

# MODELING OF HIGH-SPEED FLYWHEEL DESIGNS FOR TECHNOLOGICAL EQUIPMENT

## *Modelowanie konstrukcji szybkobieżnych kół zamachowych w urządzeniach technologicznych*

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**Abstract:** The article analyzes the design of mechanical energy drives and their use areas. Based on the analysis, the kinetic energy drive designs based on the composite material's flywheel, capable of working with a high frequency of rotation. The most optimal flywheels in terms of accumulation of kinetic energy and at the same time the maximum strength of the design are proposed, and their numerical simulation is carried out. The modal analysis results established the values and forms of the eigenfrequencies of oscillations of rotors with flywheels of various structures, which allows controlling the process of overclocking, knowing the limit values of the maximum permissible frequency of rotation of the flywheels. Numerical modeling established that the flywheel's shape and its mass significantly affect the rotor speed limit with the flywheel. At the same time, the flywheel with the lowest mass but the highest frequency of rotation has the maximum specific energy intensity per unit of mass, which determines it as the most effective option in terms of the cost of material and the use of this design in devices for energy accumulation during the operation of technological equipment. The calculation results also show that the lamb flywheel has the most incredible absolute energy intensity. Simultaneously, the costs of the composite material above 68% are compared with the flywheel, which has the maximum specific value of the energy intensity per 1 kg of its mass.

**Keywords:** energy efficiency, moment inertia, eigenfrequencies, rotor, carbon fiber

**Streszczenie:** W artykule przeanalizowano konstrukcję napędów mechanicznych oraz obszary ich zastosowania. Na podstawie przeprowadzonej analizy opracowano projekt napędu kinetycznego opartego na sprzęgle z materiału kompozytowego, przeznaczonego do pracy z wysoką częstotliwością obrotową. Zaproponowano najbardziej optymalne koła zamachowe pod względem akumulacji energii kinetycznej i jednocześnie maksymalnej wytrzymałości konstrukcji oraz przeprowadzono ich symulację numeryczną. Na podstawie wyników analizy modalnej ustalono wartości i postaci częstotliwości własnych oscylacji wirników ze sprzęglami o różnych konstrukcjach, co pozwala na sterowanie procesem, znając graniczne wartości maksymalnej dopuszczalnej częstotliwości obrotów. Na podstawie modelowania numerycznego ustalono, że kształt sprzęgła oraz jego masa mają istotny wpływ na ograniczenie prędkości obrotowej. Jednocześnie sprzęgło o najmniejszej masie, ale największej częstotliwości obrotów ma maksymalną jednostkową energochłonność, co świadczy o tym, że jest to najbardziej efektywny wariant pod względem kosztów materiałowych i zastosowania tej konstrukcji w urządzeniach do gromadzenia energii podczas pracy urządzeń technologicznych. Porównano koszt dla sprzęgła o zawartości materiału kompozytowego powyżej 68% z kosztem sprzęgła, które ma maksymalną wartość jednostkową energochłonności na 1 kg masy.

**Słowa kluczowe:** sprawność energetyczna, moment bezwładności, częstotliwość własna, wirnik, włókno węglowe

### Introduction

In connection with the active development of the world's technical progress in the XXI century, energy re-source consumption increased significantly [23]. Since the planet's fossil resources have a limited reserve, humanity is already whiter than 20 years increases the volume of energy production by developing new and improving existing methods based on the use of renewable energy sources. The energy of wind, sun, water, geothermal energy, and biofuels, whose share in total since 1999, has increased ten times [24]. The European Union countries plan to increase renewable energy sources from 20% in 2020 to 32% by 2030 [25, 26]. By

2050, an increase in energy consumption is predicted by more than two times compared with 2020 [23]. To preserve the world ecosystem, there is no other option except renewable sources. In the future, it is expected that the entire energy market will be captured by them [15]. Also, renewable sources are necessary for the regions where it is difficult and expensive to mount the power grid, while much energy is lost when transmitting it over long distances. However, one of the main aspects remains its accumulation and returns at a particular time. Currently, lithium-ion batteries and hydro accumulators used in reservoirs [27, 28] are the most common accumulation methods. Nevertheless, lithium-ion batteries are very dependent on the temperature regime and relatively short

service life and disposal problems. The main disadvantage of hydro accumulators is their cost and non-clean. Therefore, recently develops on the improvement of mechanical drives of flying type energy and their mass introduction in all areas of human life, where fast returns and high KPD are needed [29].

