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Optimization of key gear parameters to reduce weight

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Abstract. Problem. *The problems of designing, and especially improving, mechanical gears are of key importance in modern mechanical engineering and automotive transport. Gear transmissions are quite widespread relative to other mechanical transmissions because they have a number of crucial advantages. Gear transmissions are widely used in a variety of drives for vehicle components and assemblies, with modern development trends aimed at reducing their weight and size. As the size of the transmission decreases, the dimensions of other parts and assemblies also decrease, and, accordingly, their cost. Therefore, research related to the study of the interdependence of the main parameters of gears for the purpose of their further optimization does not lose its relevance.* ***Goal.*** *The main purpose of this work is to study the dependence of the mass and dimensions of the gears under study on their main parameters. Knowing the influence of various characteristics on the mass, it is possible to provide recommendations for the design of gears to achieve their optimal (smallest) dimensions, which leads to a number of significant advantages.* ***Methodology.*** *First of all, a rather detailed analysis of the scientific literature is performed in order to identify the main statements regarding the influence of certain parameters on the mass and dimensions of the designed gear. The very dependencies of the gear mass on its various characteristics are found by applying a numerical method that is entirely based on the known design dependencies for the design calculation of gears. Also, to compare the results obtained analytically, the method of calculating the mass and dimensions by creating 3D models of gears in the "Autodesk Inventor" environment is used in the work.* ***Results.*** *Based on the results obtained, it can be noted that, ceteris paribus, including gear load, the weight is almost independent of the module and the relative width ratio. At the same time, in some cases, a particular standard value can significantly affect the weight of the gear, i.e., by selecting specific values, it is possible to reduce the weight of the gear by about 15-25%.* ***Originality.*** *Useful results were obtained using a relatively affordable method. The research was conducted both analytically and with the use of modern computer-aided design systems.* ***Practical value.*** *The proposed recommendations for the rational choice of some characteristics of gears will reduce the weight and dimensions of the mechanical drive.*

Key words: *gear, optimization, face-width factor, gear weight, gear dimensions, gear ratio.*

Introduction

Mechanical transmissions are widely used in mechanical engineering and road transport. They are designed to convert the motion parameters of the input link (engine) when transmitted to actuators [1]. Among mechanical transmissions, gear transmissions are more widespread due to their numerous advantages. As is well known, a gear transmission is a mechanism that transmits rotational motion through the interaction of conjugate profiles that form a higher kinematic pair. Cylindrical and bevel gears are widely used, with cylindrical gears being easier to manufacture and assemble. Usually, these gears operate in the range of low ($<3\,\mathrm{m/s}$)and medium ($3...15\,\mathrm{m/s}$) speeds. According to the shape of the tooth profile, the following main types of gears are distinguished: involute, cycloidal, and circular tooth profile. In the machine and automotive industry, the most widespread is the involute profile, which was proposed by L. Euler in 1760. This profile has a number of technological and operational advantages.

Modern cars are equipped with a large number of actuators for various systems. For example, a glass cleaning system (wipers), a glass lifting system, etc. Development trends in components and assemblies, various systems, and automobiles in general, are aimed at optimizing them in terms of weight and size reduction. Considering any of the specific systems designed to ensure comfort, we can say that their drive elements (for example, gears) make up a significant part of the entire system. It can be said that by achieving optimal values for the gear parameters, the weight and dimensions of the entire system will also be reduced. Therefore, the problem of gear optimization is quite relevant and requires a detailed study.

Analysis of publications

The classical textbooks recommended for students in the discipline "Machine Parts" [1-3] contain some recommendations for choosing the characteristics of a gear to obtain its optimal dimensions as a result of designing it. For example, work [3] states: "with increasing ψ_d, the weight and dimensions decrease, but the width of the crown increases and the accuracy of tooth contact along the length decreases, i.e., the running-in conditions worsen". Also, [3] recommends that in helical gears, to increase the load capacity and smoothness of operation, the condition of multiplicity of the axial overlap coefficient to an integer be observed K. Then the coefficient of the width of the crown relative to the diameter of the gear is determined from dependence (1).

$$\psi_d = K \frac{\pi}{z \cdot tg\beta}, \qquad (1)$$

where z – number of gear teeth; β – angle of inclination of the teeth.

