UDK 621.833(088.8)

TO GEOMETRY, KINEMATICS AND PIN INFLEXIBILITY OF TEETH OUT CENTROID ENGAGEMET OF PLANETARY-ROTOR HYDROMOTORS

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Some questions of geometry and kinematics of the trohoid hooking of planetary-rotor hydromotor are considered. Pin inflexibility of points, necessary for opening of static vagueness at the decision of task about distribution of the normal loading among points, is determined.

Key words: trochoid hooking, geometry, kinematics, pin tensions, inflexibility of indents.

Entry. Last years interest in planetary-rotor hydromotors grew considerably, that was explained, from one side by perfection of geometry and technology of making of gear-wheels, making and on the other hand - by the row of their advantages before other types of hydromotors, such as, simplicity of construction, subzero unevenness of circulating moment, high starting moment, small sizes and weight. The basic working element of planetary-rotor hydromotors, making working chambers of variable volume, is a toothed pair of the internal hooking with the difference of teeth of gear-wheels that catch, equal to one. In such hooking the profile of tooth of one of gear-wheels is outlined by equidistant of epi - or gipotrochoids, and second - by the arc of circle. Epi - and gipotrochoids appear as trajectories of points related to the movable circle that is rolled without skidding on an immobile circle. Points that form the initial trochoid profile of indents always lie out of centroid, that is why hooking got the name outcentroid. The farther a point that outlines, from movable productive circumference, the more trochoid hooking, that is characterized by the coefficient of centroid [8] (in future coefficient K).

$$K = \frac{R_c}{R} = \frac{R_c}{ez} \qquad (1)$$

where - R_c is a radius of circle of location of indents centers of z with a circular profile; e - is an excentricity of toothed pair.

The choice of coefficient K substantially influences the geometry of teeth profiles. On fig. 1 formation of teeth profiles of the epitrochoid hooking is shown.

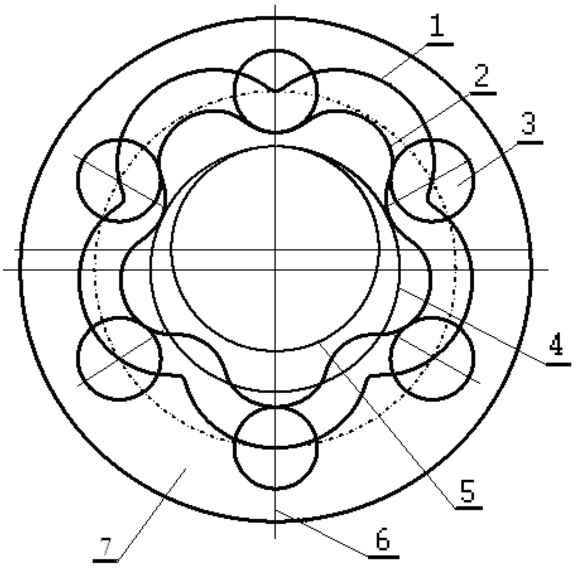


Fig. 1. Formation of teeth profiles of the epitrochoid hooking.

At a rolling-off, without skidding, of movable centroid 4 of outside immobile centroid 5, gear-wheel 7 with the teeth of circular profile 3, tightly coupled with centroid 4, carries out planetary motion, here centers of teeth 3 describe the branches of epitrochoid 1. The practical profile of teeth is outlined by equidistant 2 of epitrochoids 1, id est it is from an epitrochoid in the distance of the radius of tooth 3 with a circular profile.

On fig. 2 formation of teeth profiles of the outcentroid gipotrochoid hooking is shown.

