



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
ANTANAS GUSTAITIS AVIATION INSTITUTE
DEPARTMENT OF AERONAUTICAL ENGINEERING

Paulius Mažeika

**SMOOTH STEP CHANGING DUCTED FAN WITH BIMATERIAL BLADES,
ANALYSIS OF BLADE MECHANICS**

Master's degree Thesis

Study programme AEROSPACE ENGINEERING,
Code 6211EX060

Vilnius, 2024

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APPROVED BY
Head of Department

(Signature)
Darius Rudinskas
(Name, Surname)

(Date)

Paulius Mažeika

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(Title, Name, Surname)

(Signature)

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Deadline for completion of the final work according to the planned study schedule.

THE OBJECTIVES:

Master Thesis Assignment for Aerospace Students: Analyze and design a bimaterial blade of a vertically lifting unmanned aerial vehicle. The blade is designed for a ducted fan for optimum performance of both under static conditions and when flying at 46 m/s. The blade shall maintain a specific optimum geometry during the smooth pitch change according to the angles of intermingling set at its ends.

Academic Supervisor Giedrius Jočbalis

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

	Paulius Mažeika, 20173701	
	(Studento vardas ir pavardė, studento pažymėjimo Nr.)	
	Antano Gustaičio aviacijos institutas	
	(Fakultetas)	
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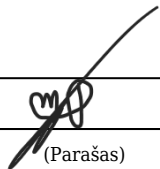
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Patvirtinu, kad mano baigiamasis darbas tema „Tolygiai žingsnį keičiantis kanalinis ventiliatorius su dvi-medžiaginėmis mentėmis, mentės mechanikos analizė“ yra savarankiškai parašytas. Šiame darbe pateikta medžiaga nėra plagijuota. Tiesiogiai ar netiesiogiai panaudotos kitų šaltinių citatos pažymėtos literatūros nuorodose.

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Annotation
The master's thesis investigates the smooth step-changing ducted fan bimaterial blade across three different flight modes. The aim of the work is to use numerical methods to perform blade twisting for a set flight mode in order to obtain the projected geometries. Additionally, the study aims to investigate how different 3D printing methods affect the accuracy of numerical results compared to projected geometries and the stress when the blade is twisted. The analytical part provides an overview of propeller types, examples of applications, design methods, and analysis programs. Blade modeling is performed using software "XRotor", "SolidWorks", and analyzed with "COMSOL Multiphysics". The investigation part consists of two blade surface evaluation methods and two different printing method simulations using the density-based topology optimization method of "COMSOL Multiphysics". The thesis concludes with a presentation of the findings from the investigation and simulations. Structure: introduction, 3 chapters, conclusions, references and appendixes. Thesis consist of 73 p. of text, 66 figures, 8 tables, 42 bibliographical entries.

Keywords: Duct, blade, bimaterial, modeling, simulation, topology optimization.
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Anotacija										
Baigiamajame magistro darbe tiriamas kanalinio ventiliatoriaus dvi-medžiaginės mentės žingsnių keitimo metodas trimis skirtingais skrydžio režimais. Darbo tikslas yra skaitiniais metodais atlikti mentės susukimą nustatytam skrydžio režimui siekiant gauti projektuojamas geometrijas. Be to, šiuo tyrimu siekiama ištirti, kaip skirtingi 3D spausdinimo metodai daro įtaką skaitinių rezultatų tikslumui, lyginant su projektuojamomis geometrijomis, ir įtempį, kai mentė yra susukama reikalingam skrydžio režimui. Analitinėje dalyje apžvelgiami propelerių tipai, panaudojimo pavyzdžiai, projektavimo metodai, analizės programos. Mentės modeliavimas atliekamas naudojant programinę įrangą „Xrotor“, „SolidWorks“ ir analizuojamas su „COMSOL Multiphysics“. Tiriamąją dalį sudaro du skirtingi mentės paviršiaus paklaidos vertinimo metodai ir du skirtingi 3D spausdinimo metodai, naudojant „COMSOL Multiphysics“ tankiu pagrįstą topologijos optimizavimo metodą. Išnagrinėjus teorinę medžiagą, paruošus metodiką ir atlikus skaitinius tyrimus ir analizes, pateikiamos baigiamojo darbo išvados. Darbą sudaro: įvadas, 3 skyriai, išvados, literatūros sąrašas ir priedai. Darbo apimtis – 73 p. teksto, 66 paveikslai, 8 lentelės, 42 bibliografiniai šaltiniai.										
Prasminiai žodžiai: Kanalas, propeleris, dvimedžiagis, modeliavimas, simuliacijos, optimizavimas.										

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INTRODUCTION

Aim.

Design and analyze the ducted fan blade that will be able to change steps in a smooth manner by twisting the root and tip of the blade while maintaining the same airfoil chords.

Object of Project.

A ducted fan blade with the ability to change airfoil steps depending on the flight mode in a smooth manner and keeping the same airfoil chords. The first geometry is the cruising flight geometry, and is assumed to be a base geometry for the other two geometries. The second geometry is the maximum flight speed geometry, and the third geometry is the take-off flight mode geometry. The last two geometries are assumed to be variable and shall be achieved when the base geometry is applied with specific angle displacement boundary conditions.

Investigation problem.

The optimal error evaluation method is unknown. Two methods are assumed to evaluate the blade surface error. The first is to use the Cartesian coordinate system. The second is to use the cylindrical coordinate system. One of these methods is optimal and shall output a lower average blade surface error value.

The impact of the average blade surface error value could lead to a filament distribution approach. The first printing method is to print the blade using two filaments separately. The second printing method is to print the blade using two mixed filaments.

Consequently, four different topology optimizations are required in accordance with the blade surface error evaluation methods and the filament distribution approach. Analyze and compare the results to accept the optimal error evaluation method and the printing approach.

The stress values and the areas of occurrence when the blade is twisted are unknown.

Tasks to solve the problem.

To achieve the necessary goals of project need to be fulfilled in order these tasks:

1. Analyzing of literatures sources;
2. Design and prepare three geometries of the ducted fan blades using *XRotor* software. First, the geometry shall be the base geometry during cruising flight mode. The second geometry shall be the maximum flight speed geometry. The third geometry shall be the take-off flight mode geometry. Extract the required chord beta angles;

3. Prepare and design a 3D base blade digital model (cruising flight mode) using *SolidWorks* or *Catia* computer-aided design (CAD) software. If necessary, apply modelling requirements to satisfy 3D printing rules or printer capabilities.
4. Perform an analysis of geometries surface error evaluation, two filaments distribution analysis, and twisting stress analysis using *COMSOL Multiphysics* computer-aided engineering (CAE) software.
5. Compare the results of the analyses and draw conclusions.

The novelty and relevance of the theme.

The application of 3D printing in the creation of bimaterial blades introduces a significant level of innovation. The 3D printing allows for precise control over material distribution, layer thickness, and internal structure, enabling complex designs that would be difficult with traditional manufacturing methods. By using 3D printing, it is possible to select filament material from a wide variety. This flexibility opens the door to innovative bimaterial combinations, allowing custom blades with specific mechanical properties.

With 3D printing, the design of the ducted fan and its blades can be easily customized to meet specific requirements. This adaptability is highly relevant for prototyping, experimentation, and customization in industries such as aerospace. Furthermore, 3D printing can reduce manufacturing costs and time compared to traditional methods. This is especially relevant for low-volume production or rapid prototyping, where traditional tooling and setup can be more expensive and time-consuming. Furthermore, 3D printing can contribute to sustainability by minimizing material waste. 3D printing can utilize recycled filaments, aligning with sustainability goals.

A smooth step-changing ducted fan blade could increase the efficiency for transition velocities of ducted fan type engines and could be a competitor for fixed-pitch and variable-pitch propellers. Variable-pitch propellers change their geometry by rotating blades around their mounting axis. The smooth step-changing blade could change its geometry by twisting the blade along its axis. Therefore, it could be a more efficient solution than using the variable pitch mechanism.

The smooth-step ducted fan blade could be a solution to reduce the weight of the aircraft or UAV. In addition, it could increase flight distances by increasing the aerodynamic properties of the blade and reducing fuel consumption.

This thesis was presented at the 26th Conference for Young Researchers “Science – Future of Lithuania.”

1. ANALYSIS OF THE LITERATURE

1.1. Blades overview

Propeller is a machine element which transmit power by converting its rotation into thrust force. It has a profile of aerofoil shape. This profile utilizes Bernoulli's principle to levitate the aerial vehicle. As the fluid flows over the blade, a pressure difference is formed between the rear and front side of the blade. This causes a net force to develop in the direction opposite to the gravity (Patel et al., 2017).