The feasibility of following this recommendation in the transmission calculation is somewhat questionable; the impact of the ψ_d coefficient is discussed in more detail in the relevant section of this paper. In addition to the above coefficient, recommendations for the selection of other gear characteristics are also often given. However, when designing mechanical transmissions, in particular gears, it is necessary to be guided primarily by the relevant standards. Currently, standards [4,5] for the design of spur gears are in effect in Ukraine. In this work, the calculation of gears was carried out also taking into account the current DSTU standards.

The problem of designing the minimum mass of a single-stage cylindrical gearbox with helical teeth is of real interest, since such mechanical transmissions are widespread. Paper [6] presents the problem of minimizing the mass of the structure of such a reducer along with the determination of the dimensions of the shafts, gearing, and housing using genetic algorithms (GA). It can be seen that the proposed optimal design with GA has the potential to provide significantly better solutions than traditional design methods. At the same time, GA provides a better understanding between different parameters (such as service life and weight). Gear materials have a major impact on weight. For this reason, a study was conducted in which two different types of gear wheel materials were considered. The optimal design solutions obtained for both cases were compared with the results of conventional design. In both cases, the objective function was subjected to a set of 45 constraints. The characteristics considered during the optimization are of a mixed nature, i.e., continuous, integer, and discrete, 11 in total. The results obtained by GA show a significant improvement over the results obtained by conventional design (weight reduced by 12%). While in the second case, the weight was reduced by 20%. Comparison of the two optimal design solutions for both cases revealed a reduction in mass. An interesting relationship between mass and service life was also presented for both cases. From this study, it can be concluded that the required service life should be reduced to less than 10,000 hours before a significant mass reduction occurs. The proposed GA can be easily modified to meet the multi-objective optimization of gearbox design. In addition, other objective functions can be considered in the same vein - production costs are just an example.

When designing a two-stage spur gearbox with helical gears, it is usually necessary to operate with a large number of variable characteristics (usually more than ten). This makes the design quite complicated. Given all the complexity, a genetic algorithm (GA) is proposed in [7] to solve the gear design problem. The goal is to minimize the volume limited by the inner surface of the gear case. The proposed optimal design with GA has the potential to provide significantly better solutions than traditional design. This paper shows how

GA can be used to solve the challenging problem of minimizing the volume of a gearbox. The objective function was subjected to a set of 37 constraints. The design variables considered during the optimization are of a mixed nature, i.e., continuous, objective, and discrete, totaling 12. The optimal design solution was compared with traditional design. The results obtained with the GA show a significant improvement over the results obtained by traditional design (i.e., a volume reduction of approximately 20%). The proposed GA can be easily modified to optimize multi-objective design. Additional stages and other objective functions can also be considered. This optimization example illustrates the effectiveness of the proposed approach and also serves as further proof of the power and versatility of GA in the design of multi-stage mechanical transmissions.

In [8], the volume and carrying capacity of the transmission are optimized. To solve the problem, three different approaches are applied and the MATLAB optimization toolkit, genetic algorithm, and multi-criteria optimization method are used. In the first two methods, the mass is minimized at the first stage, and then a verification calculation is performed. The third method treats the optimization problem as a multi-criteria one. The width, modulus, and number of teeth are used as optimization parameters. Constraints are imposed on the strength parameters. A comparison of the results shows that the result obtained by the multicriteria evaluation is more significant than the results obtained by the other methods.

In [9], to increase the load-bearing capacity of a gear transmission, optimization of the gearbox, extending its service life, and reducing its size are of great importance. Thanks to Visual Basic programming mixed with MATLAB, the efficiency and quality of design are significantly improved. The genetic algorithm and genetic tools of MATLAB are used in the computations because they offer advantages in programming, high reliability, and high efficiency.

