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BEARINGLESS ROTOR SYSTEM MAIN COMPONENTS DESIGNING

Bearingless rotor system design optimizes mechanical simplicity, eliminates frictional losses typical of conventional bearing systems, and improves the overall efficiency of the rotor system. Based on the findings of the research, it is possible to determine that composite materials can be applied in order to improve the performance of the rotorcraft rotor system. A theoretical analysis of the influence of input parameters on the aerodynamic quality of the main rotor of a rotorcraft was carried out. The strength and aerodynamic quality of the designed parts were calculated using the finite element analysis method. The energy efficiency of the use of composite materials is substantiated, which will ensure better efficiency and competitiveness of the aircraft.

Key words: composites, bearingless rotor system, flexbeam, helicopter blade.

Introduction and formulation of research objectives. Aircraft performance is the result of aerodynamic, gravitational and propulsive forces acting on the aircraft. Aircraft share some common features in their structural and aerodynamic design. The structural design attempts to minimize the weight of the aircraft without losing the strength of its structure. The aerodynamic design tries to maximize the lift force without increasing the drag force on the aircraft. The aircraft components exposed to the atmosphere determine the aerodynamic forces of its performance. Some of these components are movable and are used to generate desirable aerodynamic forces to control the linear and angular motions of the aircraft during flight [1]. The objective is to create a bearingless rotor system (BRS) that combines established input parameters with innovative performance improvement methods. This system should demonstrate advanced aerodynamic principles while also focusing on safety, efficiency, and adaptability. This research aims to advance the capabilities of bearingless rotor systems in unmanned aerial vehicles.

Analysis of recent publications on this issue. Bearingless rotor is one of the advanced rotor systems that has been used in rotorcraft in during the last few decades. It presents various advantages, such as a significant reduction in the number of the components to assemble and reduced maintenance costs. However, the structural configuration of a bearingless rotor is complicated, as is its dynamic behaviour. Fig. 1 shows main components of a bearingless rotor system. Those are rotor blade, single or multiple flexbeams, torque tube, lead-lag damper and hub plate. The distinguishing features of the bearingless rotor are a torsionally soft flexbeam and a torsionally-stiff torque tube. Due to elastic deformation of the flexbeams the role of structural hinge is implemented. A torsionally stiff torque tube, which is soft in bending, is used to transmit the pitch control torque to the outboard end of the flexbeam. This structural configuration of a bearingless rotor causes unique structural characteristics. Also, multiple load paths and interrelation of the multiple components features significant geometric nonlinearity. As a result, it requires complicated structural modelling and

appropriate numerical validation due to its multiple load paths, as produced by the single or multiple flexbeams and the torque tube [2].

Figure 1. Bearingless rotor system design

Bearingless rotor has no mechanical flapping hinges and rotatable joints and the bearing for the adjustment of the angle of incidence is replaces as well with an elastomer bearing. Because no conventional mechanical bearings are used, maintenance can be reduced considerably. Large forces act on the root of the rotor blade and therefore the bearingless rotor with elastomer bearing is only suited for smaller helicopters. This system was introduced by Aerospatial with the Spheriflex rotor.

With this new design, a soft but high-strength structural element called the "composite flexbeam" is installed at the inner end of each rotor blade. This element allows the angle of the rotor blades to change as needed to generate aerodynamic lift.

With no bearings, the hub became structurally simpler, requiring no lubrication system or disassembly process for maintenance. This helps extend the intervals between inspections and maintenance, as well as reducing the helicopter's weight [3].

BRS is designed for BK117 D-3, Sikorsky S-97 Raider and Raider X, SB-1 Defiant, Sikorsky X2, AH-1Z Viper. Helicopters with bearingless main rotor systems stand out for their superior performance, marked by reduced mechanical complexity, lower vibrational loads, improved maneuverability, enhanced safety features, higher structural resilience, increased payload capacity, efficient power transfer, and the integration of advanced materials. These advancements collectively position helicopters with bearingless main rotor systems as formidable and high-performing assets in the diverse landscape of rotary-wing aviation [4].

