МІНІСТЕРСТВО ОСВІТИ ТА НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
КАФЕДРА КОНСТРУКЦІЇ ЛІТАЛЬНИХ АПАРАТІВ

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___________ Святослав ЮЦКЕВИЧ
«____» ____________ 2023 р.

КВАЛІФІКАЦІЙНА РОБОТА

ЗДОБУВАЧА ОСВІТНЬОГО СТУПЕНЯ «МАГІСТР»

ЗІ СПЕЦІАЛЬНОСТІ

«АВІАЦІЙНА ТА РАКЕТНО-КОСМІЧНА ТЕХНІКА»

Тема: «Застосування композитних матеріалів для покращення характеристик гвинтокрилих безпілотних літальних апаратів»

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Київ 2023

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
DEPARTMENT OF AIRCRAFT DESIGN

PERMISSION TO DEFEND
Head of the department,
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"___" _______________ 2023

QUALIFICATION PAPER

FOR A MASTER'S DEGREE

ON SPECIALITY

"AVIATION AND AEROSPACE TECHNOLOGIES"

Topic: "Composite Materials Application for Rotorcraft Unmanned Aerial Vehicle Performance Improvement"

Fulfilled by:	___________	**Oleksandr ZHOSAN**
Supervisor: **PhD, associate professor**	___________	**Vadim ZAKIEV**
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Environmental protection adviser: **PhD, associate professor**	___________	**Lesya PAVLYUKH**
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Kyiv 2023

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Аерокосмічний факультет
Кафедра конструкції літальних апаратів
Освітній ступінь «Магістр»
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Освітньо-професійна програма «Обладнання повітряних суден»

ЗАТВЕРДЖУЮ
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«_____» _____________ 2023 р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи здобувача

ЖОСАНА ОЛЕКСАНДРА ЮРІЙОВИЧА

1. Тема роботи: «Застосування композитних матеріалів для покращення характеристик гвинтокрилих безпілотних літальних апаратів», затверджена наказом ректора від 20 вересня 2023 року № 1853/ст.

2. Термін виконання роботи: з 25 вересня 2023 р. по 31 грудня 2023 р.

3. Вихідні дані до роботи: безпілотний літальний апарат, аеродинамічні характеристики профілів лопаті, механічні характеристики різних композиційних матеріалів, конструкція роторної системи гвинтокрила.

4. Зміст пояснювальної записки: вступ; оглядова частина, яка містить опис різних композиційних матеріалів, технологій виробництва деталей, порівняння несучих систем гвинтокрилів; основна частина, яка містить розробку ефективної лопаті та гнучкого елементу; розрахункова частина з результатами моделювань застосування композиційних матеріалів; окремі розділи, присвячені питанням охорони праці та навколишнього середовища.

5. Перелік обов’язкового графічного (ілюстративного) матеріалу: безпідшипникова несуча система гвинтокрила, проект лопаті та гнучкого елемента цієї системи, результати моделювань та симуляцій в SolidWorks.

6. Календарний план-графік:

№	Завдання	Термін виконання	Відмітка про виконання
1	Огляд літератури за проблематикою роботи. Аналіз різних видів композитів.	25.09.2023 – 01.10.2023	
2	Порівняльний аналіз несних роторних систем гвинтокрилів.	02.10.2023 – 15.10.2023	
3	Аналіз методів покращення характеристик роторної системи з-за допомогою композитів.	16.10.2023 – 29.10.2023	
4	Моделювання композитної лопаті та гнучкого елементу ротора.	30.10.2023 – 12.11.2023	
5	Написання розділів по охороні праці та навколишнього середовища.	13.11.2023 – 26.11.2023	
6	Написання та оформлення пояснювальної записки.	27.11.2023 – 10.12.2023	
7	Подача роботи для перевірки на плагіат.	11.12.2023 – 17.12.2023	
8	Попередній захист кваліфікаційної роботи.	18.12.2023 – 19.12.2023	
9	Виправлення зауважень. Підготовка супровідних документів та презентації доповіді.	20.12.2023 – 24.12.2023	
10	Захист кваліфікаційної роботи.	25.12.2023 – 31.12.2023	

7. Консультанти з окремих розділів:

Розділ	Консультант	Дата, підпис	
		Завдання видав	Завдання прийняв
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8. Дата видачі завдання: 25 вересня 2023 року

Керівник дипломної роботи ____________ Вадим ЗАКІЄВ

Завдання прийняв до виконання ____________ Олександр ЖОСАН

NATIONAL AVIATION UNIVERSITY

Aerospace Faculty
Department of Aircraft Design
Educational Degree "Master"
Specialty 134 "Aviation and Aerospace Technologies"
Educational Professional Program "Aircraft Equipment"

APPROVED BY
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_________ Sviatoslav YUTSKEVYCH
"___" _______________ 2023

TASK

for the qualification paper

OLEKSAND ZHOSAN

1. Topic: "Composite materials application for rotorcraft unmanned aerial vehicle performance improvement", approved by the Rector's order № 1853/ст from 20 September 2023.
2. Period of work: since 25 September 2023 till 31 December 2023.
3. Initial data: unmanned aerial vehicle, aerodynamic properties of airfoils, mechanical characteristics of various composite materials, the construction of the rotorcraft rotor system.
4. Content: the introduction; the overview section containing a description of various composite materials, composite parts manufacturing technologies, rotor system comparison; the main section containing the development of the effective rotorcraft blade and flexbeam; the calculation section with the results of modeling with application composite materials; separate sections dedicated to the labour and environmental protection.
5. Required material: bearingless rotor system design, the design of the rotorcraft blade and flexbeam, and the results of modeling and simulations in SolidWorks.

6. Thesis schedule:

№	Task	Time limits	Done
1	Literature review of references. Various types of composites analysis.	25.09.2023 – 01.10.2023	
2	Comparative analysis of rotorcraft's rotor systems.	02.10.2023 – 15.10.2023	
3	Analysis of rotor system performance improvement methods using composites.	16.10.2023 – 29.10.2023	
4	Modeling composite blade and flexbeam.	30.10.2023 – 12.11.2023	
5	Execution of the parts, devoted to environmental and labor protection.	13.11.2023 – 26.11.2023	
6	Review and creation of explanatory note.	27.11.2023 – 10.12.2023	
7	Submission of the work to plagiarism check.	11.12.2023 – 17.12.2023	
8	Preliminary defense of the thesis.	18.12.2023 – 19.12.2023	
9	Making corrections, preparation of documentation and presentation.	20.12.2023 – 24.12.2023	
10	Defense of the qualification paper.	25.12.2023 – 31.12.2023	

7. Special chapter advisers:

Chapter	Adviser	Date, signature	
		Task issued	Task received
Labor protection	PhD, associate professor Katerina KAZHAN		
Environmental protection	PhD, professor Lesya PAVLYUKH		

8. Date of assignment of the task: 25 September 2023

Supervisor: ____________ Vadim ZAKIEV

Student: ____________ Oleksandr ZHOSAN

РЕФЕРАТ

Кваліфікаційна робота « Застосування композитних матеріалів для покращення характеристик гвинтокрилих безпілотних літальних апаратів » містить:

86 сторінок, 30 рисунків, 11 таблиць, 17 літературних посилань

В роботі було розглянуто роторну система гвинтокрила, досліджено застосування композитних матеріалів для підвищення ефективності гвинтокрилів, довговічності елементів системи ротору та загальних експлуатаційних можливостей. Метою даної роботи є розробка роторної системи гвинтокрила з покращеними характеристиками ефективності за рахунок впровадження композитних матеріалів, з фокусом на покращені льотних характеристик під час різних етапів експлуатації.

В дослідницькій частині роботі було проведено оцінку продуктивності 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 компонентів роторної системи, виготовлених з композитних матеріалів.

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

Результати даної роботи можна використати з метою виготовлення, збірки та тестування компонентів гвинтокрила з використанням композитних матеріалів для підтвердження їх покращених характеристик продуктивності. Будуть надані рекомендації щодо оптимізації конфігурації роторної системи гвинтокрила, з наголосом на те, що запропоновані композитні компоненти можна легко інтегрувати без значущих змін у базовій конструкції.

Магістерська робота, безпілотний літальний апарат, безпідшипникова система ротора, композиційні матеріали, аеродинамічний аналіз, аналіз напружено-деформованого стану

ABSTRACT

Qualification paper “Composite Materials Application for Rotorcraft Unmanned Aerial Vehicle Performance Improvement” contains:

86 p., 30 fig., 11 tables, 17 references

Rotorcraft performance improvement through the application of composite materials; application composite materials for enhancing the performance of rotorcraft in terms of efficiency, durability, and overall operational capabilities were described in this study. The aim of the master thesis is the 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.

In the research and development part evaluation of rotor system performance with theoretical preliminary modeling was performed, emphasizing the optimization of aerodynamic efficiency using tools such as SolidWorks Simulation and Flow Simulation modules. SolidWorks software was used for the modeling and strength analysis of rotor system components made from composite materials.

Aim was achieved with introduction of a simple modern design for rotorcraft systems applying composite materials, along with the development of innovative rotor blades to enhance performance. The study will contribute to advancing the application of composites in rotorcraft design.

Results can be used for fabrication, assembly, and testing of rotorcraft components using composite materials to validate their performance improvements. Recommendations will be provided for optimizing the rotorcraft's rotor system layout, emphasizing that the proposed composite components can be seamlessly integrated without necessitating significant alterations to the fundamental structure.

Master Thesis, Unmanned Aerial Vehicle, Bearingless rotor system, composite materials, aerodynamic simulation, stress-strain analysis

Contents

LIST OF ABBREVIATIONS

AoA – Angle of Attack;

BERP – British Experimental Rotor Program;

BET – Blade Element Theory;

BRS – Bearingless Rotor System;

CFD – Computational Fluid Dynamics;

EASA – European Union Aviation Safety Agency;

FAA – Federal Aviation Administration;

FM – Figure of Merit;

HOGE – Hover Out of Ground Effect;

ISO – International Organization for Standardization;

MT – Momentum Theory;

MTOW – Maximum Take-Off Weight;

PPE – Personal Protective Equipment;

RTM – Resin Transfer Molding;

RUAV – Rotorcraft Unmanned Aerial Vehicle;

UAV – Unmanned Aerial Vehicle.

INTRODUCTION

Due to the constantly evolving nature of the aerospace engineering industry, the incorporation of innovative materials has become an essential component in the process of determining the future of rotorcraft design. A comprehensive analysis of the properties of modern composite materials is presented in the first section of this thesis. This investigation includes a detailed comparison of the advantages and disadvantages of these materials. The purpose of this section is to provide a foundational understanding of the distinctive qualities that make composites an important choice in the construction of rotorcraft.

At the same time, the introduction focuses into a thorough evaluation of a number of different rotor systems, highlighting the significance of selecting the configuration that is the most appropriate to meet the specific requirements of modern rotorcraft. Through the process of drawing comparisons between various rotor systems, this research lays the basis for an informed investigation into the applications and benefits that are offered by composite materials.

Methodologies for improving rotor systems are the subject of the second section of this thesis, which is devoted fully to the subject. This part examines the strategic application of composite materials as a means of addressing the deficiencies that have been identified and improving the performance of rotorcraft vessels. Through the use of a methodical approach, the purpose of this section is to define a road map for the integration of composites into the design of rotorcraft, with the goal of optimizing key parameters in order to achieve increased operational capabilities, durability, and efficiency.

Through the third part of this research, a preliminary analysis is carried out, with the focus being on two key aspects: the aerodynamics of the rotor blade and the structural analysis of the flexbeam in a bearingless rotor system. This analysis builds upon the foundation that has already been established. The purpose of this section is to provide insights into the potential improvements that can be achieved through the integration of composite materials. This will be accomplished by employing advanced tools and techniques, such as SolidWorks for modeling and simulation.

Because the primary objective of this thesis is to design a unique rotor system for unmanned aerial vehicles (UAVs), the comprehensive approach that was adopted in each part of the research contributes to a complete awareness of the challenges and opportunities that are inherent in the design of modern rotorcraft. Not only does the incorporation of SolidWorks in the later stages guarantee theoretical robustness, but it also ensures practical viability, thereby laying the groundwork for the implementation of proposed improvements in the performance of unmanned aerial vehicle rotorcraft.

This thesis aims to advance discussion on composite material applications in modern rotorcraft by means of this multifaceted exploration. Its goal is to fill the gap between theoretical innovation and practical innovation in the field of aerospace engineering, which is constantly evolving. This research not only improves our understanding of the capabilities of composite materials, but it also places them in a position to be a key driver in the continual growth of rotorcraft technology. The ultimate goal of this research is to contribute to the development of rotor systems for unmanned aerial vehicles that are efficient, durable, and high-performing.

The exceptional attributes of composite materials are highlighted in the context of advancements in UAVs. These materials have a high strength-to-weight ratio, which enhances the performance capabilities of rotorcraft UAVs. This optimization improves factors such as maneuverability, fuel efficiency, and payload capacity. Their natural design flexibility is important, as it allows for aerodynamic optimization that is useful in various operational environments. Moreover, composite materials demonstrate corrosion resistance, which guarantees extended operational lifespan for UAVs, and possess a low radar reflectivity, improving their stealth capabilities for secret missions. Essentially, the use of these materials in rotorcraft UAV construction serves as a revolutionary approach, increasing durability and operational effectiveness.

PART I. COMPOSITE MATERIALS APPLICATION IN ROTORCRAFTS

The aerospace industry's constant drive to enhance the performance of commercial and military aircraft is continuously accelerating the advancement of high-performance structural materials. Composite materials are extremely attractive for aviation and aerospace applications due to their outstanding strength and stiffness-to-density ratios and physical properties.

Approximately four decades ago, one of the initial applications of present composite materials involved the application of boron-reinforced epoxy composite for the skins of the empennages of the F14 and F15 jet fighters. At first, composite materials were primarily employed in secondary structures. However, with advancements in knowledge and material development, their application in primary structures has expanded. The integration of composite materials into military helicopters began during the 1970s. The objective is to decrease the weight of helicopters while maintaining their strength by utilizing composites, which are considered as a substitute for aluminum alloys. Throughout the ongoing process, it is evident that both material groups are being used efficiently, as the cost factor is considered equally significant to performance. The construction of the V22 Osprey army tilt rotorcraft involved the utilization of reinforced plastic material, mostly carbon, which accounted for 57% of its weight. Reinforced plastics will have a more significant impact on the upcoming generation of rotorcrafts. Advanced composite materials are increasingly prevalent on aircraft each year. The use of fiberglass, carbon, or aramid fibers in the manufacturing of helicopter components has experienced significant expansion. However, rotorcrafts have consistently maintained a closer connection with composite materials compared to fixed-wing aircraft. In the aerospace industry, the evaluation of a material's strength is rarely performed without taking its weight into account. The main benefit of composite structures lies in their reduced weight, rather than any superior strength compared to similar metallic structures. Since the early stages, rotorcraft manufacturers have effectively utilized this concept due to its essential nature. Weight is a crucial factor in fixed-wing design, but it is even more critical in rotorcraft design. This is primarily because early rotorcraft engines were known for their lack of power.

1.1. Definition of composite materials

A composite material is described as a material composed of two or more distinct phases and the interfaces between them. At a macroscopic scale, the phases are indistinguishable, but at some microscopic scales, the phases are clearly separate and each phase exhibits the characteristics of the pure material [1]. In this chapter, we are only describing the characteristics, analysis and processing of high-performance structural composite materials. These composites are characterized by the presence of a reinforcing phase and a matrix phase. The reinforcing phase is commonly composed of graphite, glass, ceramic, or polymer fibers, while the matrix is typically made of polymers, although it can also be ceramic or metal. The fibers are responsible for the strength and rigidity of the composite component, while the matrix acts as an adhesive for the reinforcements, distributes mechanical loads throughout the part, allows the forming of the material into a desired form, and provides the primary protection against environmental factors for the composite component. In Fig. 1.1, we can see the distinct cross section of graphite fibers in an epoxy matrix.

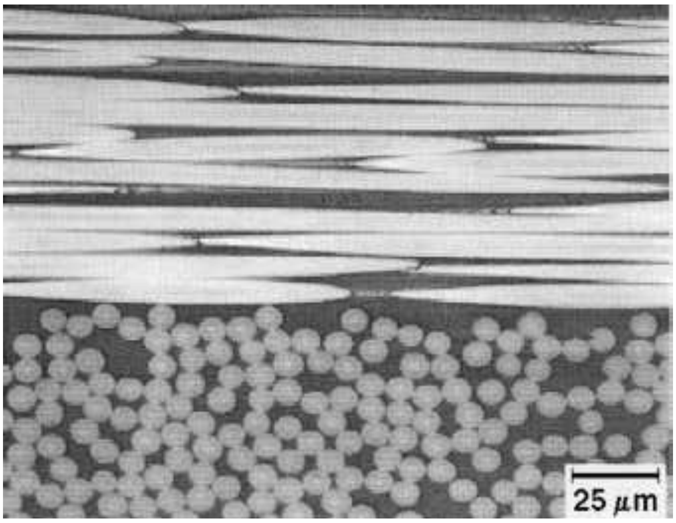


Figure 1.1. Cross section of a graphite fiber-reinforced epoxy polymer

Probably the single most important difference between fibrous and particulate composites and indeed between fibrous composites and conventional metallic materials, relates to directionality of properties [2]. Particulate composites and conventional metallic materials are, nominally at least, isotropic, i.e., their properties (strength, stiffness, etc.) are the same in all directions, fibrous composites are anisotropic, i.e., their properties vary depending on the direction of the load with respect to the orientation of the fibers. This anisotropy is overcome by stacking layers, each often only fractions of a millimeter thick, on top of one another with the fibers oriented at different angles to form a laminate [1]. But in exceptional situations, the laminate will remain anisotropic, but with a smaller amount of variation in properties across different directions. In the majority of aerospace applications, another approach is taken to optimize the properties of the laminate for the specific loads it will experience. This involves stacking layers with different orientations in a specific sequence, ranging from a small number to several hundred, to best withstand the expected loads. By applying this approach, it is possible to keep material and consequently reduce weight, a critical factor in the aviation and aerospace industry.

Another advantage of composite materials is that, generally speaking, they can be formed into more complex shapes than their metallic counterparts [3]. This not only decreases the quantity of elements contained in a specific component, but also minimizes the necessity for fasteners and joints. The benefits of this approach are twofold: fasteners and joints can be potential weak points in a component, as a rivet requires a hole which can concentrate stress and potentially initiate cracks. Additionally, a reduced number of fasteners and joints can result in a shorter assembly time. While shorter assembly times are desirable, they must be balanced against the increased time required for fabricating the component initially. In order to create a composite component, the separate layers, typically already filled with resin ("pre-preg"), are precisely cut into their desired shapes, which will vary to some degree. These layers are then arranged in a specific order on top of a solid or framed structure called a former. The former is used to maintain the shape of the uncured layers during the curing process. After that, this assembly passes a range of temperature and pressure conditions in order to "cure" the material. Next, the product passes an in-depth inspection to verify compliance with dimensional tolerances and to confirm the success of the curing process. It is essential to detect any potential formation of bubbles or voids in the laminate, which might occur from contamination of the raw materials.

1.2. Properties and fabrication of composites

Composite materials are complex. The properties of the constituents are different and the fiber properties are anisotropic [1]. In many of the applications in which composite materials are used, they can be considered to be constructed of several layers stacked on top of one another. These layers, or laminate typically exhibit properties similar to those of orthotropic materials. Orthotropic materials have three mutually perpendicular planes of material property symmetry [2]. Figure 1.2 shows a laminate with its coordinate system and two of the planes of symmetry.

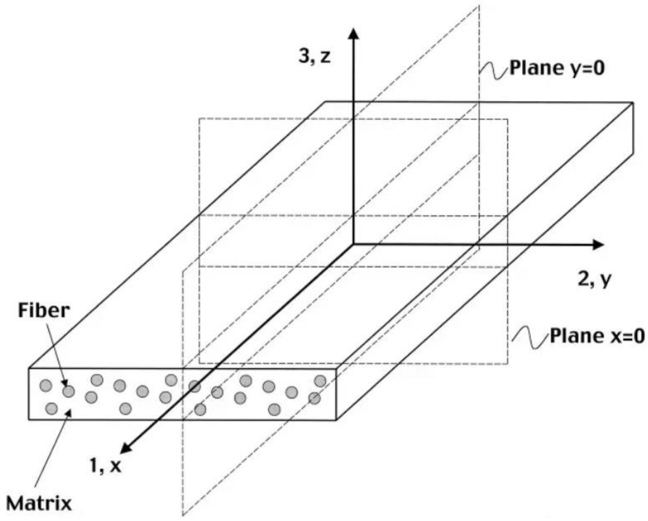


Figure 1.2. Laminate coordinate axis and planes of symmetry

The laminate consists of a single layer of reinforcement embedded within the matrix. The properties of the laminate are determined by the combination of the reinforcement's elastic and strength properties with the characteristics of the matrix. The properties of the laminate are affected by various factors, including the properties of the constituents, the quantity of reinforcement, the shape of the reinforcement, and the arrangement and spread of the reinforcement.

The reinforcement provides the strength and stiffness of the composite. Increasing the amount of reinforcement increases the strength and stiffness of the composite in the direction parallel to the reinforcement. The effect of the form of the reinforcement is not as simple. However, some general observations can be made. Laminate reinforced by long, continuous, parallel fibers have greater strength and stiffness than laminate reinforced by short, randomly oriented fibers [3]. Woven fiber reinforced laminate typically demonstrates higher strength in the direction perpendicular to the principal fiber orientation compared to unwoven fiber reinforced laminate. The strength and stiffness of a laminate, which is reinforced by unwoven continuous fibers, decrease when the angle of loading shifts from being parallel to the fibers to being perpendicular to the fibers. Table 1.1 shows typical values for some properties of composite materials made of unwoven continuous fiber reinforcements.