The aim of [10] is also to reduce the weight of gears. It is believed that the bending strength and surface strength of the wheel teeth are among the main criteria for performance. Also in this work, a three-dimensional solid model was created, which can be created in any CAD software, specifically in this case, the model was created in Autodesk Inventor 2015. This model of cylindrical spur gears is imported into ANSYS software, and then the contact and bending stresses that occur during the operation of the gear can be calculated. This paper presents the results of the calculation of spur wheels used in the gearbox of an excavator impeller located in open-pit coal mines in Bardhi i Madh - Fushë Kosovë, and then the shape of the spur wheel was optimized using ANSYS software. More precisely, how much material can be removed from the gear body without compromising the gear engagement properties. A number of components were taken into account in the optimization process, including material strength, load, and manufacturing quality. The use of the design optimization method proposed in this paper allows to reduce its weight by about 20% (initial and final weight of the spur gear is 669.58 kg and 538.48 kg, respectively), which in turn reduces the cost. Based on the results of the shape optimization, the spur gear model presented here was built in CATIA V6.

The main objective of [11] is to optimize the design and analyze the design of gear wheels for gearboxes that transmit power at different speeds, i.e., 2500 rpm, 5000 rpm, and 7500 rpm. The analysis was also performed for different wheel materials, cast iron, cast steel, and aluminum alloy. Currently, the most common materials for wheels and shafts are cast iron and steel. In this work, aluminum alloy was considered as a material to reduce the weight of the product. The analysis is performed in the Cosmos software, a product of Solid Works. The data required for calculation and design are taken from reference books. Modeling and assembly are performed in Solid Works.

The paper [12] considers the problem of multicriteria optimal design of a worm-cylindrical reducer with a lower Archimedean worm arrangement. A design and mathematical model of the reducer is developed and, using the example of parametric optimization of the specified reducer according to the selected criteria, the effective optimization parameters are determined and the problem of distributing the total gear ratio of the reducer is investigated. The method of "admissible sets" is used to solve the optimization problem. The results of the numerical analysis of the information set of the designed gearbox are presented. To ensure the crankcase lubrication system and reduce the height of the gearbox, a change in the algorithm for calculating the spur gear is proposed.

Recommendations for the distribution of gear ratios by gear stages are analyzed and recommendations for the selection of optimally rational design solutions under various constraints are given. The following conclusions are drawn based on the results of the research: the proposed method of optimally rational design of multi-stage gearboxes, in particular, worm-cylinder gearboxes, is quite universal and can be used both in engineering and educational practice; the applied method of gearbox design allows not to limit the number of quality criteria, but to take into account each of them and actively manage the process of choosing optimally rational solutions; the analysis of existing recommendations for the distribution of the total gear ratio for worm-cylinder reducers showed that they do not always have or do not always satisfy the declared optimization condition and require further refinement; an algorithm for calculating gears, in particular, a cylindrical gear of a worm-cylinder reducer with a lower worm location, is proposed to ensure the crankcase version of gearbox lubrication and minimize the height of the reducer.

Purpose and Tasks

To improve the quality and efficiency of the design of spur gears, which, as previously proven, are quite often used in all branches of modern engineering, a thorough study of their main parameters is required. Also, based on the results of previous, already presented works on gear optimization, it is necessary to identify the main and most effective developments. And finally, having the results of the influence of the main properties of gears on their weight and dimensions, it is possible to provide recommendations that will be really useful at the design and calculation stage.

In order to optimize the weight and dimensions of spur gears, it is necessary to evaluate the influence of their main characteristics on the weight and dimensions. This assessment should be performed using as many methods as possible. In this paper, these will be the following methods:

1) "analytical" method (by means of numerical processing);

2) experimental method (by using modern CAD).

Brief theoretical information on the calculation of gears

In this section, we will briefly review the main stages of gear calculation, their characteristics, and determine the methodology for designing a spur gear in the course of the study.

During the operation of a gear transmission, a pressure force is generated between the teeth of the mating gears F_n (normal force directed along the meshing line). In addition, the friction force is generated by the sliding of the teeth between them. Under the influence of these forces, the teeth are in a complex state of tension. Therefore, two main stresses have a decisive influence on their performance – contact stresses σ_H in the surface layers of the teeth and bending stresses σ_F in the cross-sections of the teeth.

In modern calculation methods, among the two stresses, contact stresses σ_H, are considered the main ones in most cases, since they remain constant within the specified dimensions of the gears, and bending stresses σ_F can be reduced by increasing the modulus.