The purpose of the article - development of a rotorcraft rotor system with improved performance characteristics through the strategic integration of composite materials, focusing on increased efficiency during various operational phases.

Methods of theoretical research. Designing a helicopter rotor system involves a complex process to ensure optimal performance, stability and safety. The two critical components in this system are the flexbeam and the rotor blade. The design process typically follows key steps that revolve around defining desired parameters and adhering to specific restrictions.

Table 1

Manufacturing restrictions of the system components

Dimensional Parameters	Units	Value
Length (single part)	m	<0.5
Width (single part)	m	<0.16

By establishing these limitations (table 1), I ensure that the manufacturing equipment operates within defined parameters, aligning with constraints and capabilities of the machinery. This practice aids in achieving precision, accuracy, and consistency in the fabrication of components or products. Moreover, adhering to a designated working volume promotes efficiency, minimizes errors, and streamlines the manufacturing workflow.

Table 2

Performance goals and inputs of the bearingless rotor system

Performance Parameters	Units	Value
Power loading, PL	kg/kW	>8.5
Thrust, $T = W$	kg	60
Disk loading, DL	kg/m^2	20
Mass of blade	kg	<0.2
Number of blades, N_b	-	3
Mass of flexbeam	kg	<0.1
Maximum speed	m/s	56

In engineering and optimization processes, it is common to create a table 2 that outlines both desirable goals and input variables. This table functions as a task framework for equations, providing a structured approach to achieving desired outcomes.

Table 3

Operating conditions

Operating Parameters	Units	Value
Nominal RPS, n	s^{-1}	30
Maximum RPS	s^{-1}	40
Safety factor	K_σ	2
Angles of attack range	$\alpha°$	-6 … 6
Maximum engine power (at 30 s^{-1})	kW	7
Air density (standard), ρ	kg/m^3	1.225
Kinematic viscosity ($t = 10$ ℃), υ	m^2/s	$1.42 \cdot 10^{-5}$

This structured presentation (table 3) of operational parameters serves the purpose of simplifying the analytical process by offering a clear and organized overview of the variables influencing the system.

A schematic image (fig. 2) is provided for the sample to speed up the design bearingless rotor system.
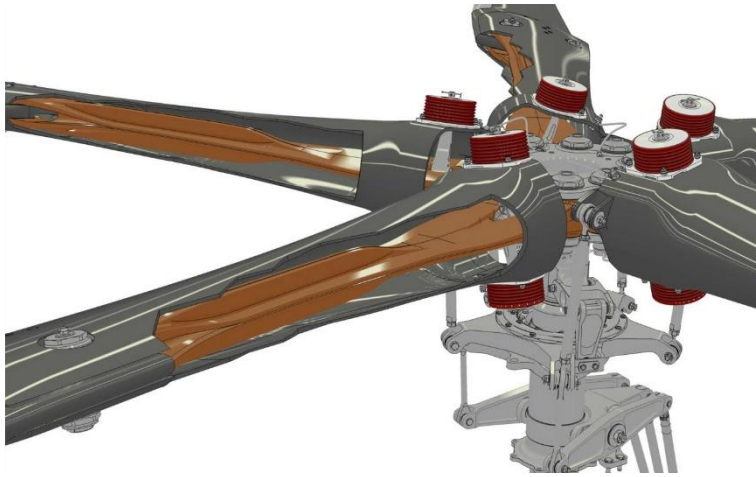

Figure 2. Airbus H145 bearingless rotor system scheme

In this study, the analysis of a rotor in hover conditions is approached with the blade element theory. The equations developed for blade element theory form our preliminary calculations, enabling a detailed examination of the aerodynamic forces acting on individual blade elements.

