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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
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EVALUATION OF TECHNIQUES FOR DETERMINING THE LOADING OF A CYCLOIDAL SATELLITE ROLLING BEARING

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Abstract. Relevance. In the mining industry there is a need for small-sized winches, gearboxes, slewing mechanisms and various motion drives that transmit high torques and can provide high transmission ratios. These are mechanisms based on gears with intermediate rolling bodies (IRB) and, in particular, a gear with intermediate rolling bodies and free cage (IRBFC). The most heavily loaded unit of IRB gears is the rolling bearing of the cycloidal satellite located on the generator. In its own way, this bearing is a bearing. For the correct selection of such a bearing, it is necessary to determine the resultant force acting on the rolling bearing of the cycloidal satellite. No methods for determining this force have been found in the public domain. Objective. Determination and evaluation of techniques for determining the loading of the rolling support of a cycloidal satellite. Methods. Vector decomposition and reduced force methods were used to achieve the objective. Results and Conclusions. Two methods for determining the force on the rolling support of a cycloidal satellite are presented: the method of vector decomposition and the method of reduced force. According to the derived methods the calculations were performed and the results were obtained. The analysis of the obtained results according to which the error of calculations of both methods is 6,5 % is carried out. Therefore, the convergence of the results is proved. The calculation using the vector decomposition method can be recommended for use for verification calculation, since the resulting force acting on the rolling support and is obtained by this method is the largest from the two methods. Therefore, it will ensure the reliability of the selected bearing. The method of the leading force can be recommended as a method for preliminary (design) calculation, since its implementation requires less time and gives an acceptable result for the preliminary selection of the satellite bearing of the gear with intermediate rolling elements and free cage.

Keywords: geo-environment, mining equipment, gearbox, rolling bearing, intermediate rolling bodies, cycloidal satellite, cycloidal profile, mechanism, cycloid, force

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ЦИКЛОИДТЫ СПУТНИКТІҢ ДОМАЛАУ ТІРЕГІНІҢ ЖҮКТЕМЕСІН АНЫҚТАУ ӘДІСТЕРІН БАҒАЛАУ

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Аннотация. Өзектілігі**.** Тау-кен өнеркәсібінде жоғары айналу моменттерін беретін және жоғары беріліс қатынасын қамтамасыз ете алатын шағын жүкшығырларды, беріліс қораптарын, бұрылу механизмдерін және әртүрлі қозғалыс жетектерін пайдалану қажеттілігі туындайды. Бұл аралық домалау элементтері (PTC) бар берілістерге негізделген механизмдер, атап айтқанда, аралық домалау элементтері және бос ұстағыш (PTKSO). ПТК бар ең көп жүктелген беріліс блогы генераторда орналасқан циклоидты спутниктің домалау тірегі болып табылады. Бұл тірек өз түрі бойынша мойынтірек болып табылады. Мұндай подшипникті дұрыс таңдау үшін циклоидты спутниктің домалау тірегіне әсер ететін алынған күшті анықтау қажет. Бұл әрекетті анықтау үшін еркін қол жетімді әдістер жоқ. Мақсат**.** Циклоидты спутниктің домалау тірегінің жүктемесін анықтау әдістерін анықтау және бағалау. Әдістер**.** Бұл мақсатқа жету үшін аналитикалық геометрия, векторлық ыдырау және берілген күш әдістері қолданылды. Нәтижелер мен қорытындылар**.** Циклоидты спутниктің домалау тірегіндегі күшті анықтаудың екі әдісі ұсынылған: векторлық ыдырау әдісі және берілген күш әдісі. Ұсынылған әдістер бойынша есептеулер жүргізіліп, нәтижелер алынды. Алынған нәтижелерге талдау жүргізілді, оған сәйкес екі әдісті есептеудегі қате шамамен 6,5 % құрайды. Демек, нәтижелердің конвергенциясы дәлелденді. Векторлық ыдырау әдісін қолданатын есептеуді тексеру есебі үшін пайдалану ұсынылуы мүмкін, өйткені осы әдіспен алынған тірекке әсер ететін нәтиже күш екі әдістің ең үлкені болып табылады. Сондықтан таңдалған мойынтіректің сенімділігі қамтамасыз етіледі. Берілген күш әдісін алдын ала (жобалау) есептеу әдісі ретінде ұсынуға болады, өйткені оны жүзеге асыру аз уақытты және аралық домалау элементтері мен бос торы бар беріліс спутниктік домалау тірегін алдын ала таңдау үшін қолайлы нәтижені талап етеді.