A fixed-pitch propeller is the simplest propeller type. The propeller blades remain at a fixed pitch that cannot change. To vary the thrust that a fixed-pitch propeller produces, the speed of rotation must be changed, by means of the engine's throttle (Haygood, 2022).

The advantages of the fixed-pitch prop are its simplicity of operation for low time pilots, it is the cheapest type to install on an aircraft and it is relatively maintenance free due to absence of a constant-speed unit (CSU). Its disadvantage is it gives its maximum efficiency at only one air speed, known as 'design air speed'. At any other speed, above or below the design air speed, the prop efficiency will be reduced. (Hitchens, 2015). The fixed-pitch propeller of the UAV is presented in Fig. 1.1..



Fig. 1.1. Fixed pitch UAV propeller (prepared by author)

A variable-pitch propeller has blades whose angle can be adjusted, at the point where the root of each blade is joined to the central propeller hub. Rather than a single piece of aluminum alloy, a variable-pitch propeller is constructed in section that can move relative to another (Haygood, 2022).

While the aircraft is in takeoff, climb, cruise, and beyond, the airflow around the propellers change. By allowing for the pilot to operate the angle of propellers, pilots can ensure that the aircraft

performs optimally during these various stages. Some variable pitch propellers also allow for the feathering of blades, which refers to when the chord line of the blade and the oncoming airflow are parallel to each other. By feathering, the aircraft can greatly reduce the amount of created drag, allowing for gliding and increased engine performance (Patrick, 2019). The variable-pitch propeller of the UAV is presented in Fig. 1.2..

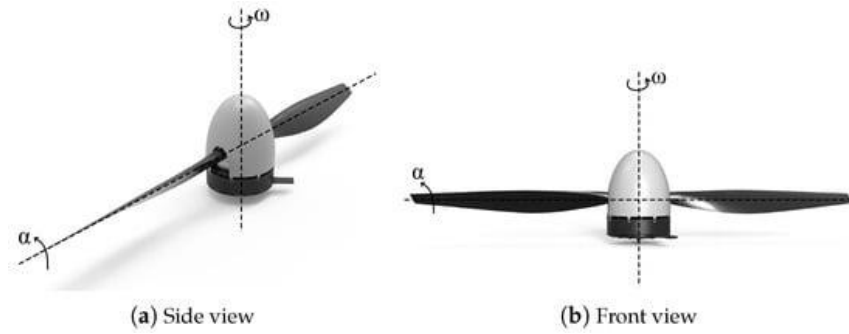


Fig. 1.2. Variable-pitch UAV propeller (Duan et al., 2024)

With variable pitch propellers, aircraft can adapt to various airspeeds, decreasing the chance of a stall while greatly improving fuel efficiency and performance (Patrick, 2019).

1.2. Blade design

The D. Bručas's (2012) "Propeleriai" book presents a basic understanding of propeller design. The author analyzes and describes the propeller geometry, size, thrust and pressure, effectivity, and power. The basic design parameters of the propeller are mentioned below (see Fig. 1.3.):

- B – number of blades;
- D – diameter of the propeller;
- r – cross-section radius (or blade element at a distance);
- x – relative section position;
- W – angular velocity.

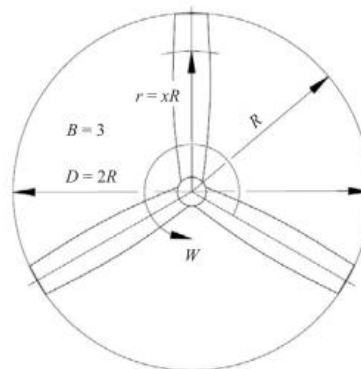


Fig. 1.3. Parameters of propeller (Bručas, 2012)

In E. Torenbeek (1976) analysis and airplane design author provides information of blade parameters for cross-section view (see Fig. 1.4.).

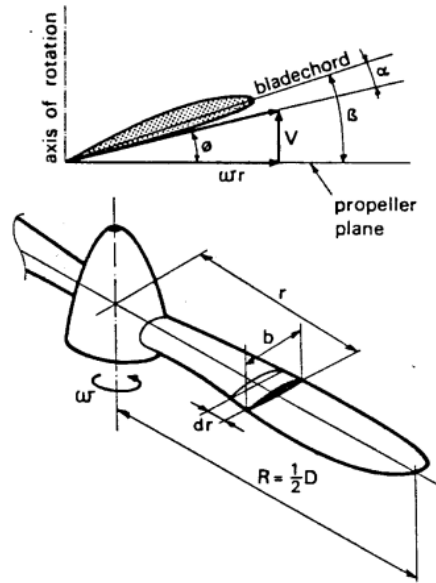


Fig. 1.4. Propeller main parameters and cross-section view (Torenbeek, 1976)

Parameters of blade cross-section:

- β – the angle between the blade chord and the propeller plane is the geometric pitch or blade angle;
- ϕ – effective pitch angle;
- V – airspeed;
- α – the angle of incidence of the blade element relative to the airstream.

1.3. Ducted fan description and usage

Ducted fan refers to a propulsion device composed of an open propeller surrounded in the duct. Compared with an isolated propeller of the same diameter, due to the enclosing effect of the duct, the formation blade tip vortex is restrained and the wake energy loss is reduced (Zhang et al., 2022). The ducted fan consist of these components (Fig. 1.5.):

- Fan shroud;
- Rotor blades;
- Stator;
- Electric motor;
- Nozzle.

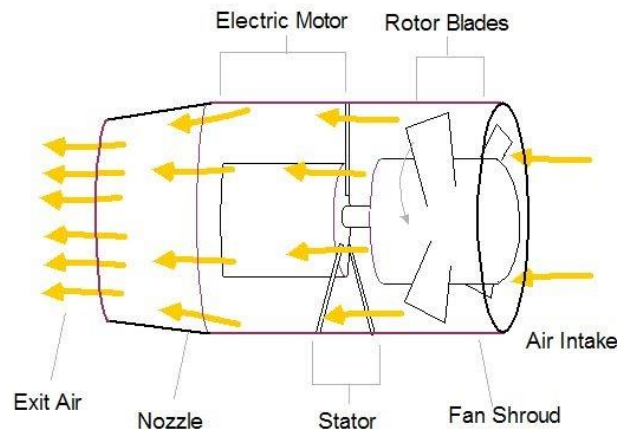


Fig. 1.5. Components of a ducted axial flow fan (Sgueglia et al., 2018)

In A. Barber book “Pneumatic Handbook” (1997) describes the ducted fan parts and the advantages of propeller type fans. The performance of a simple propeller type can be considerably improved by enclosing it within a closed-fitting open-ended cylindrical casing (Barber, 1997). Moreover, much depends on the coefficient of efficiency of the fan and its installation. A. Barber mentions few propeller design advantages. First, it has a simple construction. Second, it is low cost. The biggest advantage of the ducted fan is that it works quietly at low or moderate speeds if it is powered by an electric motor.

When a fan is designed, the clearance between the blades and the casing should be small. The smaller the clearance, the more effective the casing is in preventing recirculation at the blade tips and consequent loss of efficiency (Barber, 1997). In this case, the casing is normally designed parallel to the shaft that spins the blades and should cover the propeller and power plant. Ducted fans can produce almost two times the pressure and efficiency. Critical parameters during fan design are the number of blades, the shape of the blade, the diameter, and the clearance of the tip (see Fig. 1.6.).

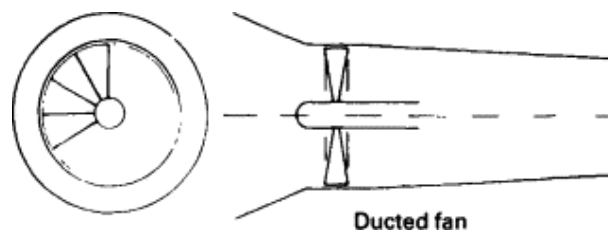


Fig. 1.6. Ducted fan view (Barber, 1997)

Ducted fans are used on:

- Aircrafts;
- Dirigible (see Fig. 1.7.);
- Hovercrafts;
- Drones;
- Ventilation systems.



Fig. 1.7. Mounted ducted fan on dirigible (Waser, 2003)

The Fig. 1.7. above shows the ducted fan mounted on the dirigible.

