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A new algorithm for helical gear design with addendum modification

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1. Introduction

Gears are used to transmit mechanical power. Helical gears have the advantage of transmitting power between axes that make a certain angle. Geometrical dimensions of the wheels from the helical gears with addendum modifications are obtained by choosing arbitrary values for the addendum modifications. This approach gives a new method of determining the helical gears geometrical dimensions based on the assumption that the sliding coefficients are equalized, on the meshing line, at the points where the meshing begins and ends and that there are no interferences between the teeth. As the sliding between the teeth flank is influencing lifetime of the gears, the minimum value of the equalized sliding can be obtained by a genetic algorithm in order to find the geometrical dimensions of the gears that will last longer. Based on the assumption of the sliding coefficients equalization between the teeth flanks the x_1 and x_2 addendum modifications are obtained together with the together with β_1 and β_2 the helix angles on the pitch cylinders while a, the distance between de axes, and Σ, the angle between the axes are given. The algorithm was implemented in MATLAB as this is an excellent scientifically tool for design [1], modelling [2] or controlling purposes [3].

2. Sliding coefficients at helical gears

At planar gears different methods for choosing the addendum modification can be found at [4 - 7]. Each of these methods focuses on increasing the service life of the gears while maintaining some given limit of their size. These methods can also be extended to spatial gears, in this case, at helical gears too. One of them can be found at [8]. The algorithm from this paper is based on the relations from [9], where the sliding coefficients are established. The kinematical scheme of the helical gear is given in Fig. 1.

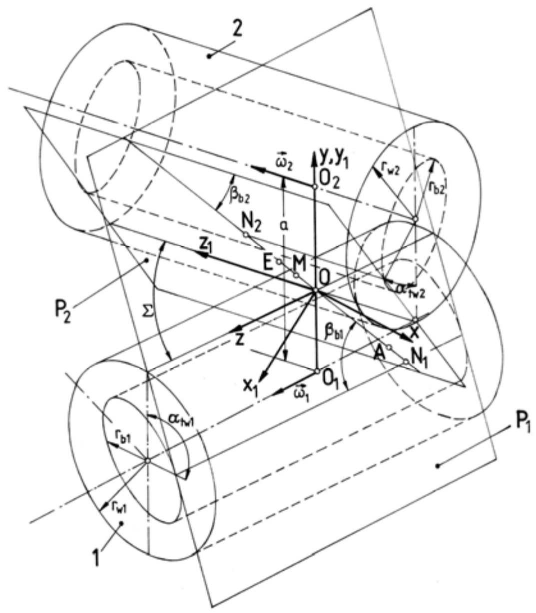

Fig. 1 The helical gear scheme

The meshing line is obtained by the intersection of the P_1 and P_2 tangent planes to the base cylinders. On this line, we have the A point, where the meshing begins, and the E point where the meshing ends. Based on [9], the sliding between the teeth flanks can be evaluated with the help of ζ_{12} and ζ_{21} sliding coefficients. ζ_{12} measures the sliding of flank *1* in regard to flank *2*, while ζ_{21} measures the sliding of flank *2* in regard to flank *1*. The sliding coefficients are determined at the A and E points which are the most far meshing points from the C point (pitch point) as here the sliding coefficients have the highest values.

$$\varsigma_{12A} = \frac{A_A^2 + B_A^2 + C_A^2}{\left(y_A + r_{w1}\right)A_A + x_A B_A} \tag{1}$$

and

$$\varsigma_{21E} = \frac{A_E^2 + B_E^2 + C_E^2}{C_E^2 - \left(y_E + r_{w2}\right)u_{21}A_E cos\Sigma - u_{21}\left[x_E cos\Sigma - z_E sin\Sigma\right]B_E} \tag{2}$$

where

$$\left.\begin{aligned} A_A &= y_A[1 - u_{21}cos\Sigma] + r_{w1} + r_{w2}u_{21}cos\Sigma \\ B_A &= x_A[1 - u_{21}cos\Sigma] + z_A u_{21}sin(\Sigma) \quad \Sigma \\ C_A &= (y_A - r_{w2})u_{21}sin\Sigma \end{aligned}\right\} \tag{3}$$

and

$$\left.\begin{aligned} A_E &= y_E[1 - u_{21}cos\Sigma] + r_{w1} + r_{w2}cos\Sigma \\ B_E &= x_E[1 - u_{21}cos\Sigma] + z_E u_{21}sin\Sigma \\ C_E &= (y_E - r_{w2})u_{21}sin\Sigma \end{aligned}\right\} \tag{4}$$

