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INFLUENCE OF ELECTROSTATIC WATER-REPELLENT COATING OF THE PROPELLER BLADES ON ITS AERODYNAMIC CHARACTERISTICS

The article presents approaches to the development of a methodology for improving the main aerodynamic characteristics of fixed and variable pitch propellers. The aim of the work is to improve the main aerodynamic characteristics of fixed and variable pitch propellers by applying an electrostatic water-repellent coating to the surface of the blades. The article solves the following tasks: analysis of the main ways to improve the aerodynamic characteristics of an air rotor when using a surface coating that provides improvement of its aerodynamic characteristics, substantiation of the method of reducing the drag of an air rotor, study of the proposed method of reducing the drag of an air rotor when applying an electrostatic water-repellent coating to its blades. The following methods are used: comparative analysis, experimental study.

The results obtained make it possible to reduce the drag of an air rotor and improve its aerodynamic characteristics, which makes it possible to increase the efficiency of the propeller group and improve its fuel and economic performance. The use of an electrostatic water-repellent coating on the blades of an air rotor makes it possible to improve its aerodynamic characteristics and increase the efficiency of the propeller group. The results of experimental studies have shown that when applying such a coating to the blades of an air rotor, it is possible to obtain greater thrust by reducing its drag and improve the fuel and economic performance of the propeller unit, namely, reduce fuel consumption.

KEYWORDS: *surface quality, screw surface quality assessment, propeller, propeller blade, propeller coating, propeller aerodynamic characteristics.*

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Statement of the problem

The coating of propellers is an important aspect of the aviation industry and has a major impact on the efficiency, durability and safety of aircraft. Propellers operate in difficult conditions and are exposed to extreme temperatures, high loads, vibrations and corrosion. Therefore, the coating applied to their surface must provide protection and reduce wear and tear and increase their efficiency. The efficiency of a propeller largely depends on the correct selection of its parameters, design, and surface coating of its blades [1, 2].

Regardless of the type of propeller (metal, composite, or other materials), the coating always plays a key role in ensuring their long-term use and flight safety. Properly selected and applied coatings can significantly improve the performance of aircraft.

The quality of the propeller surface coating determines the degree of corrosion protection, since the propeller is often exposed to moisture and other aggressive environments. The propeller surface coating also protects against erosion due to dust and sand particles that hit the blade surface during flight and gradually wear out the surface [3, 4]. The applied coating with a low friction coefficient reduces the drag of the rotor, while improving its aerodynamic properties. And heat-resistant coatings can withstand high temperatures without losing their properties [5]. An innovative technological solution is nanocoatings, which, thanks to new technologies, allow for the application of ultrathin layers of nanocoatings, which, due to their improved aerodynamic properties, not only provide protection against erosion and corrosion, but also reduce airflow resistance.

A properly selected and applied coating can significantly improve the performance of a rotorcraft. For example, reduced drag and erosion contribute to maintaining the optimal blade shape, which ensures flight stability and reduces engine load, as well as improves the economic performance of the rotorcraft.

Modern methods of approaching the selection and application of coatings on the surface of an air rotor can significantly improve the performance of aircraft, which necessitates a comparative analysis of the latest advances in this important area and a comprehensive review of existing methods of air rotor surface treatment. Thus, there is a need to justify the use of an electrostatic water-repellent coating of the propeller surface.

Analysis of recent studies and publications

Currently, many scientific studies are being conducted to improve the efficiency and reliability of propellers [6-8]. Innovations in the industry include the use of nanomaterials, composite alloys, and more environmentally friendly coatings that open up new opportunities to improve the efficiency and reliability of aircraft components.

Nanocoatings are typically single- or multi-phase solid structures deposited on an overlaying surface with a thickness of about 100 nm or less, adding certain properties or functions to the material. Different materials exhibit unique properties at the nanoscale, such as melting point, electrical conductivity, magnetic permeability, hydrophobicity, and chemical reactivity to erosion and corrosion, but also reduce airflow resistance due to improved aerodynamic properties [9-11]. The effectiveness of the process of surface protection based on nanotechnology specially designed for aeronautical applications on aircraft made of composite materials is described in [12-14].

