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THE CHOICE OF A RATIONAL TECHNOLOGY FOR MANUFACTURING THE HYDROGENERATORS-MOTORS ROTOR RIM

Pavlo M. Makarov
p.makarov_khai@gmx.com
ORCID: 0009-0008-6415-8970

National Aerospace University
"Kharkiv Aviation Institute"
17, Chkalov str., Kharkov,
61070, Ukraine

The object of research in the paper is the technology of manufacturing segments of the rotor rim of large hydrogenerators-motors. The subject of study is the design and geometrical state of the rotor rim during the operation of hydraulic units. The goal is to make a three-dimensional mechanical calculation of the rotor segment for the further determination of the most optimal technology for the rotor rim manufacturing. The following tasks are set: to study the peculiarities of the manufacturing technology of the rotor rim segments; to perform an analytical calculation and a three-dimensional calculation with the determination of the average values of stresses and deformations in the rotor segment. The used methods are: finite element method of mathematical modeling of the thermal stress state of nodes. The following results were obtained: a description of the two main manufacturing technologies of the rotor rim segments, namely the stamping method and the laser cutting method, was provided. The advantages and disadvantages of each technological process were analyzed, and it was determined that the laser cutting method should be used in the production of powerful small-scale hydrogenerators. Three-dimensional models of the rotor segment were developed and a three-dimensional mechanical calculation of this model was performed, as a result of which the value of the displacement of the rotor of the hydrogenerator at the nominal frequency of rotation, as well as the average values of the stresses in the spoke and the rim of the rotor, were obtained. Based on the results of calculations, it was established that significant tolerances in the manufacture of rotor segments can lead to changes in the shape of the rotor during its further operation, the appearance of additional vibrations and further affect the performance of the hydraulic unit. The scientific novelty consists in a combined approach to the estimation of the average values of stresses and deformation of the rotor rim, taking into account the technology of its manufacture, which includes elements of analytical mechanical calculation and calculation in a three-dimensional setting.

Keywords*: rotor rim, stamping, laser cutting, strength calculation.*

Introduction

Electricity is a basic branch of the economy of Ukraine and an integral component of the country's electrification. According to the program documents that determine the direction of the hydropower development of Ukraine, namely the "Energy Strategy of Ukraine for the period until 2035" and the "Hydropower Development Program until 2026", a significant increase in the capacities of HPPs and PSPSs through the modernization of existing hydropower units is predicted [1, 2]. As of 2021, electricity generation at the expense of hydroelectric power plants increased by 37.7% compared to 2020 [3]. One of the promising areas of hydropower development is the use of PSPSs, as they are the main source of covering peak capacities and belong to emergency reserves [4].

The main feature of the PSPS is the use of synchronous hydrogenerators-motors, the rotors of which, depending on the mode of operation, rotate in both directions and operate under conditions of frequent starts and stops, which leads to increased requirements for the strength and reliability of the nodes of such hydraulic units, with the aim of reduction of failures in the operation of such units.

Fig. 1 shows the design of the umbrella-type hydrogenerator-motor with one thrust bearing (1) placed in the oil bath of the crosspiece (3) above the rotor (9) and with the support of the collar bearing (8) on the cover of the pump-turbine. The hydrogenerator-motor is excited by an independent thyristor excitation system. The rotor sleeve (10) is connected to the shaft of the pump-turbine with flanges. An extension shaft is attached

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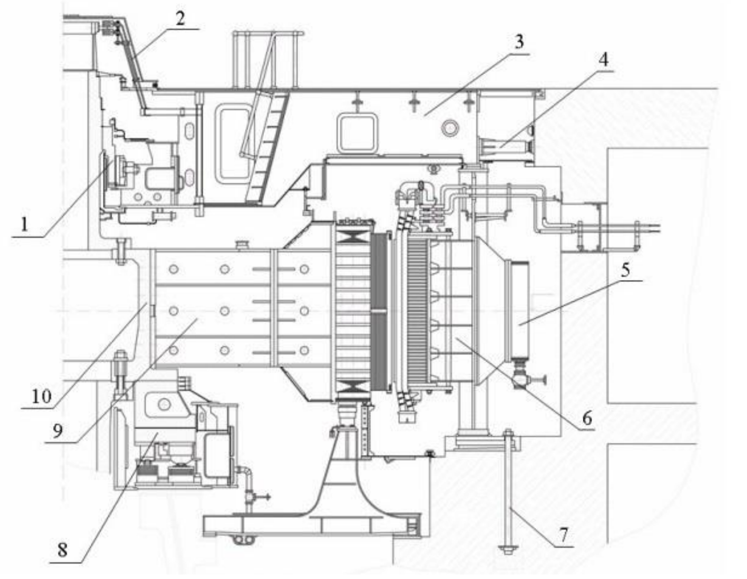