1.4. Ducted fan on UAV

In the research of X. Ren, C. Wang and G. Yi (2014) “Robust D-Stability Controller Design for a Ducted Fan Unmanned Aerial Vehicle” compares the ordinary fixed – wing aircraft with an unnamed aerial vehicle (UAV). The advantage of UAVs is that they are flexible. It does not need ground support and runways for takeoff and landing. The ducted fan UAV takes off vertically, so it can take off from various environments (e.g. city or mountains).

Another advantage of UAVs is that the ducted fan produces a higher tension compared to the isolated propeller with the same characteristic parameters. In addition, the ducted fan provides a better compact structure, less drag, low noise, and safer compared to helicopters.

The V-BAT 128 VTOL drone can be used in defence and commercial application such as search and rescue (SAR), border security, rapid tactical deployment, firefighting and disaster management, transportation, logistic resupply, infrastructure protection and security and energy and oil and gas operations. (Airforce Technology, 2021). On the below given Fig. 1.8. presents the UAV vehicle with ducted fan powerplant TOA 288.



Fig. 1.8. Unmanned aerial vehicle V-BAT 128 (Airforce Technology, 2021)

The cruising flight speed of V-BAT 128 drone is 24.2 m/s.

1.5. Experiments review

In the analysis of (2011) “Ducted Fan Aerodynamics and Modeling, with Applications of Steady and Synthetic Jet Flow Control” the authors assumed five different inputs to test the vehicle. Differences are made in the velocity speed, angle of attack range, and RPM range. The initial data table is given below (see Table 1.1.).

Table 1.1. Initial data of the ducted fan experiment (John et al., 2011)

Velocity	Angle of Attack Range	RPM Range
0 m/s	N/A	5 000 to 7 000, increments of 1 000
5,2 m/s	0° to 100°, increments of 10°	5 000 to 7 000, increments of 1 000
10,7 m/s	0° to 90°, increments of 10°	5 000 to 7 000, increments of 1 000
18,3 m/s	0° to 70°, increments of 10°	5 000 to 7 000, increments of 1 000
25,9 m/s	0° to 50°, increments of 10°	5 000 to 7 000, increments of 1 000

In the experiment of A. Akturk and C. Camci (2011) “A computational and experimental analysis of a ducted fan used in VTOL UAV systems” performed a CFD laboratory analysis using ANSYS computer software. The authors executed the analysis of a ducted fan, and the parameters are given below (see Table 1.2.).

Table 1.2. Parameters of ducted fan (Akturk & Camci, n.d.)

Rotor hub diameter	52 mm
Rotor tip diameter	120 mm
Rotor blade span	34 mm
Max. Blade thickness at tip	1,5 mm

In the article of S. Yilmaz, D.Erdem, M.S. Kavsaoglu (2015) “Performance of a ducted propeller designed for UAV applications at zero angle of attack flight: An experimental study” scientists executed the experiment of vertical take-off and landing ducted propeller UAV (see Fig. 1.9). It was used as the zero angle of attack which simulates vertical take-off and landing. The experiments were carried out using a 7000 RPM power plant and an *APC-16 x 8E*, 2 blade propeller. Propeller profiles which were used:

- NACA0018;
- NACA0012;
- NACA4312;
- NACA7312+4312;
- NACA M21+4312.

The airfoil view of these blades are presented below in Fig. 1.10..

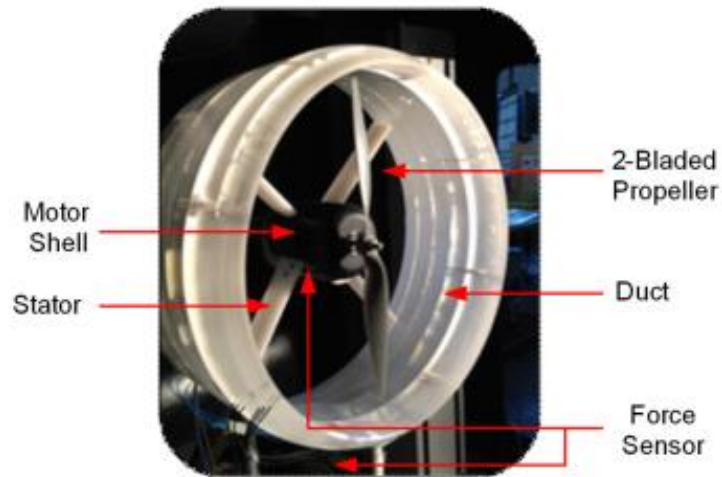


Fig. 1.9. Ducted fan experiment model (Yilmaz et al., 2015)

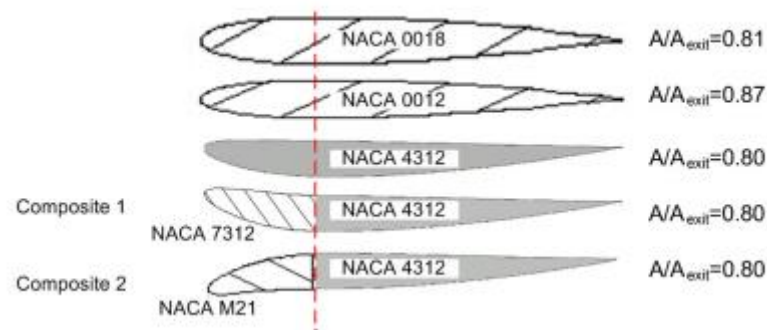


Fig. 1.10. Ducted fan blade profiles (Yilmaz et al., 2015)

For power plant design Sharman (2012) “Electric Ducted Fan – theory and practice” theory could be used for the initial input of power plant data input. The author describes the working principles of the ducted fan, propeller, and electric power plant.

W. Krusz and M. Rutkowski (2013) in article “Aerodynamic design of ducted propeller for MOSPUS project” performed the aerodynamic analysis of the ducted fan propeller. The main goal of the project was to obtain better performance from the propeller and improve its efficiency.

M. Drela and H. Youngren (2005) in article “Axisymmetric Analysis and Design of Ducted Rotors” offers different solutions during ducted fan design. This report describes the analytical formulation used for the design and analysis of a ducted propulsor with single or multiple blade rows (Drela & Youngren, 2005).

1.6. Finite element modelling review

The finite element solution may be broken into the following three stages.

1. Preprocessing: defining the problem.

The major steps in preprocessing are define keypoints/lines/areas/volumes, define element type and material/geometric properties, and mesh lines/areas/volumes as required (Nakasone et al., 2006). The amount of detail

required will depend on the dimensionality of the analysis, i.e., 1D, 2D, axisymmetric, and 3D (Nakasone et al., 2006).

2. Solution: assigning loads, constraints, and solving.

Here, it is necessary to specify the loads (point or pressure), constraints (translational and rotational), and finally solve the resulting set of equations (Nakasone et al., 2006).

3. Postprocessing: further processing and viewing of the results (Nakasone et al., 2006).

1.6.1. Mathematical analysis

Finite element equations can be derived from the governing differential equation by using the Method of Weighted Residuals (MWR). The idea of the method is to transform the differential equation into the corresponding algebraic equations by requiring that the error is minimum. These algebraic equations consist of numerical operations of addition, subtraction, multiplication and division. Such operations allow the use of calculators to determine solutions for small problems. For larger problems, a computer program must be developed and employed. The derived finite element equations are normally written in matrix form so that they can be used in computer programming easily (Dechaumphai & Sucharitpwatskul, 2018). The finite element equations for the truss element are,

$$[K]\{u\} = \{F\} \quad (1.1)$$

where $[K]$ is the element stiffness matrix; $\{u\}$ is the column matrix or vector that consists of the nodal displacement unknowns, also this variable can be marked as $\{D\}$; and $\{F\}$ is the column matrix or vector that contains the nodal loads (Dechaumphai & Sucharitpwatskul, 2018).

The quantity on the left-hand-side is called von Mises stress or effective stress and is denoted by σ_e ; in *Ansys*, it is also called equivalent stress,

$$\sigma_e = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (1.2)$$

Von Mises stress is a value used to determine if a given material will yield or fracture.

The equivalent strain, or von Mises strain, ε_e is defined by:

$$\varepsilon_e = \frac{1}{1+\nu'} \sqrt{\frac{1}{2}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]} \quad (1.3)$$

Where ν' , the effective Poisson's ration, defaults to the Poisson's ratio of the material, 0.5, or 0, depending on various applications (Lee, 2021).

From a strain tensor we can calculate the equivalent strain. Equivalent strain, as a scalar, is a straightforward variable to report strain results over a body, although it does not represent the complete information of the strain state (ANSYS, 2020).