Түйін сөздер: геоорта, тау-кен жабдықтары, беріліс қорабы, домалау тірегі, аралық домалау элементтері, циклоидты спутник, циклоидты профиль, механизм, циклоид, күш

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ОЦЕНКА МЕТОДИК ПО ОПРЕДЕЛЕНИЮ НАГРУЖЕНИЯ ОПОРЫ КАЧЕНИЯ ЦИКЛОИДАЛЬНОГО САТЕЛЛИТА

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Аннотация. Актуальность. В горнодобывающей промышленности есть потребность в использовании малогабаритных лебедок, редукторов, механизмов поворота и различных приводов движения, осуществляющих передачу высоких крутящих моментов и способных обеспечивать высокие передаточные отношения. Такими являются механизмы на базе передач с промежуточными телами качения (ПТК), а в частности с промежуточными телами качения и свободной обоймой (ПТКСО). Наиболее нагруженным узлом передач с ПТК значится опора качения циклоидального сателлита, расположенная на генераторе. В своем роде эта опора представляет собой подшипник. Для правильного подбора такого подшипника требуется определение результирующего усилия, действующего на опору качения циклоидального сателлита. В свободном доступе методик определения этого усилия не найдено. Цель. Определение и оценка методик для определения нагружения опоры качения циклоидального сателлита. Методы. Для достижения поставленной цели использовались методы аналитической геометрии, векторного разложения и приведенного усилия. Результаты и выводы. Представлены две методики определения усилия на опору качения циклоидального сателлита: метод векторного разложения и метод приведенного усилия. По предложенным методикам произведены расчеты и получены результаты. Выполнен анализ полученных результатов, согласно которому погрешность расчетов обеих методик составляет примерно 6,5 %. Следовательно, сходимость результатов доказана. Расчет по методу векторного разложения можно рекомендовать к применению для проверочного расчета, поскольку результирующее усилие, действующее на опору и полученное по данному методу, является наибольшим из двух методов. Следовательно, будет обеспечиваться надежность выбранного подшипника. Метод приведенного усилия можно рекомендовать как метод для предварительного (проектировочного) расчета, т.к. для его реализации требуется меньше времени и приемлемый результат для предварительного подбора опоры качения сателлита передачи с промежуточными телами качения и свободной обоймой.

Ключевые слова: геосреда, горнодобывающее оборудование, редуктор, опора качения, промежуточные тела качения, циклоидальный сателлит, циклоидальный профиль, механизм, циклоида, усилие

Introduction

Effective and efficient interaction with the geo-environment requires progressive methods of labour distribution and modern equipment (Aksenov et al., 2012). Mining industry very closely connects man with the geo-environment. In the eighteenth and nineteenth centuries, an industrial revolution took place, which made it possible to begin the transition from manual to machine labour, including in the mining industry. An important role was played by the emergence of lifting mechanisms, which allowed to significantly increase the efficiency of the system, because to lift a load of a certain mass the number of people involved was reduced several times. Nowadays winches are used for lifting loads, electromechanical mixers for drilling mud preparation, transport systems with various drives and turning mechanisms are used for transporting minerals. All these mechanisms have gearboxes implemented using involute or cycloidal gearing (Aksenov et al., 2012; An I-Kan et al., 2016; Lustenkov et al., 2021; Sherov et al., 2021).

The involute gearboxes use spur or bevel gears. These gearboxes can be either planetary or classical gearboxes. Classic gearboxes are multi-stage gearboxes with parallel or intersecting axes and a single parting plane. These gearboxes have large overall dimensions, high mass and low relative load capacity.

