On the Synthesis of Spatial Rack Drives Having Rotating Cylindrical Curvilinear Helicoids

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***Abstract*—The process of creating spatial mechanical transmissions, in which one of the movable links is equipped with helical surfaces, is accompanied by a permanent desire to choose the optimal geometry of the helicoid from a technological (manufacturing) and operational viewpoint. In other words, approaches are searched to reduce the cost of tooth surfaces' generation on one hand and on the other hand to increase the loading capacity, durability, and efficiency of the transmissions. An object of the study is a three-link spatial rack mechanism realizing transformation of type rotation into translation by using conjugated high kinematic joints. Based on the worked-out mathematical model, it is synthesized a surface of action, mesh region respectively, of a transmission which geometric elements of the joints, firmly connected with the rotating link, are curvilinear helicoids.**

***Index Terms*—rack drives, mathematical modeling, synthesis, cylindrical curvilinear helicoid, action surface**

I. Introduction

The development of industrial manufacturing of machines, vehicles, robots, and manipulators, that require the usage of different types of gear mechanisms to transform the mechanical motions, demands speed and efficiency in their manufacturing and application into practice. Their extended usage creates a necessity to develop and refine the scientific-applied research, oriented to the synthesis and design of new types of gear transmissions to meet the demands of the practice in the best way. Significant acceleration of the solution of these tasks is achieved by the application of the methods of mechanical - mathematical modeling, considering the geometric and kinematic characteristics of transmissions.

Institute of Mechanics – Bulgarian Academy of Sciences is a major scientific center in Bulgaria, in which for decades scientific and applied research in the field of spatial mechanical transmissions are carried out. These studies [1], [2], dedicated to the synthesis and design of new and improved gear types, contribute to the creation of original, as geometric concepts, high-reduction motion transformers.

Among those studies, are the articles [3]-[5] oriented to the synthesis of spatial motion transformers, called rack drives, which main purpose is to realize motions transformation of type rotation into translation. The successful implementation into the techniques, of these mechanisms with new kinematic and strength characteristics is slowed down by the insufficient studying of the general principles of this transformation, due to the lack of offered specific approaches to mathematical modeling, oriented to their synthesis.

The existing in the specialized literature studies, dedicated to the science of gearing theory [1], [6]-[10] and those – that treat the science of geometric synthesis of gear mechanisms [11]-[16] consider the processes and devices, which are related to the rotation transformations between crossed, parallel and intersected shafts. And the number of publications about three-link gear systems that are called rack drives is insignificant.

In popular literature sources, rack meshing is treated as instrumental meshing when cylindrical involute gears (with straight or helical teeth) are generated. In this case, the link, which purpose is a translation motion of the rack drive, is the cutting tool, called an "instrumental tool rack" [17]-[19].

The rack transformers are object of the study in [20]. There, the kinematics of the plane rack mechanisms, called "rack cylindrical mechanisms" is briefly explained. The technological structure and geometrical parameters of the non-spatial rack mechanism and the cylindrical straight-teeth gears are considered in [20]. It is defined the algorithm of geometrical synthesis and technological limitations on the geometric parameters of these mechanical transmissions. The special type gear mechanism, realizing a variable function of motion transformation of type $R \leftrightarrow T$ (rotation into translation) is studied in [21]. A theory is offered, which is illustrated by a defined calculation, design, and manufacture of an experimental model. An analysis of "Wildhaber - Novikov" is fulfilled in publication [22]. There, an analysis of the tooth contact and calculation of Hertz contact strength is accomplished. Another research in the field of rack drives [23] is dedicated to the geometric design, meshing simulation, and stress analysis of pure rolling rack and pinion mechanisms.

The current theoretical study is a continuation of the author's consistent and detailed studies in the kinematic and geometric theory of spatial three-link rack mechanism, which realizes the transformation of type rotation into translation. In particular, the efforts are dedicated to the basic synthesis of spatial rack drives which rotating link has cylindrical circular helicoids. It

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includes the solution of the following tasks: synthesis of the helicoids with a generatrix - an arc of a circle, synthesis of the mesh region, and synthesis of the active tooth surfaces of the gear rack, which are conjugated with the generated helicoids.