Table 1.1

Typical properties of composite materials: laminates reinforced with unidirectional continuous fibers

Property	Unit	E-glass epoxy	Aramid epoxy	Graphite epoxy	Boron epoxy
Parallel to the fibers					
Tensile strength σ_x^T	MPa	1100	1380	1240	1296
Tensile modulus E_x^T	GPa	39.3	75.8	131	207
Poisson`s ratio ν_{xy}	-	0.25	0.34	0.25	0.21
Total strain ε^T	%	2.2	1.8	1.21	0.66
Compressive strength σ_x^C	MPa	586	276	1100	2426
Compressive modulus E_x^C	GPa	39.3	75.8	131	221
Shear strength τ_{xy}	MPa	62	44.1	62	132
Shear modulus G_{xy}	GPa	3.45	2.07	4.83	6.2
Transverse to the fibers					
Tensile strength σ_y^T	MPa	34.5	27.6	41.4	62.7
Tensile modulus E_y^T	GPa	8.96	5.5	6.2	18.6
Compressive strength σ_y^C	MPa	138	138	138	310
Compressive modulus E_y^C	GPa	8.96	5.5	6.2	24.1
Specific gravity	-	2.08	1.38	1.52	2.01
Fiver volume V_f	%	~50	~60	~62	~50

The table shows the strength and elastic properties of a laminate made of several laminate stacked on top of one another with all the fibers aligned in the same direction. The properties in the direction parallel to the fibers are much greater than the properties in the direction perpendicular to the fibers. This variation of properties with the orientation of the

laminate axis is called anisotropy [2]. The single laminate serves as a building block. The engineer can select the orientation and number of each of the laminate in a laminate and design the laminate such that it has the required response. The engineer should possess a comprehensive understanding of the unique aspects associated with the design of a laminate. Balance and symmetry are two key components. The existence of balance and symmetry in the laminate simplifies the analysis process and provides it with conventional response characteristics. Balance in a laminate refers to the requirement that for every laminate with a positive angle of orientation, there must exist a laminate with an equal but negative angle of orientation. Both laminates must possess identical mechanical and physical properties. Controlling the laminate's overall response to loading, both during service and fabrication, is important. Symmetry in laminates refers to the presence of an identical laminate, with the same type and orientation, located equidistantly below the midplane of the laminate. Symmetry also affects the way the laminate responds to applied
loads.

If a laminate is not balanced and symmetrical, it will twist or bend when in-plane loads are applied. Laminates may also extend or contract when bending loads are applied. Whether the results are good or bad depends on whether they were planned or unplanned during the de-sign of the laminate. Figure 1.3 shows how the plies are oriented and stacked in a laminate [1].

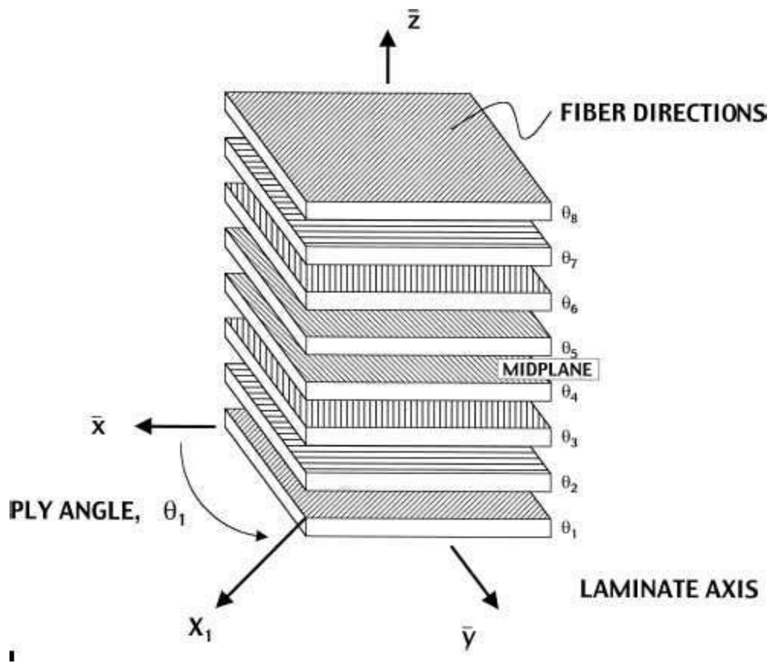


Figure 1.3. Orientation and location of ply in a laminate

The process of manufacturing components from composite materials varies from that of traditional engineering materials due to the significant influence of the reinforcement's geometry on the properties of the composite. The structural designer must take into account the challenges related to processing the composite part in order to ensure that the reinforcement volume fraction, reinforcement geometry, and other material properties can be economically manufactured. The variety of composite applications has driven the advancement of various methods for manufacturing structural composites.

One of the main factors contributing to the success of composites is their simple fabrication process and the wide range of production methods available, which vary in complexity and cost. Structural and decorative composites can be created using a variety of techniques, ranging from simple hand lay-up processes without molds to advanced methods involving complicated molds, woven 3D reinforcement preforms, and computer-controlled resin infusion and curing guided by artificial intelligence. The selection of the manufacturing method for a part, whether it be open or closed molds, compression molding, or an automated system, is determined by the part's configuration, as well as key manufacturing factors such as volume, production speed, and market conditions. The fabrication methods for composites can be categorized as either open or closed molding, with the selection of the appropriate technique being determined by the factors mentioned previously.

We can group most of the processes into two classes: open molding and closed molding [3]. The main distinction is that open molds are one piece and use low pressure or no pressure and closed molds are two pieces and can be used with higher pressure.

Open-mold processes

Open-mold processes such as spray-up, wet hand lay-up, autoclave, filament winding, vacuum infusion, pultrusion, or combinations of these techniques are the most common open-mold methods to produce composite products [3].

These manufacturing methods are suitable for a wide range of products, such as aerospace structures, tanks, piping, boat hulls and structures, recreational vehicle components, commercial truck cabs and components, structural members, and plumbing applications (e.g., tubs, showers, pools, and spas).

In the process of spray-up and wet hand lay-up open molding, the mold surface is usually characterized by an excellent degree of smoothness and serves as the visible exterior of the final product. Mold preparation is a basic aspect of all open molding techniques. Prior to spray-up, hand lay-up, or vacuum infusion, the mold surface is prepared by applying a release agent for easier removal of the composite part. Additionally, a "gel coat" may be applied to the mold, which is a colored layer of resin that forms the visible surface of the final part [4].

In the process of spray-up fabrication, the thermoset resin and chopped reinforcing fiber are sprayed together into the prepared mold. Prior to curing, the randomly applied mixture of fiber and resin can be compressed using manual rollers to create a more compact and solid component. In a hand lay-up process, the resin and reinforcement (typically a fabric or random fiber mat) are placed into the mold, compressed using rollers, and then left to harden. Frequently, hand lay-up is used in tandem with spray-up techniques, depending on the structural specifications of the component. Typically, these techniques can achieve fiber volumes ranging from 15% to 25%.

Several variations of the fundamental procedure exist. A vacuum bag composed of a watertight and non-sticky material can be positioned on top of the lay-up. Following that, a vacuum is created within the bag. The external atmospheric pressure acts to remove any empty spaces and remove trapped air and extra resin from the bag. An alternative method involves using a pressure bag. The bag is positioned parallel to the lay-up, and the mold is then enclosed with a pressure sheet. Either air or steam pressure applies between the bag and the plate. Vacuum infusion is an open molding process that is highly suitable for large components due to several significant factors. Vacuum infusion employs a hermetically sealed film that covers the entire component, applying vacuum pressure on the reinforcement material and preventing any volatile resin substances from being released into the surrounding environment. The resin is added once the entire reinforcement is placed in the mold and the vacuum membrane is applied, which helps eliminate problems related to the resin's working time before it solidifies [5].

At last, higher quantities of reinforcement can be attained due to the compression of the reinforcement through vacuum pressure, and only the required quantity of resin is applied. Reported values have indicated reinforcement volume fractions reaching up to 70%. Autoclaving is a prevalent open-mold technique in the aerospace industry, which varies slightly from the preceding processes. An aspect that sets this process apart is the complete placement of the assembly (including the lay-up and supporting unit) within an autoclave. An autoclave is a big container designed to apply heat and pressure to the lay-up material during the curing process.

Autoclaves are usually cylindrical, with an end that opens for full access to the interior. They have provision to pull vacuum on the lay-up assembly and they often have multiple temperature sensors that are used to monitor the temperature of the part during cure. The curing takes place under pressure, 1–10 bar and at elevated temperature [3]. The lay-up assembly is slightly different (Fig. 1.4). The top surface of the lay-up is covered with a perforated or porous release film and if necessary, bleeder plies of dry cloth are added to absorb excess resin. Then the assembly is sealed within a nonporous sheet material and placed into the autoclave. The application of pressure and control of temperature is critical. This process offers better quality control than other low- or no-pressure molding processes.

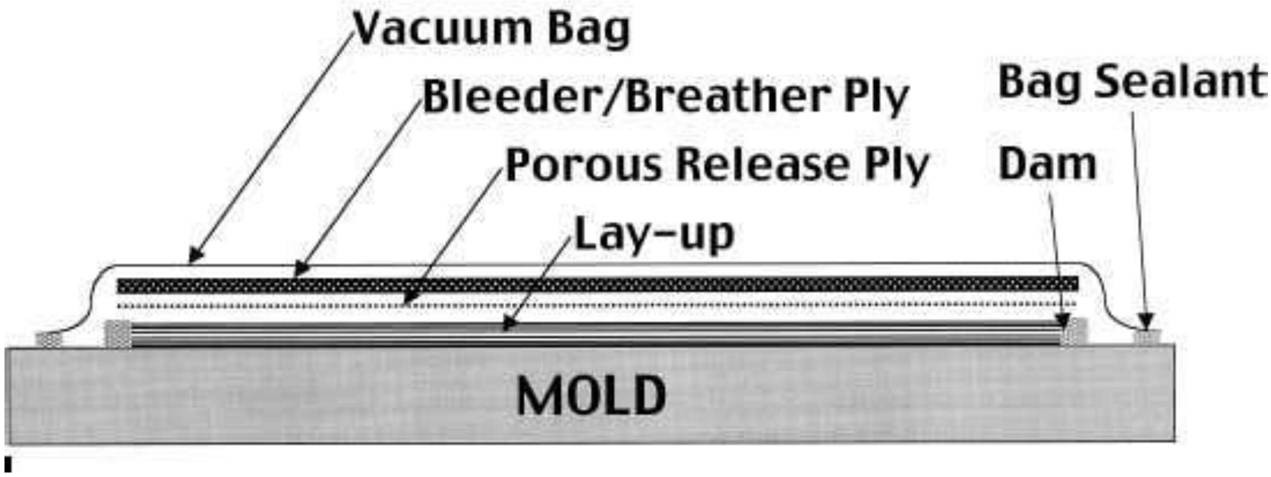


Figure 1.4. Cross section of the composite laminate lay-up and vacuum bagging processing method

Closed-mold processes

The closed-mold processes use a two-part mold or die. When the two parts are put together, they form a cavity in the shape of the article to be molded. The molds are usually made of metal with smooth cavity surfaces. Higher pressures and temperatures than those in open molding are usually used [3].

The processes produce very accurate moldings. Most of the processes are attractive for mass production. Matched die molding is a closed-mold process. There are variations to this process. The main variations concern the form of the starting material and the manner in which it is introduced into the mold. In some cases, the reinforcement is first made into a preform and placed in to the mold and then a metered amount of resin is added – this is known as resin transfer molding, or RTM (Fig. 1.5).

RTM is a widely used technique for production of components that require accurate dimensional tolerances, since the outer surface of the part is determined by the tool surface. In other cases, a resin–reinforcement mixture is made and a premeasured amount placed into the mold. The molding compound can be introduced automatically or manually. The molding temperatures range from 100°C to 140°C. Pressures range from 7 to 20 bar. Cure cycles can be as short as minutes. The selection of a fabrication process depends on several factors, including the materials to be processed, the size and design of the article, the number of articles and the rate of production. Processes differ in their capacity to use different forms of reinforcement and to achieve the proper distribution and amount of reinforcement.

The chemistry and rheology of the resin are important factors in process selection. Closed molds require higher temperatures and pressures. The size and shape of the article to be produced affect the selection. Very large articles such as boat hulls and vehicle bodies and components are more easily and economically produced in open-mold processes. Shapes that are surfaces of revolution are ideal for filament winding. Very large cylindrical containers have been fabricated by this process.

In most open-mold processes, the molds are made of low-cost materials and are easily fabricated but have shorter lives. Autoclave processing of composites, while considered an open-mold technique, requires accurate, robust tools because of the relatively high temperatures and pressures used in the autoclave. Autoclave techniques are well suited to large structural components for aerospace applications; hence, dimensional accuracy of the tools is critical.

Open-mold, hand lay-up processes have higher labour cost. If one is making a large number of parts and requires high production rates, mold life and labour cost are important factors. Open-mold processes are usually more costly in these two areas than closed-mold processes. Also, some closed-mold processes can be automated. Automating the fabrication of advanced composites and improving processing science for composites are two current goals. The advantages of advanced composites are lighter weight, higher strength- and modulus-to-weight ratios, flexibility in design and fabrication and usually fewer parts per component. Automating the fabrication process could result in a reduction in labour cost and an improvement in quality. The computer-aided manufacturing technology could be utilized to reduce the total labour hours. The application of higher precision control technology could improve quality and lower rejection rates. Work in processing science should result in increased understanding of the cure process, which will aid the development of resin systems and automating production cycles.

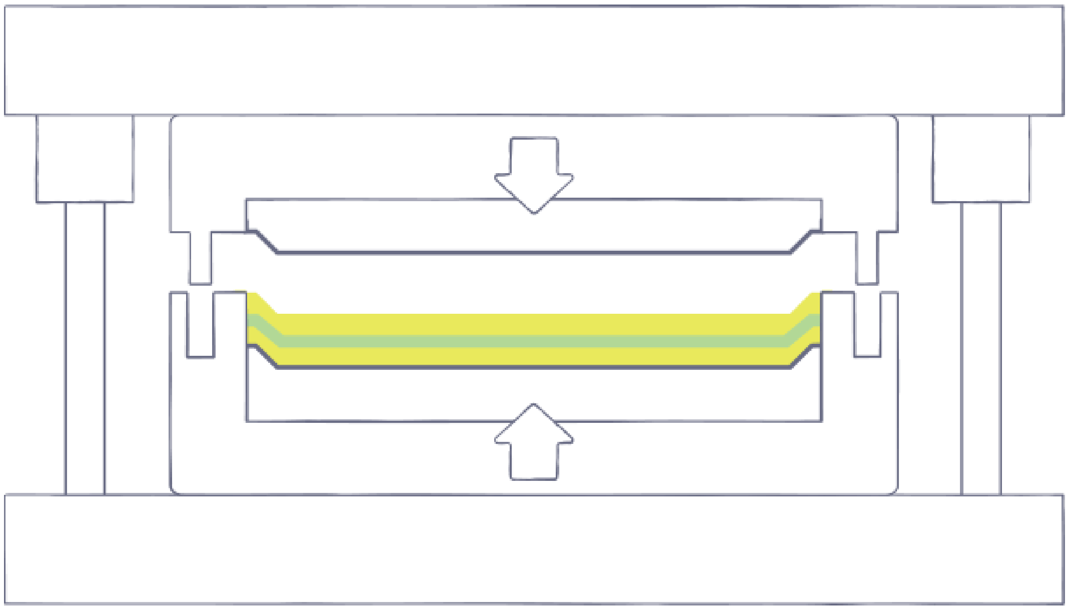


Figure 1.5. Cross section of RTM fabrication method

Fabrication processes for other matrix materials are important for the use and continued development of these composites. However, not as much work has been done in these areas. The use of these materials represents a small part of the overall uses of composite materials [3].

1.3. Definition and performance of the rotorcraft unmanned aerial vehicle

UAV is an aircraft without a human pilot on board. The vehicle is controlled either autonomously by attached microprocessors or telemetrically by an operator on the ground. UAVs can be used to execute observation or detection missions through automatic or remote control. They are mainly used in mapping applications, environmental change monitoring, disaster prevention response, resource exploration, etc. Compared to other flying vehicles and satellite remote sensing technology, UAVs have two advantages when capturing aerial photographs: low cost and high mobility.

While rotorcraft UAVs and conventional helicopters may appear distinct in terms of their applications, they share a fundamental similarity in their aerodynamic principles. Both these aerial platforms rely on rotary-wing systems to achieve lift and maneuverability and understanding the aerodynamics that underlie both is essential for appreciating the interplay between these two technologies. By exploring this common ground, we can gain valuable insights into the broader field of rotary-wing aviation and the transfer of knowledge and innovation between rotorcraft UAVs and traditional helicopters.

Traditionally helicopter airframes have been made from aluminum alloys, usually from the aluminum-copper 2000 series and the aluminum-zinc-magnesium-copper 7000 series. In all cases a wide range of precipitation-hardening treatments has been applied to the alloys to give the required range of mechanical properties from maximum damage tolerance to maximum yield strength. Fiber resin forced polymer matrix composites can have increased specific strengths and stiffnesses and the use of these materials can potentially save airframe mass [6].

An early use of composite materials in rotor blades was the replacement of the metal blade in the Westland Sea King helicopter. This was in order to increase the fatigue life of the blade. No attempt was made either to reduce the blade mass or to take advantage of the improved properties of the composite material to optimize the blade aerodynamics. Since then, blades have been developed which have had non-linear variations in airfoil section, thickness chord and twist and programs such as the British Experimental Rotor Programme (BERP) have used composites to produce complex shapes, particularly at the blade tip, in order to increase aerodynamic efficiency [7]. Because of the need for excellent dimensional accuracy, manufacturing methods are often based on the use of closed cavity molds, although approaches based on the use of air bags or foams to force the pre-preg composite against a female mold have also been used. Rotor blades, whether made from metal or composite, can be regarded as long tubes and there is extensive use of honeycomb or foam material in the center of airfoil sections (Fig. 1.6). The principal fibers used in rotor blades are based on carbon or S-glass. Early rotors used glass fibers, while later designs have been based on carbon fibers for the main spar of the blade, with trailing edges being built up over a honeycomb core by the use of glass fibers. In contrast with the extensive use of aramid fibers in the airframe, there is little use of aramids in current rotor blades. Fatigue lives of rotor blades have increased over a 30-year period from around 1000 h to the current standard of 10 000 h. With the increasing use of composites, either as a main structure or as the core of an otherwise tubular metal blade, there have been proposals for the replacement of the current safe-life design methodology with one that has a much longer, even indefinite life, backed by intermediate inspections. This would be a damage-tolerant design approach. However, in all cases, there is a need to examine visually the rotor blades on a very frequent, often daily, basis to check for the presence of barely visible impact damage. This form of damage in composites can reduce compressive strengths. This is because the fibers are free to buckle in the presence of matrix cracking. Damage tolerance is greater when the plies are at 45° to the loading direction. However, strength and stiffness will be at a maximum when the plies are parallel to the loading direction [7].

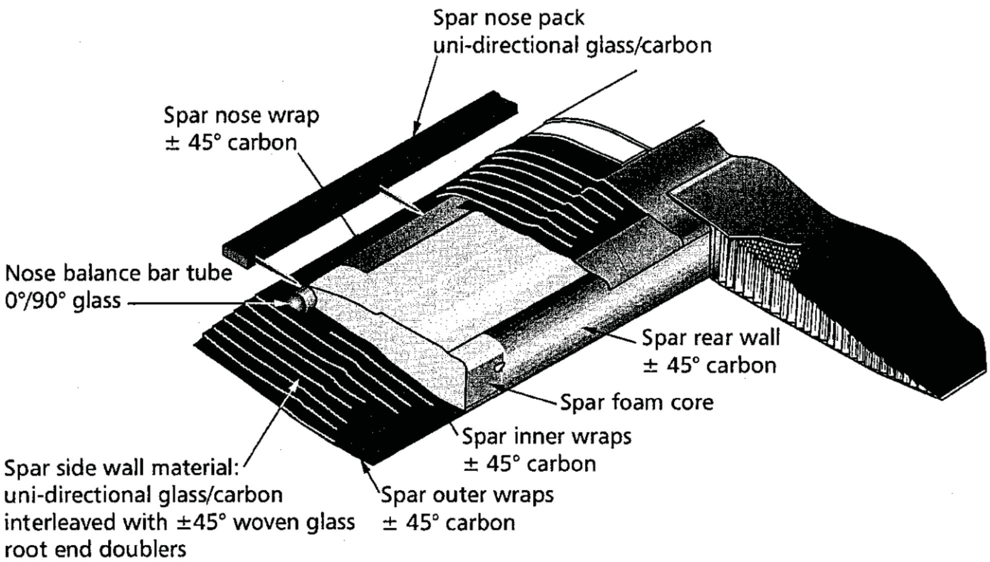


Figure 1.6. Composite blade showing the various composites used

The integration of composite materials in helicopter blades and rotor systems has ushered in a new era of rotary-wing aircraft design. The foremost advantage of using composites lies in the significant reduction of mass, resulting in lighter helicopters. This not only enhances fuel efficiency and payload capacity but also contributes to improved maneuverability and extended operational ranges. Additionally, composite materials have refined the aerodynamics of helicopter components, reduced drag and optimizing airflow to boost overall performance. Furthermore, these materials have increased the service life of helicopters, thanks to their resistance to corrosion, fatigue and wear and tear, offering cost savings and prolonged operational capabilities. In essence, the combination of mass reduction, aerodynamics improvement and increased service life represents a triad of benefits that underpin the transformation of helicopter technology.

1.4. Rotor systems comparison

The rotor system of a rotary-wing aircraft, commonly referred to as the helicopter's "heart," holds a paramount significance in determining the overall performance, safety and versatility of the rotorcraft. This crucial component not only provides lift but also imparts essential qualities to the helicopter's flight characteristics. The design and configuration of the rotor system profoundly influence various aspects of rotorcraft operation, including stability, maneuverability, efficiency and adaptability to different mission profiles [7]. The stability of a rotorcraft is intricately tied to the characteristics of its rotor system. The design choices, such as rotor configuration and control mechanisms, impact the helicopter's ability to maintain a steady and controlled flight. Stability considerations are vital for ensuring the safety of both the rotorcraft and its payloads. Rotor system efficiency is a critical factor affecting fuel consumption and overall operational costs. The design of the rotor blades, their flexibility and the control mechanisms influence how efficiently the helicopter converts engine power into lift. Efficient rotor systems contribute to longer endurance, extended range and improved fuel economy. The rotor system plays a crucial role in managing vibrations and noise generated during helicopter operation. Innovations in rotor system design, such as bearingless rotor systems [6], aim to reduce vibration levels, enhancing both comfort for occupants and minimizing structural fatigue. Understanding the nuances of different rotor systems is essential for rotorcraft designers, engineers and operators. Each configuration presents a unique set of advantages and challenges and the selection of a particular rotor system depends on the specific requirements of the helicopter's intended use. This comprehensive influence of the rotor system underscores its pivotal role in shaping the performance of rotary-wing aircraft.