Gearboxes based on cycloidal gearing are mainly performed only with planetary arrangement and have increased load capacity in relatively compact overall dimensions (Efremenkov et al., 2022). Chain gearboxes with cycloidal gearing are quite widely used in industry (Li et al., 2020; Wang et al., 2019; Zhang, et al., 2020; Hsieh et al., 2014; Li et al., 2018). But in mechanisms for mining equipment, intermediate rolling element (IRB) gearboxes are more often used because of their greater compactness and load capacity compared to chain gearboxes (Aksenov et al., 2012; Pankratov, 1998; Lustenkov et al., 2019; Lustenkov, 2010). In general, gears with PTC allow the mechanism to obtain a complex of advantages: compactness, high values of the overlap coefficient, a wide range of transmission ratios, sufficiently high efficiency, and continuity of contact in meshing (Pankratov, 1998; Lustenkov, et al., 2019; Lustenkov, 2010; Ivkina, et al., 2012; Prudnikov, 2018); Lustenkov, 2020; Mohamad et al., 2022). The most promising of the PTC gears for heavy-duty applications is the intermediate rolling element and free cage gear (IRIFG) (Efremenkov et al., 2021). This gear, and consequently the mechanisms based on it, has an increased efficiency due to the reduction of sliding friction in the meshing, greater compactness and load capacity due to better distribution of loads between the transmission links.

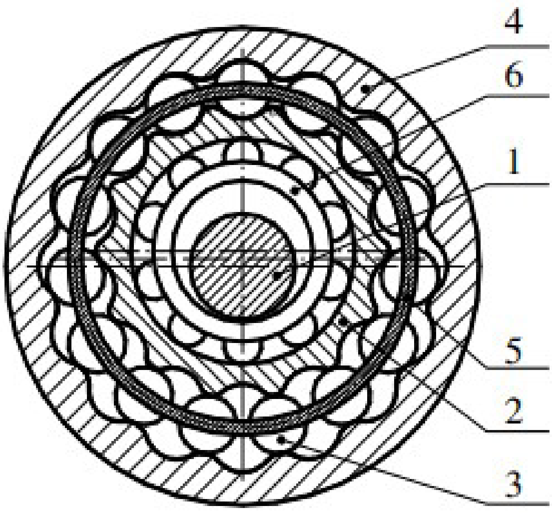

Figure 1 – Scheme of the gear with intermediate rolling elements and free cage (cross section)

The gear with PTCSO (Fig. 1) consists of input shaft 1 with eccentric, cam 2, rolling elements 3 located in the cage 5, crown 4 and rolling bearing 6 mounted on the eccentric shaft 1 and located under the cam 2. The output link in this transmission, i.e. the link connected to the output shaft of the mechanism, can be either cam 2 or crown 4. These links carry the greatest load when the mechanism is operating. As follows from the gear layout (Fig. 1), the transmission of forces and energy takes place in the meshing between links 2, 3 and 4. But the most loaded link is bearing 6 under cam 2, which is a satellite in the considered transmission. Such a bearing is present in the design of almost all PTC gears and chain gears with cycloidal meshing (Hsieh et al., 2014; Lustenkov et al., 2019).

The bearing beneath the satellite cam is the most heavily loaded element of the PTCA transmission. Its reliability and proper selection in general determines the reliability and durability of the entire mechanism and this is especially important for mechanisms operating in harsh conditions, such as mining equipment and transport systems used in human interaction with the geo-environment.

At present, very little information is found in scientific and methodological works on determining the load specifically on the bearing under the satellite of cycloidal gears. Various techniques for determining the load on this bearing are considered (Palyanitsina et al., 2021; Korshak et al., 2019; Korshak et al., 2020), but there are no recommendations on the application of one or the other. Therefore, the evaluation of techniques for determining the load capacity of the rolling bearing under the satellite of a transmission with PTCSO is relevant.

Thus, the aim of the work is to compare the methods of determining the load capacity of the cycloidal satellite bearing of the transmission with PTCSO and to formulate recommendations on the application of the obtained results.