II. Synthesis of Rack Transmissions Having Cylindrical Curvilinear Helicoids

The process of creating three-link spatial mechanical transmissions, in which one of the movable links is equipped with helical surfaces, is accompanied by a permanent desire to choose the optimal geometry of the helicoid from a technological (manufacturing) and operational viewpoint. In other words, approaches are searched to reduce the cost of tooth surfaces' generation and to increase the loading capacity, durability, and efficiency of these transmissions.

One approach in this direction is the transition from linear [24] to curvilinear helicoids, in their capacity as tooth surfaces [6], [7], [11].

In the theoretical and applied aspect, the main place among the helical surfaces belongs to the ordinary helical surfaces (cylindrical helicoids) [7], [25]. Depending on the type of generatrix line, helical surfaces are linear when the generatrix is a straight line and curvilinear (for example, in gear set of type "Novikov" - as tooth surfaces are used helicoids generated by an arc of a circle). The synthesized helicoids are applicable as active tooth surfaces of the rack drives.

A. Synthesis of Cylindrical Circular Helicoids Σ_c

It is considered a helicoid, that is formed by the right-handed motion of the generating circle C_I with a parameter $p_s = constant$ in the coordinate system $S_p(O_p, x_p, y_p, z_p)$ as the applicate axis $O_p z_p$ is the axis of the helical motion (See Fig. 1). Let's in the coordinate system S_p, the directed cylinder C_0 with the directed helical line on it l_0 are defined, so the cylinder's equation is as:

$$\bar{\rho}_0 = (r_0 \cos\vartheta)\bar{i}_p + (r_0 \sin\vartheta)\bar{j}_p + (p_s\vartheta)\bar{k}_p \quad (1)$$

where r_0 is a radius of the directed cylinder C_0; ϑ - an angular parameter of the helical motion (of the helical line l_0); p_s - an axial parameter of the helical motion; $\bar{i}_p$, $\bar{j}_p$, $\bar{k}_p$ - unit vectors of the coordinate axes of the S_p.

In an arbitrary point O_I from l_0 is given a right-handed coordinate system $S_I(O_I, x_I, y_I, z_I)$, so that the axis $O_I y_I$ coincides with the tangent line to l_0 in point O_I, and the axis $O_I x_I$ is perpendicular to the $O_p z_p$ and it is directed from the cylinder C_0. In accordance with the symbols given in Fig. 1, the axial parameter of the helical line l_0 is:

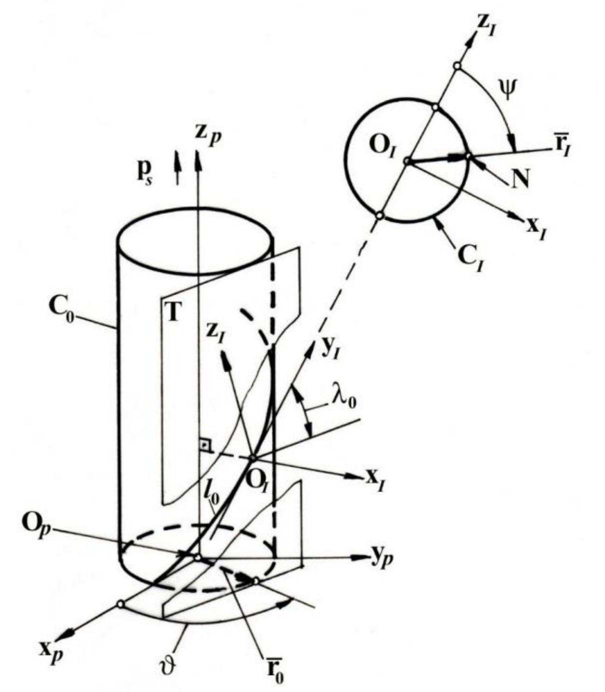

Figure 1. Scheme of a circular (curvilinear) cylindrical helicoid generation.

$$p_s = r_0 \tan\lambda_0, \quad (2)$$

where λ_0 is the ascent angle of l_0.

Let's describe the circle C_I in the coordinate system S_I, as follows:

$$x_I = r_I \sin\psi, \;\; y_I = 0, \;\; z_I = r_I \cos\psi, \quad (3)$$

where r_I is the radius of the circle C_I; ψ - an angular parameter of the C_I.

