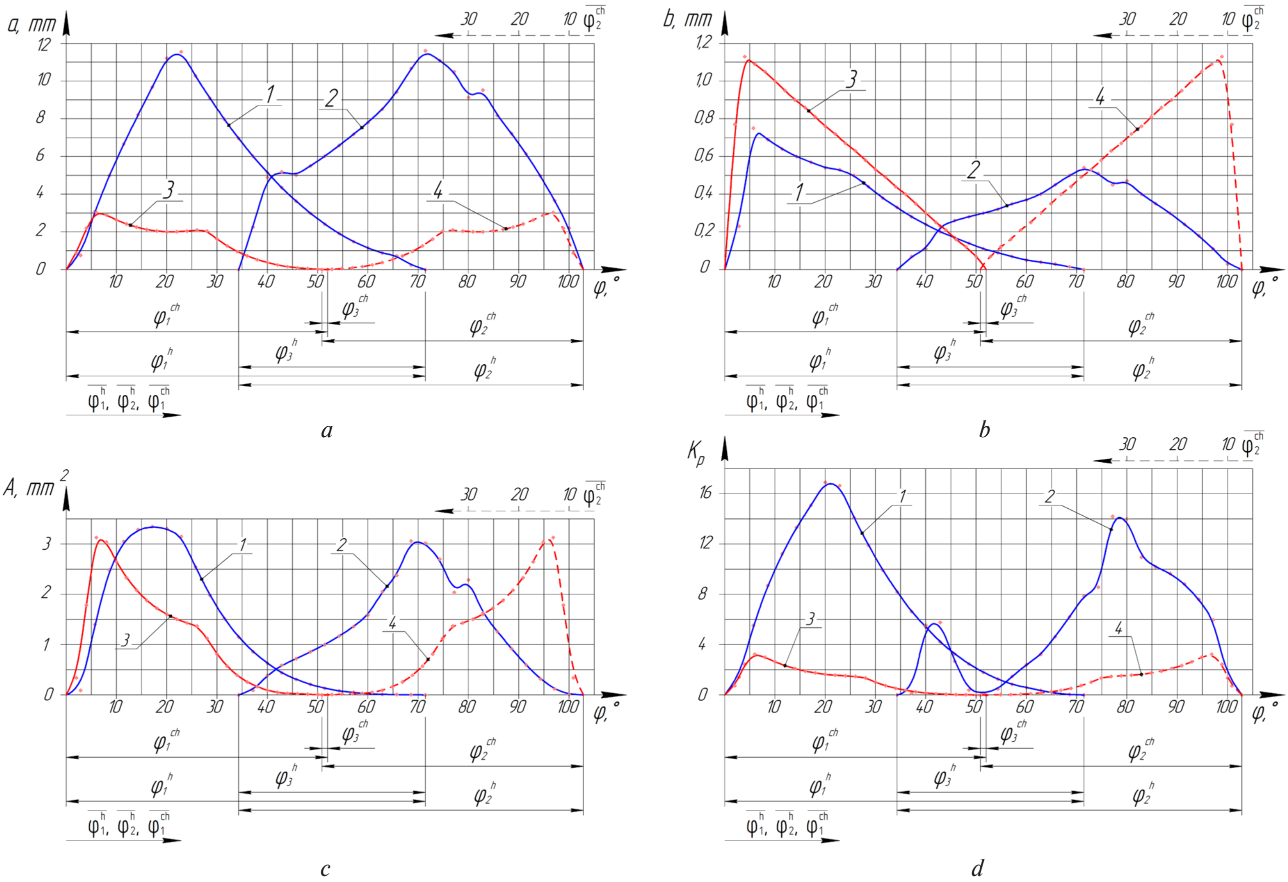


Fig. 8. Results of graphic computer modelling:

a – cutting width; b – cutting thickness; c – cutting area; d – cutting force coefficient; 1 – the input edge, cut-down hobbing; 2 – the output edge, cut-up hobbing; 3 – the right profile, contour gear hobbing; 4 – the left profile, contour gear hobbing; φ – sweep angle of workpiece, degrees; φ_1^h – operation angle of cut-down hobbing; φ_2^h – operation angle of cut-up hobbing; φ_3^h – angle of simultaneous operation of input and output edges of the gear hob; φ_1^{ch} – angle of machining the left profile by contour gear hobbing; φ_2^{ch} – angle of machining the right profile by contour gear hobbing; φ_3^{ch} – angle of conditional simultaneous operation by contour gear hob; $\overline{\varphi_1^h}, \overline{\varphi_2^h}, \overline{\varphi_1^{ch}}, \overline{\varphi_2^{ch}}$ – direction of rotation of the machining workpiece

proves that cutting with a bigger thickness is more profitable rather than cutting with a bigger width. And the most effective is cutting layers with a small thickness with several hundredths of millimeters.

The efficiency of treatment increases if the cutting thickness is leveled or increased. This enables shortening the cutting distance and decreasing energy consumption. As a result, the productivity and tool life increases.

To define the coefficient of relative energy consumption we use the formula of mechanic operation

$$W = P \cdot V \cdot T,$$

where P is force; V is velocity, m/minute; T is time, seconds.

Having equal cutting speed and time (time of machining one intertooth gap) we derive the coefficient of relative energy consumption

$$K_W = \int_{\varphi=0}^{\varphi=\max} K_p(p)dp.$$

The calculated values of the coefficient of relative energy consumption for traditional finishing worm gear hobbing and worm contour gear hobbing are equal; correspondently $K_W = 8.36$ and $K_W = 1.2$, which shows 7 time decrease in energy expenditures.

Conclusion and prospects of further development. The important results of the research include:

- possible variants of interaction of tool cutting edge with machining surface were determined;
- the mathematic model of the cutting processes under various characteristics (geometry) of interaction of cutting edge and machining surface was developed;
- the level number of astatism of single-mass oscillating conservative system was increased due to the change of characteristics (geometry) of interaction of cutting edge with machining surface which is adequate to the introduction of integrating element into the system;
- the method of contour gear hobbing which provides equal cutting conditions for the left and right profiles of the machining gear was synthesized which is impossible to achieve under gear hobbing due to its special

features; the scheme of machining a gear by the set of two contour gear hobs was considered.

The synthesized method has several advantages:

- decrease in energy consumption for the machining process by 6...7 times;

- increase in endurance of machine tool kinematics (due to decrease in cutting force by 4...5 times and the availability of reverse of worm separating gear pair depending on the treatment of the left or right profiles);

- saving of machining time at the level of conventional finishing gear hobbing under two-pass treatment.

References.

1. Hromniuk, S. I. and Hrytsai, I. Ye., 2014. A design of constituents of total error and exactness of gears at the radial-rotatory method of gear cutting. *Journal of National Technical University "Kharkiv Polytechnic Institute": scientific research journal special issue: Problems driven*, 31(1074), pp. 24–28.

2. Antoniadis, A., 2012. Gear skiving – CAD simulation approach. *Computer-Aided Design journal*, 44(7), pp. 611–616.

3. Karpuschewski, B., Knoche, H-J. Hipke, M. and Beutnera, M., 2012. High Performance Gear Hobbing with powder-metallurgical High-Speed-Steel. In: *Procedia CIRP. 5th CIRP Conference on High Performance Cutting*, 1, pp. 196–201.

4. Hyatt, G. A., Piber, M., Chaphalkar, N., Kleinhenz, O. and Mori, M., 2014. Review of New Strategies for Gear Production. In: *Procedia CIRP. 6th CIRP International Conference on High Performance Cutting*, 14, pp. 72–76. Available at <https://www.researchgate.net/publication/263049750_A_Review_of_New_Strategies_for_Gear_Production/> [Accessed 17 May 2017].

5. Stein, S., Lechthaler, M., Krassnitzer, S., Albrecht, K., Schindler, A. And Arndt, M., 2012. Gear hobbing: a contribution to analogy testing and its wear mechanisms. In: *Procedia CIRP. 5th CIRP Conference on High Performance Cutting*, V 1, pp. 220–225. Available at: <http://www.sciencedirect.com/science/article/pii/S2212827112000406 [Accessed 17 May 2017].