These rotor systems come in various configurations, each designed to address specific engineering challenges and operational requirements. In this comparative analysis, we will delve into four distinct types of helicopter rotor systems: fully-articulated, rigid and bearingless. Each of these systems exhibits unique characteristics and trade-offs, shaping the capabilities and limitations of the helicopters they propel. Notably, the teetering rotor system (semi-rigid) will not be included in this comparison, as it requires a two-blade configuration and our focus is on rotor systems with three blades. This exploration aims to provide a comprehensive understanding of the design principles and functional distinctions among these rotor systems and also to select the rotor system concept that will be taken for the design and analysis of the most efficient system.

A **fully articulated** rotor system (fig. 1.7) usually consists of three or more rotor blades. The blades are allowed to flap, feather, and lead or lag independently of each other. Each rotor blade is attached to the rotor hub by a horizontal hinge, called the flapping hinge, which permits the blades to flap up and down.

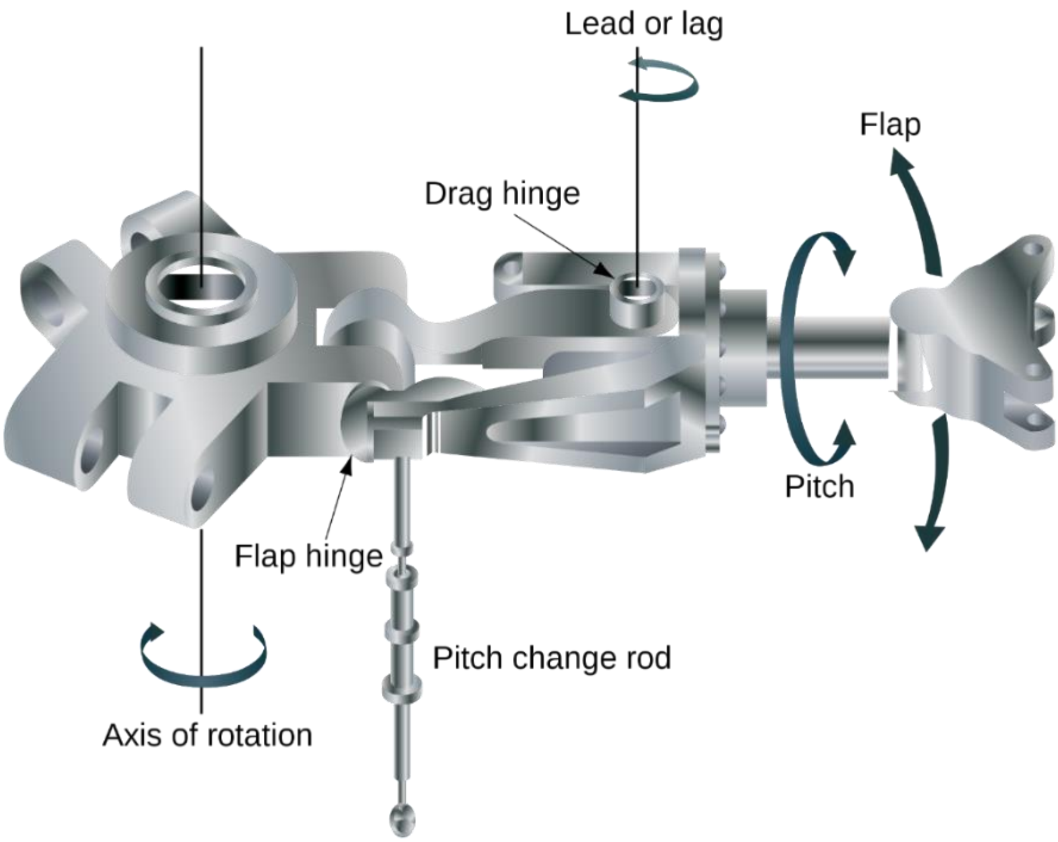


Figure 1.7. Fully articulated rotor system design

Each blade can move up and down independently of the others. The flapping hinge may be located at varying distances from the rotor hub, and there may be more than one. The position is chosen by each manufacturer, primarily with regard to stability and control. Each rotor blade is also attached to the hub by a vertical hinge, called a drag or lag hinge, that permits each blade, independently of the others, to move back and forth in the plane of the rotor disc. Dampers are normally incorporated in the design of this type of rotor system to prevent excessive motion about the drag hinge. The purpose of the drag hinge and dampers is to absorb the acceleration and deceleration of the rotor blades. The blades of a fully articulated rotor can also be feathered, or rotated about their spanwise axis. To put it more simply, feathering means the changing of the pitch angle of the rotor blades [7].

The **rigid** rotor system (fig 1.8) is mechanically simple, but structurally complex because operating loads must be absorbed in bending rather than through hinges. In this system, the blade roots are rigidly attached to the rotor hub. Rigid rotor systems tend to behave like fully articulated systems through aerodynamics, but lack flapping or lead/lag hinges. Instead, the blades accommodate these motions by bending.

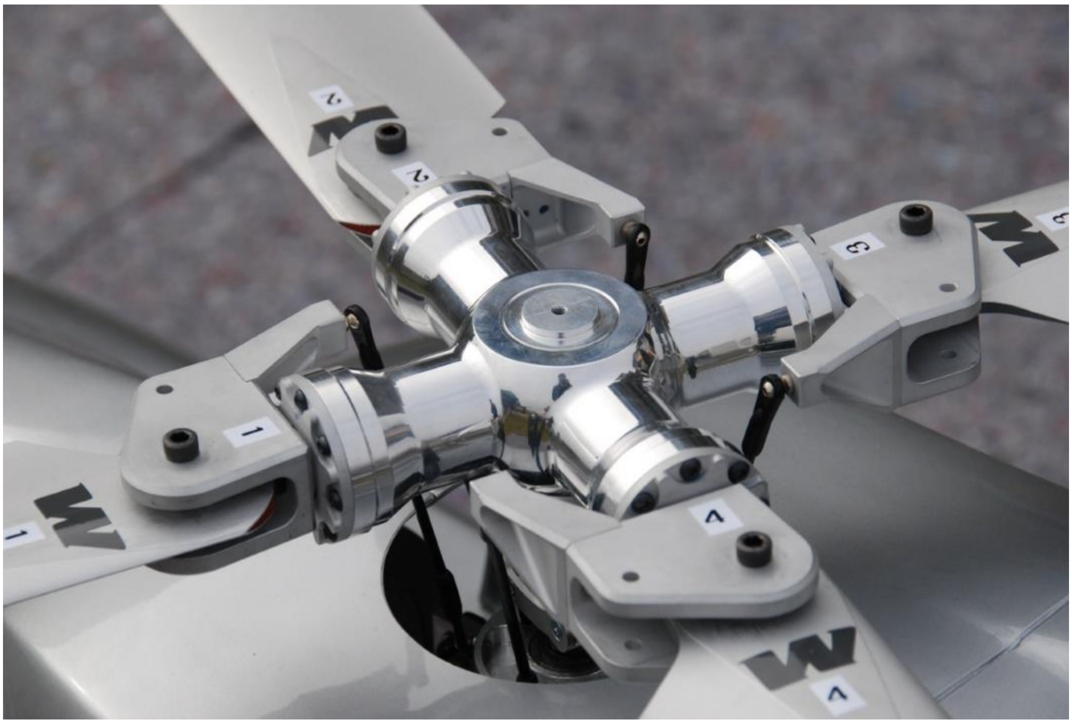


Figure 1.8. Rigid rotor system design

They cannot flap or lead/lag, but they can be feathered. As advancements in helicopter aerodynamics and materials continue to improve, rigid rotor systems may become more common because the system is fundamentally easier to design and offers the best properties of both semirigid and fully articulated systems. The rigid rotor system is very responsive and is usually not susceptible to mast bumping like the semirigid or articulated systems because the rotor hubs are mounted solid to the main rotor mast. This allows the rotor and fuselage to move together as one entity and eliminates much of the oscillation usually present in the other rotor systems. Other advantages of the rigid rotor include a reduction in the weight and drag of the rotor hub and a larger flapping arm, which significantly reduces control inputs. Without the complex hinges, the rotor system becomes much more reliable and easier to maintain than the other rotor configurations. A disadvantage of this system is the quality of ride in turbulent or gusty air. Because there are no hinges to help absorb the larger loads, vibrations are felt in the cabin much more than with other rotor head designs [7].

Bearingless rotor (BRS) 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. 1.9 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 [6].

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.

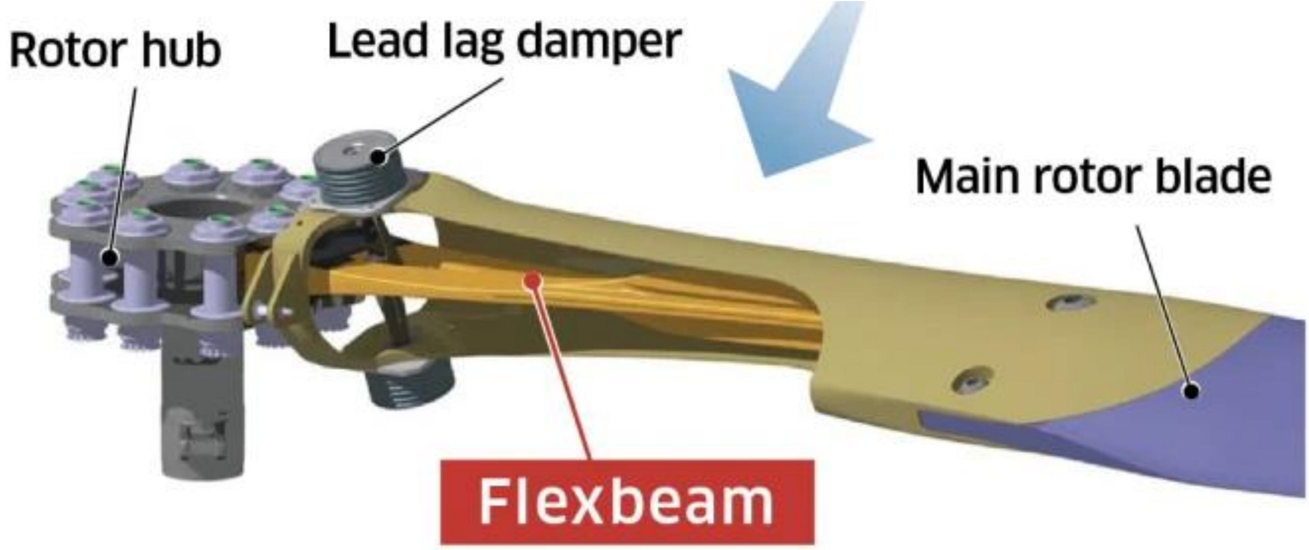


Figure 1.9. Bearingless rotor system design

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.

BRS is designed for BK117 D-3, Sikorsky S-97 Raider and Raider X, SB-1 Defiant, Sikorsky X2. 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.

Conclusion to the part I

To summarize, the analysis of composite materials in this section of the master's degree project provided a comprehensive understanding of their importance in rotorcraft applications. Composite materials, consisting of several different elements, provide a unique combination of mechanical properties, such as superior strength-to-weight ratios and customized anisotropic behaviors. The attributes of composites make them highly desirable for rotorcraft construction due to their ability to achieve performance improvements, reduce weight, and enhance structural integrity. However, it is important to recognize the variety of issues and challenges that occur when incorporating composite materials into rotorcraft engineering. Challenges of significant complexity result from issues such as delamination, impact resistance, environmental durability, and high production costs. After analyzing the main types of rotor systems, it is clear that using a bearingless rotor system is a superior option for improving the performance of RUAVs when compared to traditional fully articulated or rigid rotor systems. The bearingless rotor systems provide several simple advantages, such as decreased mechanical complexity, reduced vibrational loads, improved maneuverability, enhanced safety features, increased structural resilience, higher payload capacity, efficient power transfer, and the integration of advanced materials. These advantages collectively contribute to a significant improvement in overall UAV performance.

The removal of conventional bearings in a bearingless rotor system leads to a more streamlined and simplified mechanical structure, which decreases the requirement for maintenance and improves reliability. The built-in reduction in vibrational loads not only guarantees a smoother operation but also extends the lifespan of structural components. The increased flexibility of bearingless rotor systems, which is fundamental in UAV applications, offers accurate control and quick response in dynamic operational situations.

While fully articulated and rigid rotor systems have their advantages, the extensive performance advantages provided by bearingless rotor systems make them the most optimal choice for RUAVs. They offer an attractive option for UAV applications that prioritize efficiency, reliability, and maneuverability.

PART II. ROTORCRAFT UNMANNED AERIAL VEHICLE PERFORMANCE

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 [8].

2.1. Rotorcraft performance

Rotorcraft design involves different disciplines within the aeronautical sciences and due to that it is a highly challenging and complex process. Consider first the disciplines that dictate the performance of a rotorcraft but individually cannot answer the questions demanded by the subject of rotorcraft performance. These disciplines are aerodynamics, aircraft structure and aircraft propulsion.

Aerodynamics is the study of the flowfield and the forces generated by the relative motion between the rotorcraft parts and the surrounding air. It involves calculating the velocity, temperature and pressure field arising due to relative motion between the body and the air. The velocity and pressure fields predict the flowfield and the forces due to friction. The pressure and friction forces acting at each point of the surface of the body give rise to lift, drag and side forces. The study of aerodynamics helps one to calculate these forces and to design surfaces with high lift and low drag. The ratio L/D is called the aerodynamic efficiency. Aerodynamic forces affect the stability, control and handling qualities of the rotorcraft. A stable rotorcraft returns to its original equilibrium position after it experienced a small disturbance. Rotorcraft stability can be both static and dynamic. Static stability is an essential requirement for the rotorcraft to be dynamically stable. Dynamic instability gives rise to different kinds of motion or oscillations. In the third part of this work the issue of high efficiency and stability of the helicopter will be revealed as much as possible by designing and analyzing parts of the rotor system.

A rotorcraft structure is subjected to aerodynamic and structural loads. The primary function of the structural engineering group is to efficiently and optimally design the structure so that is strong enough to safely withstand these loads under different operational conditions. These loads can even be due to gusts, impacts or vibrations. The subject of rotorcraft structure deals with the analysis of stress and strain. It predicts the conditions under which structural deformations, elastic instability, structural fatigue, fracture and failure occur. An important objective of the structural design process is to maximize strength-to-weight ratio of the structure. In this work, only those components that make up the rotor system will be considered, as a rotorcraft is an unmanned aerial vehicle that carries external payloads.

The primary job of the rotorcraft propulsion discipline is designing an engine powerful enough to lift the rotorcraft up, thus accelerating it to desirable airspeeds. Since the engine goes up in the air along with the rotorcraft, it must be reliable, lightweight and must have the least possible drag during the flight. The topic of the powerplant will be revealed in this work minimally. The main goals of the practical work are set specifically for the aerodynamic and structure performance of the rotorcraft [8].

The subject of rotorcraft performance is a part of the mechanics of flight; only the translational motion of the aircraft is considered by applying Newton's laws of motion. The study of rotorcraft performance deals with as its subject some of the most important questions about flight that cannot be answered by the other disciplines. Some of these questions are: how much is the take-off distance, what is the angle of climb, what is be the fastest possible rate of climb, what is the cruising speed of the rotorcraft, what is the geographic range covered and the time of the flight, how much energy is consumed, what is the radius of turn, what is the fastest possible turn rate, etc. The content of these questions directly constitutes what we mean by performance parameters.

The various aircraft performance parameters will now be considered systematically by decomposing the flight into its various phases. These parameters depend on the phase of flight to which they belong. Starting from the beginning, these phases are take-off, climb, cruise, turn, descent and landing.

In this work following performance parameters will be used to compare different rotorcrafts: maximum take-off weight (MTOW), maximum and cruise speeds, range, endurance, service ceiling, hover ceiling, rate of climb, payload capacity, energy efficiency, noise level, safety features, operating costs and environmental impact.

MTOW is the maximum weight, typically specified by the manufacturer and regulated by aviation authorities, at which the rotorcraft lifts-off and becomes airborne without compromising its structural integrity, flight performance and safety. It is a critical safety parameter in rotorcraft operations.

Maximum Cruise Speed represents the highest sustainable airspeed at which a rotorcraft can safely and continuously fly, considering structural integrity, performance capabilities and regulatory compliance. Adhering to the Maximum Cruise Speed limits is essential for maintaining the safety and airworthiness of the rotorcraft during cruise flight operations.

Range represents the maximum distance a rotorcraft can operate on a single load of fuel or energy, factoring in efficiency, payload, environmental conditions and regulatory compliance. Adhering to the specified range limitations is essential for effective mission planning and operational safety.

Endurance for rotorcraft represents the maximum amount of time a rotorcraft can remain airborne on a single load of fuel or energy, considering factors like efficiency, payload, environmental conditions and regulatory compliance. Adhering to specified endurance limitations is essential for effective mission planning and ensuring the rotorcraft's safe and controlled flight.

Service ceiling defines the maximum altitude at which a rotorcraft can maintain a stable horizontal flight without exceeding its performance limits. It is a critical parameter for missions involving high altitudes or challenging terrain. Adhering to the specified service ceiling is essential for ensuring the safety and effectiveness of rotorcraft operations.

Hover ceiling, or Hover Out of Ground Effect (HOGE) ceiling, defines the maximum altitude at which a rotorcraft can maintain a stable hover while out of ground effect. It is a critical parameter for assessing a rotorcraft's performance in situations where hovering at higher altitudes is required. Adhering to the specified hover ceiling is essential for ensuring the safety and effectiveness of rotorcraft operations.

Rate of climb for a rotorcraft is defined as the vertical speed at which the helicopter can ascend in meters per second ($^{m}/_{s}$). It quantifies the rotorcraft's ability to gain altitude quickly and is usually measured during a climb under specified conditions.

Payload capacity is a critical performance parameter that specifies the maximum weight a rotorcraft can carry, including passengers, cargo and any additional equipment or provisions. Understanding payload capacity is essential for mission planning, as it directly affects the rotorcraft's ability to transport people and goods while maintaining safe and efficient flight.

Energy efficiency is a multifaceted concept that includes various aspects of design, technology and operational factors. It encompasses the rotorcrafts' ability to efficiently convert fuel or electrical energy into useful thrust or lift while minimizing waste. Achieving high energy efficiency is crucial for reducing operational costs, environmental impact and maximizing mission effectiveness. It involves optimizing powerplant performance, minimizing weight and adopting advanced aerodynamics and control systems. Efficient rotorcraft contributes to cost savings, increased endurance and a smaller environmental footprint.

Noise level is a critical consideration in helicopter design and operation. It encompasses noise generated by rotor blades, engines and other components and it has a significant impact on passenger or environmental comfort and community acceptance. Efforts to reduce rotorcraft noise include advancements in technology, adherence to regulations and the implementation of noise abatement procedures to minimize the acoustic footprint of these rotorcrafts.

Safety features for damage tolerance monitoring involves a range of technologies, practices and design principles to ensure the structural integrity and airworthiness of rotorcrafts. These features are crucial for the safe operation of rotorcraft, as they allow for early detection and mitigation of damage or wear, minimizing the risk of structural failures and enhancing overall safety.

Operating costs are a critical factor in budgeting and financial planning. Businesses must manage these expenses efficiently to maintain profitability and long-term sustainability. Effective cost management strategies can help reduce operating costs and improve a company's overall financial health.

Rotorcraft have various **environmental impacts**, including emissions, noise pollution and habitat disturbance. Efforts are ongoing to mitigate these impacts through advancements in technology, better operational practices and adherence to environmental regulations. As the rotorcraft industry continues to evolve, a growing emphasis on environmental sustainability is driving innovation and positive changes in rotorcraft design and operations.

Composite materials offer a high strength-to-weight ratio, which means they can provide the same or even greater structural strength as metals while being significantly lighter. This weight reduction directly contributes to an increased MTOW, as the rotorcraft can lift a higher payload relative to its own weight. Composite materials can be moulded into more streamlined and aerodynamic shapes. This reduces air resistance during take-off and horizontal flight, allowing the rotorcraft to achieve lift more efficiently, also providing higher maximum speed and lover noise permissions. Lighter rotorcraft, achieved through the use of composites, require less fuel to produce the thrust necessary for propulsion. With reduced fuel consumption, the rotorcraft can travel farther without needing to refuel. These enhancements lead to extended flight durations, enabling rotorcraft to meet mission requirements, minimize environmental impact and achieve cost savings in various operational scenarios. Composite materials can be especially beneficial in electric rotorcraft designs. Electric rotorcraft, powered by batteries, can benefit from the weight reduction provided by composites, which enables longer flight durations on a single charge. The reduced weight of the rotorcraft, facilitated by composites, allows a larger portion of the overall weight capacity to be allocated for mission-specific payload. This can include additional equipment, sensors, or cargo. Safety features often incorporate advanced monitoring and data collection systems that provide valuable insights into the health and performance of composite parts. This data helps maintenance teams make informed decisions, proactively address issues and optimize the service life of these components. Advanced safety systems, such as vibration monitoring and load management, can mitigate the risk of damage to composite parts by preventing them from operating outside their safe operational limits. This extends the service life of these components by minimizing stress and wear. Incorporating sensors between composite layers during the manufacturing process represents a cutting-edge approach to enhancing rotorcraft safety, performance and longevity. This technology empowers operators and maintenance teams with real-time insights, leading to safer and more reliable rotorcraft operations. Sensors, including strain gauges, accelerometers and temperature sensors, can be embedded between the layers of composite materials during the layup and curing processes. This integration enables these sensors to become an integral part of the composite structure.

2.2. Methods of rotorcraft unmanned aerial vehicle performance improvement

In the pursuit of enhancing rotor system performance, a critical approach involves the utilization and optimization of key parameters such as the thrust coefficient C_T and power coefficient C_P.

$$C_T = \frac{T}{\rho A v_{tip}^2} = \frac{T}{\rho A \Omega^2 R^2} \tag{2.1}$$

where T – rotor thrust; ρ – fluid density; Ω – rotational frequency; R – rotor radius.

$$C_P = \frac{P}{\rho A v_{tip}^3} = \frac{P}{\rho A \Omega^3 R^3} \tag{2.2}$$

By focusing on these coefficients, which characterize the efficiency and effectiveness of the rotor, engineers can systematically analyze and refine blade geometry, rotational speed, and other design elements. This optimization process contributes to the overall improvement of the rotor system, ensuring a balance between thrust production and power consumption for more efficient and effective helicopter performance [9].