Defining main rotor parameters for primary design. Both good hover performance and safe autorotational capabilities call for a large *rotor diameter*. The advantages of a larger rotor diameter are lower disk loadings, lower average induced velocities and lower induced power requirements. The operating thrust coefficient to give the best power loading is

$$C_T = \frac{1}{2}\left(\frac{\sigma C_{d0}}{\kappa}\right)^{2/3} \text{ for best power loading} \tag{1}$$

which depends on airfoil section (C_{d0}), rotor solidity and induced power factor (κ). Using this result, the disk loading for minimum power loading will be

$$DL = \frac{1}{2}\rho(\Omega R)^2 \left(\frac{\sigma C_{d0}}{\kappa}\right)^{2/3} \tag{2}$$

This equation determines the optimum radius of the rotor to maximize power loading at a given MTOW. Solving for the main rotor radius gives

$$R = \sqrt{\frac{W}{\pi DL}} \text{ for a conventional single rotor} \tag{3}$$

$$R = \frac{1}{\sqrt{2}}\sqrt{\frac{W}{\pi DL}} \text{ for a coaxial rotor} \tag{4}$$

The work considers only the rotor system taken separately, but the aerodynamic layout is coaxial, so Eq. 3.22 will be used.

According to Eq. 4 and selected numerical values of the design parameters

$$R = 0.75 \ m \tag{5}$$

Considering that the rotor system includes a flexbeam in addition to the blade the manufacture of such a rotor is possible.

A high rotor *tip speed* helps to maintain the local velocities and decrease the angles of attack on the retreating blade, thereby delaying the onset of blade stall for a given blade area and advance ratio. A high tip speed also gives the rotor a high level of stored rotational kinetic energy for a given radius and helps reduce design weight. Because $P = \Omega Q$, a high tip speed reduces the rotor torque required for a given power. However, there are two important factors that work against the use of a high tip speed: compressibility effect and noise. Ideal tip speed for this work is $M_{tip} = 0.6 \approx 204 \ ^m/_s$. But this tip speed is the best only for hover regime. Taking into account that the engine rotational frequency has limitation at hovering, the tip speed

$$V_{tip} = 2\pi R n = 141 \ ^m/_s \tag{6}$$

This speed ensures a low noise level at high altitude, as well as maximum efficiency at maximum flight speed at the advancing blade.

To define chord length *blade loading coefficient* is given

$$\overline{C}_L = 6(^{C_T}/_\sigma) \tag{7}$$

Typical values of $\overline{C}_L$ for helicopter range from about 0.4 to 0.7. In this work $\overline{C}_L = 0.5$ and $\sigma = 0.08$, so

$$l_b = 0.45 \ m \ \text{and} \ c_b = 0.1 \ m \tag{8}$$

As main geometric blade parameters are defined, *airfoil section* can be chosen.

After comparing lift and drag force curves, on the basis of the analysis carried out in the bachelor thesis, an aerodynamic airfoil Boeing-Vertol VR-5 was selected. Since the velocities at the blade cross-sections are subsonic, an airfoil with high lift capabilities was chosen, which characterizes the selected airfoil.
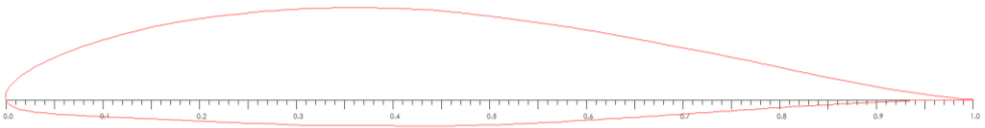

Figure 3. VR-5 airfoil

Discussion of main results. To enhance helicopter's blades, we depend on sophisticated 3D models to conduct accurate aerodynamic simulations. These digital counterparts are crucial for analyzing the forces produced by various sections of the rotor blades, especially during hovering. The main goal is to analyze and comprehend the precise aerodynamic forces involved, enabling engineers to enhance helicopter designs for enhanced efficiency and safety. Essentially, these 3D models are used to conduct aerodynamic simulations, acting as virtual laboratories to analyze the forces

generated by different segments of the rotor blades. This research contributes to the ongoing advancement of helicopter technology.

