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Optimization of bevel gear parameters

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Abstract. Problem. *Design problems, and especially the improvement of mechanical drives, take one of the most important places in modern mechanical engineering. Various drives are now very widespread, which include mechanical reducers very often. This work examines in detail the issue of optimizing bevel gears, which are used when it is necessary to transmit motion at a certain angle (usually 90°).* ***Goal.*** *The purpose of the work is to determine the optimal (rational) parameters of the bevel gear from the point of view of reducing its mass and dimensions. That is, it is necessary to obtain the dependence of the mass of the transmission (gear wheels) on its gear ratios.* ***Methodology.*** *To solve the problem, the modern parametric design system "Autodesk Inventor Professional" is used in this work. To obtain dependencies, it is necessary to choose the most common types of bevel gears, so it is also important to perform a brief analysis of bevel gear types.* ***Results.*** *As a result of the study, it was found that gear ratios of 4 or more are the most optimal for gears with circular teeth, and for spur bevel gears, gear ratios from 3.15 to 5 are the most optimal. The lower weight of a gear with circular teeth can be explained by its greater load capacity (approximately 1.5 times).* ***Originality.*** *The originality of the approach lies in addressing a rather complex optimization problem not through the development of intricate analytical models and their subsequent analysis, but by performing 3D modeling in the solid modeling environment "Autodesk Inventor Professional" using built-in functions, followed by processing of the obtained results.* ***Practical value.*** *Modern trends in the development of various mechanical drives are primarily focused on reducing their mass and dimensions. As the dimensions of the transmission decrease, the dimensions of other parts and components also decrease, and accordingly, their cost. The use of the obtained optimal gear ratios enables the design of transmission components with reduced geometric dimensions at the early stages of development.*

Keywords: *mechanical drive, mechanical reducer, bevel gear, optimization, gear ratio.*

Introduction and Analysis of publications

Mechanical transmissions are widely used in engineering. The main task of mechanical transmissions is to transform the movement parameters of the engine during transmission to the executive bodies of the machine. For example, in cars, mechanical transmissions are used when it is necessary to change the value of the speed and direction of movement, to increase the torque [1]. That is, with the help of a mechanical transmission, the mode of operation of the engine is coordinated with the mode of operation of the executive device of the machine. The role of the reduction gear in modern mechanical engineering has grown significantly due to the wide spread of high-speed engines. Due to the great importance of gears in mechanical engineering, a lot of attention is paid to their improvement and development, especially to the reduction of dimensions and weight [2-4]. It is customary to divide mechanical transmissions into two main groups: transmissions based on the application of friction (belt, friction); transmissions based on the use of engagement (gear, worm, screw, chain).

The most widespread, due to numerous advantages, are gear transmissions. The main advantages of these gears: high load capacity, greater durability and reliability of operation, high efficiency, stability of the transmission ratio (no slippage), the possibility of application in a wide range of speeds, powers and transmission ratios (gear ratios) [1]. Among the disadvantages

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of gears are increased requirements for manufacturing accuracy, noise at high speeds, and high rigidity. But these disadvantages do not reduce the advantages of gears over others.

If it is necessary to transmit motion between shafts whose axes intersect at a certain angle (more often), a bevel gear is used. It should be noted right away that bevel gears are more difficult to manufacture and install than cylindrical gears. Axial forces act in the conical engagement, which leads to the complication of support structures. Bevel gears are widely used in road transport and agricultural machinery, for example, the main gear of cars and tractors, the rear wheels of which are driven.

It can be stated that the optimization problem of bevel gears is of considerable significance [5-6]. In some papers, this task is specified [7]. In this paper, the main optimization parameter is the gear ratio.

A manufacturing simulation for bevel gear cutting has been developed in [8]. The simulation of the tool, workpiece and kinematics is performed as well as a geometrical penetration calculation in. Within the paper [8] the analysis and optimization of bevel gear cutting processes regarding tool wear have presented. The calculated results from simulation have been compared to tool wear from experimental cutting trials.