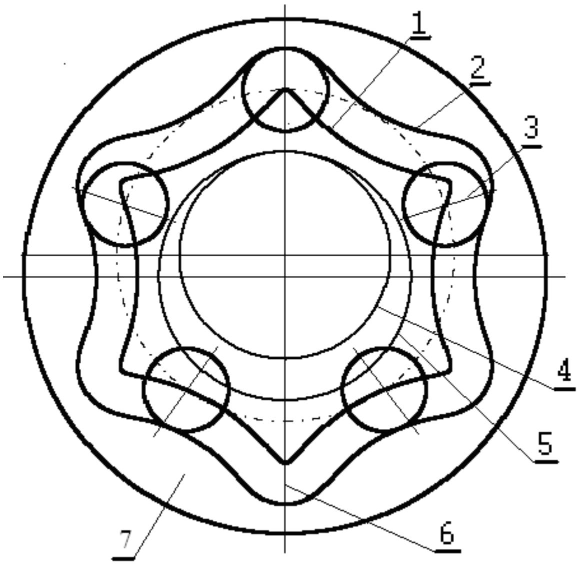


Fig. 2. Formation of teeth profiles of the gipotrochoid hooking.

At a rolling-off, without skidding, of movable centroid 4 in the middle of immobile centroid 5 gear-wheel with the teeth of circle profile 3, tightly coupled with centroid 4, carries out planetary motion, here centers of teeth 3 describe the branches of gipotrochoid 1. Practical profile of teeth, gear-wheel 7, outlined by equidistant 2 of gipotrohoid 1, that is it is from gipotrochoid in the distance of the radius of tooth 3 with a circular profile.

Number of branches of epitrochoids 1 and epitrochoid teeth 2 is always one less than number of teeth 3 with a circular profile (fig.1), and number of branches of gipotrochoid 1 and gipotrochoid teeth 2 is always one more than number of teeth 3 (fig. 2). The main distinctive feature of geometry of such hooking is a simultaneous binary touch of all teeth of internal and external gear-wheels, that are theoretical pre-condition for creation of the reserved volumes of working chambers, located between two contiguous pairs of teeth. It is necessary for work of hydromashine, that the working chambers of festering and weathering were situated for different parties of line of centers 6 (see fig. 1 and 2).

Problem. To research of geometry of extracentroid toothed hooking with the profiles of teeth of one of gear-wheels, outlined by eqiudistant of epi- or gipotrochoid, and constrained - by the arc of circle, a number of works is devoted [1, 2, 4, 5, 6 and other]. In the indicated works the questions of geometry of hooking are examined with epi- and gipotrochoid profiles of teeth, as a rule, separately. Thus different parameters that are not general for both the curves are fixed in basis of leadingout of equalizations of epi- and gipotrochoid. Often these parameters are even unconnected directly with the geometrical parameters of hooking, such as: number and radius of teeth with a circular profile; coefficient K; corner that characterizes position of tooth in relation to a pole. Such approach does not result in community of calculation dependences and hampers the comparative analysis of hooking with epi- and gipotrochoid profiles. Epi- and gipotrochoid belong to one family of cyclic curves. Both the curves find application during profiling of teeth of this hooking, that is why it is expedient to examine them jointly. For the receipt of general equalizations, as epi- so gipotrochoid profiles of teeth, it is necessary to educe parameters that are general for both the curves. In addition, these parameters should be set so that they simultaneously were the parameters of hooking, characterizing its main distinctive features.

Results of researches. In the trochoid hooking, radiuses of centroids (initial circles) are equal to product of excentricity of *e* on the numbers of teeth of cog-wheels that catch. So radius of movable centroid R=ez, where *z* is a number of general tangencies of the united gear-wheels (in the real hooking this is a number of teeth with the profile outlined by the arc of circle). Radiuses of centroids that belong to the gear-wheels from epi- and gipotrochoid profiles of teeth are accordingly.