Defining the main cross-sections of a rotor system flexbeam involves considering the different loading conditions and section experiences. According to Fig. 4, flexbeam for bearingless rotor system has two main sections:

Section 1 experiences both tension and bending simultaneously and responsible for accommodating the flapping motion of rotor blade in a rotor system. Flapping refers to the up-and-down motion of the blades as they rotate around the rotor hub. This motion is essential for maintaining a balanced lift distribution across the rotor disk and optimizing the efficiency and stability of the rotorcraft.

Section 2 is responsible for changing the pitch angle of a rotor blade in a rotor system plays a pivotal role in controlling the lift and thrust generated by the blades during rotation. This section is subjected to both tension and torsion, as it needs to withstand the axial forces associated with tension and the twisting moments associated with torsion. The ability to efficiently change the pitch angle is crucial for flight possibilities of the rotorcraft.

The flexbeam being a component needs to be designed with low mass, low torsional stiffness, low bending stiffness and high strength to allow large twist motion with low dynamic stresses.
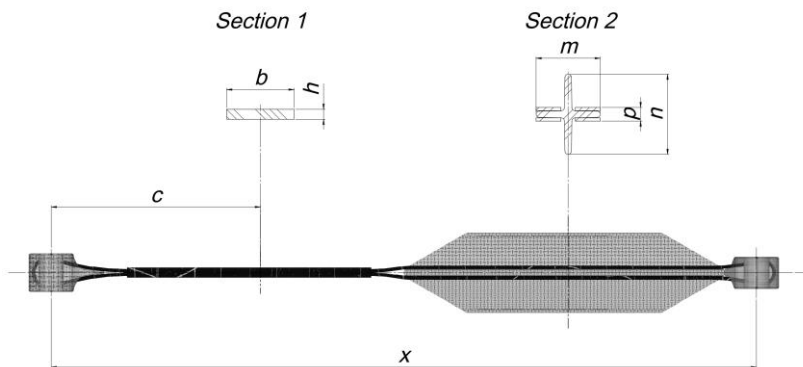

Figure 4. Flexbeam and main cross-sections

The material properties of a structure significantly influence the cross-section calculation, playing a pivotal role in determining its mechanical behaviour and response to external forces. The material should have a low modulus of elasticity for minimal deformation resistance under bending loads but at the same time it should withstand and be stiff under tension loads; should be tough to absorb energy and resist the initiation and propagation of cracks; should be able to endure repeated loading without experiencing fatigue failure; should have good resistance to corrosion; should exhibit sufficient torsional strength to resist failure under torsional loads; low density and low technological complexity for manufacturing parts with constant properties.