Several types of strength calculations have been developed to take into account the operating conditions of the teeth and the main causes of gear failure:

– calculation of the active tooth surfaces for endurance by contact stresses (for closed gears with tooth surface hardness $HB \leq 350$ this calculation is a design calculation);

– calculation of tooth surfaces for contact strength under peak loads (performed to prevent residual deformation or brittle breakage of active tooth surfaces under overloads);

– calculation of teeth for bending endurance (this calculation is a design calculation for open gears and closed gears with tooth surface hardness $HB > 350$);

– calculation of the bending strength of the teeth under peak loads (performed to prevent residual deformation or brittle breakage of the teeth under overloads).

In our case, we will use the first type of calculation, since the study is performed for closed gears.

The calculation of the teeth for contact endurance is performed for engagement at the pole, since the crumbling of the teeth begins at the pole. To derive the calculation formulas, we use the Hertz theory for initial contact along the line. Some assumptions are also made:

1) the teeth are considered as two cylinders that are in contact with their constituent parts (the radii of these cylinders are assumed to be equal to the radii of curvature of the tooth profiles at the meshing pole);

2) the load is considered to be evenly distributed along the tooth length;

3) the contacting profiles are considered to be undivided by the lubricating film.

In the design calculation, the diameter of the initial gear circumference (or center distance) is determined. Since the width of the tooth ring is unknown at the design stage, it is expressed as the ratio of the tooth ring width to the diameter $\psi_{bd} = b_W / d_W$, then the initial diameter of the gear is calculated using dependence (2).

$$d_W = \sqrt[3]{\frac{2T \cdot K_H \left(Z_M Z_H Z_\varepsilon\right)^2 (u+1)}{\psi_d \left[\sigma_H\right]^2 u}}, \qquad (2)$$

where T – torque on the gear shaft; K_H – design load factor; Z_M – coefficient that takes into account the mechanical properties of the materials of mated gears; Z_H – coefficient that takes into account the shape of the mating surfaces of the gears at the meshing pole; Z_ε – coefficient that takes into account the total length of the contact line; u – gear ratio of the designed transmission.

Let's also briefly consider the main stages of the verification calculation of the gear by bending stresses. The highest stresses occur at the root of the tooth in the area of the involute to fillet transition. To obtain the basic design dependencies, let's consider an approximate bending calculation based on the following assumptions:

– the entire meshing load is transmitted by one pair of teeth and applied to the tooth axis (worst case), and instead of the theoretical two-pair meshing, it will be a single-pair meshing;

– the tooth is assumed to be a cantilever beam (worst case), for which the hypothesis of flat sections or, in other words, the methods of material resistance are valid.

Finally, the bending stresses are determined by dependence (3).

$$\sigma_F = \frac{2T \cdot K_F Y_\varepsilon Y_F}{\psi_d \cdot z^2 \cdot m^3}, \qquad (3)$$

where K_F – design load factor; Y_ε – coefficient that takes into account the total length of the contact line; Y_F – tooth shape coefficient; z – number of gear teeth; m – gearing module.

In our case, this calculation will be a check, so the following condition must be met $\sigma_F < \left[\sigma_F\right]$.

In the next section, based on the design dependence (2) for the design calculation, the dividing diameters of the gears will be determined at different values of ψ_d. Using the results obtained, it is possible to estimate the dependence of the diameter and, accordingly, the mass of the gear on ψ_d.

A verification calculation for bending stresses will also be performed for each of the cases, but the results are not presented for reasons of reducing the volume of the article itself.

Obtaining the dependence of gear mass on its main parameters by analytical method

To assess the interdependence of transmission parameters and their impact on the weight and dimensions of the transmission, it is necessary to calculate their values under different conditions.

Based on the design dependencies for the design calculation of spur gears given in the previous section, the dividing diameter of the gear d_w was calculated at different values of the tooth ring width ratio and the gearing module. Next, we need to estimate the weight of the designed gears.