In defining an efficiency factor for a helicopter rotor many parameters are involved, such as disk area, solidity, blade aspect ratio, airfoil characteristics and tip speed. The power loading parameter is one measure of rotor efficiency because a helicopter for a given weight should be designed to hover with the minimum power requirements, so, the ratio T/P should be made as large as possible. However, the power loading is a dimensional quantity and so a standard nondimensional measure of hovering trust efficiency called the ***figure of merit*** has been adopted. The figure of merit is equivalent to a static thrust efficiency and defined as the ratio of the ideal power required to hover to the actual power required:

$$FM = \frac{ideal\ power\ required\ to\ hover}{actual\ power\ required\ to\ hover} < 1 \qquad (2.3)$$

The ideal power is given by the simple momentum result in Eq. 3.12. In practice, FM values between 0.7 and 0.8. State-of-the-art rotors may have figures of merit approaching 0.82 and this probably represents the upper limit for a helicopter rotor with conventional technology.

Rotor solidity, σ, is defined as the ratio of total blade area to the disk area

$$\sigma = \frac{N_b c}{\pi R} \qquad (2.2)$$

where N_b – number of blades; c – chord length; R – rotor radius.

Values of σ for helicopters vary from about 0.06 to 0.012. Smaller helicopters generally tend to have lower solidity rotors.

Rotors that are designed for high forward flight and/or high maneuverability requirements require higher solidity for a given diameter and tip speed. Because rotor noise is considerably reduced when the rotor is operated at lower tip speeds, the development of high-lift airfoils that operate efficiently over the diverse range of conditions found within the rotor environment has always been an important design goal.

The selection of the ***number of blades*** for a rotor is usually based on dynamic rather than aerodynamic criteria, so it is based on the minimization of vibratory loads, which is easier for rotors that use a larger number of blades. A larger number of blades also leads to weaker tip vortices, thus potentially reducing the intensity of any airloads produced by blade-vortex interactions but their number will be increased. Hover performance is primarily affected by rotor solidity and number of blades are secondary [9].

The proper use of ***blade twist*** can significantly improve the figure of merit of the rotor. In forward flight, rotors with a high nose-down blade twist (greater than 15°) may suffer some performance loss. This is because of the reduced angles of attack can be produced on the tip of the advancing blade, resulting in a loss of rotor trust and propulsive force. Some degradation in high-speed cruise performance is noted with the higher blade twist. Blades with very large twist rates, while offering performance benefits in hover, may suffer reduced or even negative lift production on the advancing blade tip and are obviously to be avoided. A survey of existing rotor designs shows that most helicopter blades incorporate a negative linear twist between 8° and 15°. This twist range is a compromise between maximizing the *FM* of the rotor in hover at MTOW, while simultaneously avoiding any detrimental effects on forward flight performance.

The ***tips of the blades*** play a very important role in the aerodynamic performance of the helicopter rotor. The blade tips encounter the highest dynamic pressure and highest Mach numbers and strong trailed tip vortices are produced there. A poorly designed blade tip can have serious implications on the rotor performance.

Usually, small amounts of taper over the blade tip region can help to significantly improve the figure of merit in hover. A 2:1 taper over the tip region seems about optimum for a helicopter blade.

Sweeping the leading edge of the blade reduces the Mach number normal to its leading edge, thus allowing the rotor to attain a higher advance ratio before compressibility effects manifest as an increase in sectional drag and an increase in net rotor power required.

The choice of ***airfoil sections*** for helicopter rotors requires special consideration because significant improvements in rotor performance can be realized with the optimal selection of airfoil shapes. On the advancing side of the rotor disk the blade sections may reach high subsonic speed and in high-speed forward flight they may penetrate into the transonic flow regime. This causes wave drag and if the shock strength become sufficiently severe, shock induced flow separation and stall may be produced [9].

On the retreating side of the disk, the blade tip sections operate at subsonic speeds, but at much higher angles of attack, eventually close to stall. Therefore, the blade sections must be thin enough to maximize the drag divergence Mach number, while simultaneously they must have some minimum thickness and incorporate some camber to give a relatively high coefficient of lift but still maintain low pitching moment throughout. No single airfoil profile will meet these requirements and it must be designed to reach a compromise between the requirements of all flight conditions, both at low and high airspeeds and also at high thrusts. In general, the goal is to find airfoil sections that balance the advancing blade requirements (high drag divergence Mach number) with those of the retreating blade (high maximum lift at low Mach numbers), while maintaining a good overall lift-to-drag ratio throughout. This will help to maximize rotor efficiency throughout the flight envelope.

Conclusion to the part II

Optimizing rotorcraft performance heavily relies on the implementation of precise aerodynamic input control. By optimizing the control mechanisms and ensuring accurate responsiveness to aerodynamic inputs, the rotor system can be adjusted to operate at maximum efficiency during different operational phases. The level of accuracy not only improves overall performance but also contributes to a safer and more controlled flight experience.

Overall, the methods described for improving the performance of rotor systems, which involve precise control of aerodynamic input, integration of extra safety measures, and increased awareness of aerodynamics, together establish a strong basis for advancing the capabilities of rotorcraft. This comprehensive strategy not only seeks to improve the effectiveness and security of rotor systems but also demonstrates an interest to continued development of rotorcraft technology. In order to deal with the complex challenges associated with modern aviation, the implementation of these techniques becomes critical in determining the future of rotorcraft design and operation.

Theoretical calculations are important for improving the performance of rotor systems, but their effectiveness can be improved by practical experimentation. Theoretical models offer valuable insights and predictions, serving as a basis for understanding and optimizing rotor dynamics. However, the practical complexities of aerodynamics and mechanical interactions can introduce complications that are not fully taken into account in theoretical models. Experiments are necessary for confirming and enhancing theoretical predictions by providing real-world proof. The combination of theoretical calculations and practical experiments guarantees a comprehensive approach to improving the performance of rotor systems, reducing the difference between simulation and real-world performance.

PART III. DESIGN OF THE BEARINGLESS ROTOR SYSTEM

This research begins by establishing key input parameters for designing a bearingless rotor system, with the goal of redefining the capabilities of rotorcraft performance. The main objective of this work is to develop and design a creative composite rotor system without bearings, using the methodologies described earlier [10]. These methodologies involve precise control of aerodynamic input, incorporation of extra safety features, and increased understanding of aerodynamics and composites behavior.

The objective is to create a bearingless rotor system 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.

3.1. Design parameters for bearingless rotor system

Designing a helicopter rotor system for a UAV 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 3.1

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 3.1), 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 3.2

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 3.2 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 3.3

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 3.3) of operational parameters serves the purpose of simplifying the analytical process by offering a clear and organized overview of the variables influencing the system.

Implementation accelerometers to monitor vibrations and accelerations, providing real-time data on the structural health and dynamic behaviour of the flexbeam. Additionally, include bending sensors to detect deformations and stresses, enabling early detection of potential issues and enhancing the overall reliability of the rotor system.

To ensure the structural integrity of the rotor blade, integrate pressure sensors along the spar. These sensors can effectively monitor changes in air pressure, offering insights into the aerodynamic forces acting on the blade. Sudden variations in pressure may indicate potential damage or stress on the spar, allowing for timely intervention and maintenance to prevent catastrophic failure.

The design of the rotor system will rely on theoretical calculations to obtain initial parameters for the design. These calculations will serve as a foundational basis. Subsequent modifications and refinements will be implemented through an iterative approach, allowing for adjustments based on simulations. This iterative methodology ensures that the rotor system is continually optimized, taking into account evolving requirements, performance considerations and unforeseen challenges throughout the design process.

A schematic image (fig. 3.1) is provided for the sample to speed up the design UAV bearingless rotor system.

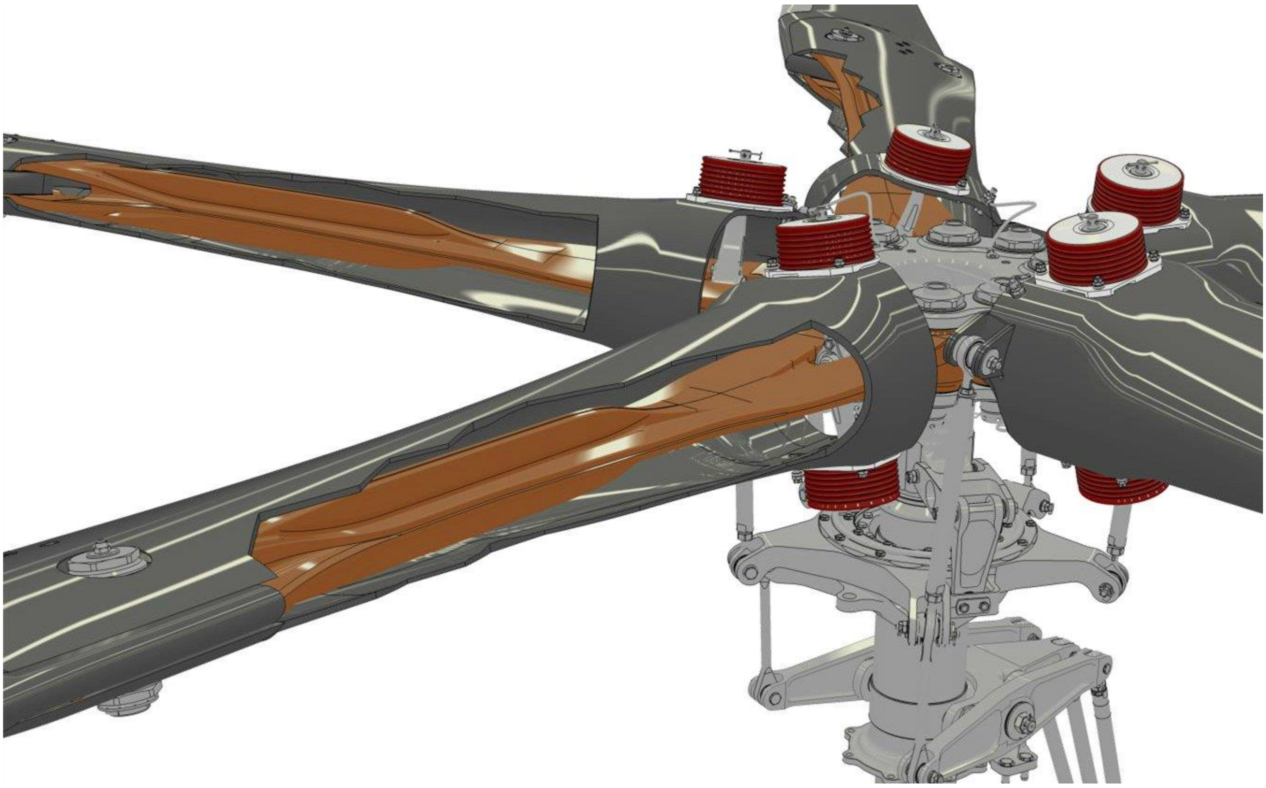


Figure 3.1. Airbus H145 rotor system scheme

To streamline the design task, the rotor system will be exclusively examined in the take-off phase of operation. Focusing solely on the take-off regime allows for a simplified analysis, facilitating a targeted approach to address specific challenges associated with lift generation and initial ascent. This narrowed focus aims to enhance the efficiency of the design process, enabling a more detailed exploration of factors critical to the rotor system's performance during the crucial takeoff phase.

3.2. Bearingless rotor system components and loads

The analysis of inertial, gravitational and aerodynamic forces acting on helicopter rotor blades is a fundamental aspect of designing and understanding the performance of rotor systems. Analysing these forces is crucial for ensuring optimal performance, stability and safety throughout a helicopter's operational envelope.

Two main theories have been developed to evaluate the helicopter's rotor performance: the Momentum Theory (MT) and the Blade Element Theory (BET).

The Momentum Theory. Hover is a very unique flight condition. Rotor has zero forward speed and zero vertical speed. The rotor field is azimuthally axisymmetric. It will be assumed that the flow through the rotor is one-dimensional, quasi-steady, incompressible and inviscid. Also, fluid is flown through rotor is ideal.

A general equation governing the conservation of fluid mass applied to this finite control volume can be written as

$$\iint_S \rho\vec{V} \cdot d\vec{S} = 0, \tag{3.1}$$

where $\vec{V}$ is the local velocity and ρ is the density of the fluid. This equation states that the mass flow into the control volume must equal the mass flow out of the control volume. Similarly, an equation governing the conservation of fluid momentum can be written as

$$\vec{F} = \iint_S \rho d\vec{S} + \iint_S (\rho\vec{V} \cdot \overrightarrow{dS})\vec{V} \tag{3.2}$$

For an unconstrained flow, the net pressure force $\vec{F}$ on the fluid inside the control volume is zero. $\vec{F}$ is simply equal to the rate of change with time of the fluid momentum across the control surface, S. Because the force on the fluid is supplied by the rotor, by Newton's third law the fluid must exert an equal and opposite force on the rotor. This force is the rotor trust, T. An equation governing the conservation of energy in the flow can be written as

$$W = \iint_S \frac{1}{2}(\vec{V} \cdot d\vec{S})\left|\vec{V}\right|^2 \tag{3.3}$$

These general equations of fluid mass, momentum and energy conservation may now be applied to a hovering rotor.

From the assumption that the flow is quasi-steady and by principle of conservation of mass, the mass flow rate $\dot{m}$, must be constant within the boundaries of the control volume. Therefore, the mass flow rate is

$$\dot{m} = \iint_\infty \rho\vec{V} \cdot d\vec{S} = \iint_2 \rho\vec{V} \cdot d\vec{S}, \tag{3.4}$$

and the 1-D incompressible flow assumption reduces this equation to

$$\dot{m} = \rho A_\infty \omega = \rho A_2 v_i = \rho A v_i \tag{3.5}$$

where A is a rotor disk area, ω is velocity normal to chord and v_i is induced velocity.

The hovering rotor trust can be written as the scalar equation

$$T = \iint_\infty \rho\overrightarrow{(\vec{V} \cdot d\vec{S})\vec{V}} = \dot{m}\omega \tag{3.6}$$

From the principle of conservation of energy, the work done on the rotor is equal to the gain in energy of the fluid per unit time. The work done per unit time (the power) is Tv_i and this results in the equation

$$Tv_i = \iint_\infty \frac{1}{2}\rho(\vec{V} \cdot d\vec{S})\vec{V}^2 - \iint_0 \frac{1}{2}\rho(\vec{V} \cdot d\vec{S})\vec{V}^2 \tag{3.7}$$

In hover, the second term on the right-hand side of the above equation is zero so that

$$Tv_i = \iint_\infty \frac{1}{2}\rho(\vec{V} \cdot d\vec{S})\vec{V}^2 = \frac{1}{2}\dot{m}\omega^2 \tag{3.8}$$

From equations 3.6 and 3.8 it is clear that

$$v_i = \frac{1}{2}\omega \tag{3.9}$$

The momentum theory can be used to relate the rotor trust to the induced velocity at the rotor disk by using the equation

$$T = \dot{m}\omega = \dot{m}(2v_i) = 2(\rho A v_i)v_i = 2\rho A {v_i}^2 \tag{3.10}$$

The ratio $T/_A$ is known as the disk loading, which is an extremely important parameter in rotor system analysis.

The power required to hover is given by

$$P = Tv_i = T\sqrt{\frac{T}{2\rho A}} = \frac{T^{3/2}}{\sqrt{2\rho A}} \tag{3.11}$$

This power is called ideal and is entirely induced in nature because the contribution of viscous effects have not been considered in the present level of analysis. Alternatively, it can be written

$$P = Tv_i = 2\dot{m}{v_i}^2 = 2(\rho A v_i){v_i}^2 = 2\rho A {v_i}^3 \tag{3.12}$$

It is important to note that while these equations offer a robust foundation, they primarily serve as a preliminary step in the analysis. Real-world aerodynamics and the complexities of blade interactions with the surrounding air necessitate a more detailed exploration. To this end, the theory presented here focuses on defining primary forces, acknowledging that a complete understanding of the real forces acting on the blades will require the integration of Computational Fluid Dynamics (CFD).

The Blade Element Theory. Unlike the simple momentum theory, the BET can be used as a basis to help design the rotor blades in terms of the blade twist, the planform distribution and perhaps also the airfoil shape to provide a specified overall rotor performance (Fig. 3.2).

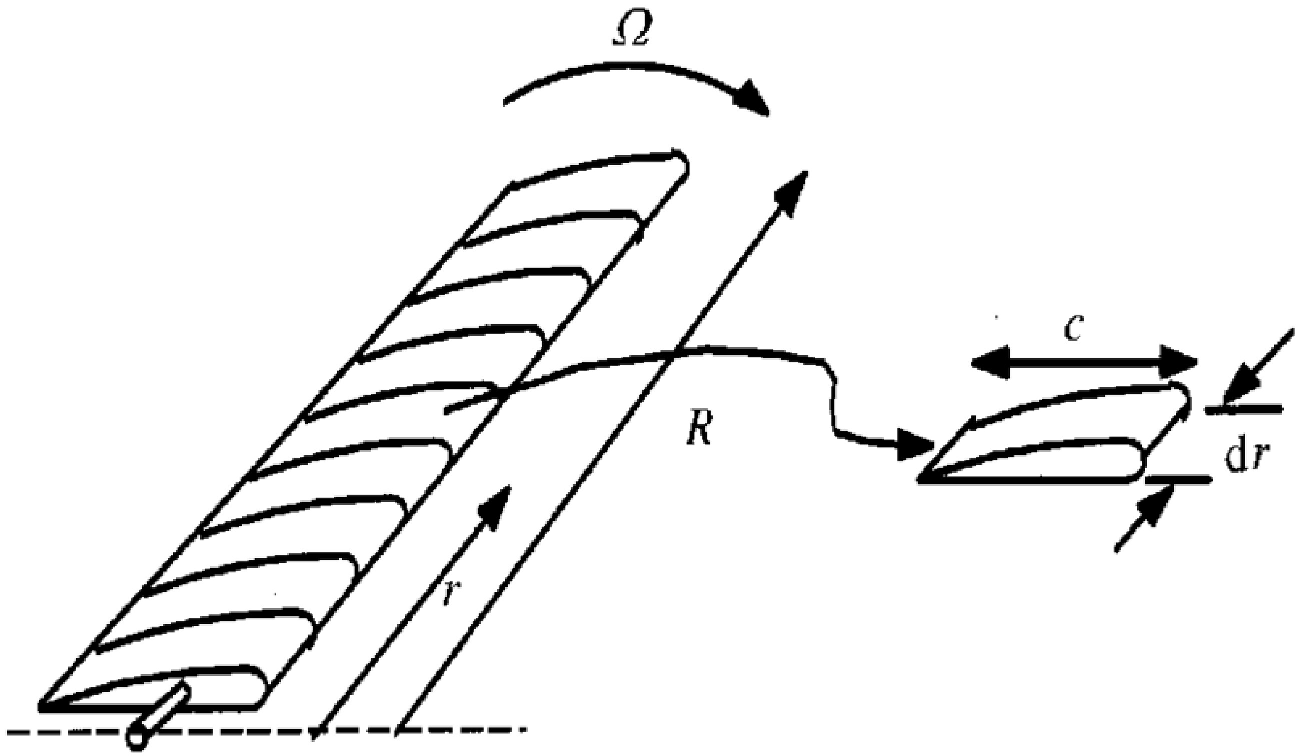


Figure 3.2. The blade element theory visualization

The resultant local flow velocity at any blade element at a radial distance y from the rotational axis has an out-of-plane component $U_P = V_C + v_i$ normal to the rotor as a result of climb and induced inflow and an in-plane component $U_T = \Omega r$ parallel to the rotor because of blade rotation, relative to the disk plane. The resultant velocity at the blade element is

$$U = \sqrt{U_T^2 + U_P^2} \qquad (3.13)$$

The relative inflow angle (or induced angle of attack) at the blade element will be

$$\phi = \tan^{-1}\left(\frac{U_P}{U_T}\right) \approx \frac{U_P}{U_T} \text{ for small angles} \qquad (3.14)$$

Thus, if the pitch angle at the blade element is θ, then the aerodynamic of effective angle of attack (AoA) is

$$\alpha = \theta - \phi = \theta - \frac{U_P}{U_T} \qquad (3.15)$$

The resultant incremental lift dL and drag dD per unit span on this blade are

$$dL = \frac{1}{2}\rho U^2 c C_l dr,$$

$$dD = \frac{1}{2}\rho U^2 c C_d dr \qquad (3.16)$$

where C_l – lift coefficient; C_d – drag coefficient; c – local blade chord.

Using figure 3.2.1 these forces can be resolved perpendicular and parallel to the rotor disk plane giving

$$dF_z = dL\cos\phi - dD\sin\phi,$$

$$dF_x = dL\sin\phi + dD\cos\phi \qquad (3.17)$$

Therefore, the contributions to the trust, torque and power of the rotor are

$$dT = N_b dF_z, \text{ where } N_b \text{ – number of blades}$$

$$dQ = N_b dF_x r,$$

$$dP = N_b dF_x \Omega r \qquad (3.18)$$

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

$$C_T = \frac{1}{2}\left(\frac{\sigma C_{d0}}{\kappa}\right)^{2/3} \text{ for best } \textit{power loading} \quad (3.19)$$

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

$$DL = \frac{1}{2}\rho(\Omega R)^2\left(\frac{\sigma C_{d0}}{\kappa}\right)^{2/3} \quad (3.20)$$

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

$$R = \sqrt{\frac{W}{\pi DL}} \text{ for a conventional single rotor} \quad (3.21)$$

$$R = \frac{1}{\sqrt{2}}\sqrt{\frac{W}{\pi DL}} \text{ for a coaxial rotor} \quad (3.22)$$

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. 3.22 and selected numerical values of the design parameters

$$R = 0.75\ m \quad (3.23)$$

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

$$V_{tip} = 2\pi Rn = 141\ {}^{m}/_{s} \quad (3.24)$$

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

$$\overline{C}_L = 6(^{C_T}/_{\sigma}) \quad (3.25)$$

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

$$l_b = 0.45\ m \text{ and } c_b = 0.1\ m \quad (3.26)$$

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.

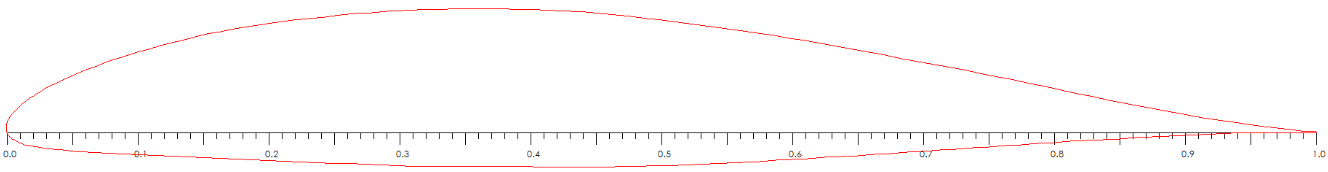


Figure 3.3. VR-5 airfoil

For the selected airfoil, coefficients of lift C_l and drag C_d were predicted using a program QBladeCE and the aerodynamic quality $^{C_l}/_{C_d}$ graph (fig. 3.4) of the airfoil was determined. Reynolds numbers ranging from 100,000 to 1,000,000 with a step size of 50,000 were chosen, along with an angle of attack range from -2° to +12°. The calculation results are presented on the figure 3.5 (a) and (b). Utilizing this coefficient values, selected based on the Reynolds number (which depends on the approaching flow velocity over the airfoil cross-section and the local chord length of the blade, eq. 3.27), the forces acting on each segment of the blade were determined using the BET (eqs. 3.16 - 3.18).