An arc of the circle C_I is realized for the variation of the ψ, which can be considered as a normal section of the active tooth surfaces Σ_c, generated from the cylindrical circular helicoid.

Then for the vector equation of this helicoid, it can be written:

$$\bar{\rho}_c = \bar{\rho}_0 + \bar{r}_I, \quad (4)$$

The vector equality (4) is an equation of the cylindrical circular helicoid Σ_c, which in its coordinate system S_p is described with the following matrix equality:

$$\rho_{c,p} = M_{S_pS_I}.r_I, \tag{5}$$

where $\rho_{c,p}$ is a column-matrix of the vector $\overline{\rho}_c$ of Σ_c, written in the coordinate system S_p; $M_{S_pS_I}$ - transition matrix from the coordinate system S_I to the coordinate system S_p; $r_I = [x_I \quad y_I \quad z_I]^T = r_I$ - a column-matrix of the vector $\overline{r}_I$, written in the coordinate system S_I.

The transition matrix $M_{S_pS_I}$ is determined by using the symbols given in Fig 1:

$$M_{S_pS_I} = \begin{Vmatrix} \cos\vartheta & -\sin\vartheta\cos\lambda_0 & \sin\vartheta\sin\lambda_0 & r_0\cos\vartheta \\ \sin\vartheta & \cos\vartheta\cos\lambda_0 & -\cos\vartheta\sin\lambda_0 & r_0\sin\vartheta \\ 0 & \sin\lambda_0 & \cos\lambda_0 & p_s\vartheta \\ 0 & 0 & 0 & 0 \end{Vmatrix}. \tag{6}$$

After substitution of (3) and (6) into (5) it is obtained:

$$\begin{aligned} x_p &= r_0\cos\vartheta + r_I A, \\ y_p &= r_0\sin\vartheta + r_I B, \\ z_p &= p_s\vartheta + r_I\cos\psi\cos\lambda_0, \end{aligned} \tag{7}$$

$$\begin{aligned} A &= (\sin\psi\cos\vartheta + \cos\psi\sin\lambda_0\sin\vartheta), \\ \mathrm{B} &= (\sin\psi\sin\vartheta - \cos\psi\sin\lambda_0\cos\vartheta). \end{aligned}$$

The first summands from the right-hand sides of the equation in the system (7) are the analytical expression of the vector $\overline{\rho}_p$, i.e. the analytical expression of the directed vector line l_0, and the second ones describe analytically the vector $\overline{r}_I$ from the equation (7), i.e.:

$$\begin{aligned} a_{I,x_p} &= a_{I,x_p}(\vartheta,\psi) = (\sin\psi\cos\vartheta + C\sin\vartheta), \\ b_{I,y_p} &= b_{I,y_p}(\vartheta,\psi) = (\sin\psi\sin\vartheta - C\cos\vartheta), \\ c_{I,z_p} &= c_{I,z_p}(\psi) = \cos\psi\cos\lambda_0, \end{aligned} \tag{8}$$

$$C = \cos\psi\sin\lambda_0.$$

Then (7) is as follows:

$$\begin{aligned} x_p &= r_0\cos\vartheta + r_I a_{I,x_p}, \\ y_p &= r_0\sin\vartheta + r_I b_{I,y_p}, \\ z_p &= p_s\vartheta + r_I c_{I,z_p}. \end{aligned} \tag{9}$$

The normal vector $\overline{n}_c$ to the Σ_c is determined from the vector equality [7]:

$$\overline{n}_{c,p} = \frac{\partial\overline{\rho}_p}{\partial\vartheta} \times \frac{\partial\overline{\rho}_p}{\partial\psi}, \tag{10}$$

which written in the coordinate system S_p has the form

$$\begin{aligned} n_{c,x_p} &= \frac{\partial y_p}{\partial\vartheta}.\frac{\partial z_p}{\partial\psi} - \frac{\partial y_p}{\partial\psi}.\frac{\partial z_p}{\partial\vartheta}, \\ n_{c,y_p} &= \frac{\partial z_p}{\partial\vartheta}.\frac{\partial x_p}{\partial\psi} - \frac{\partial z_p}{\partial\psi}.\frac{\partial x_p}{\partial\vartheta}, \\ n_{c,z_p} &= \frac{\partial x_p}{\partial\vartheta}.\frac{\partial y_p}{\partial\psi} - \frac{\partial x_p}{\partial\psi}.\frac{\partial y_p}{\partial\vartheta}. \end{aligned} \tag{11}$$