When calculating the mass of the gears, at different values of the relative width ratio, we will make some assumptions, namely, the gears will be considered cylinders with a diameter equal to the dividing diameter. You also need to determine the material of the gears. The choice of gear material depends on the purpose of the gear, its operating conditions, and geometric parameters. The main materials for manufacturing gears are heat-treatable steels, and in some cases cast irons and plastics.

In our study, we assume the material of the gears is steel 40, heat treatment is improvement, density $\rho = 7800\,\text{kg}/\text{m}^3$.

Fig. 1 shows the dependence of the initial diameter d_w on the tooth ring width ratio ψ_d (sometimes denoted ψ_{bd}).

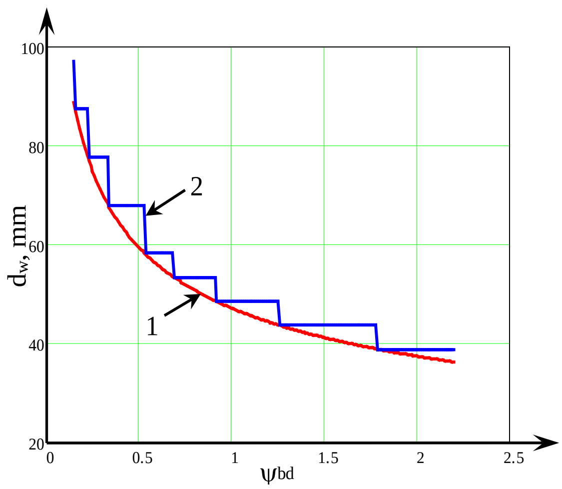

Fig. 1. Dependence of the dividing diameter on the tooth width ratio

Curve 1 shows a continuous relationship, but only standard (discrete) gear modulus values are used in production. Curve 2 shows the dependence of the actual diameter (with a standard module). Due to the discrepancy between curves 1 and 2 (Fig. 1), there is a difference between the continuous mass of the entire gear (the total mass of the two gears in meshing) and the actual mass of the gear, which is manufactured with standard module values.

In Fig. 2 shows the results of numerical calculations of the dependence of the total mass of the transmission M_{Σ} on the width coefficient ψ_d .

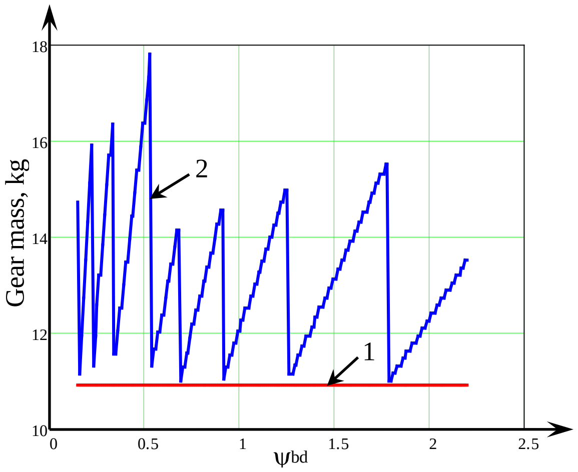

Fig. 2. Dependence of gear mass on the tooth ring width ratio

Note that, contrary to what is usually reported in the literature, the total mass does not change with a continuous module (curve 1, Fig. 2). Curve 2 (Fig. 2) demonstrates that in reality the total transmission mass strongly depends on the ψ_d ratio, but this dependence is not "logical" - because the emissions are local discrete, and with the growth of ψ_d the total mass does not increase separately. The same can be said for each wheel separately.

Reducing the weight is especially important when designing small electric drives (consisting of an electric motor and a gear mechanism), which, as noted earlier, can be quite numerous in a modern car. To reduce the weight of the gearing (gears), it makes sense to use the condition of permissible overload. Classical methods recommend taking a standard larger module in the design calculation, but overloads within 5% are allowed. In Fig. 3, in addition to the above-described curves 1 and 2, shows the results of calculating the discrete dividing diameter (depending on the choice of the standard module), taking into account the permissible overload - curve 3 (Fig. 3).