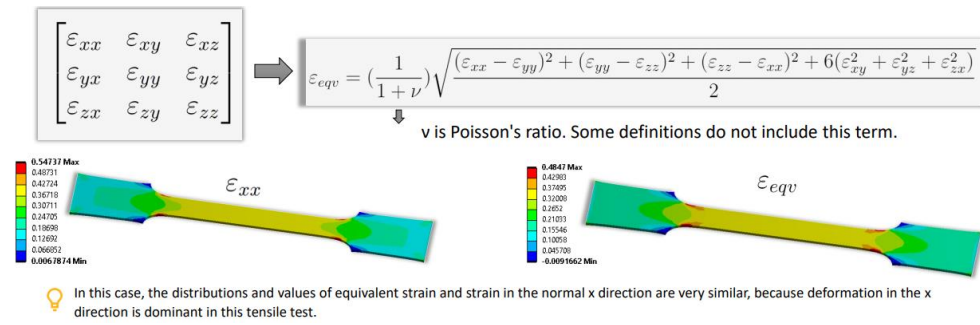


Fig. 1.11. Equivalent strain formula and graphical example (Ansys, 2020)

The material failure point is not necessarily always the breaking point or fracture point. Depending on design objectives, a material failure can be defined as occurring when the yield point or a certain amount of diction is reached (Ansys, 2020).

1.6.2. Meshing overview

Meshing is one of the most important steps in performing an accurate simulation using FEA. A mesh is made up of elements which contain nodes (coordinate locations in space that can vary by element type) that represent the shape of the geometry. An FEA solver cannot easily work with irregular shapes, but it is much happier with common shapes like cubes. Meshing is the process of turning irregular shapes into more recognizable volumes called “elements”.

There are two main types of meshing methods. For these purposes it is referring to 3D models:

- Tetrahedral element meshing or “tet”;
- Hexahedral element meshing or “hex”.

Hex or “brick” elements generally result in more accurate results at lower element counts than tet elements. If it is complex geometry, tet elements maybe the best choice (ANSYS BLOG, 2021). Correct and incorrect elements are presented below on Fig. 1.12..

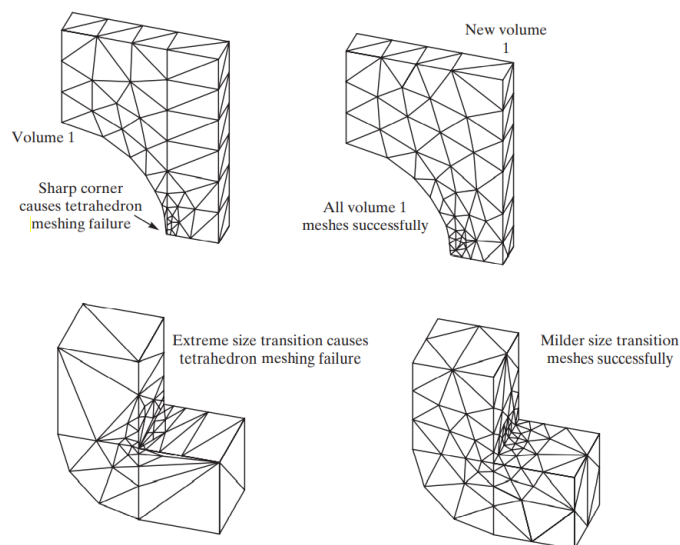


Fig. 1.12. Correct and incorrect Tetrahedral elements (Moaveni, 2014)

Meshing is important because it allows designers and engineers to create predictive models of real-world situations computationally – the more accurate mesh, the more performant the simulation will be (Spatial team, 2022).

Benefits of high-quality mesh in FEA:

- Increase simulation validity,
- Increased reliability across simulations,
- Optimal convergence,
- Reduced solve time.

The impact of low-quality mesh in FEA:

- Inaccurate simulation results,
- Low-quality or illegal cells leading to instability,
- Decreased reliability across simulations,
- Bad convergence,
- Long solve times,
- A lot of wasted time, money and manpower.

Density-based topology optimization operates on a fixed mesh of finite elements penalizing the mechanical properties of elements. This penalization uses an interpolation function to find the optimal void/solid material distribution that minimizes an objective function. The homogenization method and the Solid Isotropic Material Penalization (SIMP) method are the most popular density-based topology optimization approaches, being the latter the most implemented method in commercial software probably due to its simplicity and feasibility (Herrero-Pérez et al., 2022).

Density-based topology optimization models the mechanical properties of finite elements using a power-law interpolation function between void and solid. The interpolation function relates the design variable and Young's modulus of finite elements. This strategy allows us to use gradient-based optimization methods to address the optimization problem. The number of optimization variables is of paramount importance in the optimization process. In the ideal case, the refinement of the mesh refinement increases the accuracy of the Finite Element Analysis (FEA) and improves the evaluation of the objective function (Herrero-Pérez et al., 2022).

1.7. 3D printing overview

Fused deposition modeling, or FDM for short, is a material extrusion method of additive manufacturing where materials are extruded through a nozzle and joined together to create 3D objects. A typical FDM 3D printer, therefore, takes a polymer-based filament and forces it through a heated

nozzle, which melts the material and deposits it in 2D layers on the build platform. While still warm, these layers fuse with each other to eventually create a three-dimensional part (Carolo, 2024).

In Hudson (2020) article “3D Printer Nozzle Sizing Guide” and Berls (2024) book “Teaching Practical Theatrical 3D Printing” it is mentioned, that the standard 3D printer nozzle size is 0.4 mm. However, there is a variety of printer nozzles. With the smaller size of nozzle, the printing time can become longer, on the other hand the resolution is improved. With the larger size, the printing time can be faster, but lessened resolution quality can be expected.

Dual is the ability for a filament-based 3D printer to use at two different materials. These could be entirely different materials, or as simple as two different colour of the same material (Stevenson, 2018).

The most practical and popular reason for using dual extrusion is the ability to 3D print with dissolvable support material. This very powerful technique enables complete freedom of design; there is no longer any need to consider the complexities of support structure design or removal (Stevenson, 2018).

Figure below presents the parallel extruder 3D printing example (see Fig. 1.13.).

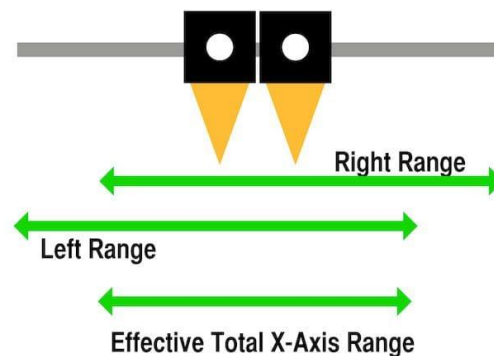


Fig. 1.13. Parallel extruder (Stevenson, 2018)

Parallel. The earliest form of dual extrusion was and, still is the simplest approach: strap on a second hot end and extruder to operate in parallel with the first toolhead. These were relatively simple to design into hardware, but had several disadvantages and are thus not favored as much these days (Stevenson, 2018). The first disadvantage of the parallel extruder is the weight issue. Two hot ends, and sometimes extruder motors as well, weigh quite a bit and impart a lot of motion momentum challenges when attempting to move the nozzles around at high speed (Stevenson, 2018). The second disadvantage occurs when one of the nozzles does not print and stays non-active. It means that it can pollute the print.

The “mixing” hot ends appears to be a single hot end and nozzle, but in fact it is a complex shape that allows more than one filament to enter it (Stevenson, 2018). The mixing printing example is presented below (see Fig. 1.14.).

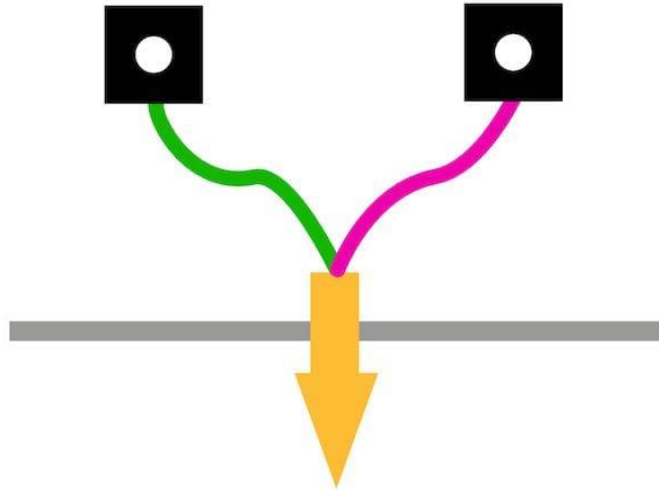


Fig. 1.14. A maxing nozzle with more than one filament (Stevenson, 2018)

Advanced slicing software manages the precision movements of the two extruders to feed material into the mixing nozzle. It is possible to extrude one material by feeding it at 100 % speed, with the other extruder at 0 %, or vice versa. It’s also possible to mix materials, for instance by running each extruder at 50 % speed (Stevenson, 2018).