Materials and equipment

Object of research. The object of the research is a mechanical cycloidal gear with PTCSO as the most promising for use in heavy-loaded mechanisms operating in cramped conditions of mine space, or with high overloads in the conditions of open-cut mining. In particular, the meshing and rolling bearing of the cycloidal satellite as a link subjected to the highest loads are considered in the PTCSO gear.

To determine the total force acting on the rolling bearing of a cycloidal satellite, we consider two methods: the vector force decomposition method and the reduced force method.

The first is the most commonly used and we have adapted it to determine the force on the satellite bearing in a PTCSO transmission.

The second method has not been found in the literature and will be discussed in detail for the first time, with respect to transmission with PTCSO.

Theoretical Provisions. As described earlier, the forces on the rolling bearing of the cycloidal satellite are derived from the forces in the gear meshing with the PTCSO. Thus, it is necessary to first determine the forces in the meshing, on each rolling element, and then proceed to determine the load on the rolling bearing.

It was noted in the literature (Pshenin et al., 2023; Kusimova et al., 2023; Korshak et al., 2023) that when a gear with PTCSO is operating, two forces occur in the meshing (Fig. 2): at the points of contact of the rolling element with the crown profile and with the satellite profile. The more important parameter for solving the task at hand is the force arising at the points of contact between the rolling elements and the satellite profile, because these forces form the load on the cycloidal satellite bearing.

As noted (Efremenkov, 2009), the determination of forces in the meshing of a gear with PTCSO is based on Hooke's law and begins with the determination of the maximum value of the force in the meshing:

$$F_{max} = \frac{T_к \cdot b}{\sum h_i^2}, \qquad (1)$$

where $T_к$ is the torque on the cycloidal satellite;

$b$is the distance from the centre of the satellite to the meshing pole;

h_i - shoulder, the distance from the line of action of the *i-th* force to the centre of the satellite.

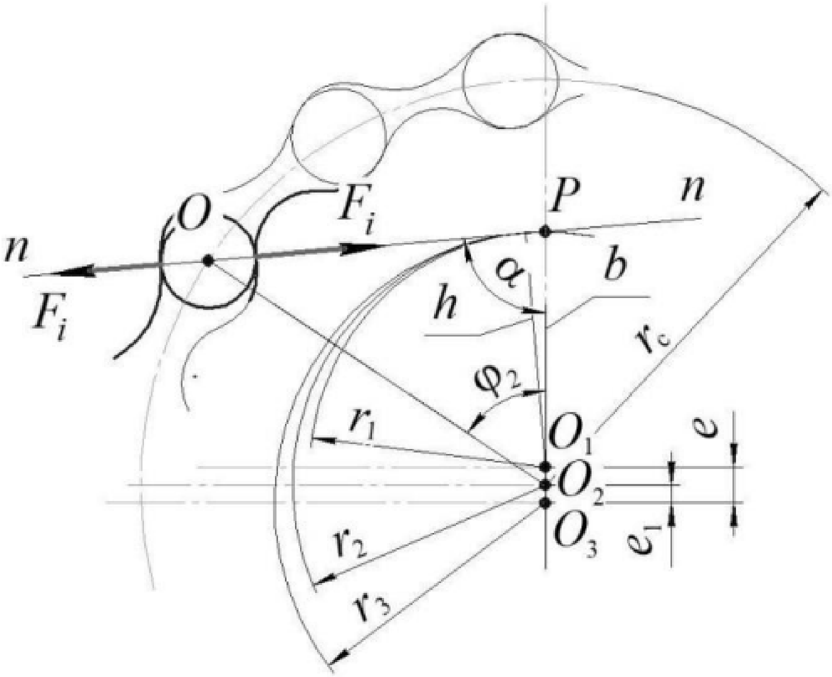

Figure 2 – Schematic of force distribution in the meshing of a gear with IRBFC

The distances h_i are calculated for each rolling element using the following formula:

$$h_i = b \cdot \sin\alpha_i. \tag{2}$$

The values of the sine of the angle α_i for each rolling element involved in the load transmission can be found from the formula:

$$\sin\alpha_i = \frac{\sin\varphi_{2i} \cdot r_c}{L_i} \tag{3}$$

here L_i is the distance from the pole *P* to the centre of the *i-th* rolling element *O*.