Knowing Re number on each blade segment, it is possible to use correct coefficients of lift and drag. Re number is defined as

$$Re_i = \frac{V_i c_i}{\nu} \quad (3.27)$$

where V_i – speed of fluid on segment; c_i – chord length of the segment; ν – fluid kinematic viscosity.

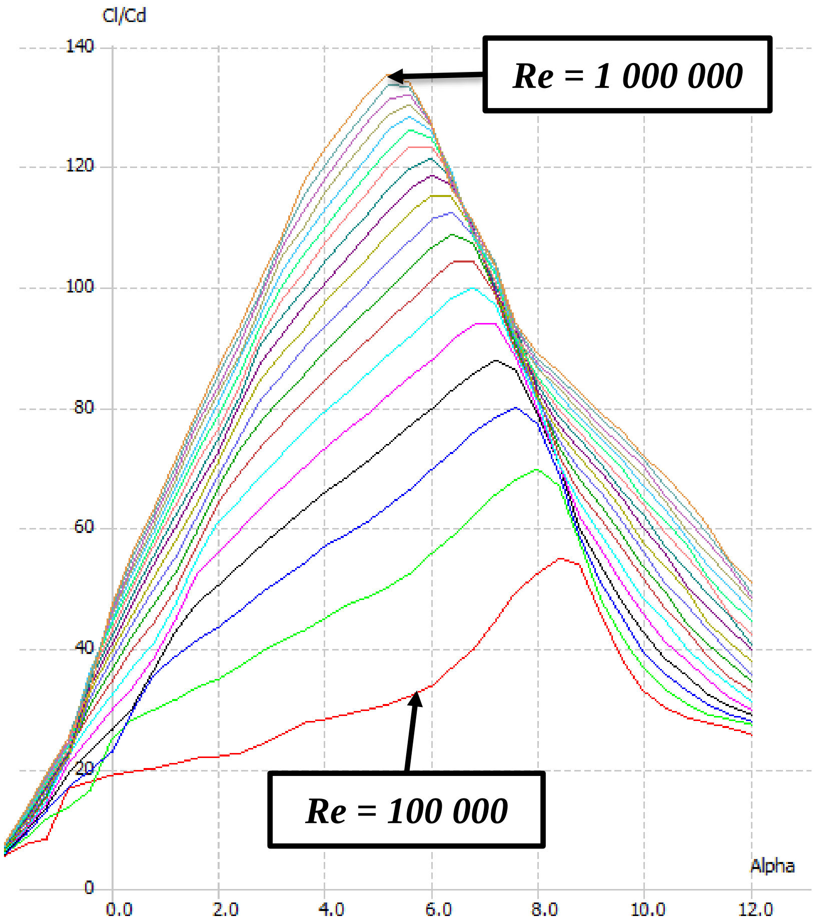


Figure 3.4. ${}^{C_l}/_{C_d}$ polar VR-5 airfoil

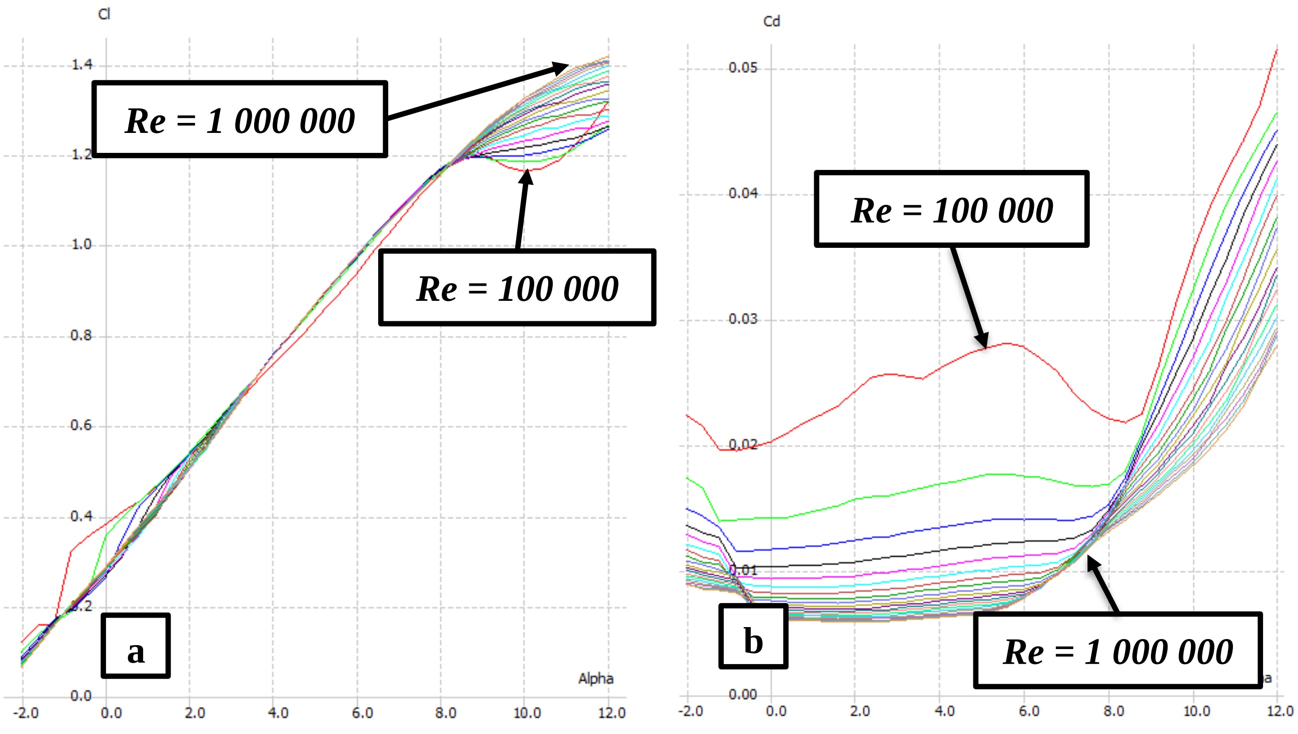


Figure 3.5. The dependence C_l (a) and C_d (b) on the AoA

Using BET parameters for each segment are defined and filled in the table.

Table 3.4

Segment parameters

Segment	1	2	3	4	5	6	7	8	9	10
dr	45	45	45	45	45	45	45	45	45	45
R_i	0.3225	0.3675	0.4125	0.4575	0.5025	0.5475	0.5925	0.6375	0.6825	0.7275
V_i	60.79	69.27	77.75	86.24	94.72	103.20	111.68	120.17	128.65	137.13
kRe	400	450	500	550	650	700	750	800	850	900
c_i	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Knowing the Re number inherent in each segment, the most effective angle of attack is chosen to provide the highest possible value of aerodynamic quality C_l/C_d for this airfoil. At the same time, we take into account that there will still be a pitch angle of the blade.

Table 3.5

Most effective angles of attack

Segment	1	2	3	4	5	6	7	8	9	10
$\alpha, C_l/C_d\,max$	5.6	5.6	5.2	5.2	5.2	5.2	5.0	5.0	5.0	4.8

Segment located on the $R_i = 0.7$ is taken as the angle reference. The range of angle pitch will be equal to $\alpha_{pitch} = 5°$, so twist angles are defined as

$$\varphi_i = \alpha_{C_l/C_d max} - \alpha_{pitch} \quad (3.28)$$

Table 3.6

Blade twist

Segment	1	2	3	4	5	6	7	8	9	10
φ_i	0.6	0.6	0.2	0.2	0.2	0.2	0	0	0	-0.2

Knowing the angles of attack, fluid speed, lift and drag coefficients, geometric dimensions of sections, we determine the forces and momentums acting on each blade segment at $\alpha_{pitch} = 5°$:

Table 3.7

Forces and momentums acting on blade segments

Segment	1	2	3	4	5	6	7	8	9	10
C_l	0.76	0.76	0.72	0.73	0.73	0.73	0.71	0.70	0.69	0.65
C_d	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
C_m	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.06	-0.05
${C_l}/{C_d}$	86.74	86.74	88.75	92.51	97.54	99.92	99.45	100.65	101.81	99.42
dL_i	7.71	10.01	12.07	14.89	18.02	21.44	24.24	27.72	31.38	33.91
dD_i	0.09	0.12	0.14	0.16	0.18	0.21	0.24	0.28	0.31	0.34
dT_i	7.69	9.99	12.04	14.85	17.98	21.40	24.19	27.67	31.32	33.85
dQ_i	0.18	0.27	0.33	0.45	0.60	0.77	0.90	1.10	1.33	1.45
dM_i	-0.06	-0.08	-0.10	-0.12	-0.15	-0.18	-0.21	-0.23	-0.26	-0.28

After this calculations rotor main parameters (3 blades) can be defined

Thrust: $T = 602.9\ N$

Required torque: $Q = 22.2\ Nm$

Required power: $P = 4182\ Wt$

Achieved power loading: ${T}/{P} \approx 14.7\ {kg}/{kWt}$

The calculations of the helicopter blade using the BET provide theoretical insights, but it is essential to acknowledge that these values are limited in their rightness and do not encompass various factors. The analysis conducted serves only as a predictive tool, to make sure we are moving in the right direction. However, it is crucial to recognize that the real-world accuracy of these results may be enhanced through CFD simulations, which account for a more comprehensive set of variables.

Furthermore, the blade analyzed in this study was specifically examined under a hovering condition. It is important to note that a blade optimized for hover may not necessarily exhibit optimal efficiency in horizontal flight, a consideration that was not addressed in this analysis. The effectiveness of the blade in other flight regimes requires separate investigation and consideration of additional aerodynamic factors.

Defining parameters of flexbeam main cross-sections

Defining the main cross-sections of a rotor system flexbeam involves considering the different loading conditions and section experiences. According to Fig. 3.6, 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.

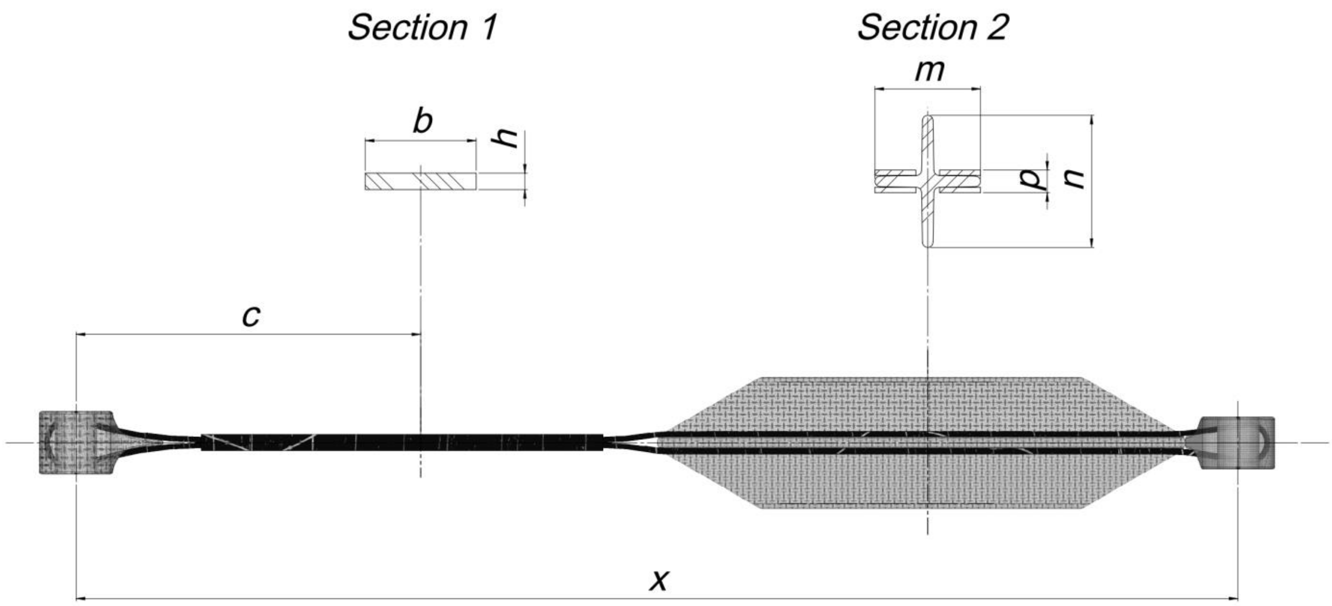


Figure 3.6. Flexbeam and main cross-sections

In the iterative design method, it is initially sufficient to define the parameters of only these two cross-sections. This is because the main analysis will be conducted in SolidWorks.

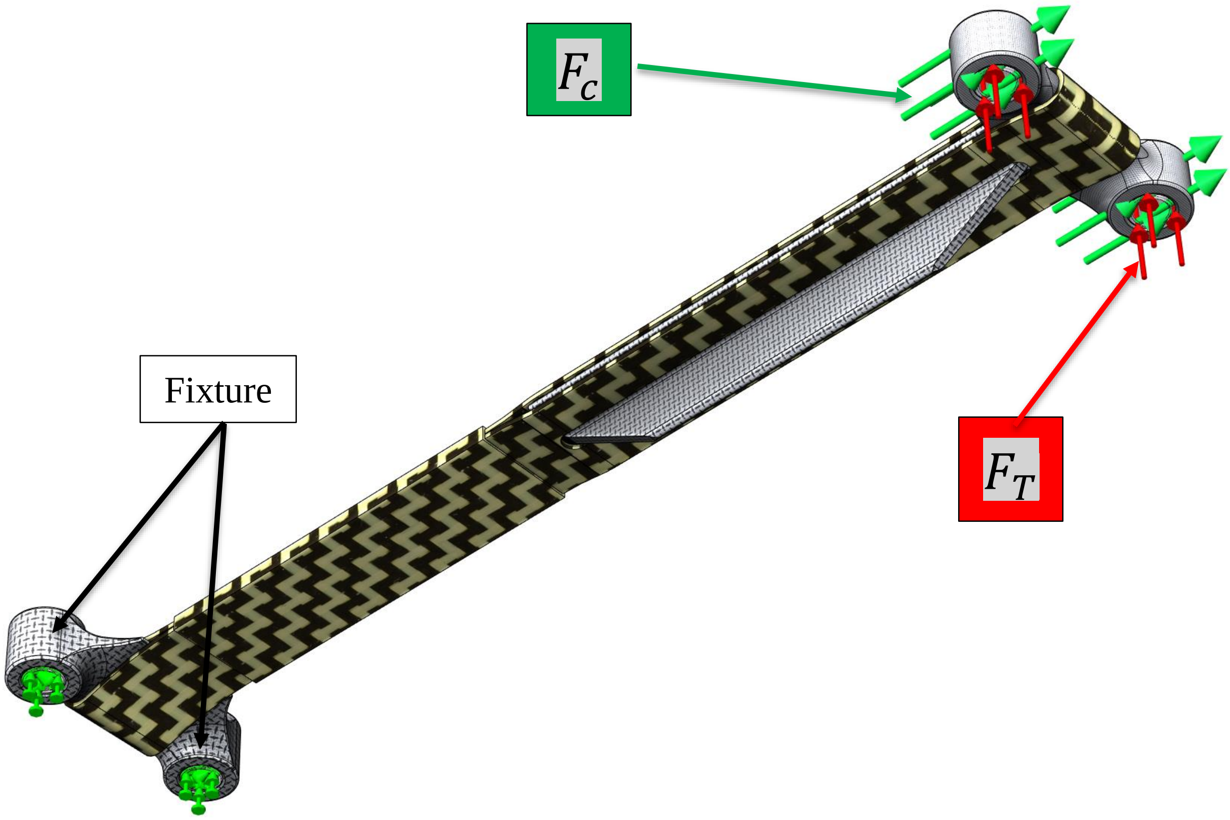


Figure 3.7. Forces (F_c – centrifugal force; F_T – blade thrust force) acting on flexbeam

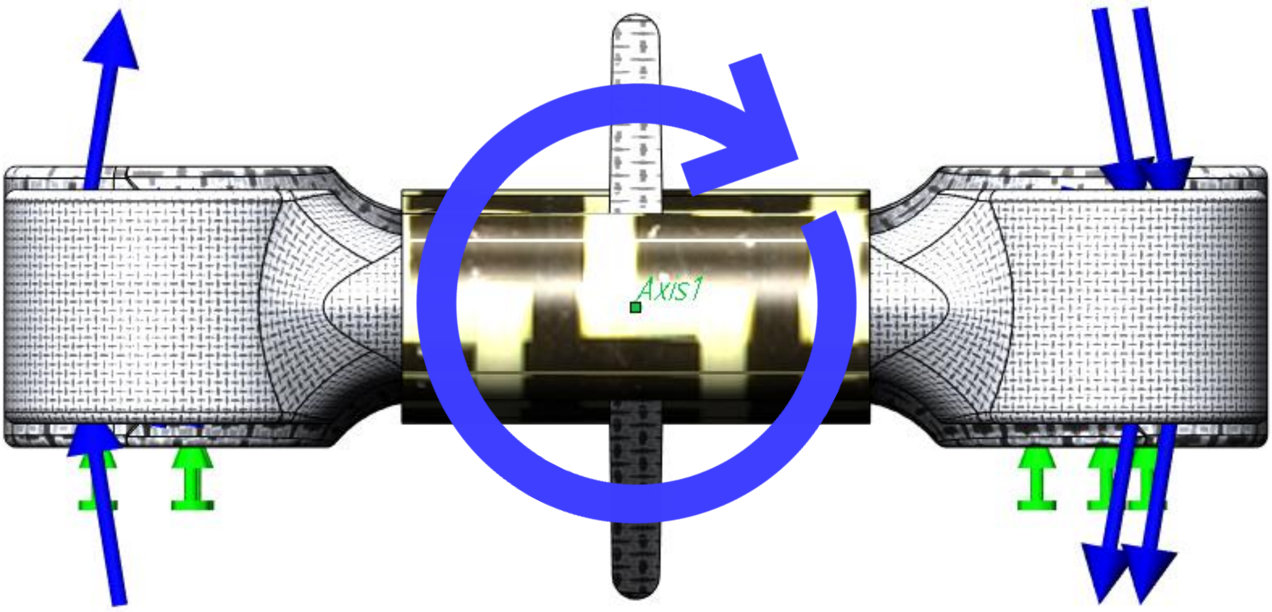


Figure 3.8. Momentum M_{pitch} acting on flexbeam

The interaction of centrifugal force, blade thrust and momentum during pitch changes influences the performance and stability of rotating blades.

The centrifugal force F_c (fig 3.7) is applied to the center of mass ($c.m.$) of the blade, but its entire magnitude is transmitted to the attachment points of the blade and the flexbeam; is defined

$$F_c = 4\pi^2 n^2 \cdot m_{blade} \cdot R_{c.m.} \tag{3.29}$$

where n – rotations per second; $R_{c.m.}$ – distance between center of mass and axis of rotation. For blade in this work $F_c = 3727\ N$.

Thrust force F_T (fig 3.7) is established above and is equal $F_T = 201\ N$.

Pitch angle ***control torque*** (M_{pitch}) (fig 3.8) is created by servomotors that tilt the swashplate. Maximum torque that is possible to achieve is $M_{pitch} = 10\ N \cdot m$.

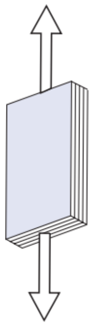
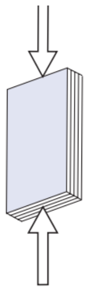
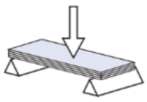
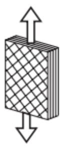
The ***material properties*** of a structure significantly influence the cross-section calculation, playing a pivotal role in determining its mechanical behaviour and response to external forces. The material should have a low modulus of elasticity for minimal deformation resistance under bending loads 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 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 (table 3.8) was used to choose the reinforcing material.

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. 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.

Table 3.8

Typical mechanical values on epoxy prepreg laminates

Volume content of fibres: E-glass-aramid ~ 50%; Carbon ~ 60%			**E-Glass**		**Aramid**		**Carbon**	
			*UD**	*F**	*UD*	*F*	*UD*	*F*
Tensile 	$\sigma_{0°}$	MPa	1100	600	1100	500	2000	800
	$\sigma_{90°}$	MPa	35	550	35	450	80	750
	$E_{0°}$	GPa	43	20	60	30	130	70
	$E_{90°}$	GPa	8	19	8	30	9	65
	ϑ	-	0.28	0.13	0.34	0.2	0.25	0.05
Compression 	$\sigma_{0°}$	MPa	900	550	250	150	1300	700
	$\sigma_{90°}$	MPa	150	500	150	150	250	650
	$E_{0°}$	GPa	42	17	75	31	115	60
	$E_{90°}$	GPa	10	16	5.5	30	10	55
Flexural 	$\sigma_{0°}$	MPa	1200	700	550	400	1800	1000
	$E_{0°}$	GPa	42	20	40	25	120	65
In-plane shear 	$\sigma_{45°}$	MPa	60	55	45	40	95	80
	$G_{45°}$	GPa	4	4.2	2.1	4	4.4	5.5
Interlaminar shear	σ	MPa	75	50	60	50	80	70

* Where *UD* – unidirectional; *F* – fabric.

For designing purposes maximum allowable stress $[\sigma_{max}] = 400\ MPa.$

Section 1: tension and bending

Centrifugal force F_c creates 3727 Newtons of tension load and it is important to define cross-section area A to resist failure

$$\sigma_{tension} = \frac{F_c}{A} = \frac{F_c}{bh} \tag{3.30}$$

Blade thrust F_T creates 201 Newtons of force perpendicular to central plane, this force is applied on $x = 0.3\ m$ from fixture, so simple bending momentum M_{F_T} is defined as

$$M_{F_T} = F_T \cdot x \tag{3.31}$$

But as this section is working under high F_c that is ≈ 18.5 times bigger than F_T, it is necessary to introduce additional momentum M_{F_c} is created by centrifugal force F_c

$$M_{F_c} = F_c \cdot \delta \tag{3.32}$$

where δ – flexbeam free end deflection under combination tension and vertical pointed loads.