Sources [15, 16] consider issues related to the aerodynamic design of propeller blades; provide basic information on the vortex theory of a propeller; present a method for accounting for terminal losses; consider a method for solving propeller aerodynamics problems and performing a calculation check; analyze the issue of choosing the most profitable propeller with an infinite and finite number of blades; propose methods and algorithms for aerodynamic design of propeller blades.

Since aerodynamic characteristics are important quality indicators, we analyzed scientific publications on the principles and methods of quality assessment. For example, publications [17-19] present a methodology for applying qualimetric methods for evaluating various objects using nonlinear functional dependencies. Scientific publications [20, 21] present a methodology for quality assessment in mechanical engineering, which presents the optimization of tolerances for the quality and accuracy of machine parts.

Researchers at the Institute of Aeronautics at Riga Technical University [22] have developed a multilayer metal-ceramic nanocoating called McBLADE, which can be used to protect compressor and turbine blades in modern titanium alloy jet engines. Each layer of the coating is extremely thin and performs a specific function. The first layer increases adhesion to the base material, and the second layer protects the titanium alloy from oxidation. The top layer provides thermal protection and abrasion resistance, which allows the components to operate at high temperatures.

Paper [23] presents a methodology for using an aircraft surface de-icing coating to reduce the labor intensity and cost of performing work in the cold season. De-icing aircraft in cold weather can be an expensive and time-consuming process. Nanocoatings have been developed that can repel water and ice, resulting in maintenance cost savings. In-flight tests on British Airways' Airbus A320 aircraft have demonstrated a 20-40% improvement in surface hydrophobicity compared to other commercially available conventional coatings. In addition, innovative coatings based on nanostructured carbon materials (such as carbon nanotubes and graphene oxide) reduce airflow resistance on the aircraft surface. This reduces fuel consumption and CO2 emissions.

A research project called ReSiSTant (Large Riblet Surface with Super Hardness, Mechanical and Temperature Resistance by nanofunctionalization) [24], funded by the EU's Horizon 2020 research and innovation program, aimed to develop advanced nanocoatings and application methods to improve performance and provide abrasion and corrosion resistance. The project focuses on ribbed surfaces consisting of very small (2-100 microns) parallel grooves to reduce passive surface drag in next-generation aircraft.

Paper [25] presents materials on computational and experimental studies of the propeller layout using numerical research methods. The use of new methods for reducing passive drag in aviation is one of the most viable approaches to reducing aviation fuel consumption, CO2 emissions, and noise generation.

Thus, the aim of the article is to improve the main aerodynamic characteristics of fixed and variable pitch propellers by applying an electrostatic coating on the surface of the blades.

Summary of the main material

Currently, considerable attention is devoted to mathematical methods for modeling the dynamics of fluids and gases, which allow replacing costly physical experiments with numerical simulations with a high degree of reliability. In many cases, these methods yield results that are unattainable through physical experimentation.

The properties of a material at the nanoscale are governed by intermolecular forces such as the Van der Waals interaction, hydrogen bonds, and electrostatic forces. These intermolecular forces operate on small length scales in the range of a few angstroms to a few nanometers. When the dimensions of the material become the same as the distances between the molecular forces (i.e., nanoscale), the material properties change dramatically [26]. Thus, coatings consisting of nanoparticles or multiple layers at the nanoscale make it possible to explore their improved physical and chemical properties in a wide range of new applications.

When the surface of a propeller interacts with an incoming air stream, it is necessary to create the least resistance, since the particles of the solid surface of the propeller will collide with particles of air molecules. It is well known that in heterogeneous systems, intermolecular interaction within a phase and between phases is distinguished. Electrostatic repulsion is a consequence of the Coulomb interaction between equally charged objects. This phenomenon is fundamental to understanding the behavior of materials in heterogeneous systems, such as colloidal solutions, biopolymers, and nanoparticles. Its control allows us to create functional materials and devices [27].