$$R_E = e(z-1); \quad R_G = e(z+1). \qquad (2)$$

From the brought dependences it is seen, that a parameter is general both for epi- and gipotrochoids. An excentricity of toothed pair in this hooking actually is a scale factor and also is a general parameter for both the curves. It is expedient to accept the radius of location of gear-wheel teeth centres with a circular profile $R_c = ezK$, where K > 1 is a cofficient of extracentroid hooking as the third general parameter. On fig. 3 the chart for the leadingout of the generalized equalizations of epi- and gipotrochoids is given. At the leadingout of equalizations of trochoids as an independent in-out parameter usually is accepted corner γ (fig. 3), that characterizes position of instantaneous center of centroid rotation corresponding position of pole of hooking P. This corner at formation of epi- and gipotrochoid changes in different intervals. So, at formation of one branch of epitrochoid a corner changes in an interval $(0 \le \gamma \le 2\pi(1+1/z))$, and at formation of one branch of gipotrochoid и - in an interval $(0 \le \gamma \le 2\pi(1-1/z))$, thus, a corner γ can not be accepted as a general parameter at the leadingout of equalizations of both the curves. By a general parameter at formation as epi- so gipotrochoid is a corner τ, that characterizes position of the profiling point related to movable centroid, and that changes at formation of both curves in an interval $0 \le \tau < 2\pi$ (see fig. 3). On fig. 3 two immobile productive circumference is shown, with the radiuses of $R_G = e(z+1)$ and $R_E = e(z-1)$, and also one movable (formative) with a radius $R = ez$. At a rolling-off without skidding of movable centroid of radius R on one of immobile centroid R_G or R_E, a point M, is hardly related to movable centroid R, and located in the distance $R_C = Kez$ from the center of *Oc*, will describe accordingly epi- or gipotrochoid. Using selected parameters and as corners γ and τ are bound by dependence of $\gamma = z\tau$, the generalized equalizations for epi- and gipotrochoid in the system of coordinates of XOY on the basis of fig. 3 will be [7]

$$x = e\left(Kz\cos\tau \mp \cos z\tau\right);\quad y = e\left(Kz\ \sin\tau - \sin z\tau\right). \qquad (3)$$

Here in future overhead signs touch to epi-, and lower to gipotrochoid.

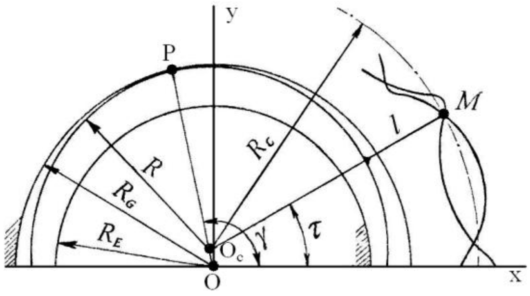


Fig. 3. Chart to the conclusion of the generalized equalizations of epi- and gipotrochoid.

On the basis of expressions (3), equalization of epi- and gipotrochoid in polar coordinates will be presented as

$$\rho = e\sqrt{K^2z^2 + 1 \mp 2Kz\cos z_T\tau};\quad \varphi = arctg\left[\left(Kz\cos\tau \mp \cos z\tau\right)/\left(Kz\sin\tau - \sin z\tau\right)\right], \qquad (4)$$

where $z_T = z \mp 1$ is a number of branches of trochoids, equal to the number of teeth with a trochoid profile in the real hooking. Equations (I) describe epi- and gipotrochoids, that are situated in relation to the system of coordinates so that beginning of one of their branches coincides with abscise axis. In a number of cases for simplification of geometrical calculations it is more comfortable to use equations, that describe the trochoids, located so that not beginning of their branches, but middle coincides with abscise axis. In this case equations of trochoids look like

$$x = e\left(Kz\cos\tau \pm \cos z\tau\right);\quad y = e\left(Kz\sin\tau + \sin z\tau\right). \qquad (5)$$

Equations of the same curves in polar coordinates look like

$$\rho = e\sqrt{K^2z^2 + 1 \pm 2Kz\cos z_T\tau};\ \varphi = arctg\left[\left(Kz\cos\tau \pm \cos z\tau\right)/\left(Kz\sin\tau + \sin z\tau\right)\right] \qquad (6)$$

The real practical profile is executed by equidistant theoretical, outlined by trochoid. It will defend from the theoretical on a size radius of r_C of the conjugating teeth outlined by the arc of circle. Equation of coordinates of profiles of the teeth outlined by equidistant of epi- and gipotrochoid will be found in formulas [3]

$$x_E = x \pm r_C y' \Big/ \sqrt{\left(x'\right)^2 + \left(y'\right)^2};\quad y_E = y \pm r_C x' \Big/ \sqrt{\left(x'\right)^2 + \left(y'\right)^2}. \qquad (7)$$

Differentiating equation (3) for parameter of τ, find

$$x' = -Kez\sin\tau \pm ez\sin z\tau;\quad y' = Kez\cos\tau - ez\cos z\tau. \qquad (8)$$