In paper [9] minimizing the volume of straight bevel gear and developing of resistance towards scoring failure in the straight bevel gear have been considered.

In [10], on the basis of the theory of the multi-body dynamics system and the principle of gear meshing, a new tooth surface error model of spiral bevel gear considering the error of machine-tool moving axis has been proposed and optimized, so as to obtain higher tooth surface accuracy and meshing efficiency

Purpose and Tasks

The aim of this work is to investigate the influence of the transmission ratio of the most common bevel gears (with straight teeth and circular teeth) on the geometric parameters of the transmission and its mass. The approach lies in the fact that the rather complex optimization task is solved not by developing complex analytical models and their subsequent analysis, but by performing 3D model in the Autodesk Inventor Professional solid modeling environment using built-in functions, with subsequent processing of the results obtained.

Analysis of Bevel Gear Structures

Briefly consider the classification of bevel gears. Bevel wheels perform: straight-toothed gears – with radial direction of the teeth (Fig. 1, a); with tangential (oblique) teeth located at an angle to the radius (Fig. 1, b); with curved (spiral) teeth: circular (Fig. 1, c, d) [7, 11]. Palloidal bevel gears are also found [11].

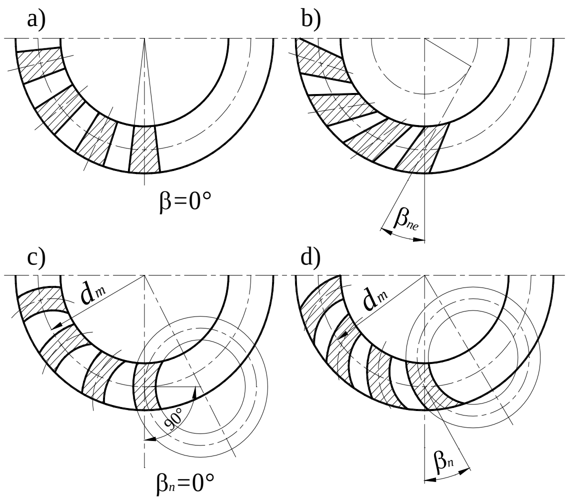

Fig. 1. Types of teeth of bevel wheels: a – straight; b – tangential (oblique); c – circular Zerol; d – circular (with non-zero spiral angle).

The most common are wheels with straight and circular teeth. The circular tooth is located along the arc of the circle along which the diameter tool moves when cutting the teeth. The angle on the circumference of the average diameter of the wheel is taken as the angle between the tangent to the circumference and the generating cone at this point. Non-zero values of the angles are performed for wheels with tangential teeth and for wheels with circular teeth.

Wheels with circular teeth are mainly used. They are less sensitive to the violation of the accuracy of the mutual location of the wheels, their manufacture is simpler and is carried out on special machines for cutting and grinding these wheels in conditions of both mass and small-scale production. The main purpose of an indirect tooth in bevel gears is the same as that of an oblique tooth in cylindrical gears, that is, circular teeth have the following advantages: multipair engagement; noise reduction, teeth are loaded gradually, as they enter the engagement field; greater load capacity compared to a straight-toothed gear. Therefore, the calculation of gear parameters will be carried out only for gears and wheels with straight and circular teeth.

Bevel wheels are also classified depending on the axial shape of the teeth. Form I is the main one for straight-toothed wheels, it is also used for wheels with circular teeth at module values of $m = 2.0...25$ mm (Fig. 2, a).