Fig. 1. General design of the hydrogenerator-motor:
1 – thrust bearing; 2 – cap; 3 – crosspiece; 4 – spacer jack;
5 – air coolers; 6 – stator; 7 – anchor pins; 8 – collar bearing;
9 – rotor; 10 – rotor sleeve

to the upper part of the rotor sleeve, on which the thrust bearing sleeve and contact rings are placed. The stator (6) is installed on the bed inside the shaft of the hydrogenerator-motor and is attached to the bed with the help of anchor pins (7). A crosspiece with spacer jacks (4) rests on the upper shelf of the stator housing. The ribbed ceiling of the crosspiece is located on the same level as the engine room floor. A stand (cap) (2) is installed in the central part above the crosspiece, inside of which a traverse of contact rings is attached. The overlap of the shaft of the pump-turbine, which is installed on the beams under the rotor of the hydrogenerator-motor, is a platform for servicing the collar bearing and brakes. The ventilation of the hydrogenerator-motor is carried out in a closed cycle with partial selection of hot air for heating the engine room. Air coolers (5) are located around the stator housing of the hydrogenerator-motor. Zones of cold and hot air are separated by upper and lower air shields. The direction of rotation of the hydrogenerator-motor in the generator mode is clockwise, in the engine mode – counterclockwise (when viewed from above).

One of the important factors that determines the performance of a hydrogen generator is vibration. Strong vibration reduces the productivity and efficiency parameters of the hydraulic unit due to the loss of electrical energy and an increase in the temperature in the machine [5]. The paper [6] provides a detailed review of damaged bearing elements as a result of overheating and established cause-and-effect relations between vibration, overheating and subsequent failure of the unit. The types of failures of hydraulic units are presented in detail in the paper [7], which also analyzes the economic losses caused by the failure of at least one unit. The presented paper is a review and really reveals many factors that affect the appearance of additional vibrations of hydraulic units.

The causes of increased vibration of the hydraulic unit, depending on the source of the disturbing force, can be divided into three types: mechanical, hydraulic, and electrical.

The mechanical ones include: imbalance of the generator rotor and turbine rotor; incorrect state and position of the hydraulic unit shaft axis; problems in bearing nodes; weak fastening of the supporting parts of the unit or their insufficient rigidity; engagement of rotating unit parts [8].

Hydraulic causes are: hydraulic imbalance of the rotor; incorrect height position of the rotor of the radial-axial turbine relative to the stator; incorrectly established combinatorial dependence in Kaplan turbines; turbine operation in cavitation modes [9].

The electrical causes of vibration of the unit are usually unevenness of the attraction of the rotor to the stator (electromagnetic imbalance), which is mainly caused by: unevenness of the air gap of the generator, exciter and subexciter; the oval shape of the generator rotor; shorting the turns of the winding of the rotor poles [10, 11].

In order to optimize the technological process, the rim of the rotor of large generator engines is made charged. It is assembled from separate segments stamped from steel with a thickness of 3–4 mm. The dimensions of the rim of the rotor of medium and large generators do not allow its transportation in an assembled form, and therefore such rims are made of separate stamped steel segments and assembled at the place of their installation.

The rim is divided by height into a number of packages, collected from separate segments and fastened with pins. In the gaps between the packages, there are built-in spacers that act as ventilation blades that provide intensive air supply to the active parts of the generator that heat up the most. The assembled rim in a heated state is wedged on the ends of the spokes with paired wedges, which ensure a tight fit of the rotor rim on the backbone.

Since hydrogenerator rotors are one of the most loaded components and undergo constant vibrations, it is advisable to carry out a mechanical calculation of the rotor rim of the hydrogenerator, taking into account the technological features of the assembly of this component. At the same time, the determining factor will be compliance with the requirements of DSTU EN IEC 60034-33:2022 [12], which specifies the permissible strength reserves for rotating parts of hydraulic units, which are up to 95% of the yield strength of the material.

Manufacturing technology of hydrogenerator rotor rim segments

As it was mentioned above, the rim of the rotor of the hydrogenerator is made in batches and is assembled from separate segments. The main methods of manufacturing segments for the rotor rim are stamping and laser cutting. The features, advantages and disadvantages of each method are considered in more detail below.