## Literature Review

The latest research confirms the relevance of the development and research in mechanical energy drives with flywheels. Namely, D. Erdemir in [5] on the example of the practical use of flywheels in rapidly charging electric buses with a drive from renewable energy sources proved that power reduction could be reached electric batteries from 60% to 72% due to energy accumulation in flywheels.

In [21], we are modeling a flywheel with variable inertia in the design of a diesel generator using a flywheel rotation, depending on the generator shaft's rotation frequency, making it possible to increase the efficiency and reduce the shock loads of the mechanism. In studies [2, 6, 7, 9, 11, 16], a comprehensive review of the energy accumulation system's technology with the flywheel is shown. Practical ways of developing this technology in the future are presented in the scheme of wind power and solar energy to prevent sharp voltage drops in power systems using optimization methods, simulation and simulation methods, and active control systems.

K. Pullen in [12] and A. Arabkooohsar in [1] presented a whole scheme of a mechanical energy storage device based on flywheel motor-generator, efficiency which reaches 85-90%. The diagram [12] is currently used on the Formula 1 cars for substantially giving the acceleration at the critical moment and the graph [1] in NASA satellites.

M. Spiryagin and P. Wolfs In [18], the modeling of the Flywheel-diesel engine's hybrid system for heavy-duty locomotives was performed, the results of which are confirmed by experimental studies. Also in the paper presents the developed integrated intelligent control system for traction. What made it possible to get fuel economy. Work [14] S. Rastegarzadeh is devoted to creating a new modular design of the rotor with a flywheel consisting of a set of rings to optimize power consumption in the subway trains made it possible to reduce energy consumption by 35%. The development and testing of the two-pole mass device with the inertia variable's flywheel are represented by S. Yang in [19], which shows the flywheel's design with four sliders. It allows changing the equivalent mass as the speed of rotation of the flywheel changes to optimize the device's operation and increase its efficiency.

J. Zhao's research was focused on inertia studies [22], which presents the technology of measuring the flywheel's inertial masses using the Mass-Spring model as the simulation models of the flywheel before or after attaching counterweights in the SIM-Mechanics application from Matlab.

R. Miyamoto and A. Goedel in [10] proposed a way to connect to an electrical network of an induction generator with a short-circuited rotor connected to a cylindrical flywheel with high inertia to reduce perturbations during a transition in the electrical grid.

The work [17] is devoted to developing a design based on Maxwell's lift forces and Lorentz to stabilize the flywheel using minimal power losses, even with a significant increase in the size of the flywheel.

The hybrid designs of electrical mechanisms using flywheels are equipped with the most advanced technical solutions, in particular W. Yang in [20] proposed an integrated triboelectric nanogenic with a flywheel and a spiral spring to improve energy collection during intermittent excitation/launches.

In [3, 8, 13], the advantages of flywheels made of light and durable materials, such as carbon fiber and nanocomposites, and identified areas of their using by a multi-criteria decision-making method for selecting and verifying the fabric of the flywheel design.

From the review of literary sources, it follows that the development of designs of flywheels and hybrid systems based on the use of regenerated energy sources is an urgent task. But in these studies, issues regarding the prospects for the benefit of flywheels in machine-building enterprises' technological equipment and the analysis of the design parameters of flywheels from composite materials by methods of finite element analysis. The use of kinetic energy drives in technological equipment is also relevant and because the machine's rotating spindle is spent either the energy of the electromagnetic field or the stop occurs with the help of friction brake mechanisms. This carries the additional costs of electricity or the need to use brake mechanisms that are wearing in the work process require repair and replacement.

Thus, the study aims to determine the optimal form and material of the flywheel for the mechanism of energy recovery from the drive of metalworking machines using finite element analysis methods.

## Research Methodology

### *Development of a mechanical energy storage concept for metalworking equipment*

Energy accumulation and storage systems using a flywheel can be divided into two main categories; The first is a system with low flywheel rotation speeds (less than 10 000 revolutions per minute); The second is a system with a high speed of the flywheel (up to 60 000 revolutions per minute). In general, the second system consists of:

- electric generator motor, which runs as an engine when charging and as a generator during discharge;
- flywheel of the rotor, which retains kinetic energy;
- magnetic bearings to reduce friction losses;
- bidirectional converter providing electrical power in both directions during charging and discharge;

- vacuum pump to create a vacuum in the rotation chamber.