This solves the momentum problem and the drip issue, but introduces another challenge: mixing latency (Stevenson, 2018).

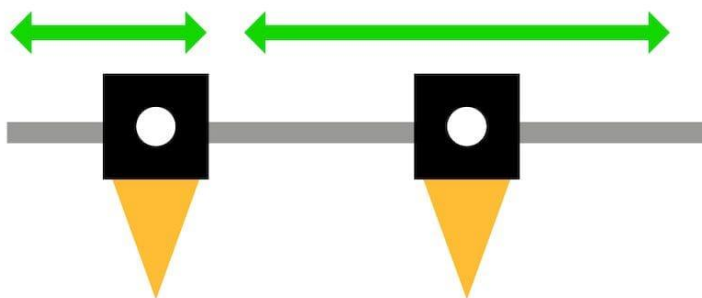


Fig. 1.15. Independent extrusions

A very recent approach is to employ dual independent toolheads. Essentially this is the same as the parallel approach, with the difference being that the two toolheads can move independently. Very often they are mounted on the X-axis, so “independent” means only on that axis; they move coincidentally on the Y-axis (Stevenson, 2018).

1.7.1. 3D materials overview

Several different PLA and TPU 3D printing filaments are analyzed. PLA stands for polylactic acid materials. TPU stands for thermoplastic polyurethane materials. The mechanical properties of the filaments are presented below in Table 1.3.. Tensile modulus, density, Poisson’s ratio, and ultimate tensile strength properties are indicated. The thermoplastic polyurethane material is only *NinjaFlex*, and the other materials are PLA. The tensile yield strength of *NinjaFlex* is equal to 4 MPa.

Table 1.3. 3D printing filaments mechanical properties (ColorFabb, 2022; Mohammed, 2022; NinjaTek, 2016; FormFutura, n.d.)

Manufacturer name	Tensile modulus, GPa	Density, g/cm ³	Poisson’s ratio	Tensile strength, Ultimate, MPa
NinjaFlex	0.012	1.235	0.36	26
eSUN	2.100	1.246	(0.36)	65
ColorFabb	3.334	1.240	(0.36)	43
FormFutura, Volcano PLA	3.900	1.270	(0.36)	39

None of the material technical data sheet documents and presents PLA Poisson’s ratio. In A. Kołodziej, P. Żur1, A. Baier and W. Borek (2019) “Influence of 3D-printing Parameters on Mechanical Properties of PLA defined in the Static Bending Test” article it was analyzed fused

deposition modelling (FDM) method printed parts. Here, the Poisson ratio is equal to 0.36 and is mentioned as a bulk mechanical property.

In S. Farah, D.G. Anderson and R. Langer (2016) article “ Physical and mechanical properties of PLA, and their functions on widespread applications – A comprehensive review” PLA material Poisson’s ratio is equal to 0.36.

The numbers in brackets indicate that the value is assumed from the literature analysis.

1.8. Conclusions from the analysis

1. The blade design would be focused on applied to the *V-BAT 128* UAV. A similar blade diameter and power plant would be used.
2. For the blade design, the NACA0012 and NACA0018 profiles would be used.
3. The cruising flight mode speed will be considered as 24.2 m/s for the propeller designing.
4. Tetrahedral mesh elements should be used, as the blade is assumed to be a complex geometry part.
5. The minimum corners length of the blade should not be less than 0.4 mm.
6. For further analysis, two different cases of the printing method would be taken into account. Firstly, printing the blade using filaments separately. Second, printing the blade using mixed filaments. These filaments would be *NinjaFlex* and second *Volcano PLA*.

2. ANALYSIS OF RESEARCH METHODS

The diagram below presents the overview of the analysis method and strategy (see Fig. 2.1).

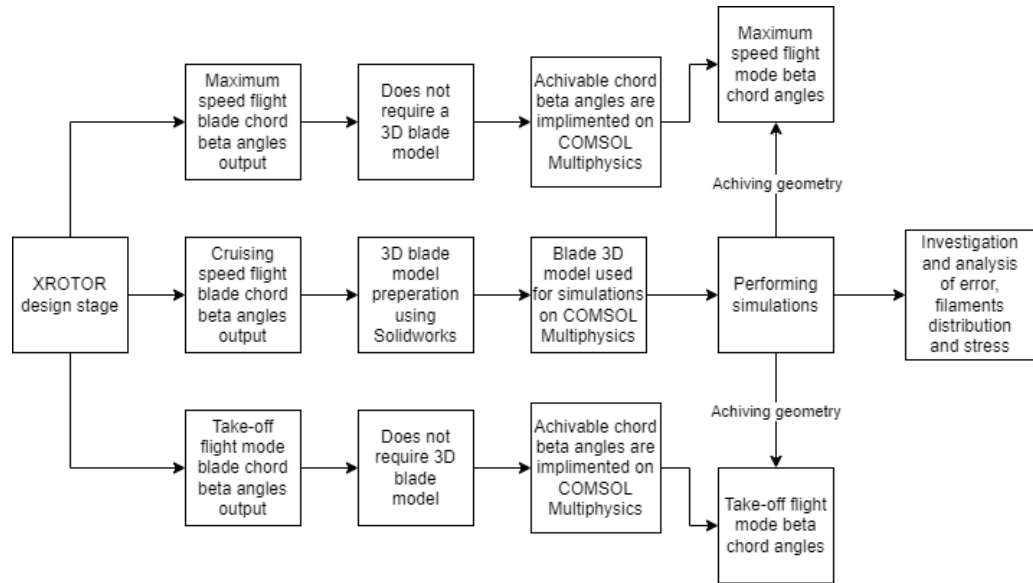


Fig. 2.1. Overview of the method and strategy

The analysis begins with the design of the blade using *XRotor* software. It is necessary to get the three flight-phase blade chord beta angles as an output. The 3D modeling with *SolidWorks* software is performed only for the cruising flight mode blade. It is accepted as base geometry, which is further used on *COMSOL Multiphysics* computer-aided engineering software. The maximum flight speed and take-off flight mode blade beta chord angles are used as achievable angles for base geometry.

2.1. Blade modelling

XRotor software is required to obtain the aerodynamic chord lengths and the required twist angles between different flight modes. Also, it exports the coordinates-based data to prepare a CAD model. The preparation of the CAD model is required for the FEM analysis of the blade.

Initial data for the ducted fan blade for the cruising flight mode:

1. Number of blades – 2;
2. Tip radius – 0.4 m;
3. Hub radius – 0.06 m;
4. Hub wake displacement body radius – 0 m;
5. Airspeed – 24.2 m/s;
6. Power plant revolutions – 3250 RPM;
7. Power plant power – 9140 W.

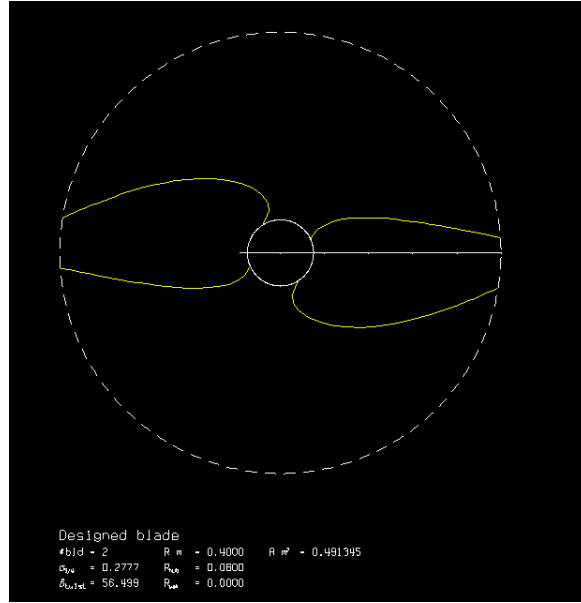


Fig. 2.2. Axial Geometry (prepared by author)

For the blade root, it was chosen to apply the NACA0018 profile and for the tip, the NACA0012 profile. Both profiles are presented in Fig. 2.3.. Furthermore, the *XRotor* software uses the main aerodynamic parameters of the profiles, such as:

1. Lifting power coefficient dependency on angle of attack;
2. Lifting power coefficient maximum and minimum values;
3. Minimal drag coefficient;
4. Lifting power coefficient at minimum drag coefficient;
5. Reference Reynolds number.