The x_A, y_A, z_A and the x_E, y_E, z_E are the coordinates of the A and E points from Fig. 1 with the following expressions and $u_{21}=\omega_2/\omega_1=z_1/z_2$ the gear ratio.

$$\left.\begin{aligned} x_A &= r_{b2}cos(\alpha_{tw2})[tan(\alpha_{ta2})-tan(\alpha_{tw2})]\frac{tan(\alpha_{tw2})}{tan(\alpha_{tw1})} \\ y_A &= -r_{b2}sin(\alpha_{tw2})[tan(\alpha_{ta2})-tan(\alpha_{tw2})] \\ z_A &= -r_{b2}cos(\alpha_{tw2})[tan(\alpha_{ta2})-tan(\alpha_{tw2})]\times \\ &\times\frac{tan(\alpha_{tw1})+cos(\Sigma)tan(\alpha_{tw2})}{sin(\Sigma)tan(\alpha_{tw1})} \end{aligned}\right\} \quad (5)$$

$$\left.\begin{aligned} x_E &= r_{b1}cos(\alpha_{tw1})[tan(\alpha_{ta1})-tan(\alpha_{tw1})] \\ y_E &= r_{b1}sin(\alpha_{tw1})[tan(\alpha_{ta1})-tan(\alpha_{tw1})] \\ z_E &= r_{b1}cos(\alpha_{tw1})[tan(\alpha_{ta1})-tan(\alpha_{tw1})]\times \\ &\times\frac{tan(\alpha_{tw1})+cos(\Sigma)tan(\alpha_{tw2})}{sin(\Sigma)tan(\alpha_{tw2})} \end{aligned}\right\} \quad (6)$$

3. Determination of the geometrical dimension

The geometrical relations used to compute the dimensions of the 1st and the 2nd helical wheels are:

- diameters of the pitch circles

$$\left.\begin{aligned} d_1 &= m_n\frac{z_1}{cos(\beta_1)} \\ d_2 &= m_n\frac{z_2}{cos(\beta_2)} \end{aligned}\right\} \quad (7)$$

- teeth declination angles on the base cylinders

$$\left.\begin{aligned} sin(\beta_{b1}) &= sin(\beta_1)cos(\alpha_n) \\ sin(\beta_{b2}) &= sin(\beta_2)cos(\alpha_n) \end{aligned}\right\} \quad (8)$$

- the number of teeth of the equivalent wheels

$$\left.\begin{aligned} z_{n1} &= \frac{z_1}{cos^2(\beta_{b1})cos(\beta_1)} \\ z_{n2} &= \frac{z_2}{cos^2(\beta_{b2})cos(\beta_2)} \end{aligned}\right\} \quad (9)$$

- meshing angle at normal plane

$$inv(\alpha_{nw}) \approx 2\frac{x_1+x_2}{z_{n1}+z_{n2}}tan(\alpha_n)+inv(\alpha_n) \quad (10)$$

- teeth declination angles on the rolling cylinders

$$\left.\begin{aligned} sin(\beta_{w1}) &= \frac{sin(\beta_{b1})}{cos(\alpha_{nw})} \\ sin(\beta_{w2}) &= \frac{sin(\beta_{b2})}{cos(\alpha_{nw})} \end{aligned}\right\} \quad (11)$$

- meshing angles at frontal planes

$$\left.\begin{aligned} cos(\alpha_{tw1}) &= cos(\alpha_{nw})\frac{cos(\beta_{w1})}{cos(\beta_{b1})} \\ cos(\alpha_{tw2}) &= cos(\alpha_{nw})\frac{cos(\beta_{w2})}{cos(\beta_{b2})} \end{aligned}\right\} \quad (12)$$

- specific cutback of the tooth head

$$k = x_1 + x_2 + \\ +\frac{\frac{d_1}{cos^2(\beta_{b1})}\left(1-\frac{cos(\alpha_n)}{cos(\alpha_{nw})}\right)+\frac{d_2}{cos^2(\beta_{b2})}\left(1-\frac{cos(\alpha_n)}{cos(\alpha_{nw})}\right)}{2m_n} \quad (13)$$