Stamping

Stamping, as a technological process of processing blanks made of metal, allows to obtain ready-made products of a flat or three-dimensional type, which differ in both their shape and dimensions. A stamp attached to a press or other type of equipment can act as a working tool during stamping. Metal stamping can be hot or cold, depending on the performance conditions. These two types of this technology involve the use of different equipment and compliance with certain technological norms.

When performing cold stamping of metal parts, the process of forming the finished product proceeds only due to the pressure of the working elements of the press on the workpiece. Due to the fact that blanks are not pre-heated during cold stamping, they do not shrink. This makes it possible to manufacture finished products that do not require further mechanical finishing. Disadvantages of cold sheet metal stamping include the high cost of equipment, and the significant economic benefit of this process is possible only with serial production.

In the last century, it was allowed to manufacture sheets of the rotor rim from St3 steel (flow stress σ_f=255 MPa), and later the switching to high-alloy steels of the 10KhSND brand, which have improved mechanical properties (flow stress σ_f=1080 MPa), began. As a result of cold plastic deformation, the crystal structure of the metal is distorted; the grains of which it is composed are drawn in one direction; strength increases and plasticity decreases. This phenomenon is called work hardening. Deforming hardened metal is more difficult, requires greater efforts and more powerful equipment. In view of this, cold plastic deformation is used less often, only for plastic metals or blanks of small cross-section (sheets, wire) [13].

Considering the fact that the production of hydrogenerators belongs to single or small series production, the use of cold stamping for the production of the rotor rim is economically impractical, and the significant deformation of the metal leads to large technological tolerances, which is unacceptable for the reliable operation of the unit.

Laser cutting

Laser metal cutting is the most advanced metal processing process. It allows to create high-quality elements from such metals and alloys as brass, copper, alloy, tool steel and stainless steel, titanium, aluminum alloys, etc.

The laser is quite widely used in various industries. Today, due to high accuracy and complex contour cutting, it is the best alternative to mechanical processing of metals. Laser cutting is also able to reduce the time of the production process and ensure high cutting accuracy, without heating the product and preserving the mechanical properties of the materials. Today, companies engaged in laser metal cutting use two types of lasers:

– solid-state (YAG) lasers, the power of which usually does not exceed 1–6 kW, and the wavelength is 1 μm;

– gas (CO_2) lasers with a power of 50–15,000 W, the active medium of which is helium, argon, nitrogen, and carbon dioxide.

Most steels are considered ideal materials for laser cutting. High-strength metals such as AISI-SAE 4130 (chromium molybdenum steel) and 4340 (chromium nickel molybdenum steel) show exceptional laser cutting accuracy. Thanks to this, there is no roughness on the cut surface.

Technological advantages of laser cutting are:

– the manufactured part acquires an ideal cut line that does not require additional processing;
– as a result of optimization of metal sheet cutting, the amount of waste is significantly reduced;
– the ability to work with the most fragile and thin materials;
– increase in productivity due to operation at the maximum speed of laser cutting.

However, the use of the laser cutting method has disadvantages related to the dimensions of the products. Currently, there are no lasers capable of processing thick-walled metals, and the maximum size of the blank sheet should not exceed 3000×1500 mm.

In accordance with modern requirements for the strength and reliability of hydraulic units, the technology of manufacturing rotor rim segments using laser cutting is the most effective.

Analytical and three-dimensional calculation of the strength of the rotor rim during the hydraulic unit assembly

As mentioned earlier, the rim of the rotor consists of a large number of sheets connected to each other by tie pins, while the height of the package of the rotor rim can reach more than 2 m. In classical analytical calculations for a static problem in an elastic setting, based on experimental thermal data, the modulus of elasticity of the rotor rim is 120 GPa. The calculation is carried out in two main stages: determination of mechanical stresses and assessment of the package joints condition.

Taking into account many years of experience of our compatriots in the design of hydrogenerators, the most effective are the analytical calculation algorithms proposed in the last century by Wiedemann Ye. [14], which will be used for analytical calculation in the future.

Table 1 shows the initial data of the hydrogenerator-motor under study.

