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ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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INVESTIGATION OF KINEMATICS AND POWER OF COMPOSITE PLANETARY GEARS FOR WIND TURBINES

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Abstract. The article presents a method of complex kinematic analysis of a mechanical wind turbine system. Input data, such as the speed of rotation of the input shaft of the gearbox, for the multi-criteria analysis of the planetary multiplier of the wind turbine were obtained from the results of computer simulation of the air flow. The fundamentals of the torque method were used to study planetary compound gears (PCG), called a multiplier. The variants of kinematic schemes of composite planetary transmission are analyzed in order to determine the most optimal distribution of the energy flow. The torque method allows not only kinematic analysis (determining the ratio of speeds), but also power analysis (determining the direction and magnitude of internal power flows), as well as determining efficiency. Relatively simple formulas for calculating the ratio of speeds and efficiency made it possible to carry out multi-purpose optimization of the parameters of the considered

PCG. As a result of the analysis, the most optimal scheme of a composite planetary gearbox was determined, taking into account the kinematics of the airflow on the wind turbine wheel.

Key words: Wind energy system, multiplier, torque method, kinematic analysis, computer modeling.

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ЖЕЛ ТУРБИНАЛАРЫ ҮШІН КОМПОЗИЦИЯЛЫҚ ПЛАНЕТАРЛЫҚ БЕРІЛІС БӘСЕҢДЕТКІШІНІҢ КИНЕМАТИКАСЫ МЕН ҚУАТЫН ЗЕРТТЕУ

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Аннотация. Мақалада ЖЭО механикалық жүйесін кешенді кинематикалық талдау әдістемесі келтірілген. ЖЭО планетарлық мультипликаторын көп критериялы талдау үшін редуктордың кіріс білігінің айналу жылдамдығы сияқты кірістер, ауа ағынын компьютерлік модельдеу нәтижелері бойынша алынды. Мультипликатор деп аталатын планетарлық құрама берілістерді (РТБ) зерттеу үшін момент әдісінің негіздері қолданылды. Энергия ағынының оңтайлы таралуын анықтау үшін күрделі планеталық берілістің кинематикалық схемаларының нұсқалары талданды. Момент әдісі кинематикалық талдауды (жылдамдық қатынасын анықтау) ғана емес, сонымен қатар қуатты талдауды (ішкі қуат ағындарының бағыты мен шамасын анықтау), тиімділікті анықтауға

мүмкіндік береді. Жылдамдық пен тиімділіктің арақатынасын есептеудің салыстырмалы түрде қарапайым формулалары қарастырылып отырған РТБ параметрлерін көп мақсатты оңтайландыруға мүмкіндік берді. Талдау нәтижесінде ЖЭО жел дөңгелегіндегі ауа ағынының кинематикасын ескере отырып, күрделі планетарлық редуктордың ең оңтайлы схемасы анықталды.

Түйін сөздер: Жел қондырғысы, мультипликатор, момент әдісі, кинематикалық талдау, компьютерлік модельдеу.

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ИССЛЕДОВАНИЕ КИНЕМАТИКИ И МОЩНОСТИ КОМПОЗИТНЫХ ПЛАНЕТАРНЫХ РЕДУКТОРОВ ДЛЯ ВЕТРОГЕНЕРАТОРОВ

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Аннотация. В статье представлена методика комплексного кинематического анализа механической системы ВЭУ. Входные данные, такие как скорость вращения входного вала редуктора, для многокритериального анализа планетарного мультипликатора ВЭУ были получены по результатам компьютерного моделирования воздушного потока. Для исследования планетарных составных зубчатых передач (ПЗП), называемыми мультипликатором, использовались основы метода крутящего момента. Проанализированы варианты кинематических схем составной планетарной передачи, с целью определения наиболее оптимального распределения потока энергии. Метод крутящего момента позволяет проводить не только кинематический анализ (определение соотношения скоростей), но и анализ

мощности (определение направления и величины внутренних потоков мощности), а также определение КПД. Относительно простые формулы для расчета соотношения скоростей и КПД позволили провести многоцелевую оптимизацию параметров рассматриваемого ПЗП. В результате анализа были определены наиболее оптимальная схема составного планетарного редуктора, с учетом кинематики воздушного потока на ветроколесе ВЭУ.