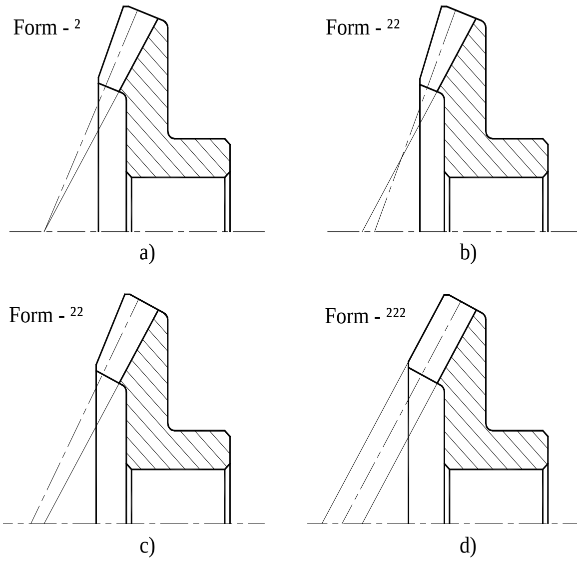

Fig. 2. Axial forms of teeth: a) – form I, the tooth decreases proportionally; b, c) – form II, the tooth decreases; d) is a tooth of equal height

Form II – mainly used for wheels with circular teeth, mm module designations (Fig. 1.2, b, c). Form III – used for wheels with circular teeth at mm (Fig. 1.2, d).

In Fig. 3 presents the areas of rational application of axial tooth shapes, that is, the axial shape of the teeth is usually chosen depending on the angle of inclination of the teeth and the ratio of the average conical distance to the diameter of the tooth cutter head.

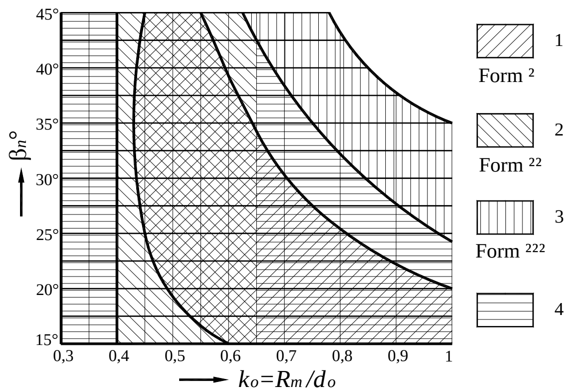

Fig. 3. Areas of rational application of axial forms of teeth: 1 – axial form of tooth I; 2 – axial shape of tooth II; 3 – axial form of tooth III; 4 – the permissible region of the axial shape of tooth II

As can be seen from fig. 3, the field of application of the axial form of teeth I covers a fairly wide range, therefore, when calculating the main parameters of gears, we will use exactly the axial form I.

Formation of a well in the ground with a complex trajectory

It has been established that if the tip shape and head rotation are changed quickly, it will be possible to control the trajectory of its movement in the soil (Fig. 1). Since the task of small-sized installations for static soil penetration is to form a well with the greatest approximation of its trajectory to a straight line, then by correcting the guidance of the soil penetration head, the problem of increasing the duration of underground puncture sections several times is overcome, namely from 15–20 m with a certain accuracy to 50–100 m. From this distance, the effective use of more complex and expensive horizontal directional drilling machines begins. Thus, the issue of increasing the distance of soil penetration by static action installations by correcting the movement of the soil penetration installation in the soil is relevant, both from a scientific and practical point of view.

Factors influencing this process are shown in the diagram in Fig. 1. First of all, it is necessary to establish a critical deviation of the working body from the initial trajectory, at which further movement becomes impossible due to the critical bending of the pipe or push rod, when its deformation can take a critical state from the strength condition.

Calculation of the main parameters and construction of a three-dimensional model of a bevel gear

The modern parametric design system "Autodesk Inventor Professional 2020" will be used to build a three-dimensional model of a bevel gear (gears and wheels). The design wizard is used to build the model. The design wizard is an important component of functional design. Engineering calculations and decision support can be used to calculate standard components (bearings, bolted joints, keyed joints, etc.) and create geometry based on standards (belt drive, chain drive, spur gear, bevel gear and worm gear), it is also possible to design and calculate shafts and springs [12]. It should be noted that the calculation of gears in the Autodesk Inventor environment is carried out according to ISO standards.