Putting the found values of derivatives in formulas (7) after transformation we will det

$$x_E = e\left(Kz\cos\tau \mp \cos z\tau\right) \mp r_C\,\frac{K\cos\tau - \cos z\tau}{\sqrt{K^2 + 1 - 2K\cos z_T\tau}};$$

$$y_E = e\left(Kz\sin\tau - \sin z\tau\right) \mp r_C\,\frac{K\sin\tau \mp \sin z\tau}{\sqrt{K^2 + 1 - 2K\cos z_T\tau}}. \qquad (9)$$

Thus, equations (9) allow at the known parameters e, z, r_c analytically build the profiles of teeth, that is outlined by equidistant both epi- and gipotrochoid. These parameters are general for both the curves and simultaneously are the parameters of hooking, simply and fully characterize their geometry.
It is more comfortable to use equations of equidistants of trochoids, when not beginning of trochoid branches, but its middle coincides with abscise axis. Equations of equidistants of trochoids look like in this case

$$x_E = e(\hat{E}z\cos\tau \pm \cos z\tau) \mp r_C \frac{\hat{E}\cos\tau \pm \cos z\tau}{\sqrt{\hat{E}^2 + 1 + 2\hat{E}\cos z_T\tau}};$$
$$y_E = e(\hat{E}z\sin\tau + \sin z\tau) \pm r_C \frac{-\hat{E}\sin\tau \mp \sin z\tau}{\sqrt{\hat{E}^2 + 1 + 2\hat{E}\cos z_T\tau}}. \qquad (10)$$

At research of loading ability of hooking it is necessary to know the brought radiuses of curvature of contacting surfaces of teeth. In this hooking the teeth of one of gear-wheels are outlined by the arc of circle, and connected by equidistant of trochoid, that is in first case teeth have a permanent radius of curvature, and in the second - variable. Thus a trochoid always has protuberant and concave parts, thus has an inflectionpoint in that a radius equals endlessness. It is known that the criterion of loading of active surfaces of teeth is contact of tension. At the calculations of pin tension, by the known formula of Hertz for the contact of two cylinders with parallel axes, it is necessary to know the brought radiuses of curvature of contacting teeth. The brought radius of curvature, both at the external and at internal touch of profiles, can be defined by a formula [7]

$$\rho_{\text{пр}\,i}(\theta) = r_C\left[1 - \frac{r_C(\pm\hat{E}^2 - \hat{E}(\pm 1)\cos\beta_i(\theta))}{ez(\hat{E}^2 + 1 - 2\hat{E}\cos\beta_i(\theta))^{3/2}}\right], \qquad (11)$$

where $\beta_i(\theta) = \theta + \frac{2\pi}{z}i$; i – sequence number of this pair of indents, counting from a hooking pole; $(0 \le \theta \le 2\pi/z)$ is a parameter a setting i position of center of the first circular tooth in relation to the pole of hooking (corner between the line of centers and radius of circle of centers of circular indents, that passes through the nearest to the pole of hooking center of tooth with a circular profile).
Got formula, allows to find the brought radiuses of curvature of pair of teeth depending on its position in relation to the pole of hooking. At calculations of the brought curvature radiuses by a formula (11) there is no need of taking into account their signs depending on the external or internal touch of teeth profiles. It eliminates errors that arise up at determination the brought radiuses of curvature near-by the inflectionpoints of trochoids also, when a denominator in a formula for determination of curvature radius of trochoid aspires to the zero, and radius of curvature of trochoid

- to endlessness [7]. From structural considerations, and also from considerations of technologicalness usually the minimum radius of cylindrical teeth $r_c \geq 2e$ is accepted. The maximal radius of cylindrical teeth is limited to the condition of absence of paring of the profiles outlined by equidistant of trochoid. Checking of profile for paring, is made by formula [1].

$$\rho_{Э\min} = \rho_{T\min} - r_c > 0, \tag{12}$$

where $\rho_{T\min}$ и $\rho_{Э\min}$ are minimum radiuses of curvature of trochoid and its equidistant. The minimum radius of trochoid curvature of is determined by a formula

$$\rho_{T\min} = \frac{ez\left[z_T\left(K^2-1\right)\left(z\pm1\right)\right]^{3/2}}{z_T\left(K^2-1\right)} \tag{13}$$

It goes out from a formula (13), that the minimum radius of curvature of trochoid is determined only by the choice of hooking parameters *e*, *z* and *K*. On fig. 4 graphic dependences of relative size of minimum radiuses of trochoids curvature $\rho_{T\min}/e$ on the numbers of teeth z_T for the different values of coefficient К are given(by continuous lines the represented dependences for епі-, and dotted - for gipotrochoid).