The interaction of atoms and molecules within a single phase is called cohesion (from the Latin cohesion) [28, 29]. It determines the existence of substances in the condensed state and can be caused by interatomic and intermolecular interactions of different nature (chemical covalent bonds, hydrogen bonds, electrostatic interaction forces, Van der Waals forces). Cohesive forces are sometimes called attraction forces. Van der Waals forces arise from the interaction of short-term dipoles and this bond is considered the weakest of all types of bonds. A short-term asymmetric distribution of charges is a temporary dipole. This dipole can polarize neighboring molecules and thereby induce new dipoles.

The ability to polarize depends on the total number of electrons in the molecule. The larger the molecule, the greater the number of electrons and the greater the intramolecular charge shifts that can occur. As a result, many short-term partial electric charges (instantaneous dipoles) are created, which create an electric field, under the influence of which electrostatic forces (forces of interaction between two charged particles) arise, causing the attraction or repulsion of individual dipoles. The larger the molecule of a substance, the more Van der Waals interactions between molecules. The work of cohesion is directly proportional to the energy of formation of two surfaces [28]:

$$W_k = 2\sigma, \quad (1)$$

where σ – surface tension of the surface.

The interaction between phases or brought into contact surfaces of condensed bodies of different nature is called adhesion, which provides a certain strong connection between two bodies due to physical or chemical intermolecular forces. Taking into account the adhesion between two liquids, between a liquid and a solid, and between two solids and air, adhesion occurs when the system wants to reduce the surface energy, so under appropriate conditions it is a spontaneous process. The adhesion work W_a characterizes the strength of the adhesive contact and is determined by the reverse breaking work of this contact per unit area, and is measured in the same units as the surface tension, J/m^2. Let's consider the diagram of the change in interfacial surface tension, Fig. 1.

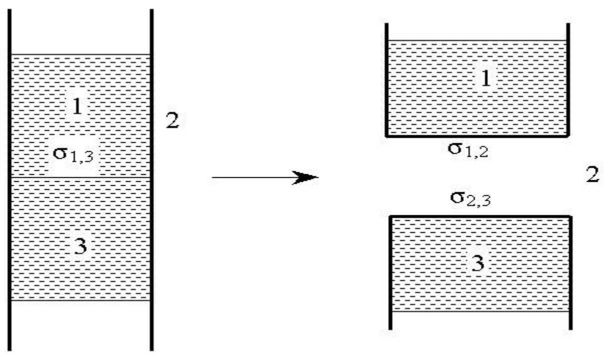


Fig. 1 - Diagram of changes in interfacial surface tensions during the separation of liquids 1 and 3, which do not mix in a gas medium 2 [24]

To obtain the relationship between the work of adhesion and surface tension, consider two liquid bodies 1 and 3 in contact with each other over an area *S* in a gas atmosphere 2 (Fig. 1) and characterized by an interfacial surface tension $\sigma_{1,3}$. When the contacting liquids are separated, two surfaces are obtained: liquid 1 with a surface tension of $\sigma_{1,2}$ and liquid 3 with a surface tension of $\sigma_{2,3}$, and the interface with a surface tension of $\sigma_{1,3}$ disappears. Thus, the work of adhesion, i.e., the work required to separate a unit surface area of one liquid from the other, according to the Dupré equation, will be determined by [28]:

$$W_a = \sigma_{1,2} + \sigma_{2,3} - \sigma_{1,2}, \quad (2)$$

where $\sigma_{1,2}$ – surface tension at the liquid-gas interface; $\sigma_{2,3}$ – solid body - gas; $\sigma_{1,2}$ – and a solid body is a liquid.

Equation (2) defines the adhesion work W_a, which characterizes the interaction of the phases (W_a is referred to as a unit surface area). The surface tension will be directed tangentially to the corresponding surface σ and will be at a certain angle to the contact plane, it is called the edge wetting angle. We denote the value of the edge wetting angle by the letter θ.