As already mentioned in the literary review, such systems are actively used in wind power, hybrid installations, in racing cars. Still, references to the use of mechanical energy drives in metalworking equipment failed to find. Therefore, the article proposes an embodiment of an automatic movement based on a stationary installation of kinetic energy accumulation based on a flywheel from a composite material with a high speed of rotation using magnetic bearings.

The rotor design concept with the flywheel, the generator, and bearings is shown in Fig. 1.

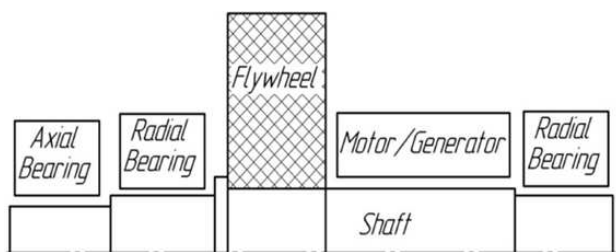


Fig. 1. Principle scheme of mechanical energy storage

Flywheels with low speed are made, mechanical or magnetic bearings maintain steel and rotor. High-speed flywheels typically use lighter but durable composite materials and use exclusively magnetic or hydrostatic bearings. The cost of the energy accumulation system with high-speed flywheels can be five times higher than the cost of systems with a low speed of the flywheel. The energy accumulation system's worth depends on the price of all parts and components used, especially from the flywheel's cost that allows a high rotation speed. Therefore, it is necessary to minimize the use of an expensive composite material in the mechanical energy storage system design for metal-cutting equipment but simultaneously achieve a sufficiently high energy density by studying the various configurations of the flywheels (Fig. 2). The flywheel designs with convex and concave radii of side surfaces were chosen based on recommendations [4] at the flywheel design's maximum flatness coefficients (Fig. 2 a, b). At the same time, it is proposed to reduce the volume of composite material, in addition to the above structures (Fig. 2 a, b), explore the flywheels with holes located around the circle (Fig. 2 c, d).

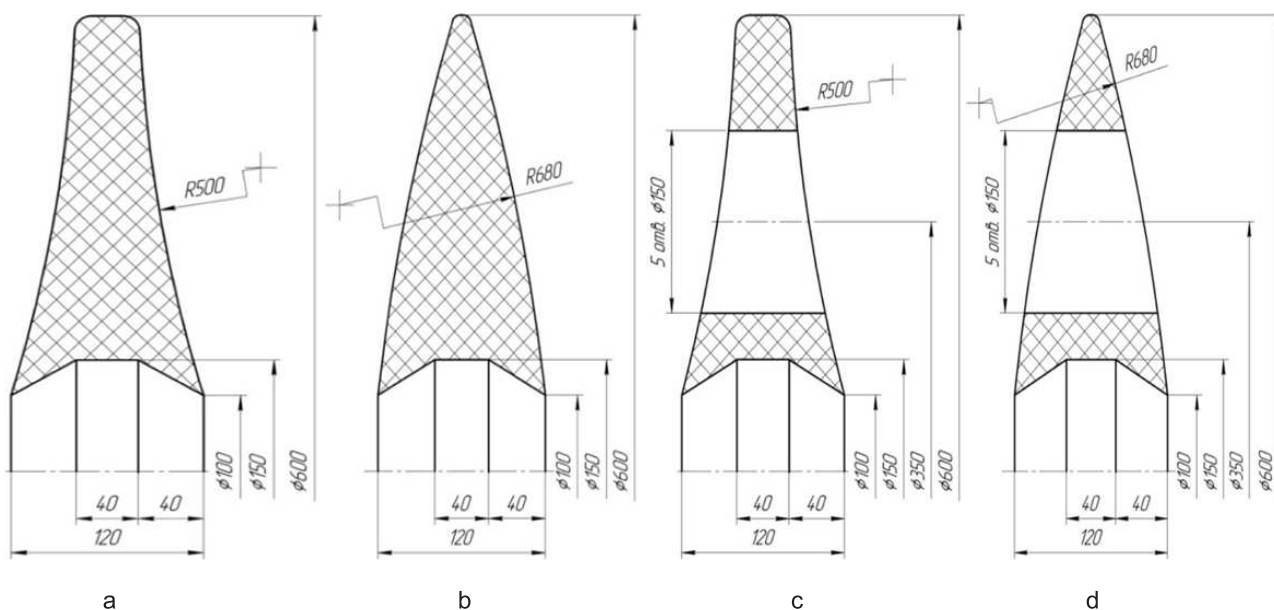


Fig. 2. Flywheel designs for research: a - with concave side surfaces; b - with convex side surfaces; c - with concave side surfaces and radially located holes; d - with convex side surfaces and radially located holes