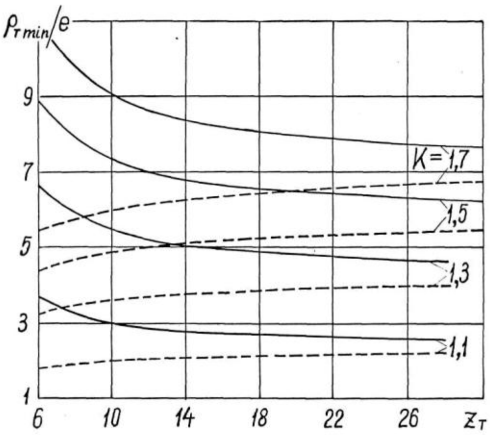


Fig.4. Graphic dependence of relative size of minimum radiuses of trochoids curvature $\rho_{T\min}/e$ from the numbers of indents z_T for the different values of extracentroid coefficient К (dependences for gipo-, are shoown by solid lines and dotted - for epitrochoid).

Graph analysis shows, that at the small values of z_T size of minimum radiuses of curvature gipo- and epitrochoids differ substantially. At the increase of numbers of teeth a difference becomes unimportant. Thus, at the small numbers of teeth more advantageous, from the point of view of pin durability, is the gipotrochoid hooking. At the calculations of hooking on durability on pin tension there is a necessity for determination of the normal loading. A task on determination of the normal loading is statically indefinable, as more than two pairs of teeth simultaneously participate in a contact. For opening of static vagueness it is necessary to know inflexibility of teeth. If to ignore deformations of bodies of gear-wheels, then at determination of pin deformations of teeth it is possible to take advantage of the known decision of task of resiliency theory about resilient rapprochement of bodies with parallel cylindrical surfaces. For this case A.I. Petrusevich got the dependence, that determines rapprochement between two points that are in the distance r_{c1} and r_{c2} from the zone of contact. For this case the indicated dependence will be presented in a kind

$$\varepsilon_i = \frac{2q_i(1-\mu^2)}{\pi E}\ln\frac{2\pi E r_{ñ}(\rho_{ýi} \pm r_c)}{q_i(1-\mu^2)\rho_{ýi}}, \qquad (14)$$

where q_i – is the specific normal loading on i tooth, counting from a pole of hooking; E and μ is the module of resiliency and coefficient of Puasson; r_c and $\rho_{ýi}$ – are radiuses of curvature of cylindrical teeth and i- tooth, outlined by trochoid equidistant (sign " +" at the external touch of profiles, and a sign of "–" is at internal); $r_c = r_{c1} = r_{c2}$ it is distance to the base points among wich a convergence is observed. Inflexibility equals the attitude of force toward the elastic moving, caused by this force. Thus, in this case inflexibility of teeth

$$C_i = \frac{\pi E}{2(1-\mu^2)\ln\frac{2\pi E r_c(\rho_{ý} \pm r_c)}{q_i(1-\mu^2)\rho_{9i}}}. \qquad (15)$$

Taking into account, that the specific normal loading is included in a formula (15) under the sign of logarithm, then an error at their determination even in two times will change pin inflexibility of teeth insignificantly. In the first approaching specific normal loading, necessary for calculations of teeth inflexibilities, is possible to determine from the condition of equality of pin tension in all contacting pairs of teeth on the known formula of theory of resiliency, that looks like for our case [8]

$$q_i = W\sigma_{H\lim}^{2}\rho_{ïði} \qquad (16)$$

where $W = \pi[E_2(1-\mu_1^{2}) + E_1(1-\mu_2^{1})]/E_1E_2$; $\sigma_{H\lim}$ - limit of pin endurance;