Table 1. Initial data for analytical calculation

Name	Notation	Dimensionality
The outer diameter of the rotor rim	D_1=5.592	m
The inner diameter of the rotor rim	D_2=4.868	m
Nominal frequency of the rotor rotation	N_H=187	rpm
Runaway frequency of the rotor rotation (maximum permissible)	N_y=262	rpm
The number of rotor poles	Z_1=32	–
The depth of the groove in the segment under the tail of the pole	H_2=0,097	m
Mass of charged rotor pole	G=1637.81	kg
The radius around the pole center of mass	R_1=3.63	m
Flow stress of material segments	S_9=240	MPa
The axial length of the rim without channels under the pole cores	L_0=1,584	m
The minimum radial width of the rotor rim segment	H_1=0.212	m
The mass of the rotor rim under the pole cores	G_{rim}=81000	kg

The defining conditions of the calculation are that the obtained stresses should not exceed: permissible 0.95 σ_f from the flow stress, for rotating parts of hydrogenerators according to DSTU EN IEC 60034-33:2022 [12], permissible (2/3) σ_f from the flow stress, for parts of the rotor of the hydrogenerator in the nominal mode of operation from 0.95 σ_f during runaway.

Analytical calculation of the rotor rim strength

The coefficient of centrifugal forces at the nominal and runaway frequencies of rotation is

$$A_N=\left(\pi\cdot\frac{N_H}{30}\right)^2=385.531\ 1/\text{s}^2;\quad A_y=\left(\pi\cdot\frac{N_y}{30}\right)^2=752.766\ 1/\text{s}^2.$$

Radius of inertia of the rotor rim

$$a=\frac{D_2}{D_1}=0.87053;\quad R_{oi}=\frac{1}{3}\cdot D_1\cdot\left(\frac{1+a+a^2}{1+a}\right)=2.619\ \text{m}.$$

Centrifugal force of poles

$$C_{\text{p}}=A_y\cdot Z_1\cdot G\cdot R_1\cdot 10^{-6}=143.212\ \text{MN}.$$

Centrifugal force of the rotor rim

$$C_0=A_y\cdot G_{\text{rim}}\cdot R_1\cdot 10^{-6}=159.702\ \text{MN}.$$

Tensile stress in the segment of the rotor rim at the runaway rotation frequency

$$Z_6=4; \quad \sigma_0=\frac{C_\text{p}+C_0}{6.26\cdot H_1\cdot L_0}\cdot\frac{Z_6}{Z_6-1}=192.129 \text{ MPa}.$$

The material of the rotor rim segment is S300MC according to DSTU EN 10149-2-95 [15] with flow stress of σ_f=300 MPa.

Margin of strength beyond the flow stress – $m=\frac{\sigma_f}{\sigma_0}$=1.561.

The diameter of the rotor rim along the bottom of the grooves under the pole shanks – $D_3=D_1-2\cdot H_2$=5.398 m.

The modulus of elasticity is taken equal to E=2.1×10^{11} N/m^2.

The average flexibility of the rotor rim per diameter is

$$L_1=\frac{D_3+D_2}{D_3-D_2}\cdot\frac{1.1}{2\cdot\pi\cdot L_0\cdot E}=1.019 \text{ m/N}.$$

Deformation of the rim per diameter, caused by centrifugal forces, at the nominal rotation frequency

$$E_2=L_1\cdot\left(C_\text{p}\frac{A_N}{A_y}+C_0\frac{A_N}{A_y}\right)\cdot10^6=0.00158 \text{ m}.$$

Deformation of the rotor rim per diameter, caused by centrifugal forces, at the runaway rotation frequency

$$E_3=L_1\cdot(C_\text{p}+C_0)\cdot10^6=0.003088 \text{ m}.$$

Wedging tension of the rotor rim, based on possible overheating of 60 °C: α=11.5×10^{-6}; $d_t=\alpha\cdot60\cdot D_2$=0.00336 m.

We accept tension for a diameter of 3.3–3.4 mm.

The rotation frequency of the separating rim at the calculated tension without taking into account the deformation of the rotor backbone

$$n_\text{separating}=N_H\cdot\sqrt{\frac{d_t}{E_2}}=273.25 \text{ rpm}.$$

As can be seen from the analytical calculation, the average values of the mechanical stresses at the runaway frequency were 192 MPa, and the deformation of the rotor rim was 0.003 m. The deformation of the rotor rim at the nominal rotation frequency is 0.00158 m.