Ключевые слова: ветроэнергетическая установка, мультипликатор, метод крутящего момента, кинематический анализ, компьютерное моделирование.

Introduction

The expediency of the study of wind turbines kinematics today is due to the increased interest of society in environmental problems and the desire to make the transition to environmentally friendly and resource-saving energy (the so-called "green" economic transition). Thus, the green approach in power engineering is associated, in particular, with the transition to alternative energy sources, including energy of moving media (Dosaev, 2021). In this regard, there is a large layer of mechanics problems dealing with the description of the motion of bodies and energy transfer. Partially, methods of computer modeling of kinematics of fluid and gas dynamics and solid bodies successfully cope with such problems (Arnaudov, et al., 2005). With their help, rather accurate both qualitative and quantitative results are obtained. However, despite the current level of development of computer technology and computing power, it is not possible to simulate the entire range of possible scenarios of behavior of complex objects in the flow of the medium within a reasonable time. The solution of problems of combined systems that transfer the potential of wind energy and its conversion is nowadays as relevant as possible for the design of energy-efficient wind turbines.

When designing wind energy systems (WES) in regions with low wind speeds, precise solutions are required to increase the rotation speed of the generator shaft. When using a multiplier, several revolutions of the generator shaft are required for one revolution of the turbine wheel. If the multiplier's design is multi-stage, the gear ratio can be increased by orders of magnitude. On the other hand, it is necessary to consider that a multi-stage multiplier can have multiple structural schemes, which allows both achieving high rotation speed and reducing efficiency and power at the generator shaft. Achieving high speed in this case implies a loss of force necessary to initiate rotor rotation, overcome the inertia of the stiff shaft, and overcome magnet sticking. It is not advisable to use multipliers with high gear ratios and an increased number of stages for wind turbines, as the performance of the complex suffers from power loss. Therefore, a properly conducted multi-criteria kinematic analysis of the WES system from the turbine wheel to the generator shaft is an important task (Giger, et al., 2011).

The study of the kinematic characteristics of the mechanical system of the wind turbine was devoted to the authors' works (Arnaudov, et al., 2019). The authors refined the enhancement of wind turbine efficiency through the reduction of

planetary gearbox wheel vibrations by altering the phase relationships of dynamic forces induced by tooth meshing. In the investigated planetary gearbox design, through appropriate selection of tooth numbers in the second stage, the theoretical limit of vibration reduction at the tooth meshing frequency exhibits an effect of 20–40 dB. In (Mihailidis, et al., 2010) the modeling of a two-stage PGT using a linkage graph is presented. A generalized kinematic and dynamic model of the two-stage PGT is created. The result serves as an indication that the model can not only predict the natural frequencies and displacement stroke shape, but also the generalized deformation stroke shapes can be simultaneously expressed. Authors (Arnaudov et al., 2019) have devoted a large amount of work to the problem of equalizing the load distribution for all powertrains. Researcher (Karaivanov, 2000) notes that increasing the accuracy of PGT manufacturing is limited by increasing costs; therefore, one of the ways to improve the compound PGT is the appropriate choice of the structural scheme and its parameters. The torque method was proposed for the study of compound PGTs (Arnaudov, et al., 2017), which allows not only kinematic analysis, but also the determination of the magnitude of torques on all its shafts (elements), the determination of the direction of power flows and the presence of power division or power circulation; as well as the simplicity of the torque method for the study of complex multi-carrier PGTs (Arnaudov et al., 2005) and for the creation of calculation algorithms for optimization (Karaivanov, et al., 2022).

Regardless of the arrangement, PGTs in wind turbines operate as multipliers. In the vast majority of cases, PGTs (with one external gear, one internal gear and a single rim planet - Fig. 1a) are used. Mainly as a stage of multi-carrier compound PGTs (Giger, 2007). As wind turbine power increases, the importance of gear quality also increases. Despite attempts to utilize new schemes (Giger, et al., 2021), three-carrier PGTs remain the most suitable for wind turbines.