To build a gearing model, with the help of the design wizard, it is necessary to enter the initial data. In the case of a bevel gear, these are: external circular module m_{te} ; the number of gear and wheel teeth – z_1 , z_2 ; width of toothed crown b; the angle of inclination of the teeth β_n. Next, it is necessary to calculate the main parameters for bevel gears with straight and circular teeth.

We will accept the following initial data necessary for the calculation: permissible contact stresses $[\sigma_H] = 450\,\text{MPa}$, permissible bending stresses $[\sigma_F] = 200\,\text{MPa}$; torque $T = 100\,\text{N}\cdot\text{m}$; angle of inclination of gear teeth with circular teeth $\beta_n = 35°$.

The strength calculation can also be performed using the design wizard in the Autodesk Inventor environment by specifying the necessary input data. We will calculate the necessary parameters with the same initial data, changing only the value of the gear ratio. We will accept the gear ratios according to the standard values of the 1st row [13]: 1.6; 2; 2.5; 3.15; 4; 5; 6.3; 8.

Calculation of the main parameters of bevel gearing with the straight teeth

Estimated outer diameter of the gear:

$$d_{e1} = k_d \cdot \sqrt[3]{\frac{T \cdot k_{H\beta} \cdot k_A \cdot 10^3}{\upsilon_H \cdot [\sigma_H]^2 \cdot (1 - k_{be}) \cdot k_{be} \cdot u^2}}, \quad (1)$$

where $k_d = 101\ \text{МПа}^{1/3}$ – for bevel gearing with the straight teeth; k_{be} – the ratio of the width of the toothed crown relative to the external conical distance; $k_{H\beta}$ – the coefficient that takes into account the uneven distribution of the load along the width of the crown at the contact strength; k_A – coefficient of external dynamic load; $\upsilon_H = 0.85$ is a coefficient that takes into account the reduction in the strength of a straight-toothed bevel gear compared to a cylindrical gear.

Next, we take the number of gear teeth $z_1 = 18$ and calculate the external circumferential modulus $m_{te} = d_{e1}/z_1$. Values m_{te} are rounded to the nearest standard value according to standards. After accepting the standard value m_{te} , the value is refined $z_1 = d_{e1}/m_{te}$ and the value is calculated $z_2 = z_1 \cdot u$. The numbers of teeth for gear wheels z_1 and z_2 are taken as integers, after which the actual value of the gear ratio is calculated $u = z_2/z_1$.

We calculate the value of the external conical distance $R_e = 0.5 m_{te}\sqrt{z_1^2 + z_2^2}$ and the width of the toothed crown $b = R_e \cdot k_{be}$, we round the value of the width b to the nearest integer.

Calculation of the main parameters of bevel gearing with the straight teeth

The calculation will also be carried out according to [11].

The outer diameter of the gear is calculated according to the formula (1), but the values of the coefficients for transmission with circular teeth will be slightly different.

For transmission with circular teeth: $k_d = 90\,\text{MPa}^{1/3}$; the coefficient that takes into account the change in the strength of a conical gear with circular teeth compared to a cylindrical one depends on the gear ratio and the material of the wheels $\upsilon_H = (u, HB)$ (Table 1).

Recall that for bevel gears with the straight teeth $\upsilon_H = \upsilon_F = 0.85$. The load capacity of bevel gears with circular teeth is on average $1.4...1.5$ times greater [1].

Table 1. Values of coefficients that take into account the change in the strength of a bevel gear with indirect teeth compared to a cylindrical gear [1]

Transmission parameters	Hardness of gear and wheel teeth		
	$HB_1 \le 350$ $HB_2 \le 350$	$HRC_1 \ge 45$ $HB_2 \le 350$	$HRC_1 \ge 45$ $HRC_2 \ge 45$
υ_H	$1.22 + 0.21u$	$1.13 + 0.13u$	$0.81 + 0.15u$
υ_F	$0.94 + 0.08u$	$0.85 + 0.04u$	$0.65 + 0.11u$