Including momentums from eqs. 3.31 and 3.32 bending stress is

$$\sigma_{bending} = \frac{6(M_{F_T} - M_{F_c})}{h^2 b} \tag{3.33}$$

where b – width and h is thickness of section.

But this section is working under combination these forces, so combined stress σ_{sec1} is equal to

$$\sigma_{sec1} = \sigma_{tension} + \sigma_{bending} \leq [\sigma_{max}] \tag{3.34}$$

It is necessary to understand the cantilever beam behavior under combination tension (F_c) and bending force (F_T). The smaller the modulus of elasticity (E) and the moment of inertia of the section (I), the greater the deflection (δ). And as the deflection increases, the moment from the centrifugal force (M_{F_c}) also increases, which leads to bending stress decreasing. Flexbeam section 1 material was used unidirectional fiber E-Glass with modulus of elasticity $E = 42\ GPa$.

Table 3.9

Cross-section 1 results

Parameter	Unit	Value
Section width, b	mm	30
Section thickness, h	mm	2
Free end deflection, δ	mm	15.4
Maximum stress, σ_{sec1}	MPa	207.3

Section 2: tension and torsion

Section 2 is very important to ensure the change of the pitch angle of the blade. Since this section is subjected to both tension and torsion, it is critical that the value of the maximum stress is permissible for the limit of material strength and fatigue. An additional condition will be the selection of the geometric shape of the cross-section so that it does not have bending stresses created by the thrust of the blade. This section should have minimal resistance to twisting, so that there are no significant stresses during operation.

To simplify calculations let's assume that the flexbeam has uniform cross-section along its length, so the angle of twist θ (in radians) is

$$\theta = \frac{TL}{GJ} \tag{3.35}$$

where T – control torque: L – flexbeam length; G – shear modulus; J – torsional constant (polar moment of inertia).

But θ values are defined in operating parameters as a $-6° \ldots + 6°$. So, it is important to theoretically predict possible shear stress τ_{sec2} approximately

$$\tau_{sec2} = \frac{Tr}{J} \tag{3.36}$$

where r – distance from the center of the cross-section.

Because of the special way this load works, the usual method isn't accurate. Instead of just using torque, the twist angle was fixed using a mix of different things. Torque is still part of it, but it's not the only thing deciding the twist in this case.

In designing the beam, a cross-shaped section was chosen. This decision was to avoid causing too much bending stress. The total area of the cross-section must meet the conditions needed for tension and shape must have the lowest possible torsional constant.

Table 3.10

Cross-section 2 results

Parameter	Unit	Value
Section width, m	mm	19.6
Section height, n	mm	19.6
Section thickness, p	mm	1.6
Maximum stress, σ_{sec2}	MPa	137.5

3.3. 3D modeling, aerodynamic and structural analyses

Bearingless rotor system 3D model

It is necessary to create an accurate 3D model of the blade and flexbeam for the next aerodynamic and structural analysis. SolidWorks 2021 was used due to its powerful and simple surface modeling tools. Also, this software offers user-friendly simulation modules.

Using the established earlier airfoil main parameters, it is possible to make a correct blade 3D model (fig. 3.9).

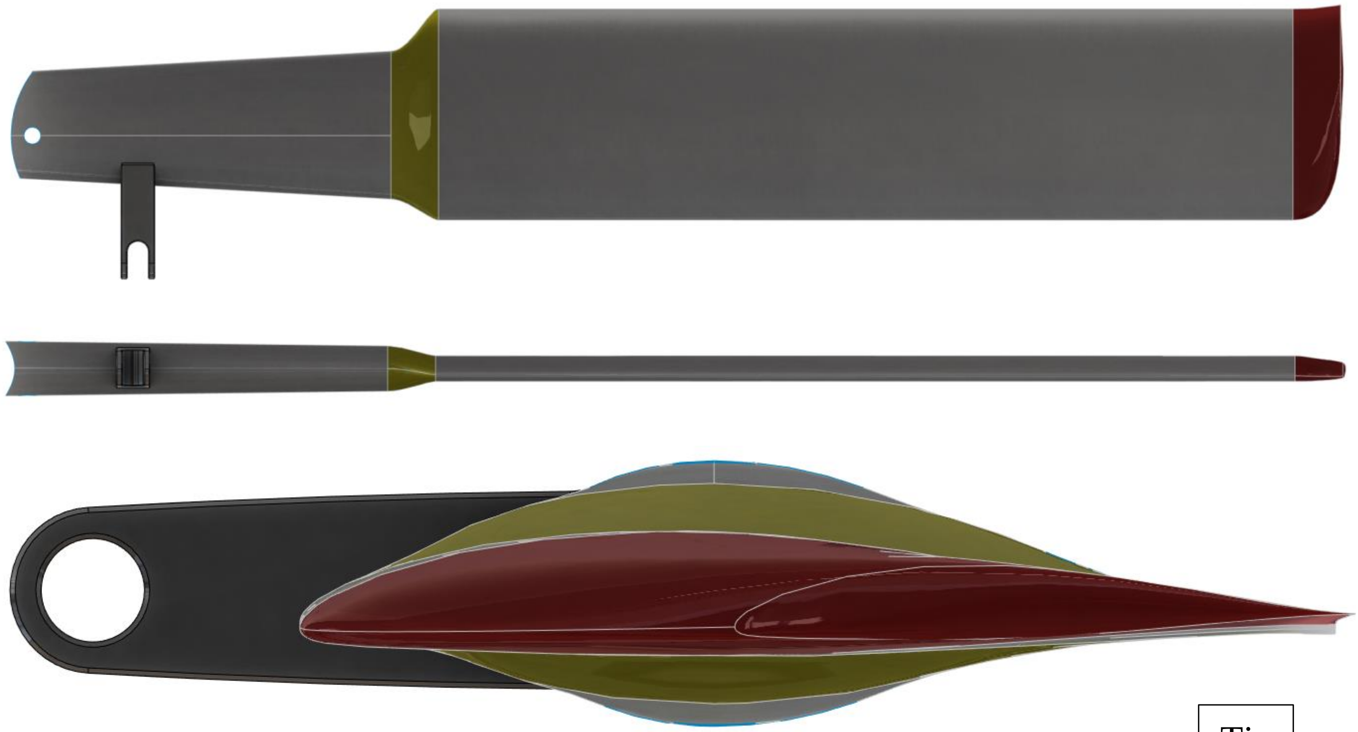


Figure 3.9. Rotorcraft UAV blade 3D model

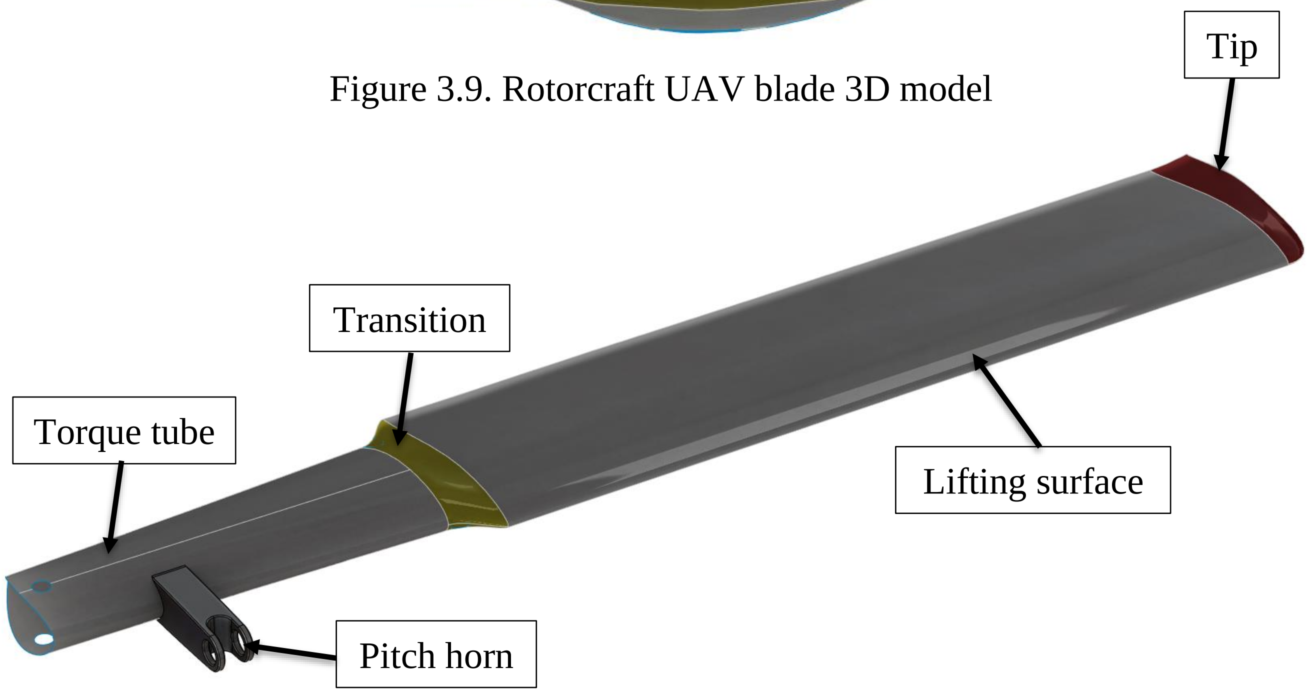


Figure 3.10. Main blade features

Helicopter blade main features (shown in figure 3.10) have a significant influence on blade performance. The torque tube must have maximum torsional stiffness; the pitch horn must be strong and stiff to control force; the transition must have a flexbeam connecting bore; the lifting surface must have the best surface finish possible; and the tip must have geometry for efficient work.

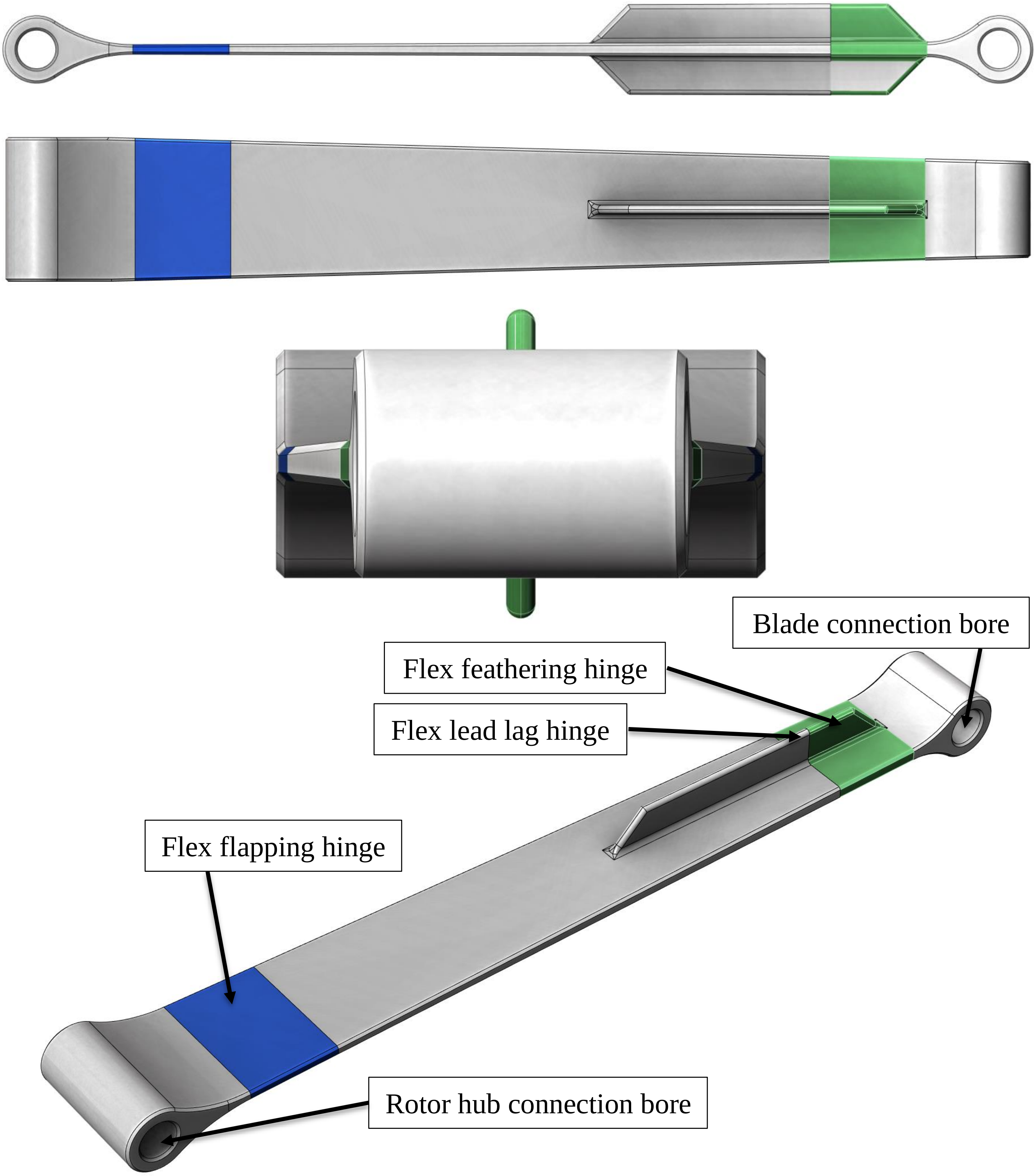


Figure 3.11. Main flexbeam features

The flexbeam's (fig. 3.11) response to different load conditions has been rigorously examined through precise calculations, providing insights into its strength and performance in practical scenarios. This model serves as a straightforward exploration of engineering design and computational analysis.

3.4. Results of simulations

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.

The precision of simulation outcomes depends on the accurate input parameters (fig 3.12). Accurate and reliable simulations require precise and appropriate input values.

As the instrumental platform for carrying out detailed aerodynamic analyses, the Flow Simulation module (fig 3.13) in SolidWorks 2021 served as the instrument. The application of this powerful instrument allowed for a detailed examination of airflow patterns, pressures, and forces, which resulted in a collection of important knowledge regarding the actions of the rotor blades of the helicopter while it was being simulated.

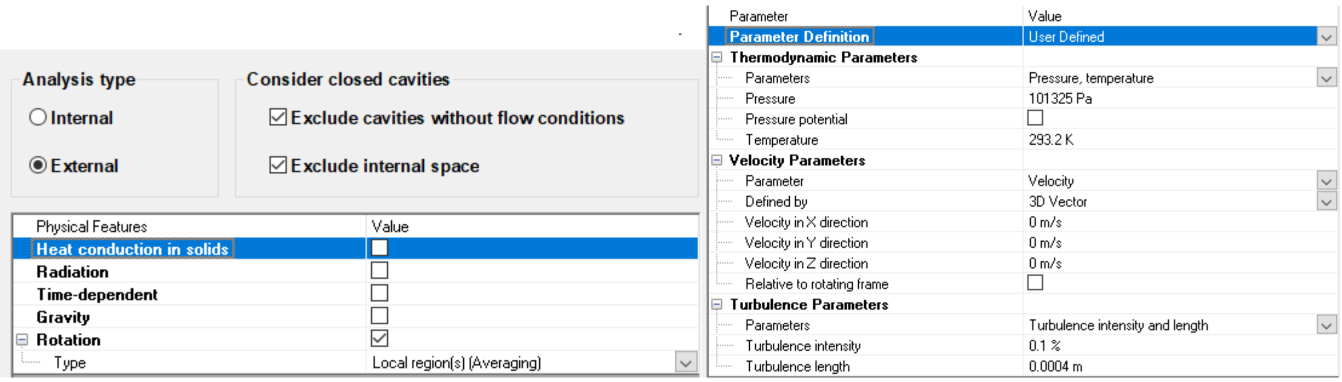


Figure 3.12. Simulation settings

Three separate aerodynamic simulations were conducted, each simulating different operational scenarios:

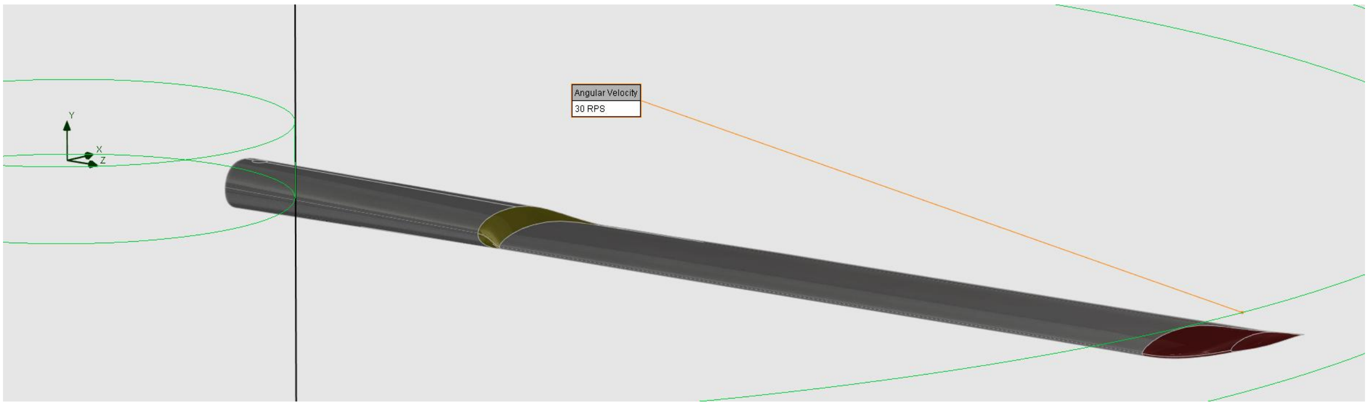


Figure 3.13. Rotating region definition

Hovering Mode Simulation (fig 3.14 – 3.15): Parameters: No horizontal velocity, consistent rotational frequency, and a 5-degree angle of attack.

Advancing Blade Simulation (fig 3.16 – 3.17): Parameters: Horizontal velocity of 56 m/ and a 5-degree angle of attack.

Retreating Blade Simulation (fig 3.18 – 3.19): Parameters: Negative horizontal velocity of -56 m/s (indicating backward movement) and a 5-degree angle of attack.

During each 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.

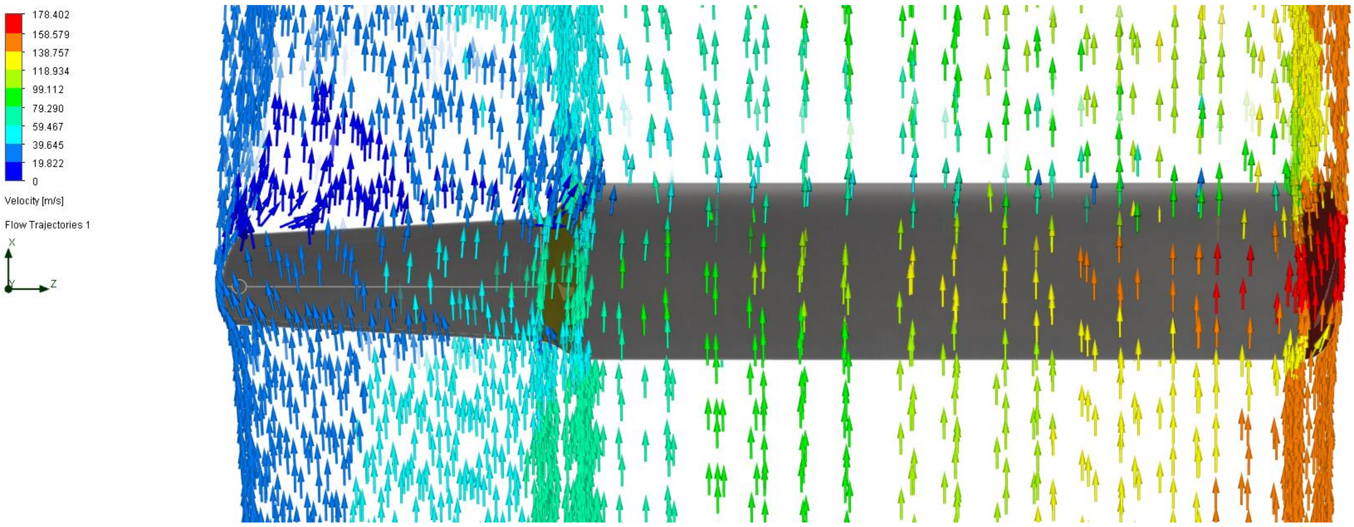


Figure 3.14. Velocity visualization in hovering mode

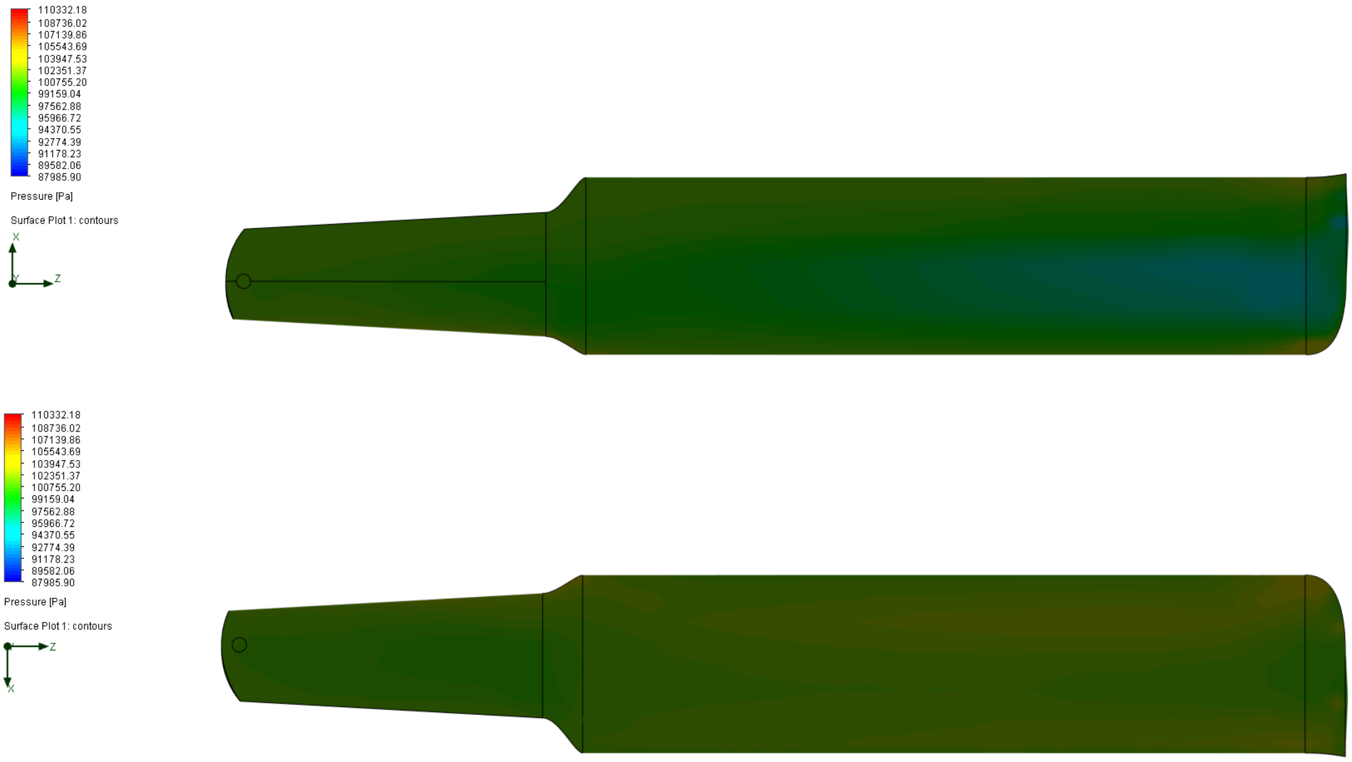
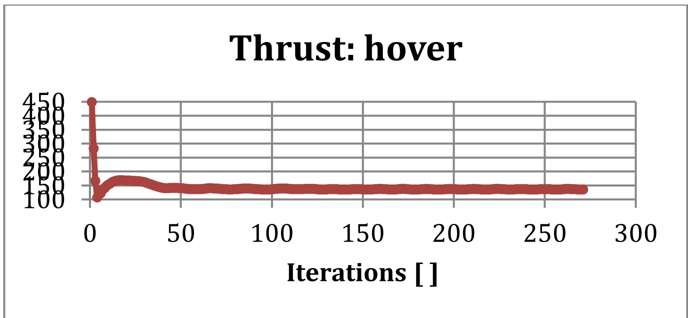
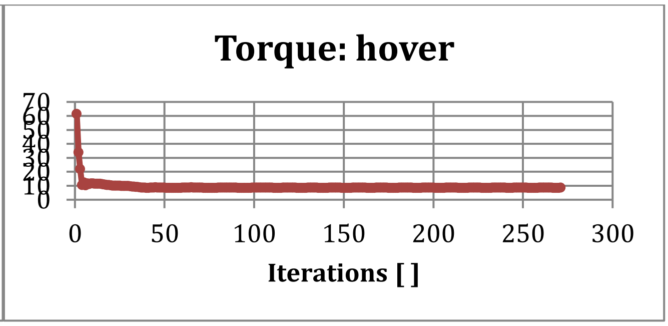