### Development of design and rationale for choosing materials for mechanical energy storage

Based on the concept (Fig. 1), the selected sizes of the flywheel, the parameters of the magnetic bearings, and the rotor's size, a design of a mechanical energy storage device is proposed, placed in a closed case with a lid (Fig. 3). As a material for the body and the cover, cast iron is used, so it is cheap and has a reasonably high weight to preserve the position's stability while working

without the use of a large number of fastening elements. To eliminate losses for friction, the flywheel in the chamber of the case will be created by a vacuum. Magnetic bearings also exclude friction in the rotor supports. As a rotor shaft material to reduce its mass, the titanium alloy WT1-0 is adopted to ensure sufficient strength.

To increase the flywheel's strength characteristics as a material, a carbon fiber HEXTOW AS4 is selected. HEXTOW Carbon Fiber AS4 is a continuous,

high-strength, spectacted PAN-based fiber (polyacrylonitrile). The flywheel, entirely made of carbon fiber, fasten directly on the rotor shaft is not possible without additional parts of the design.

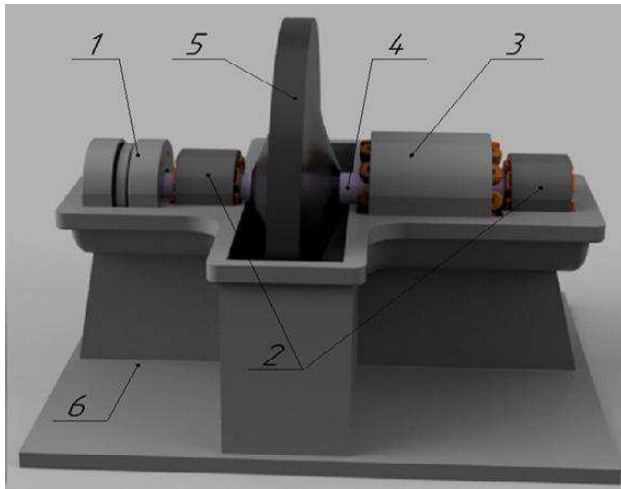


Fig. 3. 3D-model of the proposed design of the mechanical energy storage with flywheel

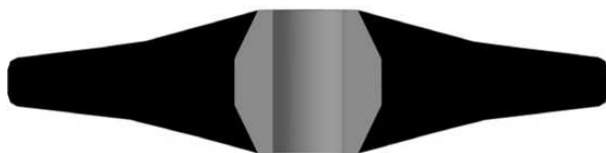


Fig. 4. Connection sleeve-flywheel

Therefore, to possibly molding a carbon fiber, its mechanical processing, and balancing separately from the rotor in the mechanical energy drive's proposed method, the flywheel is composite. It consists of a central sleeve and a direct flywheel from the composite material (Fig. 4). The mid sleeve has a base surface for planting a flywheel on the rotor shaft, the material of which is adopted by titanium alloy W1-0. The physicomechanical properties of the materials of the flywheel, the rotor shaft, and the central sleeve are presented in tab. 1.

According to the built 3D models of the designs of flywheels (Fig. 2 A-d), we define the masses of the flywheels and the inertia moments according to the formula for parts of the type of disc, and the results of the calculations are reduced to the Tab. 2.

$$I = \frac{1}{2} mR^2 \quad (1)$$

$m$  – a mass of the disk, kg;

$R$  – disk radius, m.

To determine the number of stored kinetic energy, the flywheel needs to know its maximum permissible rotation frequency. This implies the definition of its frequencies of the designed structure to eliminate resonance appearance, which is possible using programs for the finite element analysis.