The purpose of this paper is to present a methodology for a comprehensive kinematic and power (efficiency) analysis of three-carrier PGTs for a wind turbine using computer simulation of airflow kinematics and torque method.

1 Object of research

The object of research is a designed wind turbine with horizontal axis for power supply of machine workshop. Consumed power of the workshop 50 kW, wind speed 20 m/s

The kinematic scheme of the wind turbine is shown in figure 1

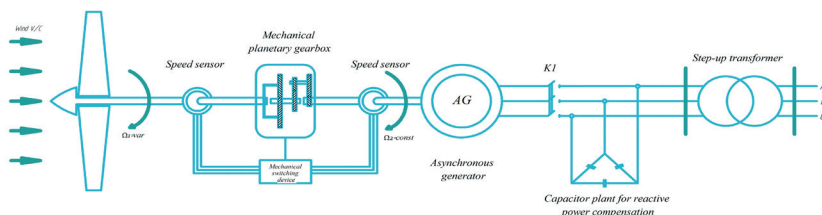


Fig 1. Kinematic diagram of wind turbine with horizontal axis, planetary gearbox

According to the selected scheme, the planetary gearbox has three stages, each stage contains three planets. In the wind turbine system, the MPR increases the angular velocity (speed) and revolutions of the generator of the wind turbine. In addition, the MPR, based on the principle of automatic gearboxes in automobiles, is simultaneously used to stabilize the output shaft speed by changing the speed ratio.

2 Methodology

2.1 Computer modeling of flow kinematics in a wind wheel

The modeling was performed using the state-of-the-art top-level CAD software Cradle CFD. The program allows to obtain detailed pictures of the kinematics of the air flow around the working surface.

In the Cradle CFD program we investigate the operation of the rotor of the wind turbine and the calculation of the streamline and the main aerodynamic forces and moments that arise on the industrial wind turbine when blowing it with wind flow.

The first step is to import the geometric model from the CAD system. It is possible to calculate both the model as a whole and a separate part of it.

The problem of stationary flow of uniform wind flow around a rotating rotor in the presence of a stationary domain was taken. This problem was taken as the main calculation scheme. The computational domain was built from 2 domains as cylinders: the outer cylinder $r = 6$ m and $L = 100$ m, and was described as a stationary translational motion of the medium, the cylindrical working area - domain, includes blades of the wind turbine, radius of 10 m and the length of 2.5 m (Isametova, 2021).

Mesh generation was carried out in semi-automatic mode in CFX-Mesh grid generator. The mesh was generated by three-dimensional hybrid tetrahedral elements with prismatic layers in the regions of the boundary layer on solid surfaces. Figures 2,3 show the steps of model building.

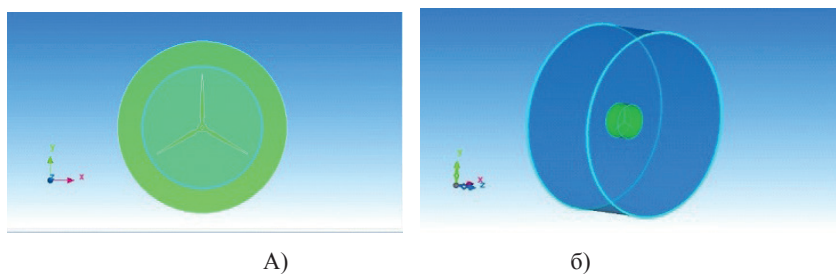


Fig 2. Computer model of wind wheel a) Calculation domain b) Rotating domain

Mesh generation was carried out in semi-automatic mode in the CFX-Mesh grid generator. The mesh was generated by three-dimensional hybrid tetrahedral elements with prismatic layers in the boundary layer regions on solid surfaces. Figure 3 shows the generated cone-volume mesh of the wind wheel