- profile angles of the basic rack at frontal planes of the 1st and 2nd helical wheels

$$\left.\begin{aligned} cos(\alpha_{t1}) &= cos(\alpha_n)\frac{cos(\beta_1)}{cos(\beta_{b1})} \\ cos(\alpha_{t2}) &= cos(\alpha_n)\frac{cos(\beta_2)}{cos(\beta_{b2})} \end{aligned}\right\} \quad (14)$$

- pressure angles in the frontal planes on the addendum circles

$$\left.\begin{aligned} cos(\alpha_{ta1}) &= \frac{r_{b1}}{r_{a1}} \\ cos(\alpha_{ta2}) &= \frac{r_{b2}}{r_{a2}} \end{aligned}\right\} \quad (15)$$

- diameters of the base circles for the 1st and the 2nd wheel

$$\left.\begin{aligned} d_{b1} &= d_1cos(\alpha_{t1}) \\ d_{b2} &= d_2cos(\alpha_{t2}) \end{aligned}\right\} \quad (16)$$

- diameters of the rolling circles for the 1st and the 2nd wheel

$$\left.\begin{aligned} d_{w1} &= d_1\frac{cos(\alpha_{t1})}{cos(\alpha_{tw1})} \\ d_{w2} &= d_2\frac{cos(\alpha_{t2})}{cos(\alpha_{tw2})} \end{aligned}\right\} \quad (17)$$

- diameters of the head circles for the 1st and the 2nd wheel

$$\left.\begin{aligned} d_{a1} &= m_n\left(\frac{z_1}{cos(\beta_1)}+2h_a^*+2x_1-2k\right) \\ d_{a2} &= m_n\left(\frac{z_2}{cos(\beta_2)}+2h_a^*+2x_2-2k\right) \end{aligned}\right\} \quad (18)$$

4. Limitations of the addendum modification

The values of the x_1 and x_2 addendum modifications obtained from the equalization condition at the beginning and the end of the meshing must satisfy the interference conditions, which are the conditions concerning the cut and the undercut of the teeth.

In order to maintain the thickness of the teeth on the head circles the following relations must be true:

- at wheel 1

$$S_{na1} = d_{a1}\left(\frac{0.5\pi+2x_1tan(\alpha_n)}{z_1}+inv(\alpha_{t1})-inv(\alpha_{ta1})\right)\times \\ \times cos(\beta_{a1}) \geq 0.5m_n \quad (19)$$

- at wheel 2

$$S_{na2} = d_{a2}\left(\frac{0.5\pi + 2x_2 tan(\alpha_n)}{z_2} + inv(\alpha_{t2}) - inv(\alpha_{ta2})\right)\times$$
$$\times cos(\beta_{a2}) \geq 0.5m_n \quad (20)$$

In order to eliminate the undercut phenomena the x_1 and x_2 addendum modification must be greater then the x_{min1} and x_{min2} values from the following formulas:

- at wheel 1

$$x_{min1} = h_a^* - \frac{z_1}{2cos(\beta_1)} \frac{tan^2(\alpha_n)}{tan^2(\alpha_n) + cos^2(\beta_1)} \quad (21)$$

- at wheel 2

$$x_{min2} = h_a^* - \frac{z_2}{2cos(\beta_2)} \frac{tan^2(\alpha_n)}{tan^2(\alpha_n) + cos^2(\beta_2)}. \quad (22)$$

5. Equalization of the sliding coefficients

In order to equalize the sliding coefficients at A and E meshing points of the helical gear expressions (1) and (2) will be used. As the equalization criterion must be obtained for different Σ angles and different a distances between the wheels, we obtain the following system of nonlinear equations:

$$\left.\begin{aligned} \varsigma_{12A}(x_1,x_2,\beta_1,\beta_2) = \varsigma_{21E}(x_1,x_2,\beta_1,\beta_2) \\ \beta_{w1}(x_1,x_2,\beta_1,\beta_2) + \beta_{w2}(x_1,x_2,\beta_1,\beta_2) = \Sigma \\ r_{w1}(x_1,x_2,\beta_1,\beta_2) + r_{w2}(x_1,x_2,\beta_1,\beta_2) = a \end{aligned}\right\} \quad (23)$$