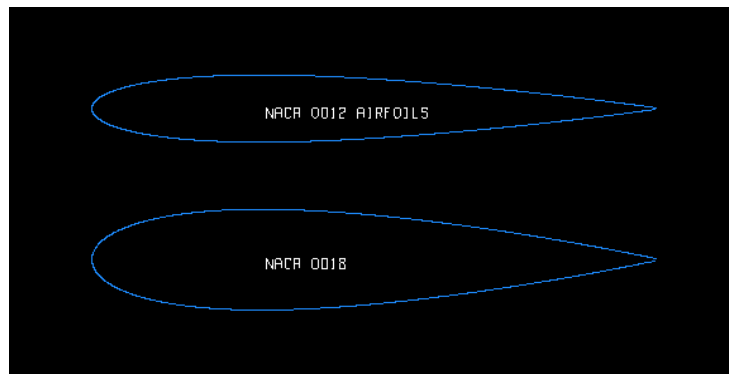


Fig. 2.3. NACA0012 and NACA0018 profiles (prepared by author)

With the initial design data given above, the blade geometry would be designed for the cruising flight mode. The cruise flight mode is assumed as the initial geometry between the maximum speed flight mode and the take-off flight mode. With modification of the flight speed value, the chord beta angles required for the maximum speed and take-off flight mode are generated. In the *XRotor* software, the maximum speed is modified to 46.2 m/s and the take-off flight speed is modified to 2 m/s. All three flight modes beta chord angles coordinate dataset were exported and modified from cylindrical coordinate system to Cartesian coordinate system.

2.2. Blade CAD preparation

The blade airfoil output coordinates in the cruising flight mode of the *XRotor* software are based on a cylindrical coordinate system. As a result, these coordinates were converted to the Cartesian coordinate system. This convergence allows to input the blade airfoils coordinates to *SolidWorks* software. These airfoils are shown in Fig. 2.4..

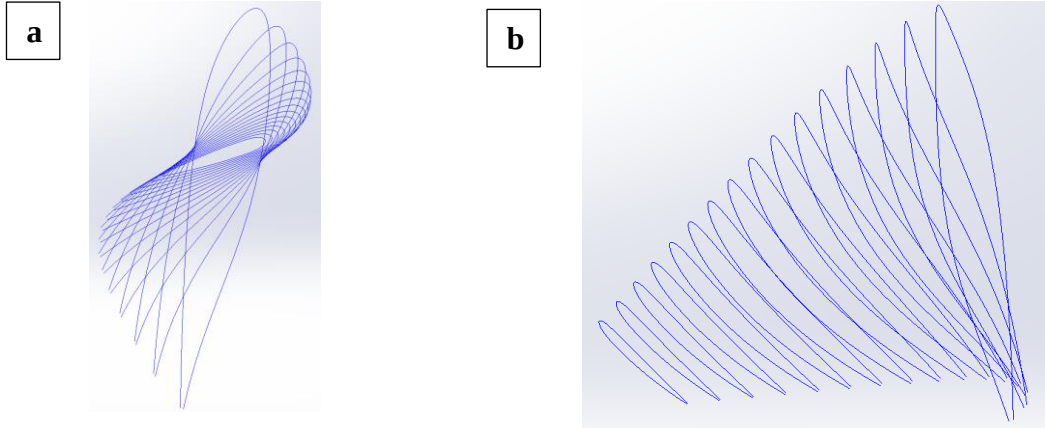


Fig. 2.4. Blade airfoils distribution: (a) left side XY, (b) right side isometric view
(prepared by author)

The trailing edge length of the blade tip is modified and equal to 1.05 mm, as shown in Fig. 2.5.. The trailing edge length of the blade root is also modified and equal to 3.55 mm (see Fig. 2.6.). The other trailing edges were modified in accordance with a range of 1.05 mm up to 3.55 mm. The minimum lengths of these corners shall be 0.4 mm because the standard 3D printer nozzle size is 0.4 mm.

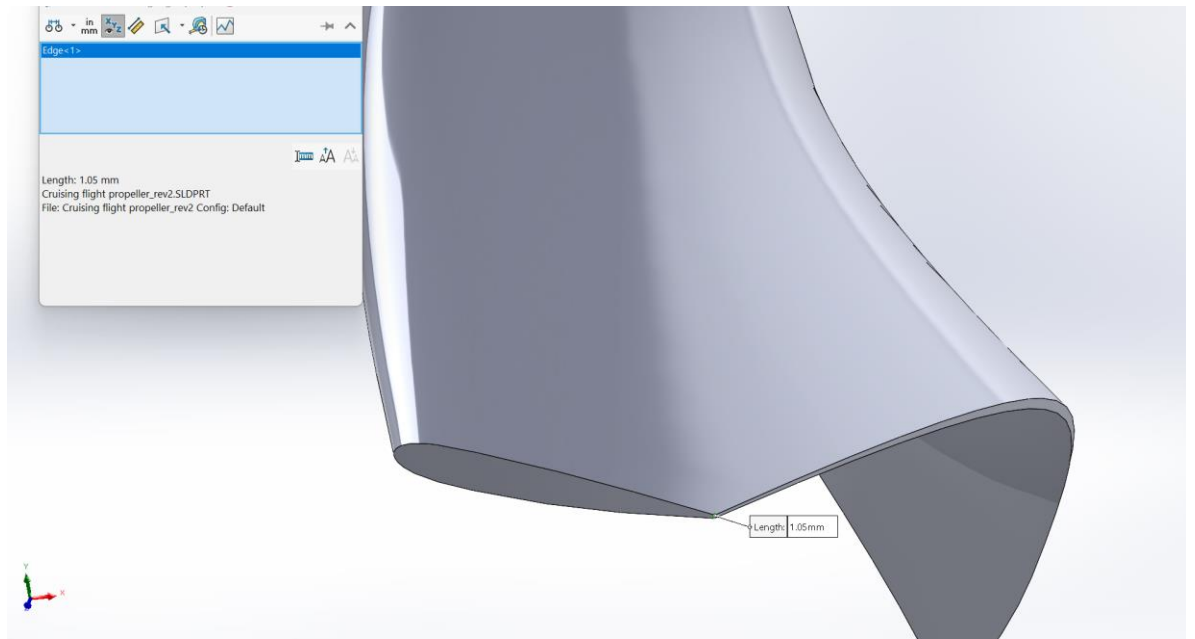


Fig. 2.5. Location and measurement of the edge of the trailing edge of the blade tip (prepared by author)

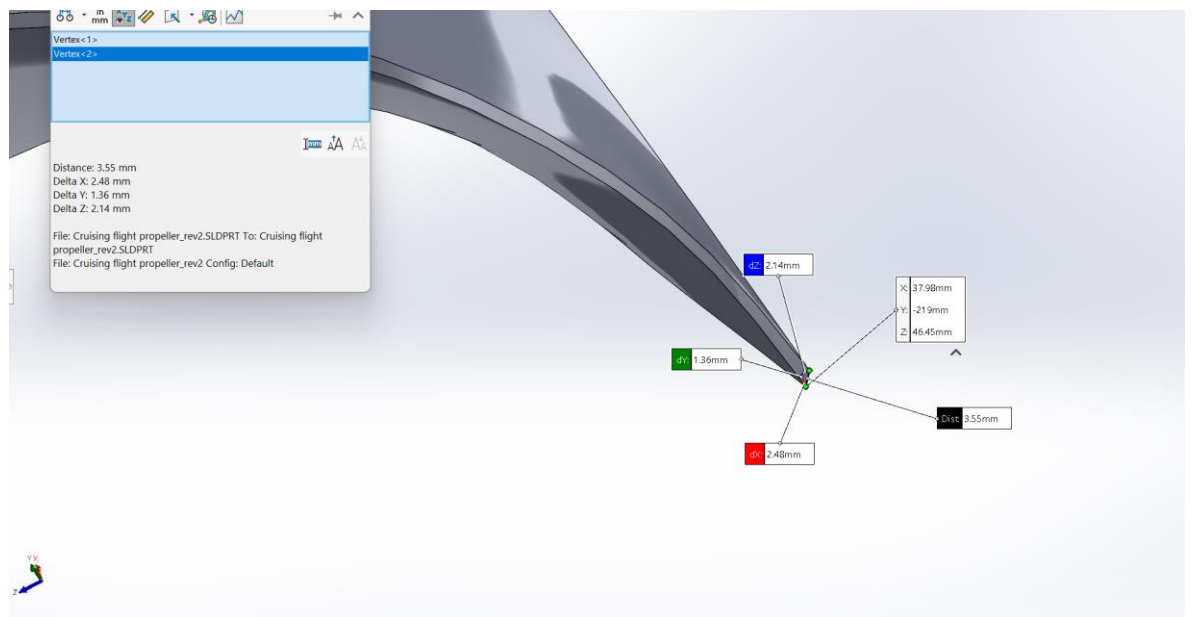


Fig. 2.6. Location and measurement of the trailing edge of the blade root (prepared by author)

After required modelling commands in *SolidWorks*, the final solid-blade model is pictured below (Fig. 2.7.).