Table 1. Physical and Mechanical Properties of Rotor Materials

Material (DIN standard)	Modulus of elasticity E, GPa	Poisson's ratio $\mu$	Density $\rho$ , kg/m <sup>3</sup>	Tensile strength $[\sigma_t]$ , GPa	Ultimate strength of compression, $[\sigma_c]$ , GPa	Yield strength $\sigma_y$ , GPa
Titanium alloy WT1-0	88	0.33	4820	0.860	0.860	0.585
Carbon fiber HexTow AS4	231	0.15	1790	4.720	4.720	-

Table 2. Results of calculations of the mass-center characteristics of flywheels

Flywheel design	Number figure of the flywheel	Mass flywheel without the basic sleeve, kg	Moment of inertia, kg · m <sup>2</sup>
With concave side surfaces	2a	27.8	1.251
With convex side surfaces	2b	28.2	1.269
With concave side surfaces and radially located holes	2c	17.9	0.806
With convex side surfaces and radially located holes	2d	16.7	0.752



## Results

### Study of eigenfrequencies of oscillations of the rotor mechanical energy storage

To prevent the resonance phenomenon during the mechanical drive of energy due to the coincidence of its oscillations with equipment fluctuations in the working workshop, we define our frequencies using the built-in MODAL ANALYSIS module in the Ansys Workbench estimated complex. Equipment fluctuations arise as a result of its work in the cutting process. The analysis results make it possible to determine the critical frequencies of oscillations and prevent these values' achievements

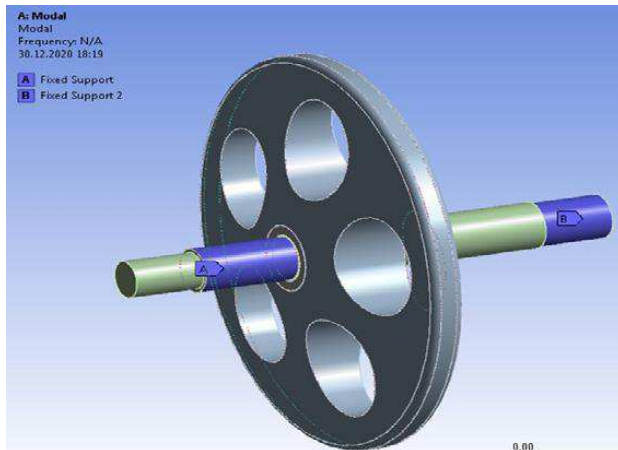


Fig. 5. Boundary conditions with finally element modeling of the rotor

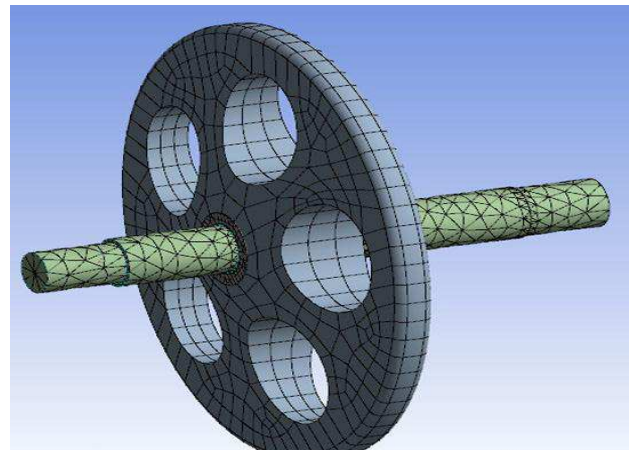
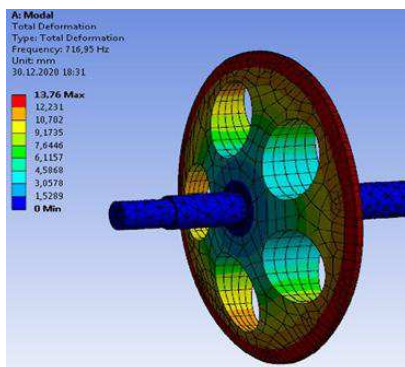
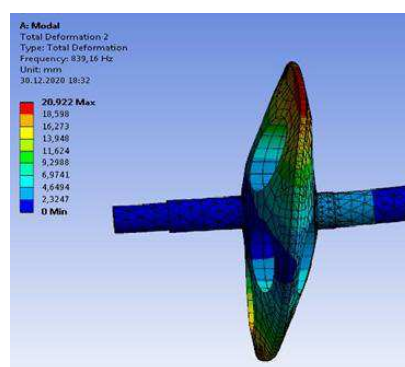