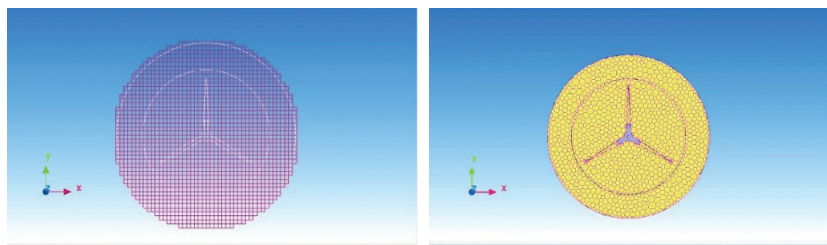


Fig 3. Fragment of triangular mesh on the surface of the nacelle and blades

Design meshes with 500 thousand, 600 thousand and 1 million cells were constructed. Analysis of the integral values obtained from the numerical results for meshes with different densities showed that the results differ by no more than 1% when the number of cells exceeds 700 thousand. This result indicates the mesh independence. Further numerical study was carried out for meshes having ≈ 700 thousand cells. The value of the variable y^+ , which characterizes the densification of the mesh near the walls, was in the range of $20 < y^+ < 60$ units, (Isaeva et al., 2016).

2.2 Torque method

As is mentioned above, created by Arnaudov for two-carrier PGTs investigation (Karaivanov, 2000), based on a lever analogy torque method (Arnaudov et al., 2017) is very appropriate for complex multi-carrier PGTs analysis (Arnaudov et al., 2005) and optimization (Karaivanov et al., 2022). The essence of this method is as follows:

Every simple PGT (including $\overline{\text{AI}}$ -PGT from Fig. 1a) has three external shafts (in Fig. 4a – shaft of sun gear 1, ring gear 3, and carrier H) which torques are in constant ratio in dependence on the ratio of teeth number of central gears (z_3/z_1). This ratio is the same as a ratio of a lever forces (Fig. 1c). Two of torques are unidirectional (T_1 and T_3) and the third is in opposite direction (T_H) and equal to the sum of both unidirectional ones. This is a reason to call them summation torque ($T_H \equiv T_\Sigma$) and another torques – difference torques, smaller difference torque $T_1 \equiv T_{Dmin}$ and bigger difference torque $T_3 \equiv T_{Dmax}$. The ratio $t = T_{Dmax}/T_{Dmin}$ is so called *torque ratio* of the PGT (Arnaudov et al., 2017). For $\overline{\text{AI}}$ -PGT in Fig. 4 this ratio is shown. For investigation of complex multi-carrier PGTs depicting of a simple PGT with the symbol of Wolf-Arnaudov is very conveniently. A PGT is presented as circle with three external shafts (Wolf, 1958) depicted with different lines according to the values of their torques – the sun gear shaft (with the smallest torque) with a thin line, the ring gear shaft with a thick line, and the carrier shaft (with the biggest torque) with double line (Fig.4b) (Arnaudov et al., 2005).

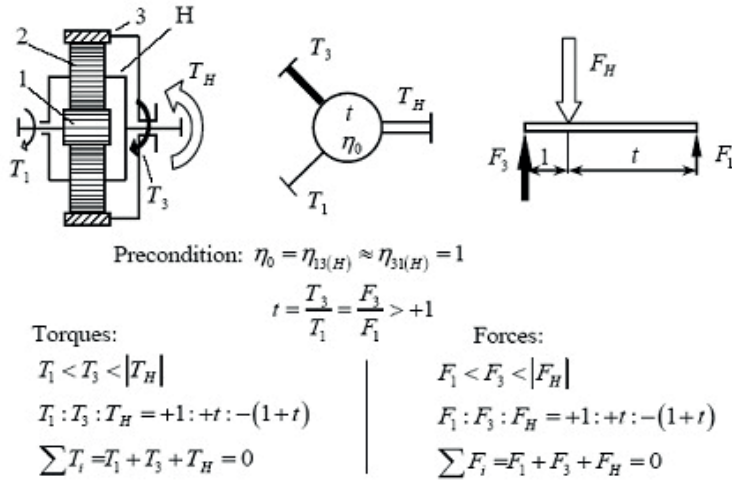


Fig. 4. Simple $\overline{\text{AI}}$ -PGT with its external torques (a), symbol of Wolf-Arnaudov (b) and a lever analogy (c).
 1 – sun gear, 2 – planets, 3 – ring gear, H – carrier.