Then from (7) and (11) the scalar components of $\overline{n}_c$ are obtained as:

$$\begin{aligned} n_{c,x_p} &= -D.(\sin\psi\cos\vartheta + \cos\psi\sin\lambda_0\sin\vartheta), \\ n_{c,y_p} &= -D(\sin\psi\sin\vartheta - \cos\psi\sin\lambda_0\cos\vartheta), \\ n_{c,z_p} &= -D\cos\psi\sin\lambda_0, \end{aligned} \tag{12}$$

$$D = [r_I^2\sin\psi\cos\lambda_0 + r_I r_0(\cos\lambda_0)^{-1}].$$

It can be easily established from (12) that the magnitude of the normal vector at any point on Σ_c is:

$$n_c = |\, r_I^2\sin\psi\cos\lambda_0 + r_I r_0(\cos\lambda_0)^{-1}\,|. \tag{13}$$

Considering the substitution of (8), the (12) is of the form:

$$\begin{aligned} n_{c,x_p} &= -a_{I,x_p}.n_c, \\ n_{c,y_p} &= -b_{I,y_p}.n_c, \\ n_{c,z_p} &= -c_{I,z_p}.n_c. \end{aligned} \tag{14}$$

Then the cosines of the angles formed by the vector $\overline{n}_{c,p}$ with the axes O_px_p, O_py_p and O_pz_p are respectively:

$$\begin{aligned} \cos(\overline{n}_c,\overline{i}_p) &= -a_{I,x_p}, \\ \cos(\overline{n}_c,\overline{j}_p) &= -b_{I,y_p}, \\ \cos(\overline{n}_c,\overline{k}_p) &= -c_{I,z_p}, \end{aligned} \tag{15}$$

and the unit normal $\overline{e}_c$ to Σ_c in the coordinate system S_p is

$$\overline{e}_{c,p} = -(a_{I,x_p}\overline{i}_p + b_{I,y_p}\overline{j}_p + c_{I,z_p}\overline{k}_p). \tag{16}$$

B. Synthesis of the Action Surface/Mesh Region

It is known [7] that the action surface and the mesh region respectively, represent the locus of the contact lines of the rack drive in the fixed space defined by the coordinate system $S(O,x,y,z)$ (See. Fig. 2) [3], [24]. Its analytical form is represented by the system of equations:

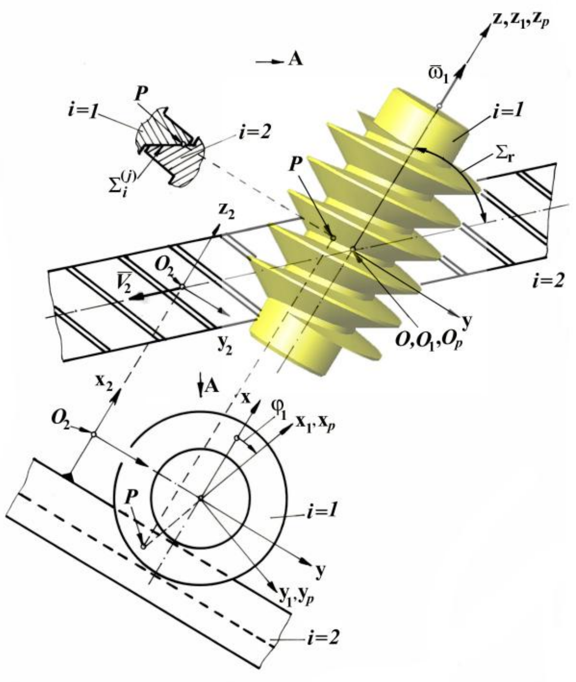

Figure 2. Geometric-kinematic scheme of spatial rack drive with rotating cylindrical helicoids.

$$\begin{aligned} &\rho_{c,S} = M_{SS_p}\rho_{c,p}, \\ &\bar{n}_{c,S}.\bar{V}_{12} = f(\vartheta,\psi,\varphi_1) = 0, \end{aligned} \tag{17}$$

where $\rho_{c,S}$ is a column-matrix of the radius-vector $\bar{\rho}_c$, written in the static coordinate system $S(O,x,y,z)$; $\rho_{c,p}$ - column-matrix of the radius-vector $\bar{\rho}_p$ of Σ_c written in its coordinate system S_p; M_{SS_p} - transition matrix; $\bar{n}_{c,S}$ - normal vector of Σ_c in an arbitrary point, written in the coordinate system $S(O,x,y,z)$; $\bar{V}_{12}$ - sliding velocity vector.