To determine the equilibrium work of adhesion of a liquid, we can use the Dupré-Young equation, which gives the calculation of the work of adhesion W_a based on the experimentally determined boundary wetting angle θ [28]:

$$W_a = \sigma(1 + \cos\theta). \quad (3)$$

When the blade operates in the air flow, the interaction between the solid surface and air will occur. To be able to visually observe the action of electrostatic forces, let us consider the interaction between the solid surface and liquid. To do this, consider the phenomenon of wetting, which occurs when a solid comes into contact with a liquid as a result of molecular interaction between them. It is well known that the wetting phenomenon consists in the fact that a drop of liquid that has fallen on the surface of a solid spreads. The mechanism of liquid spreading on the surface of a solid differs from the mechanism of liquid spreading on the surface of liquids, which is characterized by molecular mobility. Liquids spread over solid surfaces due to diffusion, capillarity, liquid volatility, and other reasons. If the molecules of a liquid interact with the molecules of a solid more strongly than with each other, the liquid spreads over the surface, i.e., wets it. The spreading continues until the liquid covers the entire surface or until the liquid layer becomes monomolecular. This phenomenon is called complete wetting.

There will be no spreading if the molecules of the liquid interact with each other much more strongly than with the molecules of the solid. The liquid will collect in drops. That is, when the repulsive forces between solid molecules are greater than the attractive forces between water molecules, there will be no spreading of water on the surface and the water will collect in drops. Between these cases, there are transitional cases of incomplete wetting when the droplet forms a certain equilibrium angle with the surface of the solid, called the edge angle, or wetting angle θ. The edge angle θ is the angle formed by a liquid droplet between the tangent to its surface and the surface of a solid. The smaller this angle, the better the liquid wets the surface of the solid. The larger this angle θ, the less the liquid wets the surface of the solid, and thus electrostatic forces (forces of interaction between two charged particles) create forces of repulsion of individual dipoles between the solid surface and the liquid. Consider the cross section of a water drop in the Fig. 2.

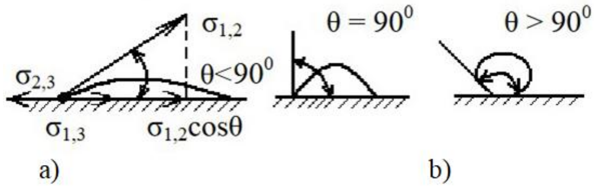


Fig. 2- Cross-section of a liquid droplet on a solid surface: a) in the cases of wetting of a solid surface; b) non-wetting of a solid surface

Thus, there are three forces per unit length of the wetting perimeter $\sigma_{1,2}$; $\sigma_{2,3}$ i $\sigma_{1,3}$. Then the condition of equilibrium of forces, expressed by the Young's equation, will be [29]:

$$\sigma_{2,3} = \sigma_{1,3} + \sigma_{1,2}\cos\theta \quad (4)$$

From here.

$$\cos\theta = \frac{\sigma_{2,3} - \sigma_{1,3}}{\sigma_{1,2}} \quad (5)$$

The value of $\cos\theta$, characterizing the ability of a liquid to wet a surface, is called wetting and is denoted by B. It is obvious that when the $\theta = 0^{\circ}$, $B = +1$, with complete non-wetting $\theta = 180^{\circ}$, $B = -1$. Of the two liquids, the one that wets a given surface better and whose spreading decreases the surface energy

of the system by a large amount. Thus, the wetting of a solid surface by a liquid can occur only when the surface tension between the solid surface and the liquid ($\sigma_{1,2}$) will be less than the surface tension between the solid and the gas ($\sigma_{1,3}$). Otherwise, the liquid will not wet the surface of the solid. The closer the polarity of the adhesive and the substrate, the stronger the contact between them.

Electrical theory attributes adhesion to the formation of a double electric layer between the adhesive and the substrate. The theoretical assessment of adhesion is currently very approximate, which is explained not only by the imperfection of the equations that calculate the forces of intermolecular bonds, but also by the fact that it is impossible to estimate the actual number of bonds per unit area (it is always less than the theoretical one, which indicates the possibility of increasing the strength of the bond). In addition, it is difficult to estimate the true contact area, which, due to the roughness of the surface layer, is sometimes much larger than what is observed visually. To ensure the strength of the joints, the roughness is often deliberately increased by special surface treatment of the materials.