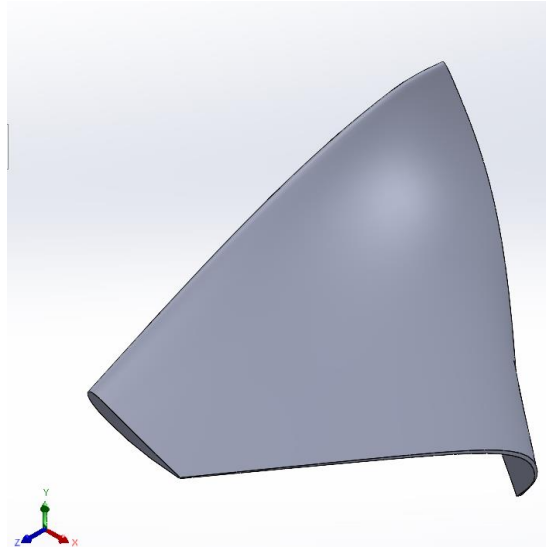


Fig. 2.7. Solid blade model, isometric view (prepared by author)

After the final step, the 3D solid model is prepared to be imported into CAE software.

2.3. Blade FEM preparation

The blade is meshed with free tetrahedral mesh, second-order elements. The minimal element size is 6 mm and the maximum element size is 8 mm. The total number of elements is 62 813. The meshed blade is presented below in Fig. 2.8..

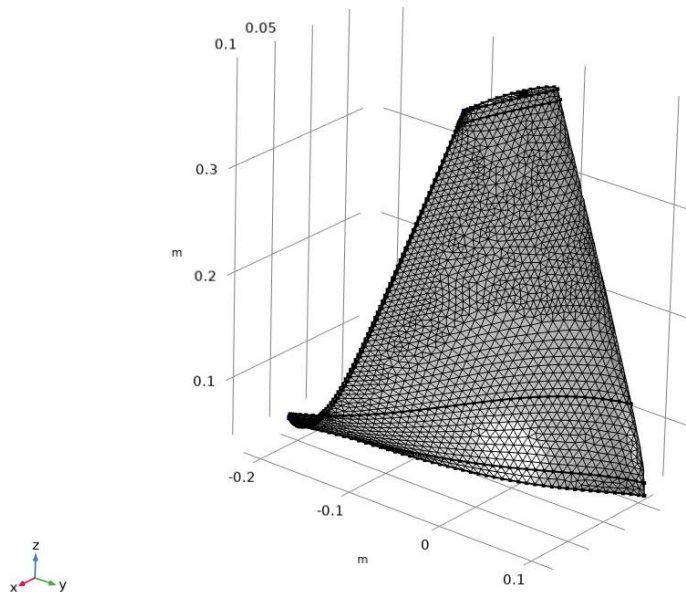


Fig. 2.8. Meshed blade (prepared by author)

For the mesh quality check, it was chosen to use the skewness method. The average element quality is 0.6765, the minimum element quality is equal to 0.1965. The elements quality is presented below in Fig. 2.9..

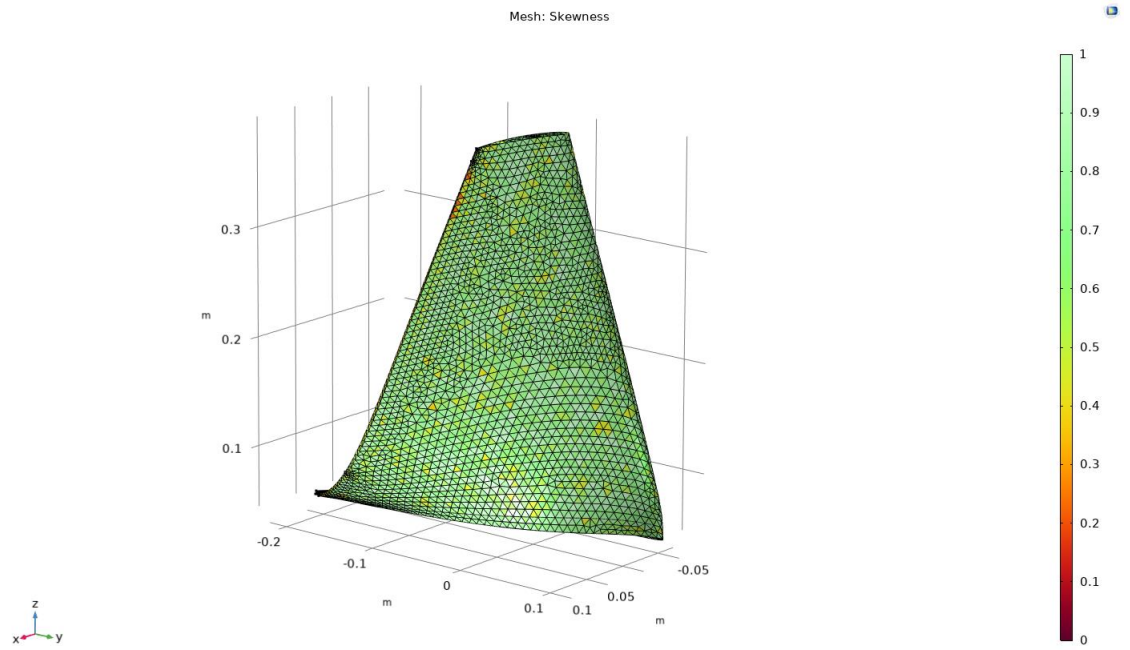


Fig. 2.9. Blade mesh quality, isometric view (prepared by author)

The lower quality elements (element quality < 0.3) are pictured below in Fig. 2.10. at the blade tip and Fig. 2.11. at the root of the blade.



Fig. 2.10. Elements quality < 0.3 at the tip of the blade (prepared by author)

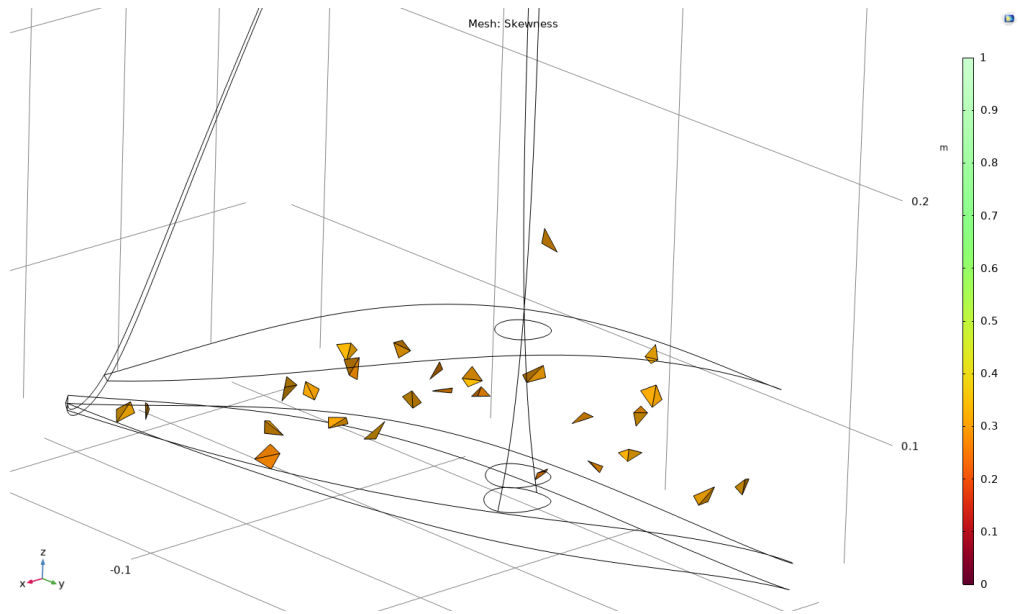


Fig. 2.11. Elements quality <0.3 at blade root (prepared by author)

Boundary conditions are applied on the tip of the blade and on the root. It is presented on Fig. 2.12. and Fig. 2.13. in the following. Both boundary conditions were applied as prescribed angle displacements. In the analysis, the tip and root surfaces are rotated along the Z-axis in different directions for maximum flight speed and take-off flight mode.