E_1, E_2 и $\mu_{1,}\mu_2$ - modules of resiliency and coefficients of Puasson of teeth materials ; $\rho_{ïði}$ - given radius of curvature of i pair of teeth ;

At $E_1 = E_2$ and $\mu_1 = \mu_2$ dependence for determination of value of W is simplified

$$W = 2\pi(1-\mu^2)E \qquad (17)$$

For example, at $E_1 = E_2 = 2{,}1\cdot 10^5$ MPa and $\mu_1 = \mu_2 = 0{,}3$ have

$$W = 2\pi(1-0{,}3^2)2{,}1\cdot 10^5 = 2{,}72\cdot 10^{-5} \text{ МПа}^{-1}$$

It is known that at hardness of teeth *HB* > 350 limit of pin endurance is related to hardness of teeth by next dependence

$$H_{HRC} = 2{,}38\cdot 10^{-2}\sigma_{H\lim} \qquad (18)$$

Thus, at hardness of indents $H_{HRC} = 60$, that is appointed for teeth of rotor, there can be the accepted limit of pin endurance

$$\sigma_{H\lim} = 60/2{,}38 \cdot 10^{-2} = 2521 \,\text{MPa}$$

Taking into account the value of $\sigma_{H\lim} = 2521$ MPa and value of $W = 2{,}72 \cdot 10^{-5}$ MPa specific normal loading, necessary for determination inflexibilities of teeth

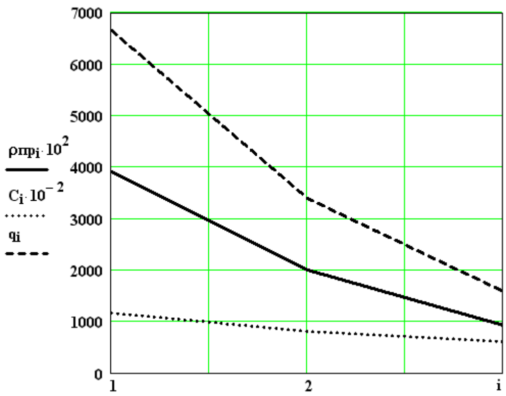
$q_i = 2{,}72 \cdot 10^{-5} \cdot 2521^2 \rho_{ïði} \approx 170 \cdot \rho_{ïði}$ Н/мм On fig. 5, a, b , c, d there are graphic dependence of the brought radiuses of curvature, inflexibility of teeth and customs possible loading on teeth. Calculations are executed for hooking with the number of cylindrical teeth of *z*=6 (fig.5 a, b) and *z*=10 (fig.5 c, d), radiuses of cylindrical teeth of *r*=2e, to the excentricity of e = 1мм and coefficients of *К* = of 1,25 (fig. 5,a, c) and of *К*=1,5 (fig. 5, b,d). It’s evident from the graphs, that with the increase of coefficient from К=1,25 to К=1,5 the specific brought radiuses of curvature, specific loading and inflexibility of teeth diminishes more than three times, that testifies to considerable influence of coefficient К on loading possibility of hooking. Longevity of hooking substantially depends on speed of skidding and acceleration of teeth of rotor. At planetary move of rotor, surface of performances of its z teeth that are located on the radius of *R* = *ezК* slide on the teeth of stator. Relative speed of points of rotor, that lie on the circle of radius of *R*=*ezК* will be found by dependences [3]

$$\upsilon = \sqrt{\upsilon_x^2 + \upsilon_y^2}\,, \tag{19}$$

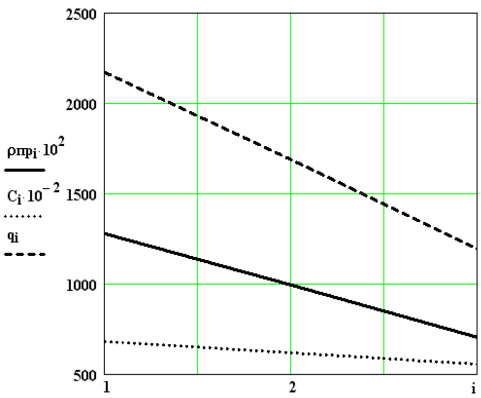
где $\upsilon_x = \dfrac{dx}{dt} = \dfrac{dx}{d\tau}\dfrac{d\tau}{dt} = \omega\dfrac{dx}{d\tau}$; $\upsilon_y = \dfrac{dy}{dt} = \dfrac{dy}{d\tau}\dfrac{d\tau}{dt} = \omega\dfrac{dx}{d\tau}$.