Figure 3.15. Pressure distribution in hovering mode





Here are the results of the simulation that was performed:

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

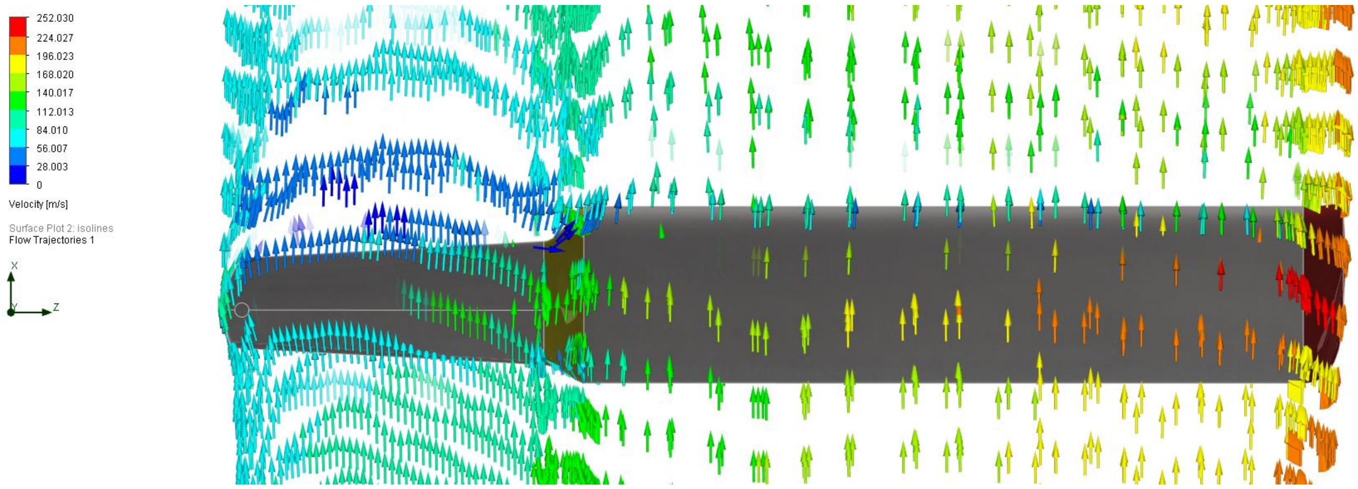


Figure 3.16. Velocity visualization in advancing mode

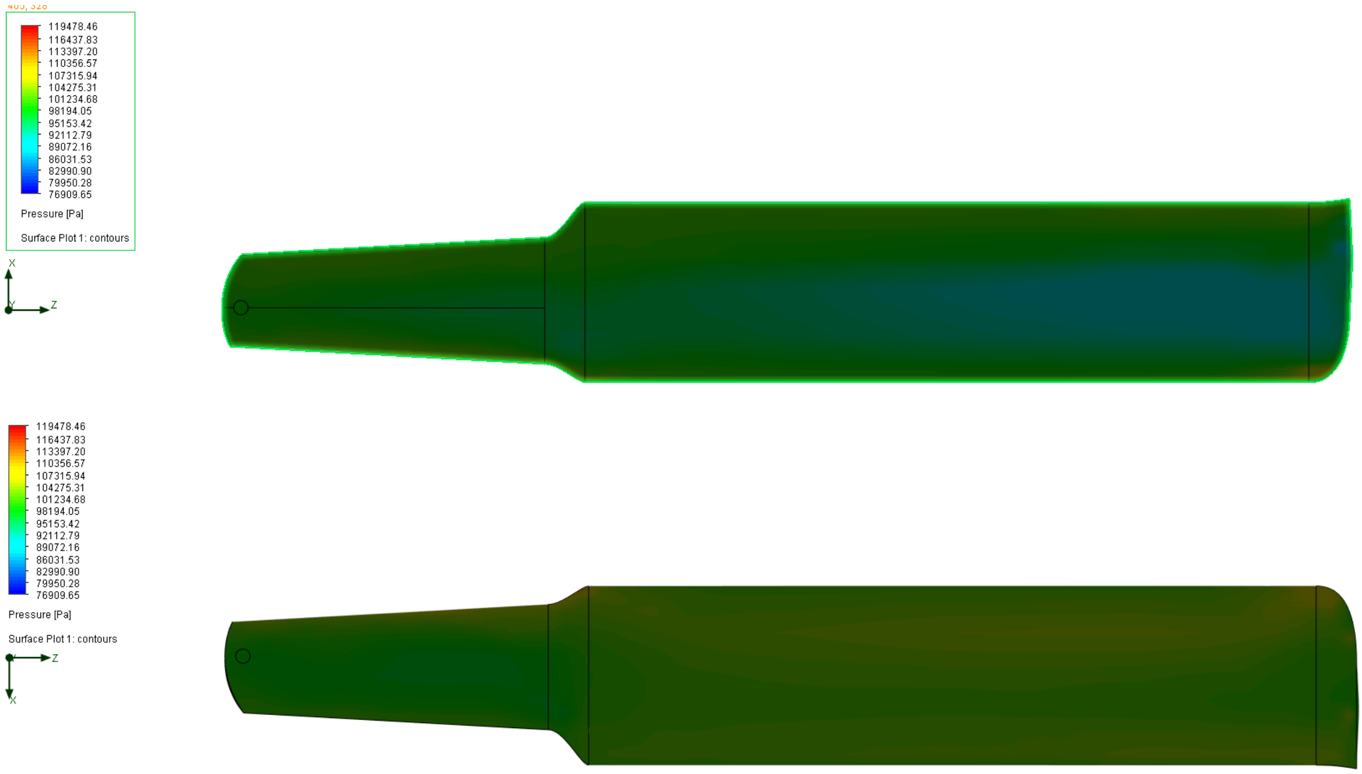
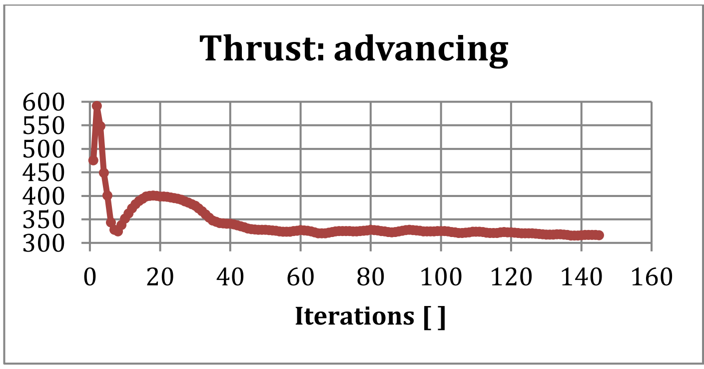
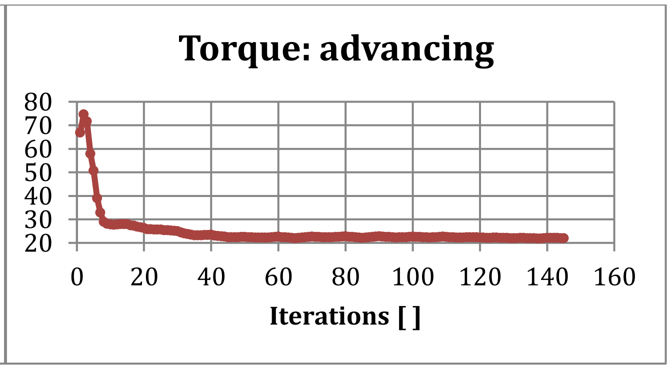


Figure 3.17. Pressure distribution in advancing mode





Here are the results of the simulation that was performed:

$$T_{advancing} = 340.63\ N; \;\; Q_{advancing} = 21.97\ N \cdot m \quad \rightarrow \quad {}^{T}\!/_{P} = 8.38\ {}^{kg}\!/_{kWt}$$

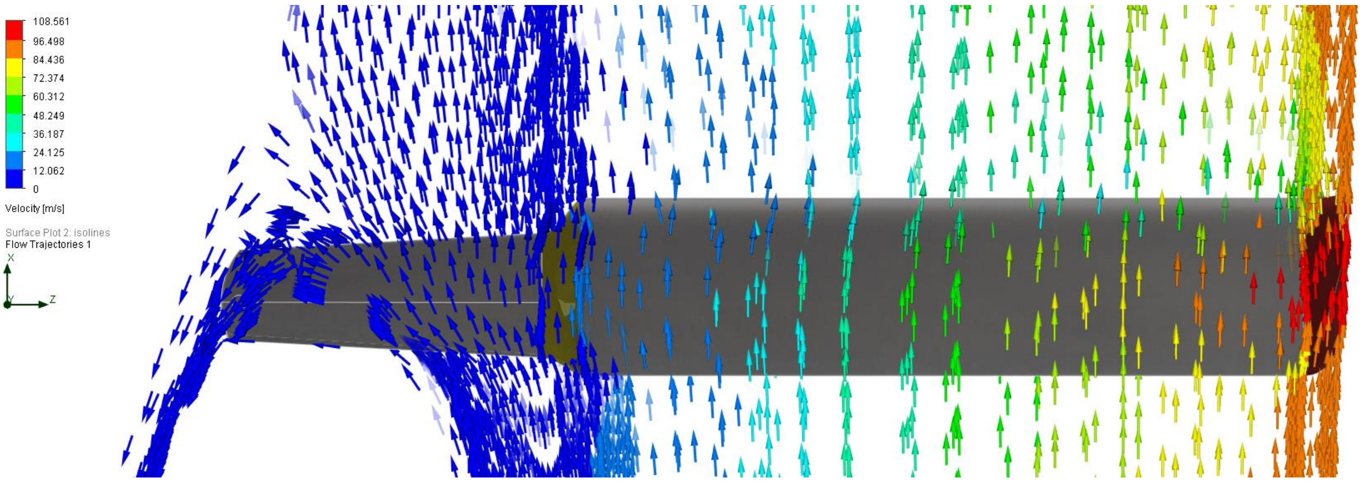
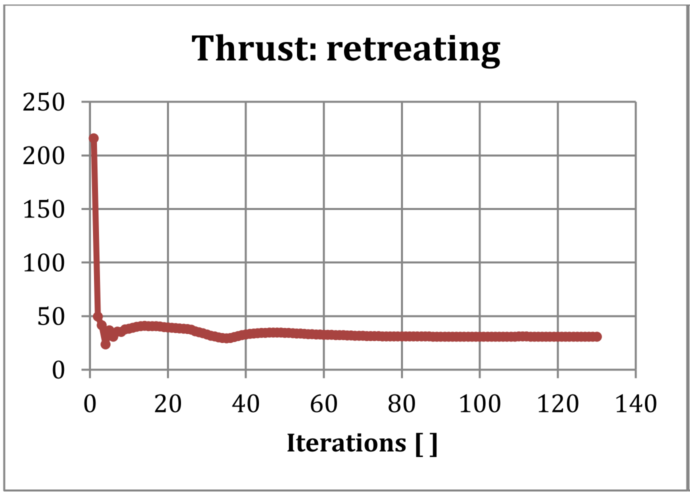
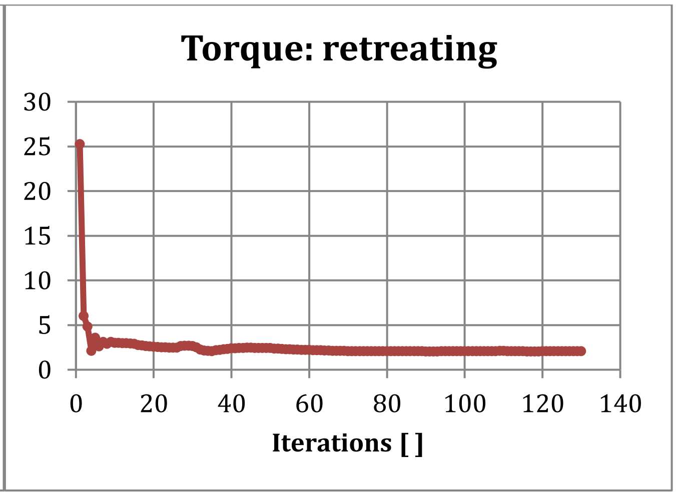


Figure 3.18. Velocity visualization in retreating mode

Figure 3.19. Pressure distribution on retreating mode





Here are the results of the simulation that was performed:

$$T_{retreating} = 34.17\ N; \;\; Q_{retreating} = 2.06\ N \cdot m \quad \rightarrow \quad {}^{T}/_{P} = 8.97\ {}^{kg}/_{kWt}$$

In the course of the research that was carried out, comprehensive aerodynamic simulations were carried out with SolidWorks for three different flight modes: hovering, advancing, and retreating. The study specifically focused on a rotor blade that had been designed. The simulations generated detailed results that provided valuable insights.

These results included the distribution of pressure and velocity, as well as the calculation of thrust and the required torque for each flight mode. These velocity distribution maps (figures 3.14, 3.16, 3.18) provide a graphical representation of the airflow patterns appearing around the blade, highlighting the variations that occur under a variety of different operating conditions. According to fig. 3.18, it can be seen that the reversed flow effect appears on the torque tube of the blade. This is because the linear speed of movement of the sections is less than the horizontal speed of movement of the blade. This effect significantly reduces the efficiency of the blade, so this torque tube must also have an aerodynamically unique shape for such a case.

In the same way, the results of the pressure distribution (figures 3.15, 3.17, 3.19) define the aerodynamic forces that are acting on the blade surfaces, which helps to an understanding of the characteristics of lift and drag. The high pressure area is located on the leading edge of the blade tip, which indicates the imperfection of the geometric shape of the blade. Optimizing this feature to move the high pressure area to the lower surface of the blade will increase efficiency.

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, 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.

During the master's thesis research, a significant difference has been identified between the theoretical calculations of blade thrust obtained from the BET and results received through aerodynamic simulations carried out in SolidWorks. This variation involves an in-depth examination of the fundamental assumptions and significant factors affecting the two methodologies.

BET applies a series of simplifications and assumptions to simulate the aerodynamic forces applied on individual sections of a rotor blade. These assumptions can include consistent inflow conditions, a constant angle of attack, and the exclusion of dynamic stall effects. Therefore, any divergence from these idealized circumstances in practical situations can give rise to differences between theoretical predictions and actual simulation results.

However, the SolidWorks simulations provided a comprehensive understanding of the complicated relationships between aerodynamic forces, covering complex flow phenomena, dynamic variations in angle of attack, and other factors that might be overlooked in less sophisticated theoretical models.

It is important to acknowledge that although BET offers valuable insights, its underlying assumptions may result in differences when compared to simulation results, which contain a greater number of real-world complexities. The difference observed underscores the significance of acknowledging the assumptions and constraints inherent in theoretical models, as real-world aerodynamics may entail complexities that exceed the capabilities of simplified calculations. To enhance our comprehension of the differences that have been noticed and contribute to the general knowledge in rotorcraft aerodynamics, it is necessary to conduct an in-depth analysis of the specific scenarios and assumptions used in both methodologies.

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.

As seen in the figures 3.20 – 3.21, the selected cross-sections meet the strength criteria for tension, bending, and torsion.

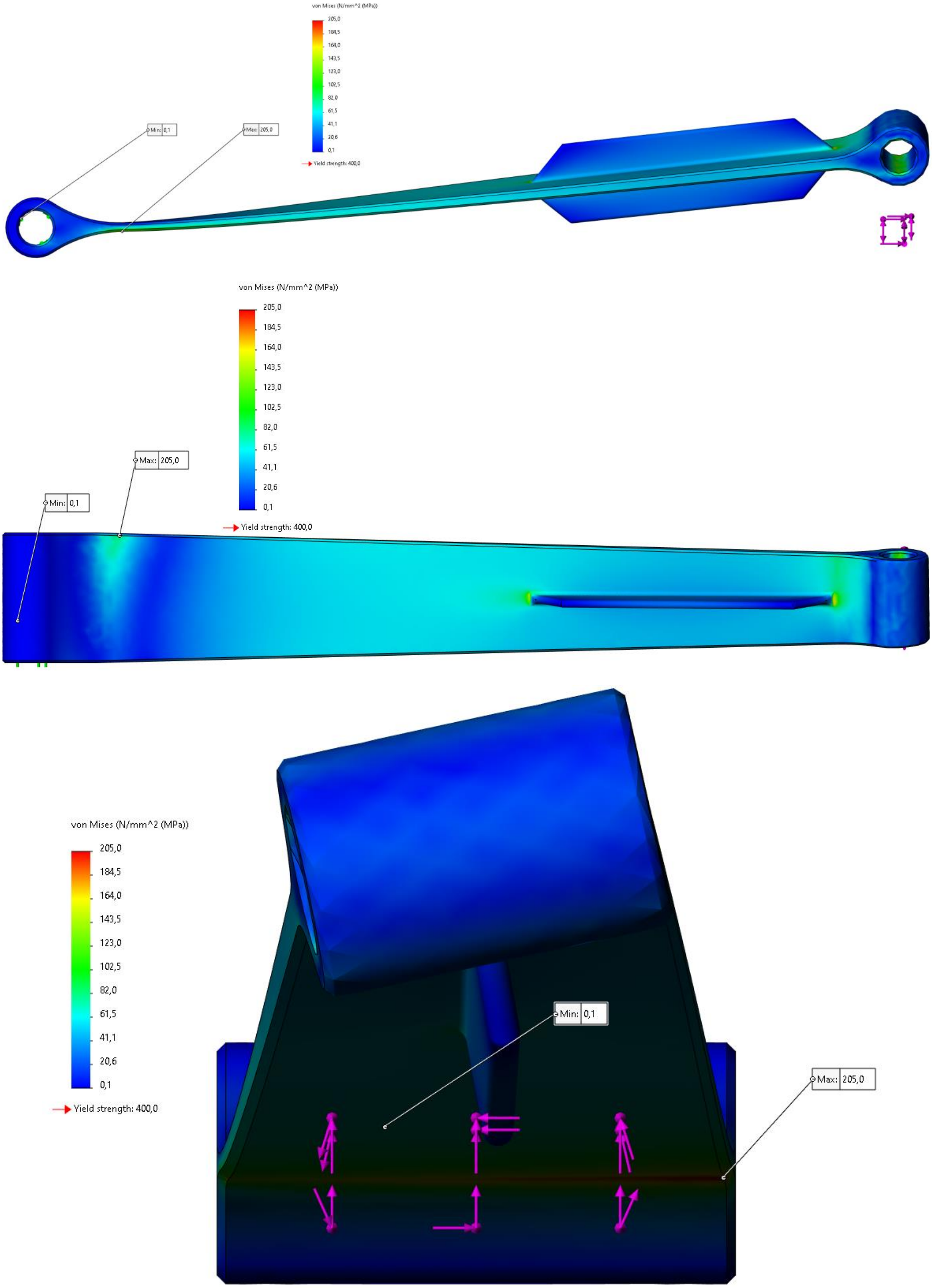


Figure 3.20. Maximum stresses in flexbeam visualization

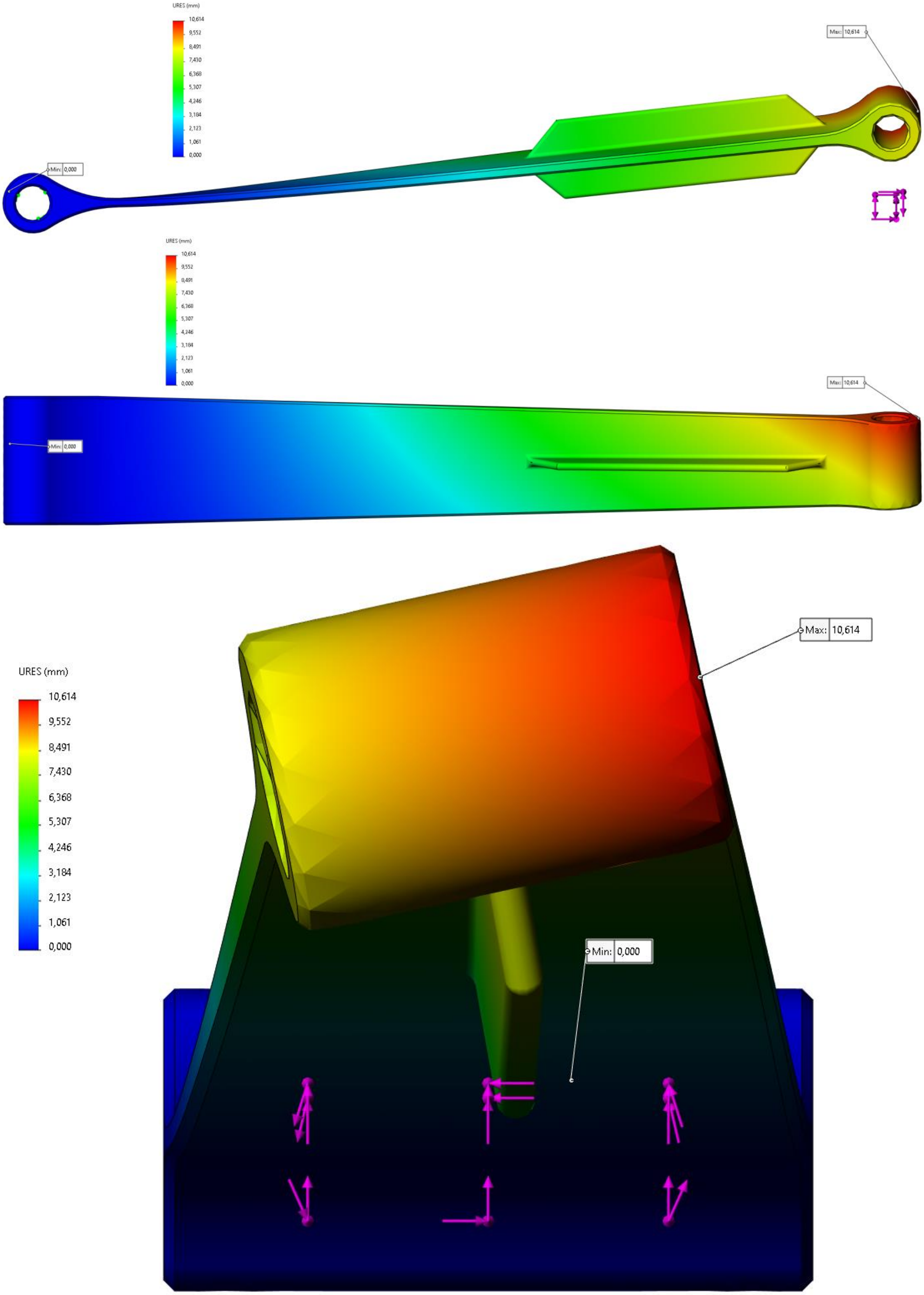


Figure 3.21. Maximum displacement in flexbeam visualization

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. 3.20) $\sigma_{max} = 205\ MPa$ 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. 3.21) $\delta = 10.6\ mm$ 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.