Three-dimensional calculation of the rotor rim strength

To clarify the values of mechanical stresses in the rotor rim, a three-dimensional strength calculation of the rotor rim was carried out in the SolidWorks software complex. The calculation grid was built for each individual element of the structure. A grid control was introduced. At the same time, there should be at least three grid elements behind the minimum geometric element. Convergence of the results was carried out by reducing the grid so that the results did not differ by more than 0.5%. The main task of the calculation is to determine the average values of mechanical stresses and deformation of the outer diameter of the rotor rim at nominal and runaway rotation frequencies. The calculation results are shown in Figs. 2–9.

As a result of the three-dimensional calculation, the average values of mechanical stresses at the runaway frequency were 278 MPa, and the deformation of the rotor rim at the nominal rotation frequency is 0.007 m per radius (per diameter 0.014 m)

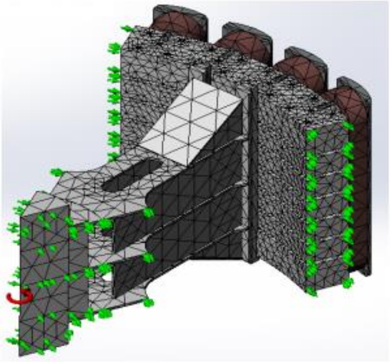

Fig. 2. Calculation grid

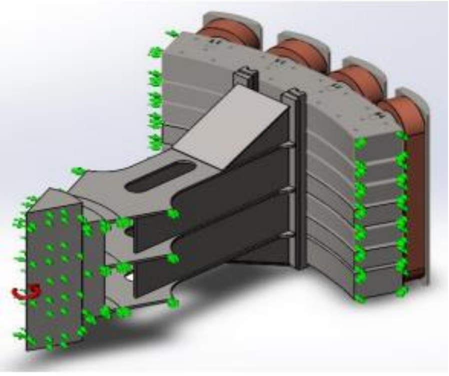

Fig. 3. Boundary conditions

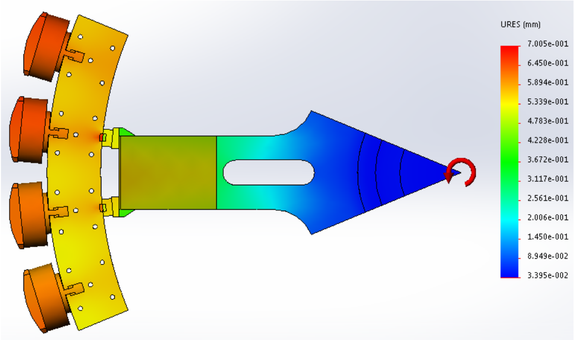

Fig. 4. Deformation of the rotor rim
at nominal rotation frequency

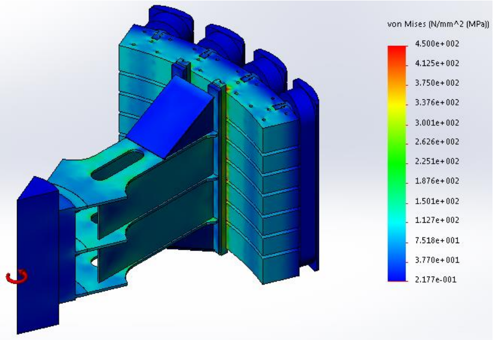

Fig. 5. The diagram of the stress of the rotor rim
at the runaway rotation frequency

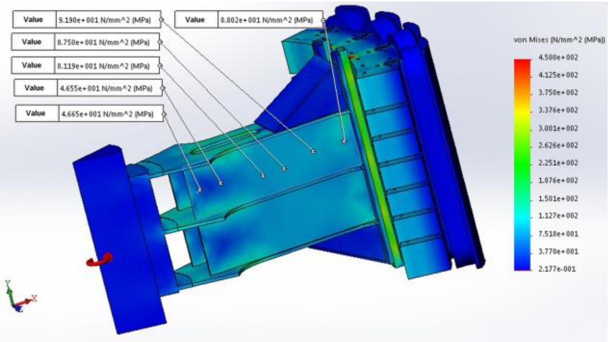

Fig. 6. Stress pattern at the runaway rotation frequency along the spoke

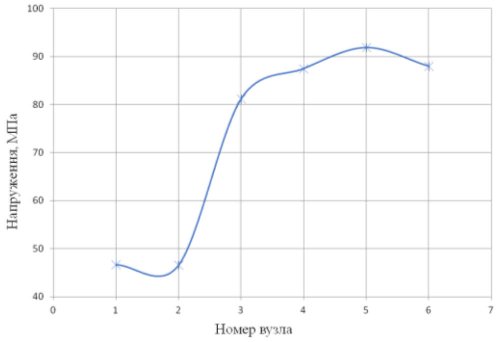

Fig. 7. The graph of the stress distribution
at the runaway rotation frequency along the spoke