The second equation from the system is based on the expressions (11), while the third is based on the expressions (17). If x_1, z_1, z_2, α_n, h_a^*, c^*, m_n, Σ and a values are given, a set of x_2, β_1 and β_2 values is obtained while the sliding coefficients ζ_{12A} and ζ_{21E} are equal, the sum of β_{w1} and β_{w2} is equal to Σ, and the distance between the axis is a. System (23) is solved using MATLAB's *fsolve()* function from MATLAB's Optimization Toolbox. *fsolve()* implements an iterative method that needs staring values for the computations. The data from Table 1 are obtained in this case for: $z_1 = 20$, $z_2 = 45$, $\Sigma = 90°$, $a = 116$ mm (distance between the helical gears axis), $\alpha_n = 20°$ (profile angle of the basic rack), $h_a^* = 1$ (height coefficient from head of the tooth), $c^* = 0.25$ (clearance coefficient from the head of the tooth), $m_n = 2.5$ mm (module). From Table 1 we can observe that the system has more solutions. The values for the x_1 are given for each row, while the x_2, β_1 and β_2 values are obtained by MATLAB. The columns from 5 to 10 are for checking the results: column 5 is equal to column 6, as the equalization succeeds; column 7 + column 8 = column 9, as the angle between the wheels axes is given; column 10 is equal to the distance between the axes. Based on these results the geometrical dimensions of the helical gears can be obtained from Eqs. (7) - (18). However, when checking the interferences, the first three lines in Table 1 are not valid as Eq. (20) is not true due to the high values of x_2 (the values are marked with *). One of the main problems is how to choose the values for Σ and a so that Eq. (23) would have solution. For the case of Σ the possible values are limited from 0° to 90°, but for the case of a we do not have a method to find a valid domain. A way of dealing with this problem is to give MATLAB more freedom while looking for the solutions. Instead of giving a fixed value for a, we can impose the condition that a should be an integer value. The results are given in Table 2.

Table 1

Equalization of the sliding coefficients at points A and E for $\Sigma = 90°$, $a = 116$ mm, $z_1 = 20$ and $z_2 = 45$ (start values: $x_2 = 0.15$, $\beta_1 = 45°$, $\beta_2 = 45°$)

x_1	x_2	β_1, °	β_2, °	ζ_{12A}	ζ_{21E}	β_{w1}, °	β_{w2}, °	Σ, °	a, mm
-0.80	3.385*	47.65	38.81	2.09643	2.09643	49.705	40.295	90	116
-0.64	3.065*	47.15	39.54	2.11205	2.11205	49.030	40.970	90	116
-0.48	2.702*	46.63	40.33	2.12802	2.12802	48.322	41.678	90	116
-0.32	2.293	46.12	41.19	2.14416	2.14416	47.583	42.417	90	116
-0.16	1.836	45.61	42.11	2.16013	2.16013	46.819	43.181	90	116
0.0	1.328	45.11	43.09	2.17539	2.17539	46.041	43.959	90	116
0.16	0.774	44.62	44.11	2.18924	2.18924	45.259	44.741	90	116
0.32	0.178	44.16	45.17	2.20078	2.20078	44.489	45.511	90	116
0.48	-0.450	43.72	46.24	2.20904	2.20904	43.743	46.257	90	116
0.64	-1.102	43.32	47.31	2.21300	2.21300	43.029	46.971	90	116
0.80	-1.772	42.95	48.37	2.21156	2.21156	42.351	47.649	90	116

6. Minimization of the equalized sliding coefficients

While solving the nonlinear system (23) several problems might appear. The transcendent equation at (10) solved with the *fzero()* MATLAB function might return a solution because:

- there are no solutions;
- the numerical method won't converge to the solution;
- the solution is a complex value, instead of real one.

When solving Eq. (23) using *fsolve()*:

- the system might not have solutions;
- depending on the start points, the numerical method may converge to a nonzero point;
- the obtained values are numerically correct however we have interferences.