Because its three shafts a simple PGT has six modes of work with $F = 1$ degree of freedom – three as a reducer and three as a multiplier. In all these cases its speed ratio is considered by *basic speed ratio* i_0 (in work with fixed carrier).

The basic speed ratio of $\overline{\text{AI}}$ -PGT is

$$i_0 = -\frac{T_3}{T_1} = -t = -\frac{z_3}{z_1}. \quad (1)$$

For other working modes with $F = 1$ degree of freedom the speed ratio can be determined as follows [5]:

$$i_{AB} = \frac{\omega_A}{\omega_B} = -\frac{T_B}{T_A}, \quad (2)$$

where ω_A and T_A are the angular velocity and the torque on the input shaft and ω_B and T_B – on the output shaft.

3 Result

3.1 Simulation results of flow kinematics in the wind wheel

Figures 5,6 show a series of diagrams of the results of computer calculations that reveal the main patterns of wind turbine streamline and point characteristic features of the flow.

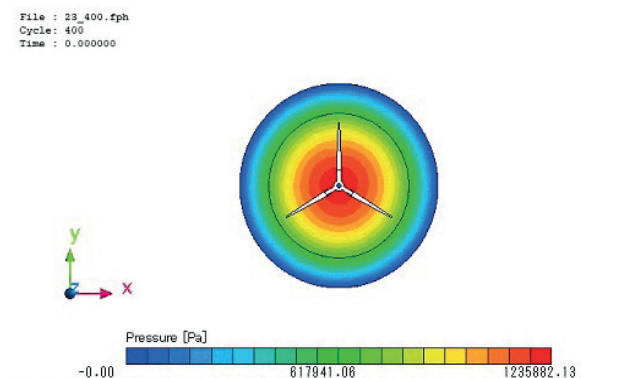


Fig 5. Air pressure

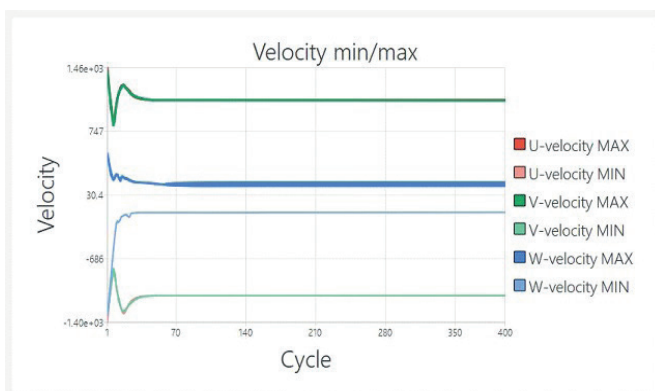


Fig 6. Wind speed components

The diagrams of the results indicate that the value of the flow velocity take maximum values of 146 m/s, which indicates a high productivity of the wind wheel of the designed wind turbine.

3.2 Three-carrier PGT for wind turbine

The simple \overline{AI} -PGT has maximal speed ratio in work with fixed ring gear $i_{IH(3)} = i_0 + 1$. The speed ratio of \overline{AI} with three planets (the most common case because good load sharing between planets) is maximum 13 and to obtain a bigger speed ratio to use a compound PGT is needed. With connecting of a few simple PGD a compound (multi-carrier) PGT obtains (two-, three-, four-carrier, etc.). The two-carrier PGTs cover the biggest part of needed speed ratios in industrial machinery (Karaivanov, 2000). In the cases of classic wind turbine whit high-speed generator, practically, a three-carrier PGT is enough (Giger, 2011).

In this paper a tested in practice three-carrier PGT is investigated (Arnaudov et al., 2019) (Fig. 7). Four coupled shafts between planetary stages exist – two external (input shaft between the carrier of the first stage HI and the ring gear of the second stage 6, and fixed shaft between the carrier of the second stage HII and

the ring gear of the third stage 9) and two internal (between the ring gear of the first stage 3 and the sun gear of the second stage 4, and between the sun gear of the first stage 1 and the carrier of the third stage HIII). The only single external shaft (of the sun gear of the third stage 7) is the output shaft of the train.