6. Pidhaietskyi, M. M., Aparakin, A. R., Skibinskyi, O. I., Kirovohrad National Technical University, 2016. *Method of milling teeth of spur gears with involute profile*. Ukraine. Pat. UA 110741 C2 Ukraine B23F 21/14, B23F 21/16, B23F 5/22.

Мета. Розробка методу чистового черв'ячного зубофрезерування на основі зміни взаємодії різальної кромки інструменту та поверхні, що оброблюється.

Методика. При дослідженні використовується метод абстрагування, на підставі якого зубофрезерування розглядається як взаємодія ріжучої кромки інструменту та оброблюваної деталі. У свою чергу, властивості системи взаємодії ріжучої кромки та оброблюваної поверхні досліджуються завдяки побудованим моделям в умовах комп'ютерного моделювання.

Результати. Висунуті вимоги до методу чистового зубофрезерування. Показані можливі варіанти системи взаємодії ріжучої кромки та оброблюваної поверхні, в умовах комп'ютерного моделювання визначено рівень сталості процесу різання при обумовлених варіантах взаємодії. Розроблена динамічна модель системи взаємодії різальної кромки інструменту та оброблюваної поверхні. Модель враховує характер (геометрію) обумовленої взаємодії, пружність, демпфування та збурення технологічної системи верстат – пристосування – інструмент – деталь (ВПІД). Визначені напрями підвищення рівня астатизму системи.

Наукова новизна. Уперше створено метод моделювання черв'ячного зубофрезерування, при якому реалізовані можливості дослідження взаємодії ріжучої кромки з поверхнею різання, у тому числі й оброблюваною поверхнею, за умови як їх співпадіння, так і не співпадіння. Уперше удосконалено процес чистового черв'ячного зубофрезерування евольвентних поверхонь, при якому поверхня різання не співпадає з обумовленою евольвентною поверхнею, а розташована до неї під кутом.

Практична значимість. Підвищено порядок рівню астатизму одномасової коливальної консервативної системи за рахунок зміни характеру (геометрії) взаємодії різальної кромки та оброблюваної поверхні, що адекватно введенню до системи інтегруючої ланки. Реалізована схема черв'ячного зубофрезерування на базі контурної взаємодії різальної кромки та оброблюваної поверхні.

Ключові слова: *динамічна модель, різальна кромка, астатизм системи, чистове зубофрезерування*

Цель. Разработка метода чистового червячного зубофрезерования на основе изменения взаимодействия режущей кромки инструмента и обрабатываемой поверхности.

Методика. При исследовании используется метод абстрагирования, на основании которого зубофрезерование рассматривается как взаимодействие режущей кромки инструмента и обрабатываемой детали. В свою очередь, свойства системы взаимодействия режущей кромки обрабатываемой поверхности исследуются благодаря построенным моделям в условиях компьютерного моделирования.

Результаты. Выдвинуты требования к методу чистового зубофрезерования. Показаны возможные варианты системы взаимодействия режущей кромки и обрабатываемой поверхности, в условиях компьютерного моделирования определен уровень устойчивости процесса резания при обусловленных вариантах взаимодействия. Разработана динамическая модель системы взаимодействия режущей кромки инструмента и обрабатываемой поверхности. Модель учитывает характер (геометрию) обусловленного взаимодействия, упругость, демпфирование и возмущение технологической системы станок – приспособление – инструмент – деталь (СПИД). Определены направления повышения уровня астатизма системы.

Научная новизна. Впервые создан метод моделирования червячного зубофрезерования, при котором реализованы возможности исследования взаимодействия режущей кромки с поверхностью резания, в том числе и обрабатываемой поверхностью, при условии как их совпадения, так и не совпадения. Впервые усовершенствован процесс чистового червячного зубофрезерования эвольвентных поверхностей, при котором поверхность резания не совпадает с обусловленной эвольвентной поверхностью, а расположена к ней под углом.