The second equation from (17) is the general form of the meshing equation [7], which according to the fact [1], [3] that the normal vector in every point of the action surface, lies in the plane parallel to the coordinate axis Ox, and concludes a constant angle with the axis Oz, then for the concrete case is of the form:

$$\tan\Delta = \frac{n_{c,y}}{n_{c,z}} = \frac{p_s - j_{21}\cos\Sigma_r}{j_{21}\sin\Sigma_r}, \tag{18}$$

where $\Sigma_r = \pi - \delta_r = \pi - (\bar{\omega}_1,\bar{V}_2)$.

The scalar components of the vector $\bar{n}_c$ in the static coordinate system are determined when the following matrix equality is used:

$$n_{c,S} = L_{SS_p} n_{c,p}. \tag{19}$$

The transition matrices in (17) and (19) are of the form:

$$M_{SS_p} = \begin{Vmatrix} \cos\varphi_1 & -\sin\varphi_1 & 0 & 0 \\ \sin\varphi_1 & \cos\varphi_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{Vmatrix},$$

$$L_{SS_p} = \begin{Vmatrix} \cos\varphi_1 & -\sin\varphi_1 & 0 \\ \sin\varphi_1 & \cos\varphi_1 & 0 \\ 0 & 0 & 1 \end{Vmatrix}. \tag{20}$$

It is obtained from (19) and (20) the following:

$$\begin{aligned} n_{c,x} &= -n_c[\sin\psi\cos E + \cos\psi\sin\lambda_0\sin \mathrm{E}], \\ n_{c,y} &= -n_c[\sin\psi\sin E - \cos\psi\sin\lambda_0\cos E], \\ n_{c,z} &= -n_c.\cos\psi\cos\lambda_0, \end{aligned} \tag{21}$$

$$E = (\vartheta + \varphi_1).$$

Analogically from (4) and (21), it is obtained:

$$\begin{aligned} x &= r_0\cos E + r_I[\sin\psi\cos E + F\sin E], \\ y &= r_0\sin E + r_I[\sin\psi\sin E - F\cos E], \\ z &= p_s\vartheta + r_I\cos\psi\cos\lambda_0, \end{aligned} \tag{22}$$

$$F = \cos\psi\sin\lambda_0$$
$$E = (\vartheta + \varphi_1).$$

If, analogously to the system (8), it is introduced:

$$\begin{aligned} a_{I,x} &= a_{I,x}(\vartheta+\varphi_1,\psi) = \sin\psi\cos E + F\sin E, \\ b_{I,y} &= b_{I,y}(\vartheta+\varphi_1,\psi) = \sin\psi\sin E - F\cos E, \\ c_{I,z} &= c_{I,z_p} = \cos\psi\cos\lambda_0, \end{aligned} \tag{23}$$

$$F = \cos\psi\sin\lambda_0,$$
$$E = (\vartheta + \varphi_1),$$

Then (21) and (22), and meshing equation (18) obtain respectively the form:

$$n_{c,x} = -n_c a_{I,x},$$
$$n_{c,y} = -n_c . b_{I,y}, \qquad (24)$$
$$n_{c,z} = -n_c . c_{I,z},$$

$$x = r_0 \cos(\vartheta + \varphi_1) + r_I a_{I,x},$$
$$y = r_0 \sin(\vartheta + \varphi_1) + r_I b_{I,y}, \qquad (25)$$
$$z = p_s \vartheta + r_I \cos\psi \cos\lambda_0.$$

$$b_{I,y} = c_{I,z} \frac{p_s - j_{21}\cos\Sigma_r}{j_{21}\sin\Sigma_r}. \qquad (26)$$

Equations (25) and (26) describe analytically the action surface/mesh region of the spatial rack drive having a cylindrical circular helicoid.