To validate the theoretical calculation flexbeam sections, a stress analysis was conducted in SolidWorks Simulation Module. The forces acting on the blade according to the BET were chosen.
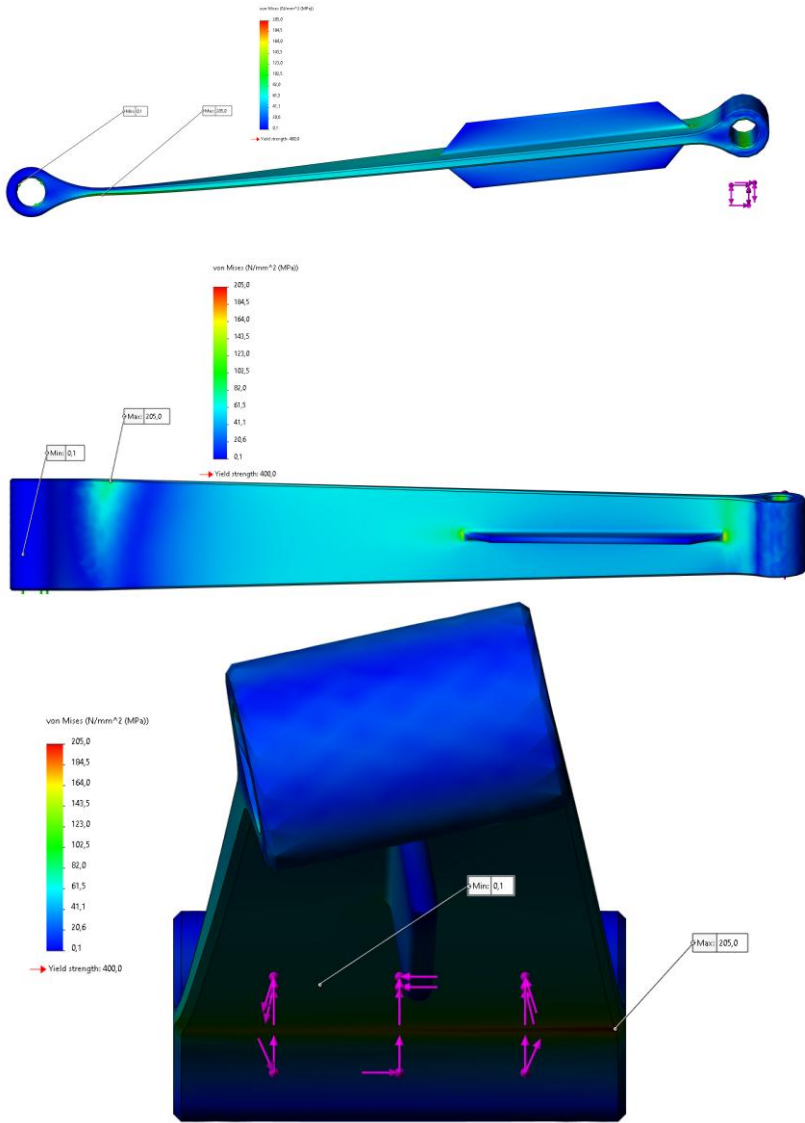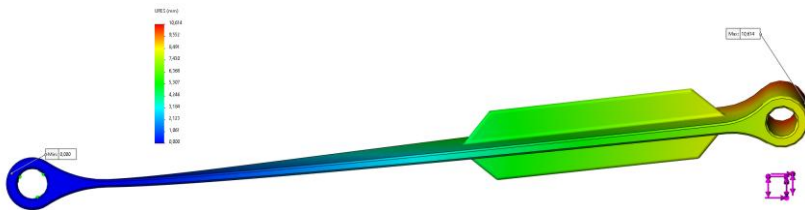
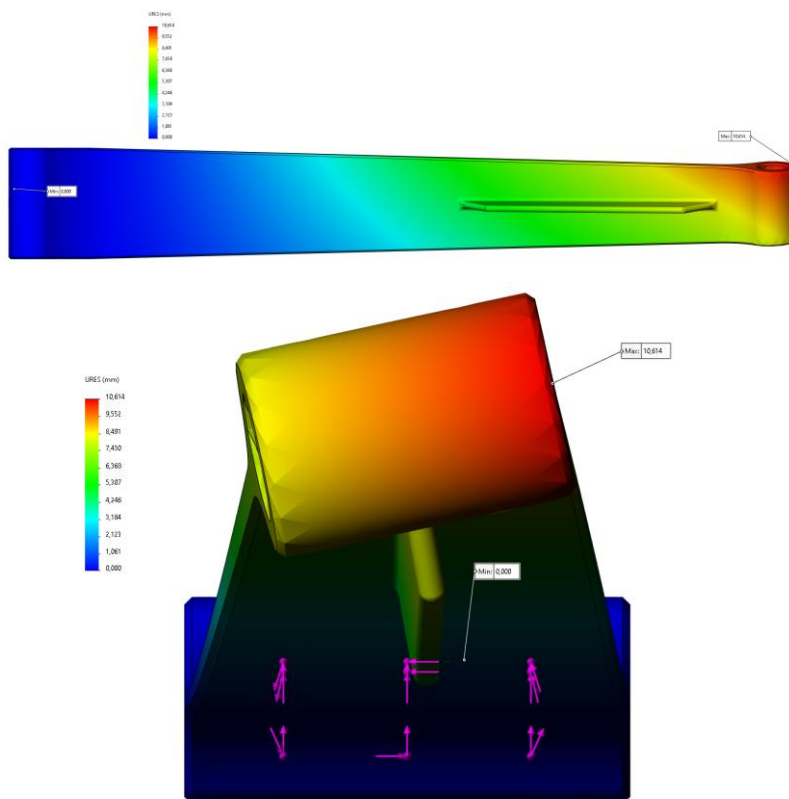Figure 5. Maximum stresses in flexbeam visualization