Adhesion performance can be determined by indirect methods, which are especially convenient if at least one of the interacting phases is a liquid, making it possible to measure, for example, the edge wetting angle θ. The wettability of some solids with water is characterized by the following edge angles: quartz - 0°, malachite - 17°, graphite - 55°, talc - 69°, paraffin - 106°, teflon - 108°. According to the literature [25-27], teflon and paraffin have the largest edge angles and have better water-repellent properties. Experimental studies were conducted to confirm the theoretical provisions of the possibility of reducing the attraction of liquid or gas by solid molecules with their surface, and hence reducing the drag of a propeller.

To conduct experimental studies of the effect of the electrostatic water-repellent coating of the propeller blades, a monobloc propeller with a diameter of 125 cm and a pitch of 57 cm was manufactured. The material from which the propeller was made was pine bars. The dimensions of the bar for making the propeller are 12 cm x 5 cm. We glued the bars together from several boards. For a workpiece thickness of 5 cm, we took 2 boards 12 cm wide, where one is 2 cm thick and the other is 3 cm thick.

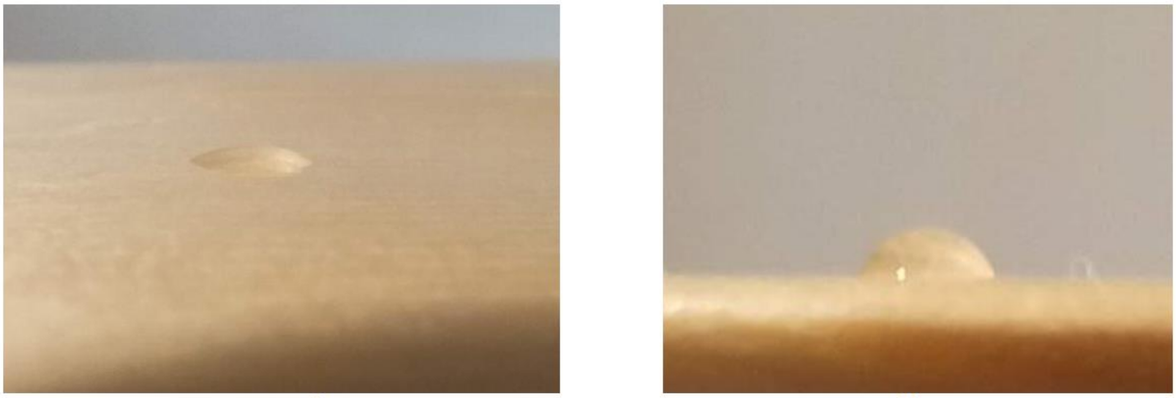
Certain areas of the screw, such as the blade tips, the leading edge near the tip, the hub surface, the bolt holes, and the center hole, require greater strength and hardness. For example, when tightening the bolts to secure the screw, the hub surface of the screw may be jammed by excessive stress, and the leading edge of the blade may be damaged if grass or other materials are caught in the screw. To provide strength and hardness to certain areas of the blade surface, we treated them with a universal waterproof adhesive. The glue is applied to the ground surface of the screw in the areas that need to be strengthened and hardened. The adhesive is quite liquid, so it penetrates deeply into the wood. Depending on the type of wood, the adhesive penetrates to a depth of 0.5 ÷ 1 mm, which makes the surface quite hard and durable.

A two-component polyurethane varnish is used for the outer surface coating of the propeller. The varnish is mixed with a hardener in a ratio of 4 to 1. It is important to add the optimal amount of hardener, as a violation of the proportion will increase the drying time of the varnish. The consumption of the varnish per blade of a 125 cm diameter screw per coating was 20 g. The application of layers of varnish on the surface of the propeller was carried out 2 times.

To assess the impact on the economic and traction performance of the designed propeller with a varnish coating and an electrostatic water-repellent coating, experimental studies of operation in real conditions were conducted on a paramotor unit with a Solo 210 engine with a power of 14 hp. According to the passport data, the maximum speed of this engine is 6200 rpm. The gear ratio is 2.5. Sky-Country Moscito-4 wing. The wing area is 27.5 m^2. The appearance of the paramotor unit is shown in the Fig. 3.