C. Synthesis of the Tooth Surfaces of the Gear Rack, Having a Rotating Cylindrical Circular Helicoid

The active tooth surfaces of the spatial rack drive are searched as a locus of the mesh region in the coordinate system of the gear rack $S_r \equiv S_2(O_2, x_2, y_2, z_2)$.

Their analytical form is given by the system of equations:

$$\rho_{c,s_2} = M_{ss_2} \rho_{c,s}$$
$$x = r_0 \cos(\vartheta + \varphi_1) + r_I a_{I,x},$$
$$y = r_0 \sin(\vartheta + \varphi_1) + r_I b_{I,y},$$
$$z = p_s \vartheta + r_I \cos\psi \cos\lambda_0, \qquad (27)$$

$$b_{i,y} = c_{I,z} \frac{p_s - j_{21}\cos\Sigma_r}{j_{21}\sin\Sigma_r},$$

where $M_{s_2 s}$ transition matrix from S to S_2. It can be easily established that it has the form:

$$M_{s_2 s} = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & j_{21}\varphi_1 \sin\Sigma_r \\ 0 & 0 & 1 & j_{21}\varphi_1 \cos\Sigma_r \\ 0 & 0 & 0 & 1 \end{Vmatrix}. \qquad (28)$$

Then the analytical type of the active tooth surfaces of the gear rack, conjugated with the cylindrical circular helicoids of the rotating link of the gear is:

$$x = r_0 \cos(\theta) + r_I a_{I,x},$$
$$y = r_0 \sin(\theta) + r_I b_{I,y} + j_{21}\varphi_1 \sin\Sigma_r,$$
$$z = p_s \vartheta + r_I \cos\psi \cos\lambda_0 + j_{21}\varphi_1 \cos\Sigma_r, \qquad (29)$$

$$\tan\psi \sin\theta - \sin\lambda_0 \cos\theta = \cos\lambda_0 \frac{p_s - j_{21}\cos\Sigma_r}{j_{21}\sin\Sigma_r},$$

where $\theta = \vartheta + \varphi_1$.

D. Curvilinear Cylindrical Archimedean Rack Drive

The system of equations, describing analytically the curvilinear cylindrical Archimedean helicoids, are obtained from (9), after substituting $\lambda_0 = 0$ [1], [3]:

$$x_p = r_0 \cos\vartheta + r_I \sin\psi \cos\theta,$$
$$y_p = r_0 \sin\vartheta + r_I \sin\psi \sin\theta, \qquad (30)$$
$$z_p = p_s \vartheta + r_I \cos\psi.$$

The analytical description of the action surface/mesh region of the curvilinear cylindrical Archimedean rack drive is received from the equations system (25) and (26), when there $\lambda_0 = 0$ is substituted correspondingly, i.e.:

$$x = r_0 \cos(\vartheta + \varphi_1) + r_I \sin\psi \cos(\vartheta + \varphi_1),$$
$$y = r_0 \sin(\vartheta + \varphi_1) + r_I \cos\psi \frac{p_s - j_{21}\cos\Sigma_r}{j_{21}\sin\Sigma_r}, \qquad (31)$$
$$z = p_s \vartheta + r_I \cos\psi \cos\lambda_0.$$

The active tooth surfaces Σ_2 of the gear rack are obtained from the equations system (29) after a substation of $\lambda_0 = 0$:

$$x = r_0 \cos(\theta) + r_I \sin\psi \cos(\theta),$$
$$y = r_0 \sin(\theta) + r_I \sin\psi \sin(\theta) + j_{21}\varphi_1 \sin\Sigma_r,$$
$$z = p_s \vartheta + r_I \cos\psi + j_{21}\varphi_1 \cos\Sigma_r, \qquad (32)$$

$$\tan\psi \sin\theta = \frac{p_s - j_{21}\cos\Sigma_r}{j_{21}\sin\Sigma_r},$$

where $\theta = \vartheta + \varphi_1$.