Normally, there are differences between theoretical calculations and simulations, but the main values approximately match.

Conclusion to the part III

To summarize, incorporating composite materials into the rotorcraft rotor system has the potential to significantly improve the performance of rotorcraft unmanned aerial vehicles. The improvement is primarily related to the fundamental benefits of composite materials, such as reduced weight, increased durability, and reduced maintenance costs. The lighter weight increases the ability to maneuver and improves fuel efficiency, while the increased durability guarantees a longer lifespan for the rotor system. Moreover, the economic attractiveness of using composite materials is enhanced by their cost-effectiveness in maintenance. With the continuous advancement of technology, the implementation of composite materials has been identified as a promising approach to enhance the efficiency, durability, and economic feasibility of rotorcraft UAVs in both civilian and military uses.

The implementation of a bearingless rotor system signifies a revolutionary method in rotorcraft design, allowed by the exclusive application of composite materials. This revolutionary system eliminates the necessity for conventional bearings, instead relying on composite material possibilities to attain both structural integrity and dynamic control.

Furthermore, the natural damping characteristics of composite materials can be effectively applied in a rotor system without bearings, effectively reducing vibrations and minimizing the requirement for supplementary damping mechanisms. Applying composites also allows designers to optimize the aerodynamic profile of the rotor, thereby further improving performance.

PART IV. LABOUR PROTECTION

Labour protection, also known as occupational health and safety or workplace safety, refers to the set of measures and regulations put in place to ensure the health, safety, and well-being of workers in the workplace. The primary goal of labour protection is to prevent accidents, injuries, and illnesses that may arise from the work environment or job-related activities.

Labour protection is a shared responsibility between employers, employees, and regulatory authorities. Employers are responsible for providing a safe working environment, and employees are expected to follow safety protocols and use provided safety equipment. Regulatory bodies establish and enforce standards to protect workers and may conduct inspections to ensure compliance.

The ultimate aim of labour protection is to create a work environment that safeguards the physical and mental well-being of employees, promotes productivity, and fosters a culture of safety within the workplace.

Composite materials, which are made by combining two or more different materials to create a new material with enhanced properties, often involve processes that can pose specific challenges. When working with composite materials, it is necessary to understand the next key considerations:

- Composite material processes, such as cutting, sanding, or molding, can generate fine dust or particulate matter. Workers should use appropriate respiratory protection, such as masks or respirators, to prevent inhalation of harmful particles.
- Ensure that workers wear suitable personal protective equipment (PPE), including safety glasses, gloves, and protective clothing. The type of PPE required may vary depending on the specific tasks involved in working with composite materials.
- Effective ventilation is crucial to control airborne dust and fumes. Implement local exhaust ventilation systems or provide sufficient fresh air to minimize the concentration of airborne contaminants in the workspace.
- Proper training for employees is essential. Workers should be educated on the potential hazards associated with composite materials, as well as the safe handling,

storage, and disposal practices.

- Maintain and make readily accessible Material Safety Data Sheets for all composite materials used in the workplace. MSDS provide information on the properties, hazards, and safe handling procedures for each material.
- Develop and communicate clear emergency procedures in case of accidents or exposure. This includes protocols for spills, fires, and medical emergencies related to the use of composite materials.
- Ensure that workers are trained in the safe operation of tools and equipment used in composite material processes. Regular maintenance and inspection of tools should be conducted to prevent accidents.
- Keep workspaces clean and organized to reduce the risk of slips, trips, and falls. Proper storage of materials and tools is essential to prevent accidents and injuries.
- Implement proper procedures for the disposal of waste generated during the handling and processing of composite materials. This includes the safe disposal of leftover materials, dust, and contaminated PPE.
- Implement proper procedures for the disposal of waste generated during the handling and processing of composite materials. This includes the safe disposal of leftover materials, dust, and contaminated PPE.

By implementing these measures, employers can create a safer working environment when dealing with composite materials, promoting the health and well-being of their workforce while minimizing the risk of accidents and long-term health issues.

4.1. Dangerous composites components

A polymer matrix (resin) is an essential component of composite structures. The most commonly used resins are polyesters epoxies and vinyl esters, in addition to more exotic resins such as Phenolics, Bismaleimide and Polyimide [11]. Each of these resins pose a health risk to the worker. All persons working with resins need to be aware of the health and exposure risks associated with each type of material they are working with; focusing primarily on the skin, lungs, and eyes. It is mandatory to wear the proper PPE at all times when working with any resin system.

A catalyst (Part ‘B’ of an epoxy system) or an initiator (MEKP) are the components that cause polymerization to take place in a resin system. Examples include methyl ethyl ketone peroxide and benzol peroxide. Working with these chemicals requires absolute adherence to safety precautions and the use of PPE appropriate to the chemicals involved. Workers must (legally) have access to MSDS — Material Safety Data Sheets and WHMIS — Workplace Hazardous Materials Information System for each and every chemical material they are required to work with [12].

The main concern with fiber reinforcements is the irritation caused by direct contact with the skin. Fibers that lodge into skin pores can be exceptional irritants. One of the worst mistaken beliefs is that 'fiberglass' dust isn't harmful. The glass fiber itself may be chemically inert, but the resin applied to it is not! Again, it is important to wear the appropriate PPE and educate workers in the proper use of the materials.

Dusts may be generated in several ways in advanced composite processes. The most common dust-generating processes are machining and finishing of cured parts and in repair of damaged parts. Much of the dust generated in these processes can be very fine and should be considered respirable. Studies of some graphite-epoxy finishing operations found respirable fractions ranging from 25% to 100% [13].

More dust is usually generated in finishing and repair processes since large surface areas are involved. Grinding, routing and sanding are frequently used methods in both processes. The repair process may require the use of abrasive blasting as well as sanding to remove existing paint or coatings. Typically, a synthetic blasting agent, e.g., plastic media blast, is used. Ingredients of the paint or coating being removed, such as lead or chromates, may also be of concern. The repair process may also require cutting or sawing to remove the damaged part area, and both may generate significant amounts of airborne dust.

In general, studies on composite dusts indicate that:

- The dusts are particulate in nature and usually contain few fibers;
- The dusts are thermally stable up to 250 °C and exhibit a high degree of cure; and
- Toxicology studies indicate the dusts should probably be controlled at levels below the PEL for inert dust, but not approaching the PEL for crystalline quartz.

Many of the solvents used in advanced composite processes are volatile and flammable. Most are skin and eye irritants, and some may be readily absorbed through the skin. Precautions must be taken when using organic solvents because they can facilitate the entry of toxic materials into the skin and organ systems. They may also enhance skin sensitization caused by the resin systems. Some (such as methyl alcohol) are poisonous, and all are capable of extracting fat from skin. Harmful effects from industrial exposures come principally from skin contact and inhalation.

Selection of the proper glove for protection is important. Permeation data are available for many industrial chemicals, especially solvents. However, in the case of resins and curing agents, not much data is available. This also is true for mixtures of solvents, as little or no testing has been done. Often the glove selection process is one of trial and error. If a skin rash or dermatitis is observed there are several possible causes: the wrong gloves may have been selected; improper work practices are being followed; the employee is deficient in personal hygiene practices; or adequate washing facilities are absent.

Several of the solvent classes most commonly found in the PMC workplace are listed below, along with general hazard information.

Several ketones are frequently found in PMC manufacture. These include: acetone (DMK), methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK) [12].

These solvents may cause eye, nose, and throat irritation, and prolonged contact with the liquid may result in defatting of the skin and resultant dermatitis. In high concentrations, narcosis is produced with symptoms of headache, nausea, light-headedness, vomiting, dizziness, incoordination, and unconsciousness. Ketones are volatile and flammable. Acetone is a popular solvent used for cleanup and may be found around the workplace in containers for this purpose [13].

Some of the lower-boiling alcohols are sometimes used in composites manufacture. These include: methanol (methyl alcohol), ethanol (ethyl alcohol), isopropanol (isopropyl alcohol).

These alcohols do not usually present serious hazards in the industrial setting. Toxicity is usually related to irritation of the conjunctivae and the mucous membranes of the upper airway. Contact with the liquid may cause defatting of the skin and dermatitis. These alcohols are volatile and flammable.

Three chlorinated hydrocarbon compounds in particular are found in the composites workplace: methylene chloride (dichloromethane), 1,1,1-trichloroethane (methyl chloroform), trichloroethylene.

Health effects typical of the group include irritation of the eyes and upper respiratory tract, dizziness, confusion, drowsiness, nausea, vomiting, and occasionally abdominal pain. Visual disturbances may also occur. Due to the solvents' defatting properties, repeated or prolonged skin contact with these liquids may cause dermatitis. Ability to depress the central nervous system is a characteristic property of all members of this group. These solvents are not particularly flammable. Many manufacturers have replaced the ketones with the above hydrocarbon solvents to reduce the risk of flammability [14].

Other solvents that may occasionally be used are: toluene, xylene, tetrahydrofuran (THF), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), gamma-butyrolactone (BLO), n-methyl pyrrolidone (NMP), n-butyl acetate, glycol ethers. Technical literature including MSDS's from the solvent supplier should be consulted about these or any chemicals used with advanced composites [15].

4.2. Workspace controls

Good workplace controls are essential in controlling exposure to process materials. Many of the materials, particularly the resins, curing agents, and fibers, present a potential dermal-exposure hazard. Many of the solvents and some of the curing agents present a potential inhalation hazard. Some materials present both a dermal and inhalation hazard. Ingestion may be a potential exposure hazard, but usually involves poor personal hygiene or contamination of eating facilities. The various types of workplace controls described below may typically be found in the advanced composite workplace [15].

Isolation (e.g., isolated storage, separate process areas, enclosures, closed systems) and local exhaust ventilation are the primary engineering controls found in advanced composites processes. These controls can be found in: resin mixing areas; heated curing areas including autoclaves; finishing and repair areas; controlling off-gases from exotherms.

Work practices, as distinguished from engineering controls, involve the way a task is performed. Some fundamental and easily implemented work practices that can be used to minimize exposures when working with advanced composites are: good employee training and education; following the proper procedures for production, process and control equipment; proper use, maintenance, and cleaning of personal protective equipment; good personal hygiene program; housekeeping; periodic inspection and maintenance of production, process and control equipment; and good supervision.

Helicopter blade manufacturing may involve repetitive tasks and prolonged periods of standing. Implementing ergonomic workstations and practices helps prevent musculoskeletal disorders and reduces the risk of injuries related to poor ergonomics. This includes providing adjustable workstations, anti-fatigue mats, and encouraging regular breaks. The handling of large and heavy materials, such as metal alloys and composite materials, poses a risk of musculoskeletal injuries if proper lifting techniques are not followed. Cutting and shaping of materials using machinery, such as saws and CNC machines, can generate sharp debris and expose workers to the risk of cuts and abrasions. Surface treatment processes, such as painting, coating, or chemical treatments, may involve the use of hazardous substances that can cause skin irritation or respiratory issues. The operation of heavy machinery, such as grinders or presses, can generate high levels of noise and vibration, potentially leading to hearing damage and musculoskeletal disorders. Certain manufacturing stages, such as heat treatment or curing processes for composite materials, involve high temperatures that pose a risk of burns or fire. Welding and grinding produce intense heat, sparks, and potentially harmful fumes, posing risks of burns, eye injuries, and respiratory issues. Assembling blades and conducting testing procedures may involve working with moving parts or high-speed rotating components, posing risks of entanglement or impact injuries.

Conclusion to the part IV

Ultimately, placing labour protection as a top priority in the manufacturing of helicopter blades is crucial for establishing a safe and conducive working environment. The complex procedures associated with manufacturing entail a multitude of potential risks, spanning from the operation of heavy machinery to exposure to chemicals and high-temperature procedures. Industries can ensure the safety and efficiency of their workforce by diligently addressing these risks.

The execution of extensive labour protection measures necessitates a multidimensional strategy. This encompasses the meticulous utilization of personal protective equipment, comprehensive training initiatives, routine equipment upkeep, and strict compliance with both local and international safety regulations. It is equally important to establish a strong safety culture, where employees are actively involved in promoting and implementing safety protocols.

The process incorporates continuous improvement, which involves conducting regular audits and assessments to ensure that safety measures are effective and current. Engaging with regulatory authorities and providing legal compliance support enhances an organization's dedication to establishing a workplace that not only meets but surpasses labour protection standards.

Investing in labour protection measures is ultimately an investment in the welfare and efficiency of the workforce. Ensuring unwavering commitment to safety in the evolving helicopter blade manufacturing industry is crucial for minimizing workplace accidents and injuries, as well as fostering the long-term sustainability and prosperity of the organization. Helicopter blade manufacturers can attain a harmonious equilibrium between operational excellence and worker welfare by cultivating a culture that places a high value on the health and safety of their employees.

PART V. ENVIRONMENTAL PROTECTION

5.1. Principles to reduce environmental pollution

Implementation eco-friendly technologies in composite structures manufacturing is a critical aspect that addresses the environmental impact of the processes involved in creating these advanced materials. Ensuring environmentally responsible practices in their production is essential for sustainable industrial growth. Industrial growth, when approached with a commitment to sustainable practices and environmental stewardship, has the potential to decrease its negative influence on the environment. Traditionally, industrial activities have been associated with pollution, resource depletion, and ecological degradation. However, advancements in technology, increased awareness of environmental issues, and evolving regulatory frameworks have paved the way for a more conscientious approach to industrial expansion.

Simple principles can be followed to reduce the impact of composite materials and their production processes:

The selection of raw materials, including resins and fibers, should prioritize environmentally friendly options. Using bio-based or recycled materials helps reduce the ecological footprint associated with composite manufacturing.

Implement processes that optimize the use of raw materials to minimize waste generation. This includes efficient cutting and molding techniques to reduce scrap and promote resource conservation.

Composite manufacturing often involves energy-intensive processes such as curing and molding. Implement energy-efficient technologies and practices, and explore the use of renewable energy sources to power manufacturing facilities.

Minimize emissions of volatile organic compounds (VOCs) and other pollutants associated with resin curing and other chemical processes. Install effective ventilation and filtration systems to control and capture emissions, preventing their release into the atmosphere.

Develop robust recycling programs to manage end-of-life composite materials and production waste. This can include the recycling of scrap materials, as well as the implementation of procedures to responsibly dispose of or reuse waste products.

Implement closed-loop systems where possible to circulate and reuse water, solvents, and other process materials. This reduces the demand for fresh resources and minimizes the environmental impact of manufacturing processes.

Conduct a thorough life cycle assessment to evaluate the environmental impact of composite structures from raw material extraction to end-of-life disposal. This holistic approach helps identify areas for improvement and guides decision-making to reduce overall ecological impact.

Adhere to or seek certifications such as ISO 14001 (Environmental Management System) or industry-specific eco-labels. Complying with recognized standards ensures that manufacturing practices meet established ecological benchmarks.

Invest in research and development to explore and adopt green alternatives and innovations. This could include the development of bio-based resins, eco-friendly curing processes, or new sustainable reinforcing materials.

Foster a culture of environmental responsibility among employees by providing education and training on the ecological impact of manufacturing processes. This awareness can lead to better adherence to eco-friendly practices.

Collaborate with environmental organizations and regulatory bodies to stay informed about the latest ecological standards and best practices. Engaging with external entities ensures alignment with broader environmental conservation goals.

By integrating these ecological considerations into composite structures manufacturing, industries can contribute to a more sustainable future. Embracing environmentally responsible practices not only minimizes the negative impact on ecosystems but also aligns with the growing global emphasis on sustainable and eco-friendly industrial processes.

5.2. Comparing with metal parts impact

Compared to conventional metal products, composite materials already have a much smaller impact on the environment.

Composite materials are an environmentally favourable option because they are recyclable. Because they can be recycled and reused, unlike conventional materials, they have less of an adverse effect on the environment. This makes composite materials a sustainable alternative by assisting in resource conservation and waste reduction.

Compared to conventional materials, composite materials have a lower environmental impact because they are produced utilising low-emission methods. Composite materials are a more sustainable option because their production takes less energy and emits fewer emissions [16].

Composite materials are excellent for usage in a variety of sectors because they have a high strength-to-weight ratio. Since they are lighter than conventional materials, the performance of the constructions that utilise them is enhanced. Additionally, by using less energy during shipping, composite materials are a more environmentally responsible option.

Composite materials offer increased strength and durability compared to traditional materials, ensuring a long service life for the structures they are used in. This reduces the need for frequent replacement, reducing waste and conserving resources.

Composite materials are safe and environmentally friendly because they don't contain any harmful elements. They have less of an impact on the environment than conventional materials because they don't discharge dangerous chemicals into the atmosphere [17].

5.3. Rotorcraft parts manufacturing influence

Helicopter parts manufacturing, like any industrial activity, can have both positive and negative influences on the environment. Understanding and addressing the environmental impact of helicopter parts manufacturing is crucial for promoting sustainable practices within the aerospace industry.

Positive influences:

Advances in material science contribute to the development of lightweight and high-strength materials, reducing the overall weight of helicopter components. This, in turn, improves fuel efficiency and reduces the environmental impact during the operational phase.

Continuous research and development efforts focus on enhancing the fuel efficiency of helicopters. Innovations in engine design, aerodynamics, and propulsion systems contribute to lower fuel consumption and reduced emissions during flight.

Manufacturers are increasingly considering the entire lifecycle of helicopter parts, from raw material extraction to end-of-life disposal. This holistic approach aids in identifying opportunities for resource conservation, recycling, and waste reduction.

The aviation industry, including helicopter manufacturers, adheres to stringent emission standards set by regulatory bodies. Compliance with these standards ensures that the environmental impact of emissions, such as nitrogen oxides (NOx) and particulate matter, is minimized.

Helicopter parts manufacturers are exploring and implementing recyclable materials, such as composites and alloys, which can be reused or repurposed at the end of their lifecycle. This reduces the demand for new raw materials and minimizes waste.

Negative influences:

The manufacturing process for helicopter parts can be energy-intensive, particularly during the production of complex components like turbine engines and composite structures. High energy consumption contributes to greenhouse gas emissions unless renewable energy sources are utilized.

Certain manufacturing processes involve the use of chemicals, coatings, and treatments that may have environmental implications. Efforts should be made to minimize the use of hazardous substances and to adopt environmentally friendly alternatives.

The manufacturing process can generate waste, including scrap materials and by-products. Proper waste management practices, such as recycling and responsible disposal, are essential to mitigate the environmental impact of manufacturing-related waste.

The extraction, processing, and transportation of raw materials for helicopter parts can contribute to deforestation, habitat disruption, and resource depletion. Responsible sourcing practices are essential to mitigate these negative environmental impacts.

Disposing of helicopter parts at the end of their lifecycle can pose environmental challenges. Efforts should be directed toward developing sustainable disposal methods, including recycling and reusing materials whenever possible.

Mitigation Strategies:

Implementing sustainable and green manufacturing practices, including the use of renewable energy, efficient processes, and eco-friendly materials, can significantly reduce the environmental impact of helicopter parts manufacturing.

Conducting comprehensive lifecycle assessments helps identify environmental hotspots and informs strategies for minimizing the overall impact, from raw material extraction to disposal.

Adopting eco-design principles involves considering environmental factors during the design phase, aiming to create products that are resource-efficient, easily recyclable, and have a reduced environmental footprint.

Establishing waste reduction programs and promoting recycling initiatives within the manufacturing process can contribute to minimizing the environmental impact of waste generated.

Investing in research and development for sustainable technologies, such as bio-based materials and advanced recycling methods, can drive innovation towards more environmentally friendly manufacturing processes.

Conclusion to the part V

In conclusion, helicopter parts manufacturing has the potential for both positive and negative environmental impacts. By adopting sustainable practices, embracing innovation, and adhering to stringent environmental standards, the industry can contribute to a more sustainable and eco-friendly aviation sector. Continuous efforts to minimize resource consumption, reduce emissions, and prioritize environmentally responsible practices are essential for a greener future in helicopter parts manufacturing.

CONCLUSION

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.

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.

In the third part, 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.

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