Genetic Algorithms (GAs) are a category of evolutionary algorithms well known to find approximate solutions to the optimization problems of difficult functions. The *gatool* function from MATLAB's Genetic Algorithm and Direct Search Toolbox is used to find the minimum of the equalized sliding coefficients. The objective function is the unpenalized function to which is added a constant positive penalty for the solutions that violate in some way the feasibility.

$$\varsigma_{12A\min} = \varsigma_{12A} + \sum_{i=1}^{k} C_i \delta_i \quad (24)$$

In Eq. (24) δ_i is 0 if constraint i is 0, otherwise is 1 and C_i is a positive constant imposed for the violation. For a set of x_1, x_2, β_1, β_2 violations are considered if:

- any of the three equations from (23) are not satisfied (no convergence to the solution);
- the values of x_1 or x_2 are creating interferences;
- computations are not possible (no convergence at (17) or complex values are obtained).

The x_1, x_2, β_1, β_2 are the parameters used in the *gatool* and the codification of the parameters is of real type. The values are used to minimize the equalized sliding coefficients as shown in Table 3. The GA will find lower equalized values of the sliding then by searching for a minimum by simply covering, with a constant given step, a certain domain for the parameters. For example, for a = 116 mm, the lowest value from Table 1 for the equalized sliding coefficients is 2.14416, while in Table 3, the lower value of 2.1329892 is obtained.

Table 2

Equalization of the sliding coefficients at points A and E for Σ = 90°, a -integer z_1 = 20 and z_2 = 45 (start values: x_2 = 0.15, β_1 = 45°, β_2 = 45°)

x_1	x_2	β_1, °	β_2, °	ζ_{12A}	ζ_{21E}	β_{w1}, °	β_{w2}, °	Σ, °	a, mm
-0.800	0.097	46.81	44.21	2.19392	2.19392	46.276	43.724	90	113
-0.640	0.782	46.50	43.30	2.18825	2.18825	46.607	43.393	90	114
-0.480	0.344	46.09	44.10	2.19794	2.19794	45.991	44.009	90	114
-0.320	-0.117	45.70	44.92	2.20575	2.20575	45.384	44.616	90	114
-0.160	0.575	45.36	44.06	2.19584	2.19584	45.657	44.343	90	115
0.000	0.054	44.94	44.99	2.20537	2.20537	44.974	45.026	90	115
0.160	0.774	44.62	44.11	2.18924	2.18924	45.259	44.741	90	116
0.320	0.178	44.16	45.17	2.20078	2.20078	44.489	45.511	90	116
0.480	0.922	43.85	44.28	2.17972	2.17972	44.778	45.222	90	117
0.640	0.232	43.35	45.49	2.19352	2.19352	43.908	46.092	90	117
0.800	-0.496	42.89	46.71	2.20313	2.20313	43.075	46.925	90	117

Table 3

Minimized equalizations of the sliding coefficients at points A and E for Σ = 90°, a - integer, z_1 = 20 and z_2 = 45 using a genetic algorithm

x_1	x_2	β_1, °	β_2, °	ζ_{12A}	ζ_{21E}	β_{w1}, °	β_{w2}, °	a, mm
-0.80509	0.109990	46.8234424	44.1902080	2.1936876	2.1936876	46.293535760	43.706464240	113
-0.86796	1.359303	47.1075663	42.1940634	2.1720332	2.1720332	47.486842852	42.513157148	114
-0.37746	1.231696	45.9720099	42.8412214	2.1797129	2.1797129	46.598141941	43.401858059	115
-0.43066	2.581124	46.4759444	40.5908757	2.1329892	2.1329892	48.096871731	41.903128260	116
0.365054	1.386262	44.2317716	43.4348752	2.1680380	2.1680380	45.415013934	44.584986066	117

7. Conclusions

In the case of opened and closed gears, where load carrying capacity is limited by freezing or wearing, the addendum modifications must equalize the sliding coefficients at the extreme points of the meshing. If the equalization is achieved the teeth flank wearing will tend to be uniform and lifetime of the gears will be increased. The algorithm gives the necessary steps, with some additional verification concerning the interferences, to obtain the wheels of the gear based on this theory. For a given Σ only a limited number of integer values can be chosen for the a value in order to find solutions (see Table 2) of Eq. (23). Further, for the validated values of a and Σ a genetic algorithm from MATLAB is used to minimize the equalized sliding coefficients in order to obtain the best lifetime for the wheels.