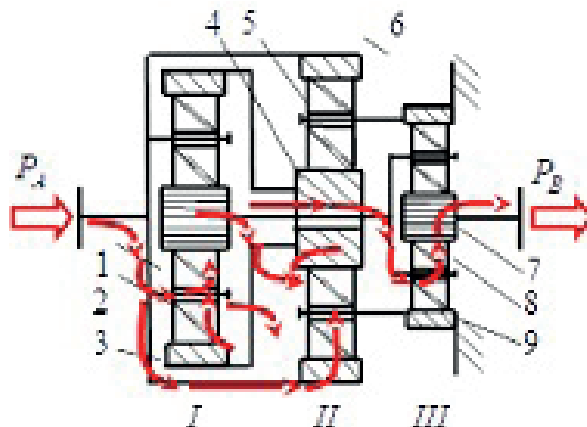


Fig 7. Three-carrier planetary multiplier for wind turbine [9].

In Fig. 8 the structural scheme of PGT in question depicted by Wolf-Arnaudov’s symbol is shown – more clary, simpler, and easy-understandable way for visualization.

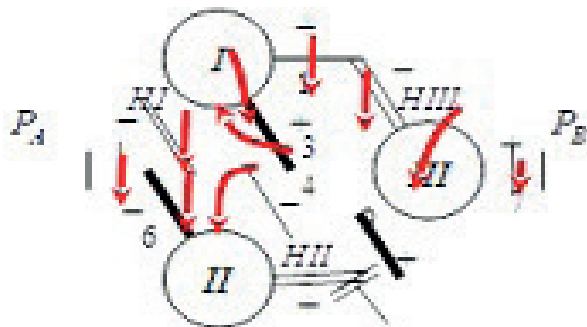


Fig 8. Structural scheme of PGT from fig. 2 through the Wolf-Arnaudov’s symbol depicted.

In both figures by red arrows internal power flows are presented. In a closed loop between the first and the second stage the power division (not circulation) exist. This is determined by method of signs (the torques directions) (Arnaudov et al., 2005). The direction of the torque on a sun gear considered positive. In Fig. 8 this is the torque on the sun gear 1. After this, considering that the directions of toques on sun gear and ring gear is the same but the direction of the carrier torque is

opposite, as well as that the torques on both ends of a coupled shaft are in opposite direction, step by step, the signs (torque directions) of all the shafts are determined. If the torques on the component shafts of the compound shaft are unidirectional – power division exists. In Fig. 3 this are shafts HI and 6 coupled in the input shaft.

3.3 Kinematic analysis

For purpose of kinematic analysis ideal torques on all the shafts are calculated. In Fig. 9 this calculation begins from the sun gear of third stage 7 (this is the output torque) accepting its value as $T_A = +1$. Others torques in this simple PGT depend on its torque ratio t_{III} (see Fig. 1). With numbers in circles the sequence of ideal torques determination is shown.

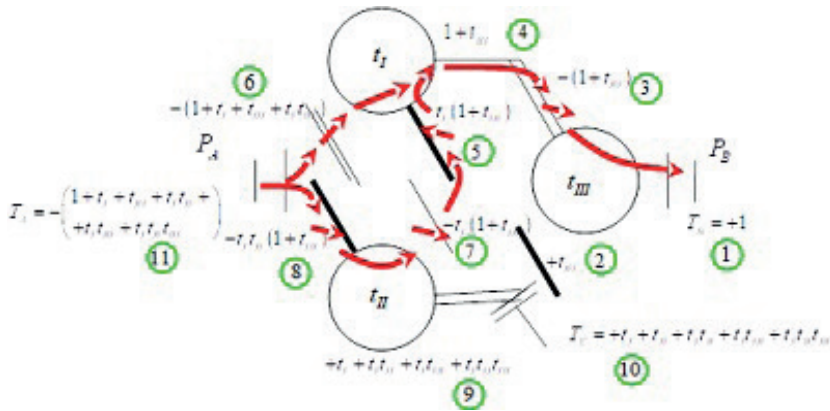


Fig 9. Ideal torques determination considering torque ratios (t_I , t_{II} , and t_{III}) of the component PGTs.