Figure 6. Maximum displacement in flexbeam visualization

The selection of E-glass fiber as the composite material for the flexbeam bearingless rotor system is strategically based on an accurate evaluation of its material properties [5]. The synergy of low flexure stiffness, high tensile stiffness and strength, toughness under cyclic loads and torsion and low-density positions glass fiber as an optimal choice given the low cost and availability, as well as simple manufacturability, promising to enhance the structural and operational performance of the rotor system in comparison with metals or even carbon fiber-reinforced composites. To get consistent mechanical properties from part to part, closed mold manufacturing technology with high pressure and high temperature was used (prepreg technology). Thus, The HEXCEL prepreg properties table was used to choose the reinforcing material.

As seen in the figures 5 – 6, the selected cross-sections meet the strength criteria for tension, bending, and torsion.

The stress and displacement simulations conducted on the flexbeam using SolidWorks have produced critical data for a comprehensive assessment of its structural performance. In the stress analysis, the internal forces and stresses experienced by the flexbeam under various loading conditions were detailed, providing insights into the structure's response to external forces. The highest stress (fig. 5) $\sigma_{max} = 205\ MPa$ is located in section 1 because it is the thinnest place of the part. The displacement simulations revealed valuable information about the deformations and movements exhibited by the flexbeam, contributing to a nuanced understanding of its mechanical behavior. The biggest displacement (fig. 6) $\delta =$

10.6 mm takes place on the free end of the flexbeam. By inputting the specific results into the analysis records, a detailed examination of stress distribution, potential weak points, and overall structural deflections can be facilitated. This integration of simulation results serves as a cornerstone for informed decision-making, enabling precise adjustments to enhance the flexbeam's resilience and optimize its performance parameters.

By decreasing the width of the segment 1, it is possible to reduce the maximum stress, which results in an extended operational service life of the component. However, it is impossible to decrease the amount of deformation under any circumstances, as this component absorbs the vibrations and forces produced on the blade. Momentum M_{F_c} created by centrifugal force F_c is bigger when displacement is bigger, and it leads to decreasing maximum stresses in flexbeam.

During aerodynamic simulation, key variables such as the distribution of pressure were analyzed. The addition of pressure surface plots greatly improved the graphical illustration of the simulation results, offering a comprehensive presentation of the aerodynamic forces involved. Furthermore, the application of particle trajectory analyses provided additional understanding of the dynamic airflow patterns surrounding the rotor blades. This scientific approach to simulation not only took into account different operational conditions but also integrated visual representations to gain greater awareness of the complex aerodynamic interactions in each scenario.