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T. A. Antal

NAUJAS SRAIGTINIŲ KRUMPLIARAČIŲ SU MODIFIKUOTO AUKŠČIO KRUMPLIO GALVUTE PROJEKTAVIMO ALGORITMAS

R e z i u m ė

Straipsnyje pateikiamas naujas sraigtinių krumpliaračių su modifikuoto aukščio krumplio galvute projektavimo algoritmas. Siekiant pailginti naudojimo trukmę taikoma keletas plokščiųjų krumpliaračių (varantysis ir varomasis krumpliaračiai išdėstyti vienoje plokštumoje) su modifikuoto aukščio krumplio galvute projektavimo metodų. Erdvinių krumpliaračių su modifikuoto aukščio krumplio galvute (jų ašys nelygiagrečios ir nesusikerta) projektavimo metodai techninėje literatūroje neaprašyti. Mechanizmo nusidėvėjimas turi įtakos krumpliaračių ilgaamžiškumui. Norint įvertinti krumplio šoninių paviršių tarpusavio slydimą, turi būti nustatyti slydimo koeficientai. Sprendimo algoritmas paremtas teorija, kuri išplečia slydimo koeficientų nustatymą, pritaikytą plokštiesiems krumpliaračiams, iki erdvinių. Slydimo koeficientai lyginami didžiausio slydimo taškuose, siekiant suvienodinti nusidėvėjimą šiuose dviejuose taškuose. Mechanizmo geometriniai matmenys nustatomi suvienodinus slydimą. Spendimui panaudota MATLAB sistema, leidžianti tiesiogiai išspręsti netiesines lygtis, jų sistemas, atlikti modifikavimą, naudojant genetinį algoritmą. Gauti sprendiniai panaudoti geometriniams matmenims apskaičiuoti. Genetinis algoritmas naudojamas siekiant iki minimumo sumažinti lyginamas slydimo vertes.

T. A. Antal

A NEW ALGORITHM FOR HELICAL GEAR DESIGN WITH ADDENDUM MODIFICATION

S u m m a r y

The paper presents a new algorithm for designing helical gears with addendum modification. Several methods are known for designing planar gears with addendum modifications in order to achieve better service lifetime. At spatial gears, with addendum modifications, no such methods are described in the technical literature. Wearing of the wheels are influencing the lifetime of the gears. Sliding coefficients are used to measure the sliding between the teeth's flank. The algorithm is based on a theory that extends the determination of the sliding coefficients from planar gears to helical gears. Equalization of the sliding coefficients is made at the points where the sliding is highest in order to make the wearing the same in these two points. The geometrical dimensions of the wheels are determined while the sliding equalization is maintained. Implementation has been achieved in MATLAB as this tool supports directly the solving of nonlinear equations, nonlinear systems of equations, as well as optimization using genetic algorithms. The nonlinear solvers are used to compute the geometrical dimensions, while the genetic algorithm is used to minimize the equalized values of the sliding.

T. A. Antal

НОВЫЙ АЛГОРИТМ ПРЕДНАЗНАЧЕННЫЙ ДЛЯ ПРОЕКТИРОВАНИЯ ВИНТОВОЙ ШЕСТЕРНИ С МОДИФИКАЦИЕЙ ВЫСОТЫ ГОЛОВКИ ЗУБА

Р е з ю м е

В статье представлен новый алгоритм проектирования винтовой шестерни с модификацией высоты головки зуба. С целью продления времени служения шестерни, используется несколько известных методов для проектирования плоских шестерней с модификацией высоты головки зуба. В случае пространственных шестерен метод проектирования с модификацией высоты головки зуба не описывается. Износ механизма оказывает влияние на износостойкость шестерни. Для оценки проскальзывания между боковыми поверхностями зубца, необходимо определить коэффициенты проскальзывания. Предлагаемый алгоритм основан на расширении известной теории оценки коэффициентов проскальзывания для плоских и пространственных шестерен. С целью уравнивания износа зубца, уравнивание коэффициентов проскальзывания производится в двух точках наибольшего проскальзывания. Геометрические размеры механизма устанавливаются после уравнивания проскальзывания. Для решения этой задачи использовалась MATLAB система, позволяющая прямым образом решить нелинейные уравнения и их системы, производить модификацию, используя генетический алгоритм. Полученные решения использованы для определения геометрических размеров. Генетический алгоритм, при этом, использован для уменьшения до минимума уравненных значений проскальзывания.

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