Depending on the initial parameters, it is defined as:

$$L_i = \sqrt{r_2^2 + r_c^2 - 2r_2 r_c cos\varphi_{2i}} \tag{4}$$

Knowing the value of the maximum force in the meshing, we determine the force on each rolling element transmitting torque from the force-arm relationship:

$$F_i = \frac{F_{\max} \cdot h_i}{b}. \tag{5}$$

Thus, the force acting at the point of contact of each rolling element with the cycloidal profile of the satellite is determined from expression (5). Now it is possible to determine the force acting on the satellite support, formed from the found forces in the meshing. First, we determine the total support force using the vector decomposition method.

Vector decomposition method. The vector decomposition method is based on the fact that the found forces in the meshing are decomposed into two components on the coordinate axes, and then the projections on the coordinate axes are summed up and transferred to the centre of the rolling support of the cycloidal satellite and summed up analytically.

The point of contact of the rolling element with the cycloidal profile of the satellite cam will be taken as the origin of coordinates, the abscissa axis will be directed horizontally and the ordinate axis vertically (Fig. 3). Each force on the satellite cam is plotted on the abscissa and ordinate axes. The projections are determined from the following expressions:

on the X axis

$$F_{x_i} = F_i \cdot \cos\theta_{1_i}, \quad (6)$$

y-axis

$$F_{x_i} = F_i \cdot \cos\theta_{1_i}, \quad (7)$$

hence и - the angles formed by the force F_i to the X and Y axes.

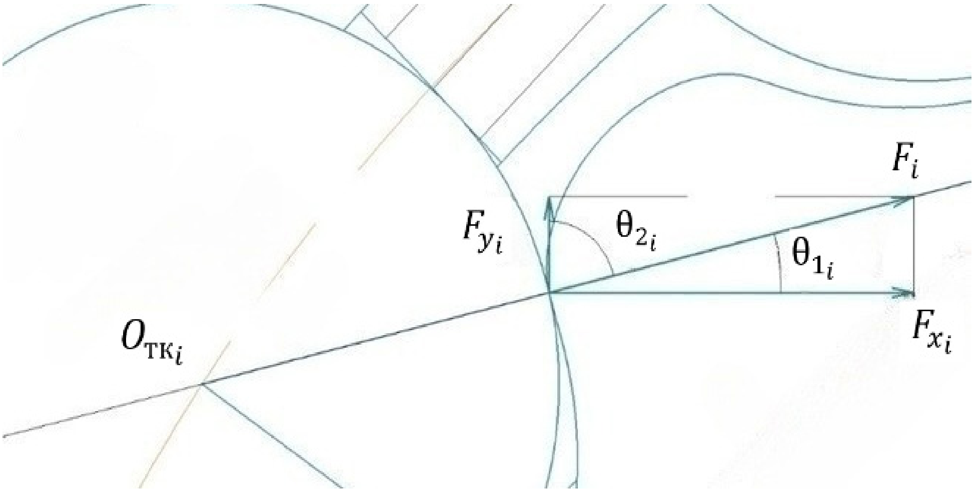

Figure 3 – Schematic of the forces generated at the point of contact between the rolling body and the satellite, projected on the ordinate and abscissa axes

Angles and are determined from the geometry of the transmission:

$$\theta_{2_i} = \alpha_i; \quad (8)$$

$$\theta_{1_i} = 90° - \alpha_i. \quad (9)$$

Now by parallel transfer all projections и concentrate in the centre of the support of the cycloidal satellite, - the point .

The total forces on the coordinate axes R_x and R_y are determined from the expressions:

$$R_x = \sum F_{x_i}; \quad (10)$$

$$R_y = \sum F_{y_i}; \quad (11)$$

Then the resultant reaction acting on the support of the cycloidal satellite is defined by the method of vector decomposition as:

$$R_{H_1} = \sqrt{R_x^2 + R_y^2}; \quad (12)$$

The resulting expression can be used to calculate the life expectancy of the satellite bearing.