Практическая значимость. Повышен порядок уровня астатизма одномассовой колебательной консервативной системы за счет изменения характера (геометрии) взаимодействия режущей кромки и обрабатываемой поверхности, что адекватно введению в систему интегрирующего звена. Реализована схема червячного зубофрезерования на базе контурного взаимодействия режущей кромки и обрабатываемой поверхности.

Ключевые слова: *динамическая модель, режущая кромка, астатизм системы, чистовое зубофрезерование*

Рекомендовано до публікації докт. техн. наук В. І. Носуленком. Дата надходження рукопису 21.04.16.

UDC 622.625.28

V. P. Franchuk, Dr. Sc. (Tech.), Prof.,
K. A. Ziborov, Cand. Sc. (Tech.), Assoc. Prof.,
V. V. Krivda, Cand. Sc. (Tech.), Assoc. Prof.,
S. O. Fedoriachenko, Cand. Sc. (Tech.), Assoc. Prof.

State Higher Educational Institution "National Mining University", Dnipro, Ukraine, e-mail: franchuk@nmu.org.ua

ON WHEEL ROLLING ALONG THE RAIL REGIME WITH LONGITUDINAL LOAD

В.П. Франчук, д-р техн. наук, проф.,
К.А. Зіборов, канд. техн. наук, доц.,
В.В. Крівда, канд. техн. наук, доц.,
С.О. Федоряченко, канд. техн. наук, доц.

Державний вищий навчальний заклад „Національний гірничий університет", м. Дніпро, Україна, e-mail: franchuk@nmu.org.ua

ПРО РЕЖИМ КОЧЕННЯ КОЛЕСА ПО РЕЙКАХ ЗА НАЯВНОСТІ ПОЗДОВЖНЬОГО НАВАНТАЖЕННЯ

Purpose. Determination of the functional correlation between power (tangential reaction) and kinematic (relative slip) parameters during nonstationary rectilinear motion of the rail wheel along the rail.

Methodology. An analytical model of the interaction between the wheel and rail on an elementary contact area taking into account the presence of normal and shearing load (thrust or braking mode) is developed. Using the analytical model, a qualitative relationship that reflects the features of the friction contact of a wheel-rail pair for various operating conditions is obtained considering the nature of the interaction of the contacting pair, which significantly differs. The mathematical description of the process is based on experimental studies of the dependence of the tractive force on the speed of relative motion (incomplete slippage - the so-called creep mode, failure of adhesion and total sliding, which leads to decrease in traction force) of D. K. Minov and A. A. Renhevych.

Findings. On the basis of theoretical studies of the parameters of vehicle motion along the rail track, a mathematical model of the tangential reaction realization by wheel in the case of nonstationary rectilinear motion is formulated. The functional relationship between the power and kinematic parameters is established, which allows predicting the operational properties and solving the problems of the dynamics of rail transport with a higher degree of accuracy.

Originality. Taking into account inelastic resistance of contacting bodies, analytical dependences are obtained to determine the current value of the force at the contact area upon the availability of longitudinal load. The interaction conditions under which the deformation can occur both within the elasticity of the materials of the contacting bodies and the violation of the surfaces contact are considered. Approximating dependences of tractive effort on the relative speed of wheel and rail movement are proposed for locomotives.

Practical value. Knowledge of the processes occurring in the contact area while transferring the torque from the wheel of the locomotive to the rail will facilitate finding the correct solution to the problem of interaction between the wheel-rail system of mining rail transport in complex mining and geological operational conditions. It helps to increase the efficiency of torque transmission at the quasi-stationary mode of vehicle movement.

Keywords: *longitudinal load, contact spot, stress, creep, rail transport*

Introduction. As an executive device of the traditional tractive unit of mine locomotive a wheel is used, acting as a friction pair by interacting with the rail. The parameters of the wheel pair must meet the requirements of optimality both from the position of performing the functions of the support element – to perceive and transfer the weight of the locomotive to the support surface and the traction drive element – to create a trac-