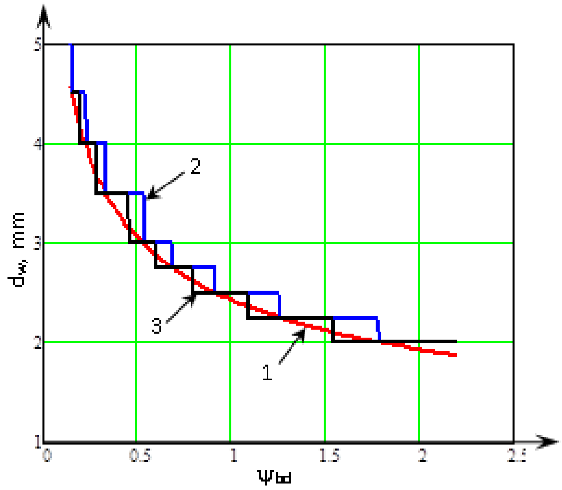

Fig. 3. Dependence of the dividing diameter of the gear on the width ratio of the tooth ring

If you take advantage of the overload tolerance when selecting the standard gearing module value, you can significantly reduce the weight and dimensions of the gear.In Fig. 4, curve 3 shows the dependence of the total weight of the gear at standard values of the module with overload.

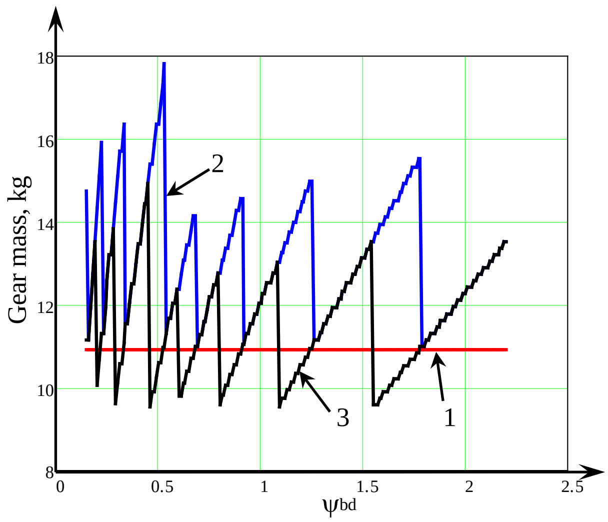

Fig. 4. Dependence of gear mass on the tooth ring width ratio

From the analysis of curve 3 (Fig. 4), the following conclusions follow: it is possible to obtain a real discrete gear mass even smaller than the continuous one (at continuous values of the modulus), and that when designing a gear, the designer must constantly monitor the gear parameters depending on the gear width coefficient, rather than using standard fixed values.

Obtaining the dependence of gear mass on its main parameters by using computer-aided design systems

When solving the problem by the numerical method, some assumptions were made, namely, the gears were considered solid cylinders. This problem can be solved in another way, by modeling gears in modern computer-aided design (CAD) systems, such as Autodesk Inventor. When solving the problem in this way, you can avoid simplifications of the wheel model and get more accurate results for calculating the gear mass.

In Autodesk Inventor, you can either simply build a model (based on preliminary calculations) or calculate the transmission. The calculation in the environment is carried out using design generators (design wizards) and is based on the 1996 ANSI, DIN, CSN and ISO standards. To prevent differences in the calculations, we will use the already pre-calculated transmission parameters and use them to build models in the program's spur gear design generator.

Fig. 5 shows a model of one of the gears used in the study.

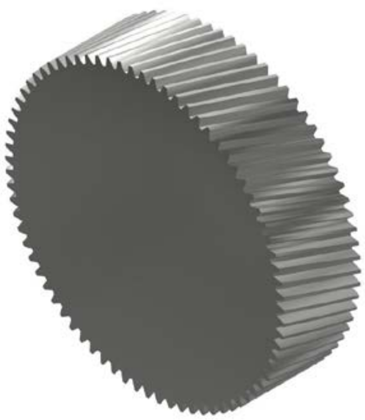

Fig. 5. An example of a gear model built using the design generator in the Autodesk Inventor environment

The above model also has some drawbacks, namely, the absence of a hub, holes for weight reduction, chamfers, rounding, etc. However, in the course of our study, the inaccuracy of the models will not have a significant impact on the assessment of the impact of the main parameters of the transmission on its weight, since all models are performed in the same form (Fig. 5).