Equalizations of gipotrochoid look like for this case

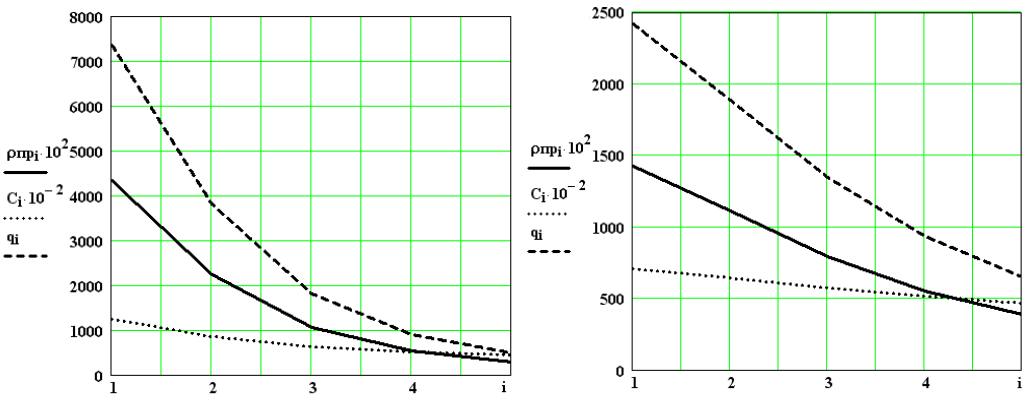
$$x = e(Kz\cos\tau + \cos z\tau); \qquad y = e(Kz\ \sin\tau - \sin z\tau). \tag{20}$$



a)



b)



c) d)

Fig. 5. Graphic dependence of the brought radiuses of curvature $\rho_{iði}$, of inflexibility of teeth C_i and specific possible loading on teeth . Calculations are executed for hooking with the number of cylindrical teeth of z=6 (a,b) and z=10 (c, d), radiuses of cylindrical teeth of r=2e, to the excentricity of e = 1mm and coefficients of K = 1,25 (a, c) and of K=1,5 (b,d)

Differentiating equalization of gipotrochoid (20) on the parameter τ we find component of speeds along the axes of x and y

$$\upsilon_x = -\omega e\left(z\sin\tau - \sin z\tau\right); \quad \upsilon_y = \omega e\left(z\cos\tau - \cos z\tau\right).$$

(21) Putting the found values of derivatives in a formula (19), after transformations will get

$$\upsilon = e\omega\sqrt{K^2 + 1 - 2k\cos z\tau} \tag{22}$$

Differentiating a function (21), will be found the acceleration of points that lie on the circle of radius of $R= ezK$ by an analogical method

$$W = e\omega_1^2\sqrt{K^2 + z^2 + 2zK\cos z\tau} \tag{23}$$

Fig. 6 gives relative speeds $Vi/e\omega$ and acceleration $Wi/e\omega^2$ of rotor teeth performances, that lie on the circle of radius $R=eKz$, that are calculated from dependences (22) and (23) for the toothed hooking with the number of teeth z = 6 and by the coefficients of K = 1,05 (Rice.6, a, б) and K = 1,85 (Rice. 6 c,d) at the change of parameter τ in limits $0 \le \tau \le 2\pi$ id est for one cycle of work of hydromotor, when the pole of hooking does one turn.