After calculating the outer diameter of the gear, d_{e1} we take the number of teeth of the gear $z_1 = 18$ and calculate the outer circumferential modulus $m_{te} = d_{e1}/z_1$ (in contrast to the straight-toothed bevel gear, the value of the average normal modulus is taken as standard m_n). We calculate the value $z_2 = z_1 \cdot u$ and round it to the nearest integer, if necessary, recalculate the gear ratio $u = z_2/z_1$. Next, it is necessary to calculate the number of teeth of a flat wheel $z_c = \sqrt{z_1^2 + z_2^2}$. The previous value of the outer cone distance $R_e = 0.5 m_{te} z_c$, the width of the toothed crown $b = R_e \cdot k_{be}$, the width value b is rounded to the integer. We calculate the preliminary value of the average cone distance $R_m = R_e - 0.5b$. Next, we calculate the value of the average normal modulus $m_n = 2 R_m \cos\beta_n / z_c$ and round up to the standard value according to standards.

Actual value of average cone distance $R_m = 0.5 m_n z_c / \cos\beta_n$, outer cone distance $R_e = R_m + 0.5b$. The value of the external circular module $m_{te} = 2R_e / z_c$.

Building models bevel gearing in Autodesk Inventor environment

Using the results of the calculation of the main parameters of bevel gears, it is possible to build models of bevel gears (with straight and circular teeth). Example of calculation results in "Autodesk Inventor" shown in Fig. 4.

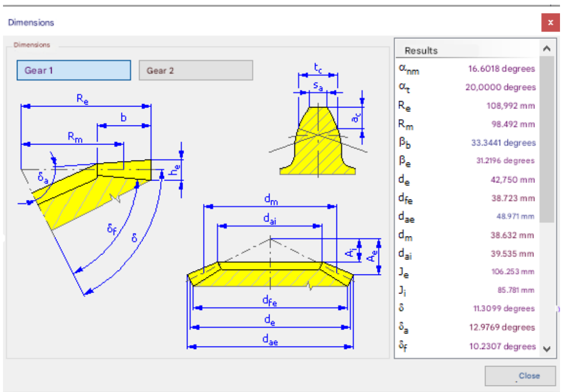

Fig. 4. The bevel gear calculation results window in the "Autodesk Inventor" environment.

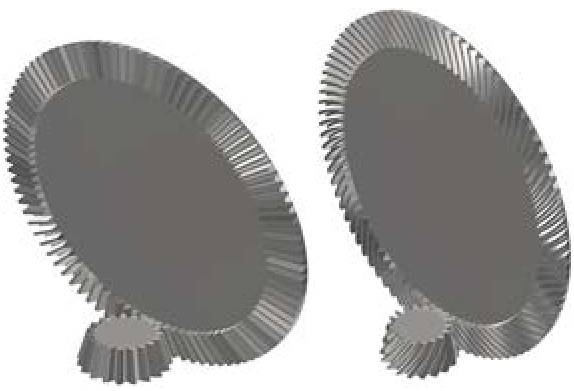

Fig. 5. Model of bevel gear, constructed by the help of Bevel Gears Component Generator in "Autodesk Inventor" environment ($u = 5$): a – straight-toothed gearing; b – gearing with circular teeth

First of all, it should be noted that the evaluation of the dimensions of the transmission, depending on the gear ratio, will be carried out for a simplified model of the gearing.

Of course, the results obtained from the analysis of simplified models of bevel gears are approximate. But the main goal is to get the dependence of the transmission mass on the gear ratio. We can say that the dependence will be approximately the same as for the real model. The results of the bevel gear construction are shown in Fig. 5.

Next, it is necessary to obtain the mass value for each gear (with eight values of the standard gear ratio). To do this, we set the same material for all gears. For example, we choose the material available in the "Autodesk Inventor" library "carbon steel". Next, the program calculates the mass of each simplified model, the results are summarized in Table 2.