Initial experimental studies were conducted with a propeller with only a varnish coating. The economic and traction performance of the paramotor unit was measured and recorded during a 5-hour flight. The results of experimental studies of the propeller with a varnish coating on its surface are presented in Table 1. After the initial tests, the propeller was removed from the paramotor unit and a drop of water was applied to its surface to assess the surface tension on the propeller's varnish coating. A photo of the water droplet on the propeller surface before and after the varnish coating was applied is shown in Figure 4, a. After the next electrostatic water-repellent coating is applied and cured, a water droplet is also applied to its surface. A photo of a water droplet on the surface of a propeller with an electrostatic water-repellent coating is shown in Fig. 4, b.

Fig. 3- Exterior view of a paramotor unit with a propeller 125×57 cm



a) b)

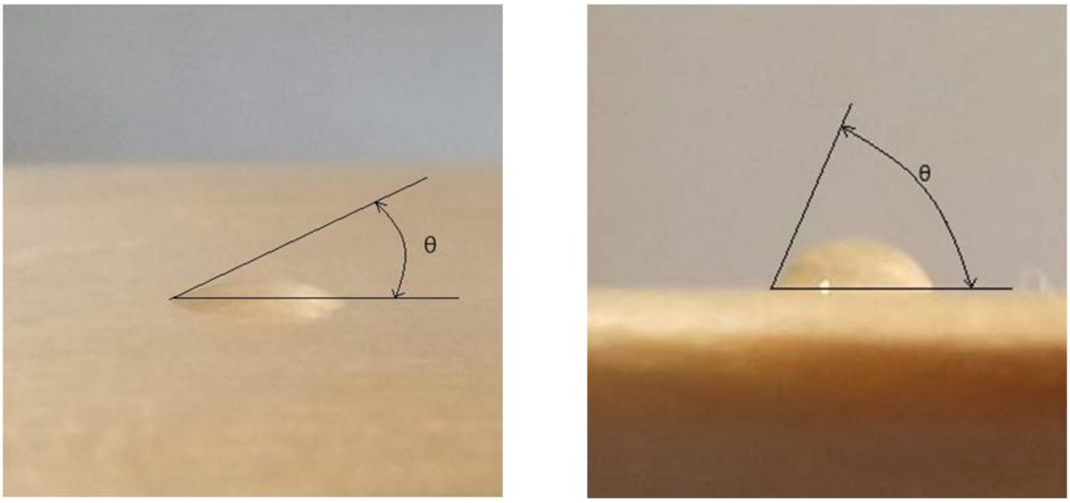
Fig. 4- A drop of water applied to the blade surface: a) with a varnish coating;
b) with an electrostatic water-repellent coating

To visualize the wetting edge angle θ, we draw tangent lines to the surfaces of the water droplet for two variants of the propeller surface - a varnished surface and a propeller surface with an electrostatic water-repellent coating. The tangent lines drawn to the surfaces of the water droplet to represent the edge wetting angle θ are shown in Fig. 5.

As can be seen from Fig. 5, on the surface of a lacquered propeller, the edge wetting angle of the surface θ is about 300, and on the surface of the propeller, which is treated with an electrostatic water-repellent liquid, the edge wetting angle of the surface θ is about 700.

To evaluate the effect of the propeller surface properties, namely, the reduction of its frontal resistance to air flow, repeated experimental studies were conducted with a propeller on the surface of which an electrostatic water-repellent coating was applied. During a 5-hour flight, the economic and traction performance of the paramotor unit was measured and recorded. The results of experimental studies of the propeller operation with two different types of surface coatings are listed in the Table 1.

The treatment of the propeller surface with an electrostatic water-repellent coating according to the proposed method showed an increase in the maximum engine speed during the operation of the propeller installation on site and in flight. According to the studies, the use of an electrostatic water-repellent coating can reduce fuel consumption by 4...6%.



a) b)

Fig. 5 - Image of the edge wetting angle θ of the propeller surface for:
a) varnish coating of the propeller surface; b) electrostatic water-repellent coating of the propeller surface

Table 1.
Results of experimental studies of the operation of a propeller with two different coatings of its surface