Based on the current study and the defined algorithms for the synthesis of spatial rack drives with cylindrical (linear and curvilinear) helicoids are elaborated typified computer programs [3], [24]. They realize the visual study of the geometric characters of the elements firmly connected with the movable link by which the motions transformation is realized.

On Fig. 3 and Fig. 4 [1] the generated curvilinear cylindrical Archimedean helicoids $\sum_1^{'}$, representing the active tooth surfaces of the rotating link $i = 1$; the mesh regions $MR^{(j)}$ $(j = 1,\ 2)$ of the curvilinear cylindrical Archimedean rack drive and the tooth surfaces $\sum_2$ of the link $i = 2$, realizing rectilinear translation [3] are graphically illustrated.

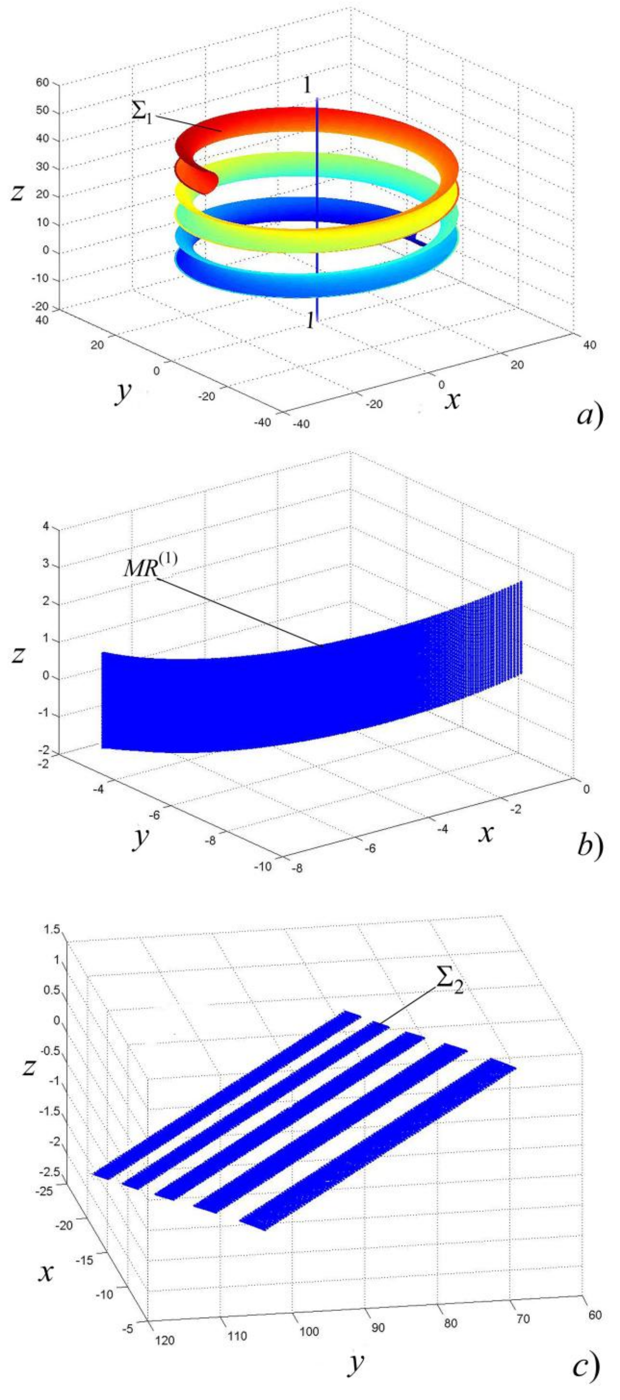

Figure 3. Spatial rack drive having a curvilinear helicoid with velocity ratio $j_{21} = 42$ and a crossed angle $\Sigma_r = 60^\circ$; number of teeth $z_1 = 1$: a) circular concave helicoids $\Sigma_1 \Rightarrow \psi \in [-\pi,\ 0]$, $r_0 = 31$ mm, $r_1 = 4$ mm, $\vartheta \in [0,\ 5\pi]$; b) mesh region $MR^{(1)}$; c) surface Σ_2 conjugated with Σ_1.