Additionally, in order to evaluate and compare the effectiveness of the rotor blades, the simulations included the examination of blade thrust and the required torque for rotation. These essential variables functioned as fundamental measures, enabling a thorough analysis of blade efficiency under different operational circumstances, specifically in hover mode, advancing blade, and retreating blade scenarios. The approach provides a numerical foundation for measuring and improving the overall effectiveness of the helicopter's rotor blades (fig. 7 - 9).
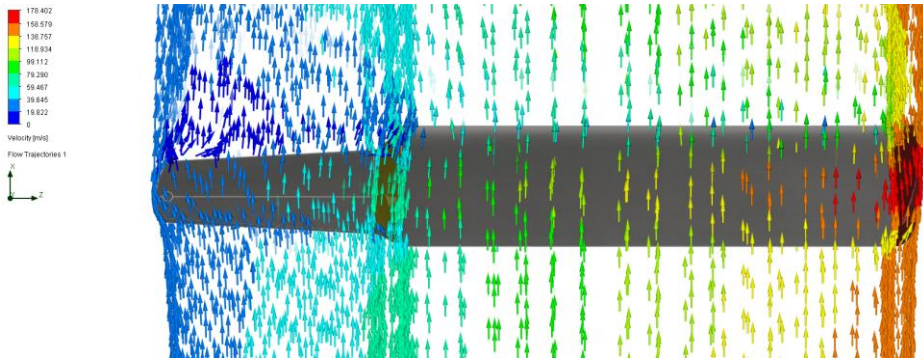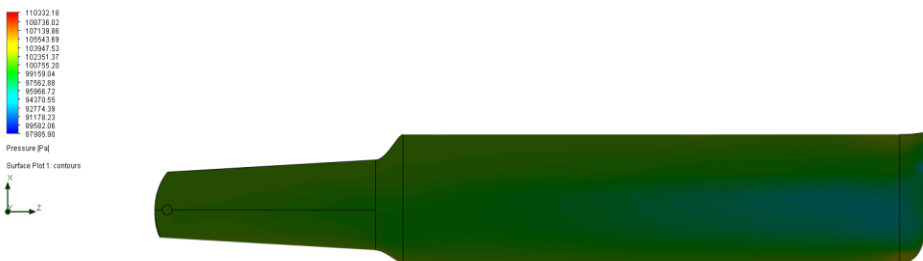

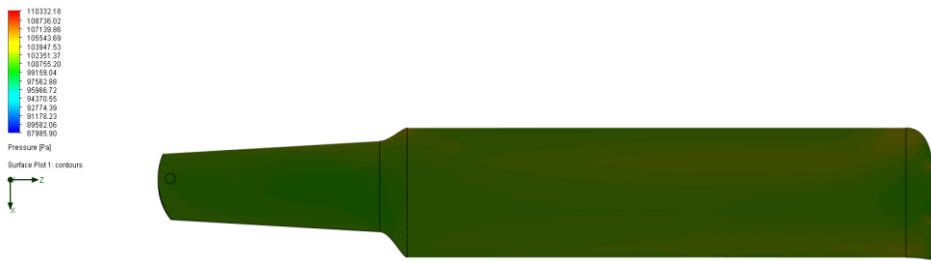Figure 7. Velocity visualization in hovering mode

Figure 8. Pressure distribution in hovering mode

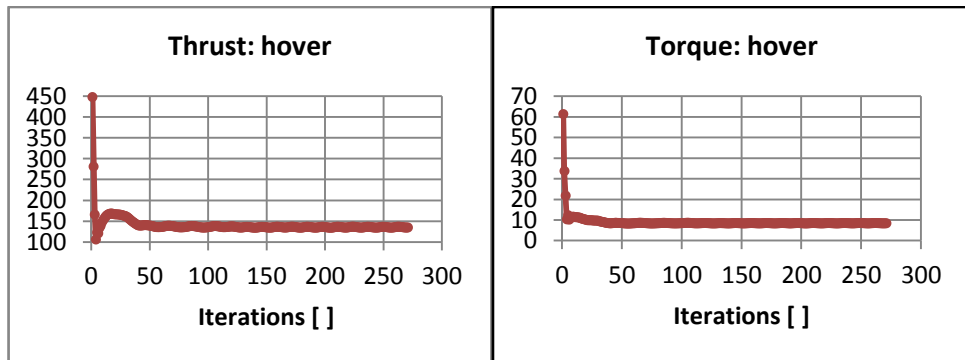
Figure 9. Thrust and torque simulation plots in hovering mode

Here are the results of the simulation that was performed:

$$T_{hover} = 140.59\ N;\quad Q_{hover} = 8.51\ N \cdot m\quad \rightarrow\quad T/_P = 8.93\ ^{kg}/_{kWt}$$

Further explanation of the blade's performance metrics is provided by the values of the thrust and required torque that have been calculated. The highest thrust value was obtained in advancing mode $T_{advancing} = 340.63\ N$ because the linear velocity at the sections was increased at the expense of the horizontal velocity. The lowest thrust value was obtained in retreating mode $T_{retreating} = 34.17\ N$ because the linear velocity at the sections was decreased at the expense of the horizontal velocity. However, the highest power loading $T/_P = 8.97\ ^{kg}/_{kWt}$ is observed when the speed

of movement of the section is the smallest, since in this case the force of drag is minimal. These values provide information on the blade's effectiveness in generating lift and maintaining rotational motion.