The reduced force method. Let us now consider the determination of the total force on the support of the cycloidal satellite by the reduced force method. The essence of the method is that the forces in the meshing of rolling elements with a cycloidal cam by parallel transfer are immediately concentrated in the centre of the satellite support. Then an arbitrary straight line is drawn through the centre, on which all concentrated forces are projected (Fig. 4). The sum of the projections of these forces will give the reduced force on the satellite rolling bearing.

Thus, the forces in the rolling elements meshing with the satellite, found by the formulas (1)–(5), we concentrate in the point (Fig. 4).

Draw an arbitrary line *p-r* through the centreO_1 b project all forces F_i onto it and find the projections of the forces from the following expression:

$$F_{H_i} = F_i \cdot \cos\mu_i, \tag{13}$$

where - angle formed by and .

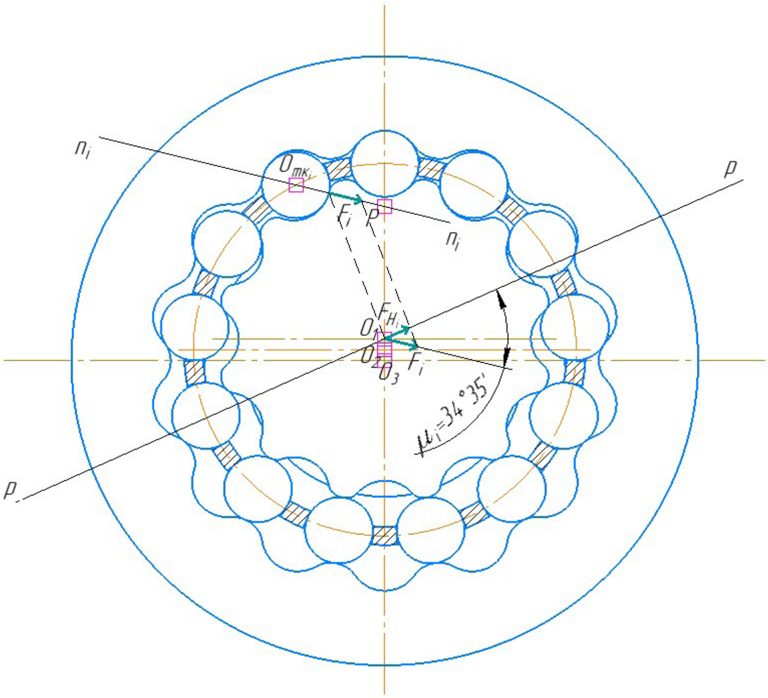

Figure 4 – Determination of force projection on an arbitrary straight line

The angle μ_i is determined from the construction. After all forces have been projected onto the line *p-p, we* can determine the reduced force on the rolling bearing of the satellite:

$$R_H = \sum F_{H_i}. \tag{14}$$

Evaluation of methods for determining the force on the rolling bearing of a cycloidal satellite. Let's carry out calculations of the force acting on the rolling bearing of the cycloidal satellite using the two methods considered above. And then compare the obtained results.

To verify the convergence of the results obtained by the two methods, we will perform the calculations using the same initial transmission parameters with PTCSO:

- number of rolling elements $Z_2 = 13$;
- radius of the producing circle r_2 =35,1 mm;
- offset coefficient $\chi = 1,3$;
- rolling element radius $r_b = 8,1$ mm

We assume the torque on the cam as for heavily loaded mechanisms, $T_к = 1000$ Nm.

Let us determine the forces in the meshing of each rolling element with the cycloidal satellite using equations (1)-(5). Let us present the obtained calculation results in the table (Table 1): forces F_i on each rolling element transmitting torque and angle α corresponding to each force$_i$.

Table 1 - Forces F_i and anglesα_i in contact points of the rolling bodies with satellite profile

Rolling element no.	1	2	3	4	5	6
F_i, kN	9,47	9,47	8,20	6,20	3,87	1,33
α_i	75º58’	76º16’	56º50’	39º46’	23º36’	7º50’

Now let us calculate the force on the rolling bearing of the cycloidal satellite using the vector decomposition method. Determine the projections of the forces found (Table 1) on the abscissa and ordinate axes for each rolling element involved in the meshing according to equations (6) and (7). The results are summarised in Table 2. Also in Table 2 we enter the values of angles иobtained from expressions (8) and (9).