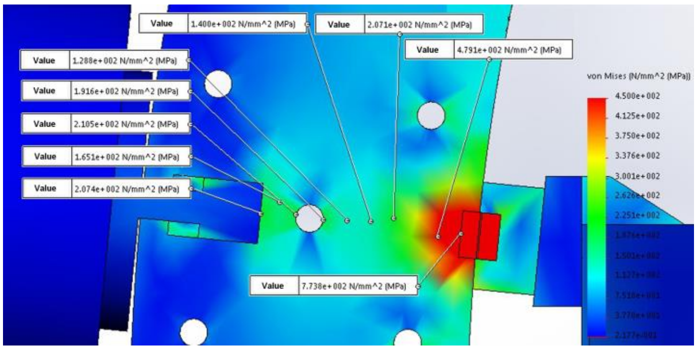

Fig. 8. The diagram of the stress of the rotor rim
at the runaway rotation frequency

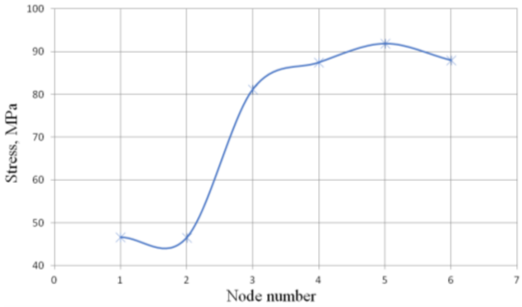

Fig. 9. The graph of the stress of the rotor rim
at the runaway rotation frequency

Conclusions

According to the results of the three-dimensional calculation of the strength of the rotor rim, it can be seen that the average values of stresses exceed the permissible 2/3 σ_f from the flow stress for parts of the rotor of the hydrogenerator in the nominal mode of operation and 0.9 σ_f from the flow stress runaway in accordance with DSTU EN IEC 60034-33:2022 [12].

When manufacturing the rotor rim by the stamping method, it is obvious that the obtained tolerances in the segments can lead to the appearance of significantly higher stresses and, as a result, even greater deformation along the diameter of the rotor rim, which will subsequently negatively affect the operation of the unit as a whole. Therefore, in the process of the rotor rim manufacturing, it is advisable to switch to laser cutting of segments, which will increase the accuracy of the manufactured node.

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Вибір раціональної технології виготовлення ободу ротора гідрогенераторів-двигунів

П. М. Макаров

Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут»,
61070, Україна, Харків, вул. Чкалова, 17

Об’єктом дослідження у статті є технологія виготовлення сегментів ободу ротора великих гідрогенераторів-двигунів. Предметом вивчення виступає конструкція й геометричний стан ободу ротора у процесі експлуатації гідроагрегатів. Мета – постановка тривимірного механічного розрахунку сегмента ротора для подальшого визначення найбільш оптимальної технології виготовлення ободу ротора. Задачі: дослідити особливості технології виготовлення сегментів ободу ротора; провести аналітичний розрахунок і тривимірний розрахунок із визначенням середніх значень напружень і деформацій в сегменті ротора. Використовуваними методами є: метод скінченних елементів математичного моделювання термонапруженого стану вузлів. Отримано наступні результати: надано опис двох основних технологій виготовлення сегментів ободу ротора, а саме метод штампування і метод лазерного різання. Проаналізовано переваги й недоліки кожного технологічного процесу, визначено, що при виробництві потужних дрібносерійних гідрогенераторів доцільно застосувати метод лазерного різання. Розроблено тривимірні моделі сегмента ротора й виконано тривимірний механічний розрахунок даної моделі, у результаті чого отримано значення переміщення ротору гідрогенератора при номінальній частоті обертання, а також середні значення напружень у спиці й ободі ротора. За результатами розрахунків встановлено, що значні допуски при виготовлені сегментів ротора можуть призвести до зміни форми ротора при його подальшій експлуатації, появи додаткових вібрацій і в подальшому вплинути на працездатність гідроагрегату. Наукова новизна полягає у комбінованому підході до оцінки середніх значень напружень і деформації ободу ротора з урахуванням технології його виготовлення, що включає в себе елементи аналітичного механічного розрахунку й розрахунку у тривимірній постановці.

***Ключові слова**: обід ротора, штамповка, лазерна різка, міцнісний розрахунок.*

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