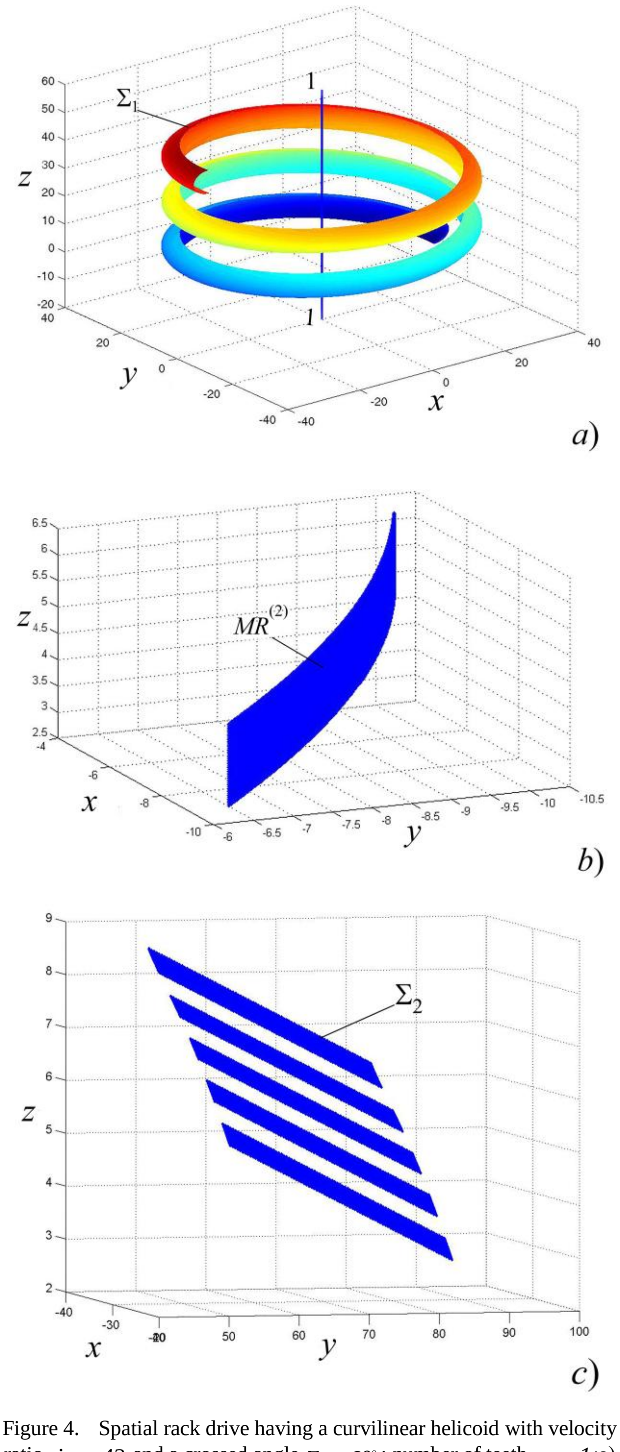

Figure 4. Spatial rack drive having a curvilinear helicoid with velocity ratio $j_{21} = 42$ and a crossed angle $\Sigma_r = 60^\circ$; number of teeth $z_1 = 1$:a) circular convex helicoid $\Sigma_1 \Rightarrow \psi \in [0,\ \pi]$, $r_0 = 31$ mm, $r_1 = 4$ mm; $\vartheta \in [0,\ 5\pi]$; b) mesh region $MR^{(2)}$ c) surface Σ_2 conjugated with Σ_1.

III. CONCLUSION

The main tasks, solved here, are: continuously development of adequate approaches for synthesis and the related to them - generation of the active tooth surfaces of different types of gears; choice of rational form of active tooth surfaces; creation of a calculating apparatus for formation of innovative transmissions, etc. The obtained results from this current study are oriented to the synthesis of a refined type of spatial gear mechanisms - spatial rack drives having cylindrical curvilinear helicoids. The presented equations of the cylindrical curvilinear helicoids are important geometric characteristics of the active tooth surfaces of the gear rack. They are related to the technological synthesis of gears with the application of these types of helical surfaces, which operate under the condition of working and/or instrumental mating. Not least in importance, it should be noted that the obtained analytical relations can be used in the organization of the procedures for measurement and control of the parameters of these surfaces in the process of their elaboration.

Conflict of Interest

The authors declare no conflict of interest.

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