Determination of ideal torques on the shafts of PGT in Fig. 4 shows values of torques on three external shafts:

On the input shaft:

$$T_A = -(1 + t_I + t_{III} + t_I t_{II} + t_I t_{III} + t_I t_{II} t_{III}) \tag{3}$$

On the output shaft:

$$T_B = +1; \tag{4}$$

On the fixed shaft:

$$T_C = +t_I + t_{III} + t_I t_{II} + t_I t_{III} + t_I t_{II} t_{III}. \tag{5}$$

By the ideal external torques equilibrium the calculations correctness may be checked:

$$\sum T_i = T_A + T_B + T_C = 0 \tag{6}$$

By formula (2) the speed ratio of the PGT can be determine as follows:

$$i_k = -\frac{T_B}{T_A} = \dots \quad (7)$$

This formula is very proper for determination of a plurality of combinations of t_I , t_{II} , and t_{III} in which a desirable speed ratio i_k is possible to obtain. By varying these parameters (t_I , t_{II} , and t_{III}) from 2 to 12, for example (Karaivanov et al., 2022). For every one of these values a relative overall dimension can be obtained too (Karaivanov, 2000). For purpose of optimization analysis, a software for overall dimension (reference diameter of pitch circle of the ring gear) under ISO 6336 load capacity calculations is developed for two-carrier PGTs (Troha, 2011). Its developing for three-carrier PGTs is in process.

All the above allows to determine values of t_I , t_{II} , and t_{III} in which the PGT with desirable speed ratio i_k and minimal overall dimensions can be obtained.

3.4 Power analysis

Direction of internal power flows depends on direction of torques on the shafts which are coupled in compound shafts of the PGT (Arnaudov et al., 2019). In the PGT in question in the closed loop between the first and the second stage there is a division of power because the direction (mathematical signs) of the torques on carrier HI (of the first stage) and ring gear 6 (of the second stage) are the same (unidirectional) (Fig. 3).

Real torques on all shafts in compound PGT may be determined in the same sequence as ideal ones (Fig. 4). Their values depend on basic efficiencies η_{0I} , η_{0II} , and η_{0III} as well as on direction of relative (rolling) powers P_{relI} , P_{relII} , and P_{relIII} of the stages (component PGTs).

Basic efficiency is the train efficiency in work with fixed carrier (as pseudo-planetary gear train). It depends on losses during relative movement of PGT elements with respect to the carrier (Arnaudov et al., 2019).

In a simple PGT relative (rolling) power has only two possible directions – from the sun gear to the ring gear or vice versa. In both cases if the real torque on the input shaft (of relative power) T'_{inp} is known the real torque on the output shaft T'_{outp} is equal to ideal output torque decreased by losses

$$T'_{outp} = \eta_0 \cdot T_{outp} \quad (8)$$

If the output (of relative power) torque T'_{outp} is known the real input torque T'_{inp} is equal to ideal input torque increased by losses

$$T'_{inp} = \frac{1}{\eta_0} T_{inp} \quad (9)$$

Considering dependences (8) and (9), in Fig. 5 real torques in PGT in question are determined. By dotted arrows directions of relative (rolling) power in stages

(simple PGTs) are shown. Relative (rolling) power directions in the second and the third stages are obviously from the ring gear to the sun gear because they both work with $F = 1$ degree of freedom and the sun gears are output shafts. The first stage works with $F = 2$ degree of freedom as a summing differential (see internal power flows directions in Fig. 10). As the sun gear is an output shaft – the relative (rolling) power direction is from ring gear to the sun gear too.