As a result of the research part, the blade shows the highest efficiency in the hovering and retreating modes, but it would be good to optimize the shape for high-speed modes, like advancing mode.

Conclusions. The achievement of rotor system efficiency in the context of this study was realized through a multifaceted approach, integrating various strategies and methodologies. Application advanced composite materials with high strength-to-weight ratios allowed for the creation of lighter and structurally strong rotor components. This reduction in weight contributes to improved overall efficiency, as the rotor system encounters lower inertial loads and requires less power for operation.

Heightened awareness of aerodynamics, encompassing a deep understanding of airflow patterns, lift generation, and drag reduction, enables informed design decisions. This awareness contributes to the optimization of the rotor system's aerodynamic efficiency, ensuring that the components are designed to maximize lift and minimize drag, resulting in improved overall performance.

The usage of advanced 3D modelling, simulation, and analysis software, such as SolidWorks, enabled an in-depth awareness of the dynamics of the rotor blade and flexbeam. This allowed iterative design improvements, optimizing the form and structure of the components for better aerodynamic performance and overall efficiency.

The design of the bearingless rotor system, combined with the integration of composite materials, presents an original approach to rotorcraft technology. This design optimizes mechanical simplicity, eliminates frictional losses typical of conventional bearing systems, and improves the overall efficiency of the rotor system.

The designed rotor system achieved all the set goals because power loading $T/_P = 8.97 \; ^{kg}/_{kWt}$, all parts are possible for manufacturing. The figure of merit for

designed rotor system is equal to 0.79, which confirms the high efficiency of the system. It is possible to improve the results even more by reducing the drag force, improving the geometric shapes of the blade, especially the tip.

<div align="center">**References**</div>

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ПРОЕКТУВАННЯ ОСНОВНИХ КОМПОНЕНТІВ БЕЗПІДШИПНИКОВОЇ СИСТЕМИ РОТОРА

Виключення звичайних підшипників у роторній системі гелікоптера та заміною їх на пружні композиційні елементи призводить до більш компактної та спрощеної динамічної конструкції, що зменшує вимоги до обслуговування та підвищує надійність вузла впродовж тривалої експлуатації. Вбудоване зниження вібраційних навантажень за рахунок пружності композиційних матеріалів та їх збільшеної міцності при згинанні не тільки гарантує більш плавну роботу всієї системи, але й продовжує термін служби інших силових компонентів. Підвищена універсальність безпідшипникових роторних систем, яка є фундаментальною для застосувань в конструкції гелікоптера, забезпечує точне керування та швидку реакцію в динамічних робочих ситуаціях.

У статті проведено теоретичний аналіз впливу вхідних параметрів на аеродинамічну якість несного гвинта гвинтокрила. Проведені розрахунки на міцність та аеродинамічну якість спроектованих деталей методом аналізу кінцевих елементів. Обґрунтовано енергоефективність використання композиційних матеріалів, що забезпечить вищу ефективність та конкурентну спроможність літального апарату.

У частині обговорення результатів було проведено оцінку ефективності роторної системи за допомогою теоретичного попереднього моделювання, з акцентом на оптимізацію аеродинамічної ефективності за допомогою інструментів, таких як SolidWorks Simulation та Flow Simulation. Програмне забезпечення SolidWorks використовувалось для моделювання та аналізу міцності та деформацій компонентів роторної системи, виготовлених з композитних матеріалів.

У статті мета була досягнута за рахунок впровадження сучасної конструкції ротору для гвинтокрилів із застосуванням композитних матеріалів, а також розробки технологічних і ефективних лопатей.

Ключові слова: композиційні матеріали, несучий гвинт, безпідшипникова система ротора.

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