Indicators	Screw 125 x 57 cm The surface of the propeller is varnished	Screw 125 x 57 cm Propeller surface with electrostatic water-repellent coating
Edge wetting angle of the propeller surface, θ, °	30	70
Increase in the edge wetting angle of the propeller surface, θ, °	0	40
Maximum engine speed in place, rpm	6030 ÷ 6050	6130 ÷ 6150
Increase in maximum engine speed on site, %.	0	1.67
Maximum engine speed in flight at a speed of 43 ÷ 45 km/h (climb), rpm	5970 ÷ 6000	6010 ÷ 6030
Engine speed in cruise mode (horizontal flight), rpm	5200…5400	5200 ÷ 5400
Thrust in place, kg	42 ÷ 44	43 ÷ 45
Increase in propeller thrust, %.	0	3.7 ÷ 4
Flight altitude, m	100 ÷ 200	100 ÷ 200
Pilot weight, kg	92	92
Weight of the paramotor unit (dry), kg	23	23
Air temperature, ℃	25	25
Fuel consumption for 1 hour of the route flight, *l*	3 ÷ 3,15	2,8 ÷ 2,9
Fuel economy, %.	0	4 ÷ 6

Conclusions

The use of an electrostatic water-repellent coating on the blades of an air rotor makes it possible to improve its aerodynamic properties and increase the efficiency of the propeller group. A methodology for evaluating the electrostatic repellent properties of a material by using water-repellent phenomena at its edge wetting angle is proposed. According to the described method of using the electrostatic water-repellent coating of propeller blades, the studies were carried out on a paramotor installation with a 14 hp Solo 210 engine and a Moscito-4 wing in flight mode and during operation on site. The results of experimental studies have shown that when applying an electrostatic water-repellent coating to the blades of an air rotor, it is possible to obtain a higher thrust by 4%, reduce its drag and improve the fuel and economic performance of the propeller installation, namely, reduce fuel consumption by 4 ÷ 6%.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of the manuscript. In addition, the authors fully complied with ethical standards, including plagiarism, data falsification, and double publication.

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ВПЛИВ ЕЛЕКТРОСТАТИЧНОГО ВОДОВІДШТОВХУВАЛЬНОГО ПОКРИТТЯ ЛОПАТЕЙ ПОВІТРЯНОГО ГВИНТА НА ЙОГО АЕРОДИНАМІЧНІ ХАРАКТЕРИСТИКИ.

У статті представлено підходи до розроблення методики підвищення основних аеродинамічних характеристик повітряних гвинтів фіксованого та змінного кроку. Метою роботи являється удосконалення основних аеродинамічних характеристик повітряних гвинтів фіксованого та змінного кроку шляхом нанесення електростатичного водовідштовхувального покриття на поверхню лопатей. У статті вирішуються наступні завдання: аналіз основних способів підвищення аеродинамічних характеристик повітряного гвинта при використанні покриття його поверхні, яке забезпечує покращення його аеродинаміки, обґрунтування методу зменшення лобового опору повітряного гвинта, дослідження запропонованого методу зменшення лобового опору повітряного гвинта при нанесенні електростатичного водовідштовхувального покриття на його лопаті. Використовуються такі методи: порівняльний аналіз, експериментальне дослідження.

Отримані результати дозволяють зменшити лобовий опір повітряного гвинта та підвищити його аеродинамічні характеристики, що дозволяє підвищити ефективність роботи гвинтомоторної групи та підвищити її паливно-економічні показники. Використання електростатичного водовідштовхувального покриття лопатей повітряного гвинта дозволяє підвищити його аеродинамічні характеристики та підвищити ефективність роботи гвинтомоторної групи. Результати експериментальних досліджень показали, що при нанесенні такого покриття на лопаті повітряного гвинта можна отримати більшу тягу за рахунок зниження його лобового опору та покращити паливно-економічні показники гвинтомоторної установки, а саме знизити розхід палива.

КЛЮЧОВІ СЛОВА: *якість поверхні, оцінка якості поверхні гвинта, гвинт, лопать гвинта, покриття гвинта, аеродинамічні характеристики гвинта.*

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Автори заявляють, що конфлікту інтересів щодо публікації рукопису немає. Крім того, автори повністю дотримувались етичних норм, включаючи плагіат, фальсифікацію даних та подвійну публікацію

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