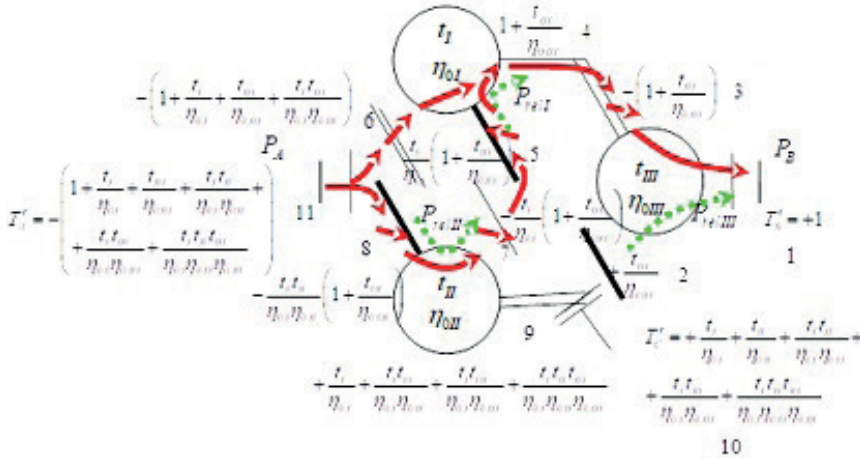


Fig 10. Real torques determination considering torque ratios (t_I, t_{II} , and t_{III}), basic efficiencies (η_{0I}, η_{0II} , and η_{0III}), and relative (rolling) power directions in component PGTs.

By the real external torques equilibrium the calculations correctness may be checked too – see formula (6).

3.5 Efficiency determination

The torque method allows efficiency η determination by real external torques (T'_A - an input torque and T'_B - an output torque, determined considering the losses) (Arnaudov et al., 2005) through *torque transformation* i_T

$$i_T = \frac{T'_B}{T'_A}, \tag{10}$$

as follows:

$$\eta = -\frac{i_T}{i_k} = -\frac{\frac{T'_B}{T'_A}}{-\frac{T_B}{T_A}}. \tag{11}$$

Taking into account that

$$T_B = T'_B = +1 \quad (12)$$

the efficiency may be determined as follows:

$$\eta = \frac{T_A}{T'_A} = \frac{1 + t_I + t_{III} + t_I t_{II} + t_I t_{III} + t_I t_{II} t_{III}}{1 + \frac{t_I}{\eta_{0I}} + \frac{t_{III}}{\eta_{0III}} + \frac{t_I t_{II}}{\eta_{0I} \eta_{0II}} + \frac{t_I t_{III}}{\eta_{0I} \eta_{0III}} + \frac{t_I t_{II} t_{III}}{\eta_{0I} \eta_{0II} \eta_{0III}}} \quad (13)$$

Preciseness of this calculation depends on preciseness of basic efficiencies η_{0I} , η_{0II} , and η_{0III} determination, i.e., losses in the component PGTs determination. Different ways for simple or more precisely determination of losses in a simple PGT exist. For simple, preliminary calculation to choose $\eta_{0I} = \eta_{0II} = \eta_{0III} = 0,97$ may be enough (Karaivanov, 2000). In multi-stage PGTs consideration of speed of sun gears of stages is advisable (Karaivanov, 2005). Influence of torque ratio no the mesh losses considering (Tkachenko, 2003) is the optimal way to obtain good results without unnecessary complication. If it is necessary, more precisely methodologies for losses calculations may be used (Arnaudov et al., 2019).

Formula (13) is very proper for determination the efficiency for the plurality of combinations of t_I , t_{II} , and t_{III} in which a desirable speed ratio i_k is possible to obtain (see paragraph 4). This allows to search the combination with higher efficiency.

Using the input data from CFD modeling, it is the angular velocity (speed) of the wind wheel and the input shaft of the planetary gearbox, the kinematic and power parameters of the designed wind turbine were calculated using the above analytical algorithms (Arnaudov's Torque Method).

4. Conclusions

1. A comprehensive kinematic model of a planetary gearbox has been developed, enabling the investigation of design parameters such as torque, power, and efficiency.

2. The combination of analytical methods and finite element analysis (FEA) allows for precise evaluations of kinematic parameters with low time investment, achieved through modeling the kinematics process flow, providing input data for analytical optimization calculations of the most advantageous wind turbine planetary gearbox (WT-PGT) configurations.

3. The torque method facilitates easy and visual determination of speed ratios and efficiencies in complex three-support PGTs. Calculations demonstrate a straightforward approach to determining the directions of internal power flows.

4. Formulas derived using the torque method for speed ratios and efficiencies of the considered PGT are highly suitable for its multi-objective optimization, aiming to obtain more suitable values of torque coefficient components (α , β , and γ) for compound simple PGTs.

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