Table 2. The results of gear mass determination

Gear ratio	Mass of bevel gears with straight teeth, kg	Mass of bevel gears with circular teeth, kg
1.588	4.312	2.606
2	4.402	2.478
2.50	4.118	2.26
3.158	3.872	1.937
4	3.864	1.621
5	3.842	1.541
6.278	3.887	1.459
8	3.996	1.316

Obtaining the dependences of the bevel transmissions mass on the values of the gear ratio

When solving the problem of optimizing a bevel gear relative to the gear ratio, it can be used the simplest (available) method, that is, do not perform a time-consuming calculation of the gear parameters, but use the capabilities of "Autodesk Inventor". We can fix the value of the engagement module and the number of gear teeth z_1 and vary only the number of wheel teeth z_2, that is, the gear ratio u. In the case of using this method, it is obvious that with an increase in the gear ratio, the dimensions of the transmission will increase, and, accordingly, its weight (Fig. 6).

It can be said that the dependencies (Fig. 6) are not correct, since each of the gears (with different gear ratios) is designed for different operating conditions (has different load capacities). In reality, it is necessary to solve other problems, namely to design gears (gearboxes) that are designed to operate under the same loads but have different kinematic capabilities (gear ratios). Therefore, we will consider precisely this problem.

In the previous section, the mass values for bevel gears (with straight and circular tooth gears) were obtained. With the help of the obtained results, we obtain the dependence of the mass on the gear ratio (Fig. 7).

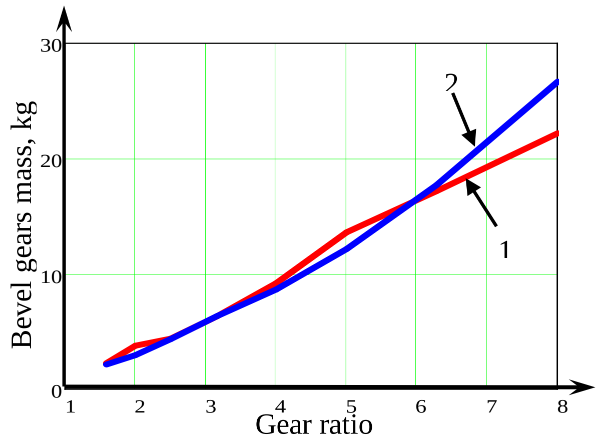

Fig. 6. Dependencies of the mass of the bevel gear on the gear ratio, with a constant value of the module:
1 – straight-toothed gearing;
2 – gearing with circular teeth

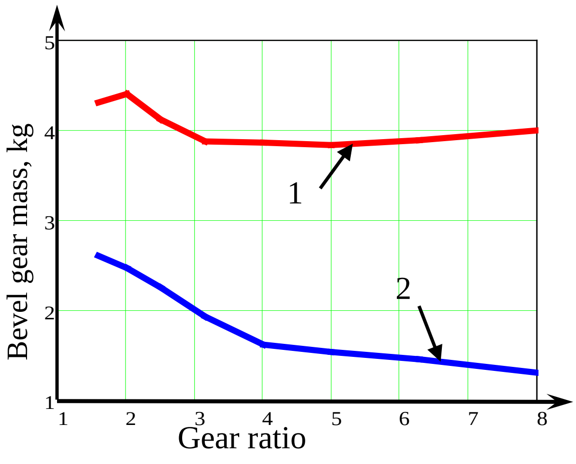

Fig. 7. Dependencies of the mass of the bevel gear on the gear ratio, with a constant value of the module:
1 – straight-toothed gearing;
2 – gearing with circular teeth

Analysing these dependencies, it can immediately be noted that the use of gears with circular teeth is more rational. The mass of the transmission with circular teeth is much smaller, accordingly, the dimensions of the drive, which includes the transmission, will be smaller. The lower weight of a gear with circular teeth can be explained by its greater load capacity, it was previously stated that the load capacity of a gear with circular teeth is approximately 1.5 times greater. That is, with the same dimensions, a bevel gear with circular teeth can transmit 1.5 times more load than a straight-toothed bevel gear.