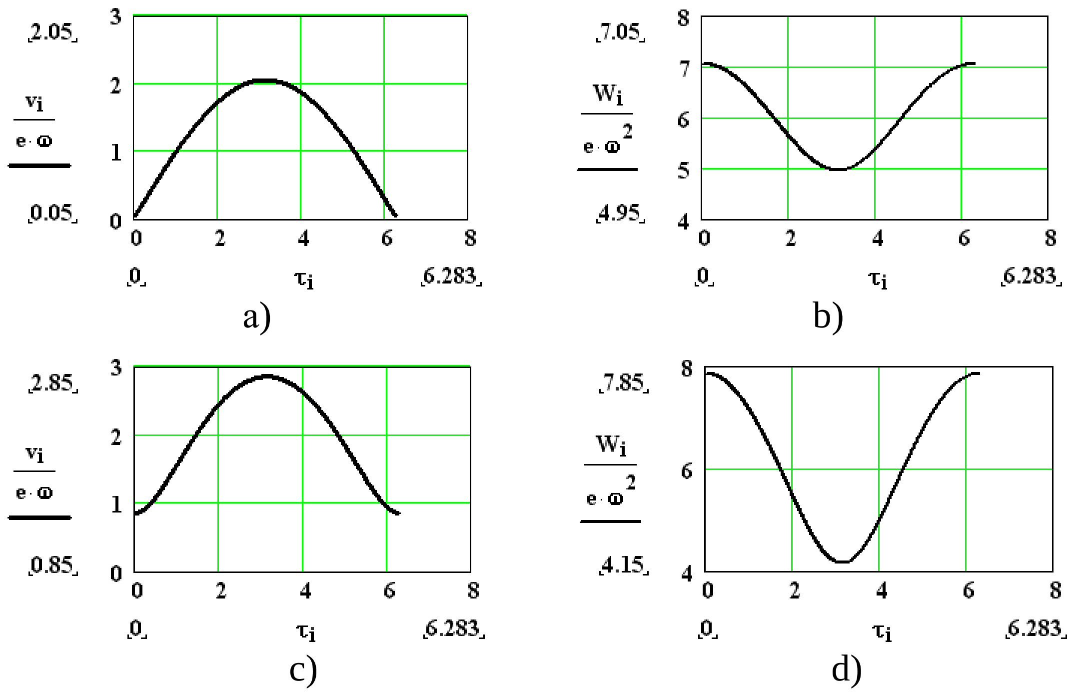


Fig. 6. Graph of dependences of relative speed of Vi/eω and relative acceleration *Wi/eω²* of performances of rotor teeth, in extracentroid hooking with the number of teeth z = 6 and by the coefficients K = 1,05 (a, b) and K = 1,85 (c, d).

From charts it is evidently that with the increase of coefficient K from K=1,05 to K=1,85 high relative speed grows from *Vi/eω* = 2,05 to 2,85 relative units, and a relative acceleration grows from *Wi/eω²* = 7,05 to 7,85 relative units.

Conclusions. A paper gives the rationale of application, as basic geometrical parameters, of the trochoids hooking, number of cylindrical indents of z and their radius of *r*, coefficient K, excentricity of toothed pair of e, and also parameter, that characterizes position of profiling point or pole of hooking and changes at formation both epi- and gipotrochoid in the same interval $0 \le \tau \le 2\pi$. Some questions of geometry and kinematics of the trochoid hooking are considered, in particular, brought radiuses of curvature are determined, as well as possible normal loading on teeth and their inflexibility that can profit at opening of static indefinableness at the normal loading on teeth.

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К ГЕОМЕТРИИ, КИНЕМАТИКЕ И КОНТАКТНОЙ ЖЕСТКОСТИ ЗУБЬЕВ ВНЕЦЕНТРОИДНОГО ЗАЦЕПЛЕНИЯ ПЛАНЕТАРНО-РОТОРНЫХ ГИДРОМОТОРОВ

Шевцов Е.Н.

Ключевые слова: внецентроидное зацепление, геометрия, кинематика, контактные напряжения, жесткость зубьев.

Резюме

Рассмотрен некоторые вопросы геометрии и кинематики внецентроидного зацепления планетарно-роторного гидромотора. Определено контактную жесткость зубьев, необходимую для раскрытия статичной неопределенности при решении задачи о распределении нормальных нагрузок среди зубьев.

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Shevtsov E.N.

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Sammary

Some questions of geometry and kinematics of the trohoid hooking of planetary-rotor hydromotor are considered. Pin inflexibility of points, necessary for opening of static vagueness at the decision of task about distribution of the normal loading among points, is determined.