Table 2 - Forces and , angles and of all rolling bodies involved in the engagement

Rolling element no.	1	2	3	4	5	6
F_{x_i} kN	9,17	9,17	6,90	3,97	1,53	0,20
F_{y_i} kN	2,27	2,27	4,50	4,77	3,57	1,30
θ_{1_i}	14° 3'	13° 44'	33° 10'	50° 25'	66° 24'	82° 12'
θ_{2_i}	75° 57'	76° 16'	56° 50'	39° 35'	23° 36'	7° 48'

Then, as described in the method above, we concentrate all projections of forces by parallel transfer and to the centre O_1 and determine the total projections of forces and on each axis according to formulas (10) and (11):

$$R_{x_i} = 30{,}94 \text{ кН},$$

$$R_{y_i} = 18{,}68 \text{ кН}.$$

Now let us calculate the resulting rolling support reaction of the cycloidal satellite using formula (12):

$$R_{H_1} = \sqrt{30{,}94^2 + 18{,}68^2} = 36{,}14 \text{ кН}$$

Next, we calculate the force on the rolling bearing of the cycloidal satellite using the reduced force method. We concentrate all forces F_i at point O_1 by parallel transfer. Let us determine the angles μ_i from the geometrical construction and, substituting into equation (13), determine the projections of these forces on an arbitrarily chosen line passing through the centre of the satellite support. The obtained results will be entered in Table 3.

Table 3 - Force projections and angles μ_i of all rolling bodies involved in meshing

Rollingele-ment	1	2	3	4	5	6
F_{H_i}kN	6,73	9,03	8,20	5,83	3,17	0,83
μ_i	45° 2'	17° 16'	2° 10'	19° 34'	35° 24'	51° 12'

Using formula (14), we find the resultant force acting on the cycloidal satellite support using the reduced force method:

$$R_{H_2} = 6{,}73 + 9{,}03 + 8{,}20 + 5{,}83 + 3{,}17 + 0{,}83 = 33{,}79 \text{ кН}.$$

Thus, the resultant force on the support of the cycloidal satellites of the transmission with PTCSO is determined by two different methods and to check the convergence, let us compare the obtained results (Table 4).

Table 4 - The values of the resulting force on the satellite support obtained by different methods

Parameter	kN	kN
Significance	36,14	33,79

The discrepancy of the obtained values of the bearing force is determined by the formula:

$$\Delta = \left| \frac{36{,}14 - 33{,}79}{36{,}14} \right| \cdot 100\% = 6{,}5\ \%.$$

The obtained discrepancy of 6.5 per cent between the calculation results of different methods shows satisfactory convergence of the results and indicates that both methods can be suitable for determining the force acting on the rolling bearing of the cycloidal satellite of the PTCSO transmission.

Conclusion

Thus, two different methods have been considered for determining the support force of a cycloidal satellite gear with PTCSO: the vector decomposition method and the reduced force method. After independent calculations, both methods showed satisfactory results, as evidenced by the difference in the obtained results of 6.5 %.

It should be noted that according to the method of vector decomposition the force on the support is R_{H1} = 36.14 kN, and according to the method of reduced force - R_{H2} = 33.79 kN. I.e. the value of force by the first method is greater than by the second method. Based on the results obtained and on the discrepancy of the final values, it is possible to recommend the method of the reduced force to be used for carrying out design, or preliminary, calculations, and the method of vector decomposition - for carrying out verification calculations. Such recommendations are justified by the time required to obtain the result of these methods. The reduced force method requires less time to perform calculations, and the result of the calculation is not significantly different from the vector decomposition method.

The latter method, however, allows the selected rolling bearing to be checked for increased load, thus improving the reliability of the selected bearing after the verification calculation. All this can generally improve the reliability and performance of equipment operating under severe conditions of limited space and increased loads.

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