The curve of the mass dependence for the straight-toothed bevel gearing decreases at gear ratios from 2 to 3.15. Then there is a slight increase in mass. That is, we can say that it is most rational to use straight-toothed bevel gearing with a gear ratio from 3.15 to 5.

The dependence curve of the mass of a bevel gear with circular teeth drops significantly at values of the gear ratio from 1.6 to 4. That is, it is most rational to use bevel gears with circular teeth with a gear ratio of 4 or more, of course, do not forget that it is not recommended to use for bevel single-stage gearboxes, the gear ratios are greater than 6.3 [14].

Conclusions

The paper analyzes the types of bevel gears. Today, the most common are bevel gears with straight and circular teeth, their relevance is justified by relative ease of manufacture and, in the case of bevel gears with circular teeth, increased load capacity. Therefore, the research was carried out specifically on bevel gears with straight and circular teeth.

The dependences of the mass of bevel gears on the values of the gear ratio were obtained, while the output data were constant, only the gear ratio changed. The following conclusions can be drawn from the obtained results:

– a bevel gear with circular teeth is more optimal (compact) from the point of view of smaller dimensions, with the same load capacity, a gear with circular teeth has less weight than a straight-toothed gear, which confirms the well-known statement;

– for straight-toothed bevel gears, the most optimal gear ratios are from 3.15 to 5, at these values, the smallest gear mass is observed, with the same load capacity of the gears;

– for gears with circular teeth, gear ratios of 4 or more are most optimal, but do not forget about the recommendations for the rational choice of gear ratio, for the bevel gears, depending on the material of the gear wheels, it is not recommended to choose gear ratios greater than 5 or 6, 3.

Using these recommendations regarding the selection of the gear ratio, it is possible to significantly optimize the dimensions and mass of the bevel gears, which leads to a reduction in the dimensions of the gearbox and, accordingly, the cost of the entire drive.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Оптимізація параметрів конічної передачі

Анотація. Проблема. *Проектування, і особливо вдосконалення механічних приводів, займає одне з найважливіших місць у сучасному машинобудуванні. Різноманітні приводи зараз дуже поширені, до них часто входять механічні редуктори. У цій роботі детально розглядається* *питання оптимізації конічних передач, які використовуються, коли необхідно передавати рух під певним кутом (зазвичай 90°).* ***Мета.*** *Метою роботи є визначення оптимальних (раціональних) параметрів конічної передачі з точки зору зменшення її маси та габаритів. Тобто отримання залежності маси передачі (зубчастих коліс) від передатних чисел.* ***Методологія****. Для вирішення задачі в цій роботі використовується сучасна система тривімірного проектування "Autodesk Inventor Professional". Для отримання залежностей обрані найпоширеніші типи конічних передач, виконано стислий аналіз типів конічних передач.* ***Результати.*** *Було встановлено, що для зубчастих коліс з круглими зубцями найоптимальнішими є передатні числа 4 і більше, а для конічних прямозубих зубчастих коліс оптимальними є передатні числа від 3,15 до 5. Меншу вагу зубчастих коліс з круглими зубцями можна пояснити їх більшою вантажопідйомністю (приблизно в 1,5 разів).* ***Оригінальність.*** *Оригінальність підходу полягає у вирішенні досить складної задачі оптимізації не шляхом розробки складних аналітичних моделей та їх подальшого аналізу, а шляхом виконання 3D-моделі передачі в середовищі твердотільного моделювання "Autodesk Inventor Professional" з використанням вбудованих функцій та подальшою обробкою отриманих результатів.* ***Практичне значення****. Сучасні тенденції розробки різних механічних приводів в першу чергу спрямовані на зменшення їх маси та габаритів. Зі зменшенням розмірів передачі зменшуються також розміри інших деталей та вузлів, а відповідно, і їх вартість. Використання отриманих оптимальних передатних чисел дозволяє проектувати компоненти передачі зі зменшеними геометричними розмірами на ранніх стадіях розробки*

Ключові слова: *механічний привід, механічний редуктор, конічні зубчасті колеса, оптимізація, передатне число*

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