Thus, based on the results of the design calculation performed in the previous sections, gear models were built for different values of the tooth ring width ratio ψ_d and the gearing module. The main advantage of using CAD is the ability to automatically calculate the mass of the designed gear by specifying its material. Thus, the value of the gear mass in each case and, accordingly, its dependence on the above parameters are obtained.

The result is quite obvious and coincides with the results of the numerical calculation.

Conclusion

A rather detailed review of scientific papers is presented. The literature analysis has shown that when solving the problem of optimizing the main parameters of gears, researchers often turn to abstract mathematical formulations of problems and their subsequent numerical solution in the "black box" mode or, in other words, a cybernetic model without taking into account real physics (only some constraints are taken into account) and engineering recommendations. That is, in reality, a quantitative analysis of specific tasks is performed without precise recommendations (of a qualitative nature).

This paper presents the results of a study of the influence of the main parameters of gears on their mass. The study was carried out by two methods, by numerical processing (analytically) and by using modern CAD. As a result of the study, it was found that the tooth ring width ratio does not affect the gear mass. It was found that it is possible to obtain a real discrete (at standard module values) gear mass even smaller than the continuous (at continuous module values) if the possibility of permissible gear overload is taken advantage of. That is, in other words, by designing the gear with an overload of 5%, which is quite acceptable and often recommended, you can achieve a weight reduction of 15-25%.

The use of the results presented in this paper (mass versus modulus and tooth width ratio ψ_d) can help the designer calculate and design a gear with optimal parameters.

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Оптимізація основних параметрів зубчастих передач з метою зменшення маси

Анотація. Проблема. *Проблеми проектування, а особливо вдосконалення механічних передач займають ключове місце в сучасному машинобудуванні та автомобільному транспорті. Зубчасті передачі достатньо поширені відносно інших механічних передач, адже мають ряд надважливих переваг. Передачі зачепленням широко застосовуються в різноманітних приводах вузлів та агрегатів автомобіля, сучасні тенденції розвитку яких направлені на зменшення їх маси та габаритів. Зі зменшенням розмірів передачі – зменшуються й габарити інших деталей та вузлів, а відповідно і* *їхня вартість. Тож дослідження, пов'язані з вивченням взаємозалежності основних параметрів зубчастих передач з метою їх подальшої оптимізації не втрачають своєї актуальності.* ***Мета.*** *Основна мета роботи полягає в дослідженні залежностей маси та габаритів досліджуваних передач від їх основних параметрів. Знаючи вплив різних характеристик на масу можна надавати рекомендації щодо проектування передач для досягнення їх оптимальних (найменших) габаритів, що веде за собою ряд суттєвих переваг.* ***Методологія****. Перш за все, в роботі виконується досить детальний аналіз наукової літератури з метою виявлення основних тверджень щодо впливу тих чи інших параметрів на масу та габарити проектованої передачі. Самі залежності маси передачі від її різних характеристик знаходяться шляхом застосування чисельного методу, який цілком побудований на відомих розрахункових залежностях для проектного розрахунку зубчастих передач. Також для порівняння отриманих аналітичним шляхом результатів в роботі використовується і метод розрахунку маси та габаритів шляхом створення 3D моделей передач в середовищі «Autodesk Inventor».* ***Результати.*** *Орієнтуючись на отримані результати, можна зазначити, що при інших рівних умовах, зокрема завантаженості передачі, маса майже не залежить від модуля та коефіцієнта відносної ширини. Водночас те чи інше стандартне значення в деяких випадках може помітно впливати на вагу передачі, тобто підбираючи конкретні значення можна досягти зменшення маси передачі приблизно на 15-25%.* ***Оригінальність.*** *Відносно доступним методом отримані корисні результати. Дослідження проводилися як аналітично так і з застосуванням сучасних систем автоматизованого проектування.* ***Практичне значення****. Запропоновані рекомендації щодо раціонального вибору деяких характеристик зубчастих передач, дозволять зменшити масу та габарити механічного приводу.*

Ключові слова: *зубчаста передача, оптимізація, коефіцієнт ширини зубчастого вінця, маса передачі, передатне відношення.*

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