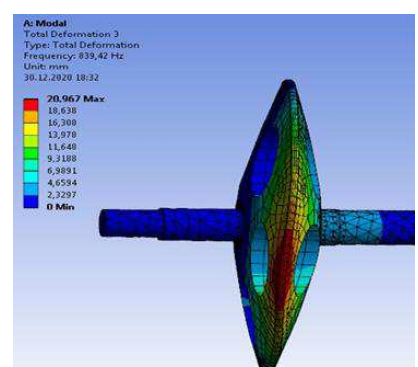
Fig. 6. A finite-element mesh of the rotor



a



b



c

Fig. 7. Illustrations of own oscillation frequencies: a - the first frequency; b - second frequency; c – the third frequency

An example of the first three-eating frequencies of oscillations for a rotor with a flywheel with convex side surfaces and radially located holes is shown in Fig. 7. Also, to control the frequency of rotation of the flywheel and preventing the exit to the resonance region, the frequency of oscillations in turns in one minute by multiplying the calculated frequency by 60 is carried out by multiplying the calculated frequency.

when the flywheel is accelerated (Tab. 3). When calculating the rotor shaft, the central bush and the flywheel bind to each other by combining the nodes with the type "Bonded" contact. This is justified because the landing of the sleeve on the shaft is carried out on triangular slots with tension, and the flywheel is connected to the central sleeve tight bond by laying the fibers into unique grooves and filling fibers with epoxy resin. Fixing in the process of modeling was made according to the raw surfaces of radial bearings, which is shown on the example of the rotor with a flywheel, which is characterized by concave side surfaces and radially located holes (Fig. 5), the finite element mesh of which is presented in Fig. 6.

Tab. 3 shows that the rotor's design with a flywheel characterized by convex side surfaces and radially located holes has the most significant value of the first one's frequency. This means that this design is most resistant to external fluctuations since entering the resonance from external sources is the least likely among the rotors' constructions.

Table 3. Researches of studies of eigenfrequencies of rotor oscillations with various designs of flywheels

Rotor with Flywheel Design	Eigenfrequencies of rotor oscillations, Hz / Rotor rotation frequency, rpm		
	1	2	3
With concave side surfaces	594 / 35640	725 / 43500	726 / 43560
With convex side surfaces	628 / 37680	803 / 48180	804 / 48240
With concave side surfaces and radially located holes	436 / 26160	469 / 28140	499 / 29940
With convex side surfaces and radially located holes	717 / 43020	839 / 50340	840 / 50400

To determine the most significant energy efficiency of the designs under consideration, we define a possible amount of pointed kinetic energy by the formula:

$$E = \frac{1}{2} I \omega^2 \quad (2)$$

$I$  – a moment of the disk inertia;  
 $\omega$  – the angular speed of the disk,  $\text{sec}^{-1}$ .

$$\omega = \frac{\pi \cdot n}{30} \quad (3)$$

$n$  – frequency of rotation of the disk, rpm.

It has been established that the rotor with a flywheel with convex side surfaces and radially located openings has the most significant kinetic energy value stored by the flywheel per 1 kg of mass. Simultaneously, the flywheel mass is 16.7 kg, which is less than that of other designs' flywheels under consideration. In absolute terms, the most significant amount of kinetic energy is 9.9 MJ at the speed of 37680 rpm allows you to accumulate a whole flywheel with convex side surfaces. Still, it has the most significant weight of 28.2 kg.

## Conclusions

1. With the help of numerical modeling of rotors with various designs of the flywheels, their frequencies are defined, which will control the limit rotation frequency with the flywheel, which will avoid its destruction. It is also established that the rotor resonance caused by the coincidence of its frequency with the frequencies of the equipment in the workshop is unlikely since the smallest first critical frequency of the rotor from all the studied structures is 436 Hz, which corresponds to 26160 rpm.
2. It has been established that the design of the rotor with a flywheel from the composite material Hextow AS4 with convex side surfaces and radially located holes at a weight of 16.7 kg has the most considerable specific amount of kinetic energy stored by the flywheel per 1 kg of mass – 0.457 MJ/kg. In absolute

ex-pression, the flywheel of this design can accumulate 7.6 MJ energy at 43020 rpm. Thus, the theoretically proved the possibility of using mechanical energy storage with the flywheel in metalworking workshops' technological equipment.

Thus, the flywheel's design with convex side surfaces and radially located holes is most optimal from the point of view of energy intensity and the composite material cost because it has a lot of 11 to 68% less than the designs under consideration.

3. Further research is aimed at a dynamic study of the rotor's accelerating dynamics with a flywheel with convex side surfaces and radially located holes under the action of centrifugal forces with a change in over-clocking time and acceleration during acceleration to modes close to the first one's frequency.

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