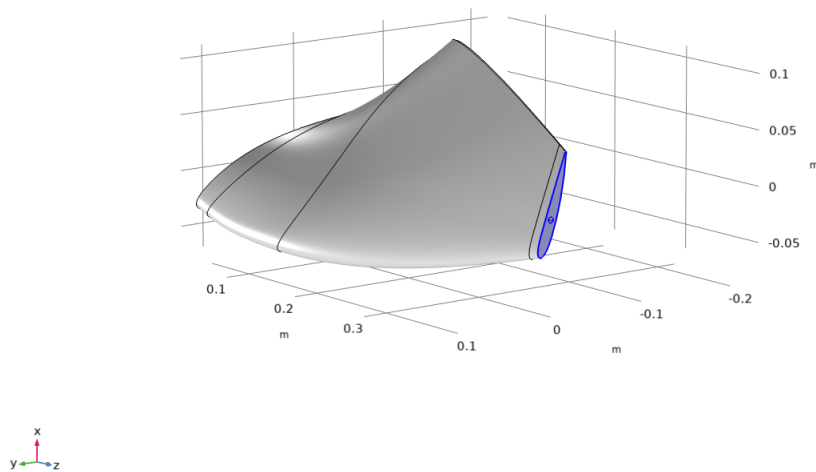


Fig. 2.12. Boundary condition on the blade tip (prepared by author)

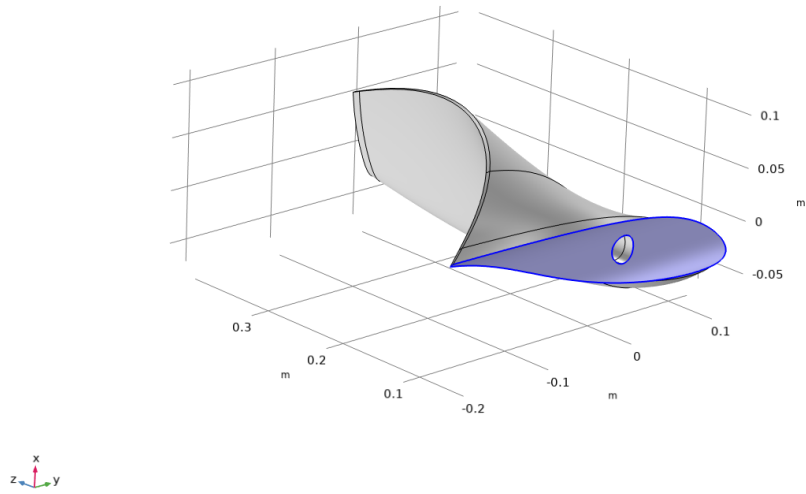


Fig. 2.13. Boundary condition on the blade root (prepared by author)

The topology optimization uses two different materials. The first material is *NinjaFlex*, which is attributed as thermoplastic polyurethane (TPU). The second material is *Volcano PLA*, which is attributed to polylactic acid material (PLA).

2.4. Blades geometry error estimation

The error determination analysis would be applied to 2/3 of the blade geometry. The 1/3 of the blade geometry is not taken into account and will not be added in the error evaluation. The reason is narrowed pitch angles at the root of the blade and at the tip of the blade. The split line is the starting point from which the blade geometry analysis is started. The graph in Fig. 2.14. indicates maximum flight speed, take-off speed, and cruising flight speed modes, and the split line position.

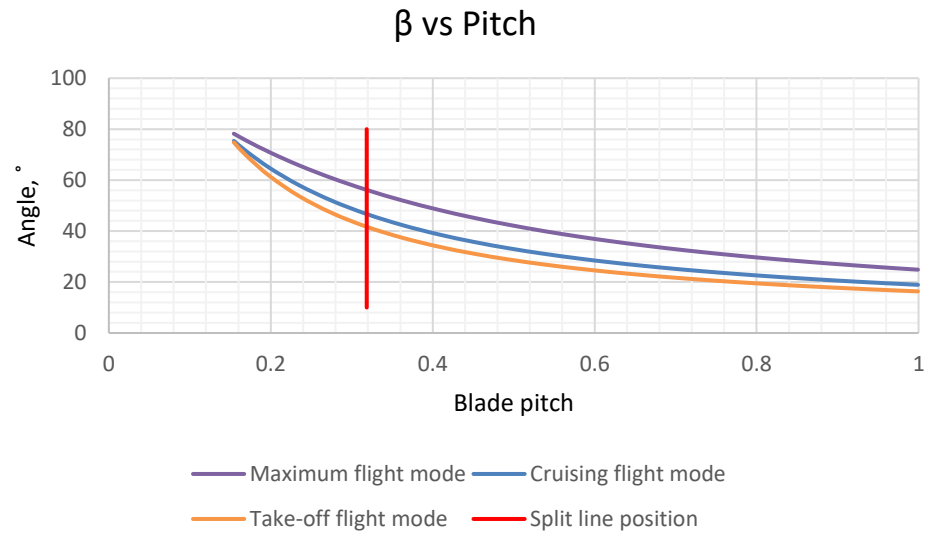


Fig. 2.14. Angle β vs pitch (prepared by author)

The blade geometry of the cruising flight mode is accepted as the base geometry for the maximum flight speed and the take-off flight mode. The diagram Fig. 2.15. presents the difference between the cruising flight mode angles, maximum flight speed angles, and take-off flight mode angles.

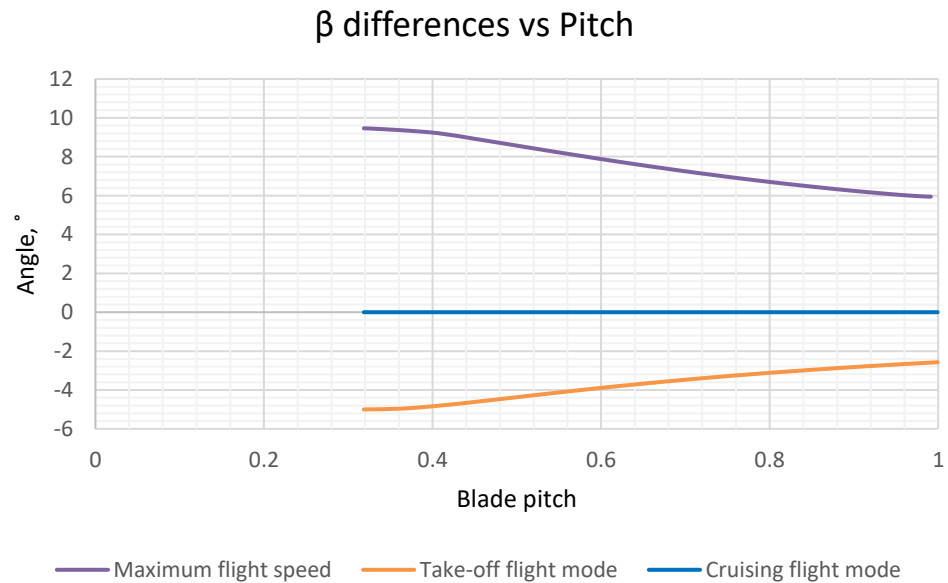


Fig. 2.15. β differences vs pitch (prepared by author)

The maximum flight and take-off flight modes geometries are simulated using *COMSOL Multiphysics* software. The base geometry has four boundary conditions. These boundary conditions are angle displacements. The first two boundary conditions are needed to obtain the maximum flight speed mode blade geometry, the base geometry blade shall be twisted at the blade tip and root. The base geometry blade tip has to be twisted in a counterclockwise direction, as is shown below (see Fig. 2.16.) on the left-hand side figure (a). The base geometry blade root has to be twisted clockwise, as

is shown below (see Fig. 2.16.) in the right-hand side figure (b). When these two surfaces are twisted at a specific angle, then the maximum flight speed geometry shall be obtained.

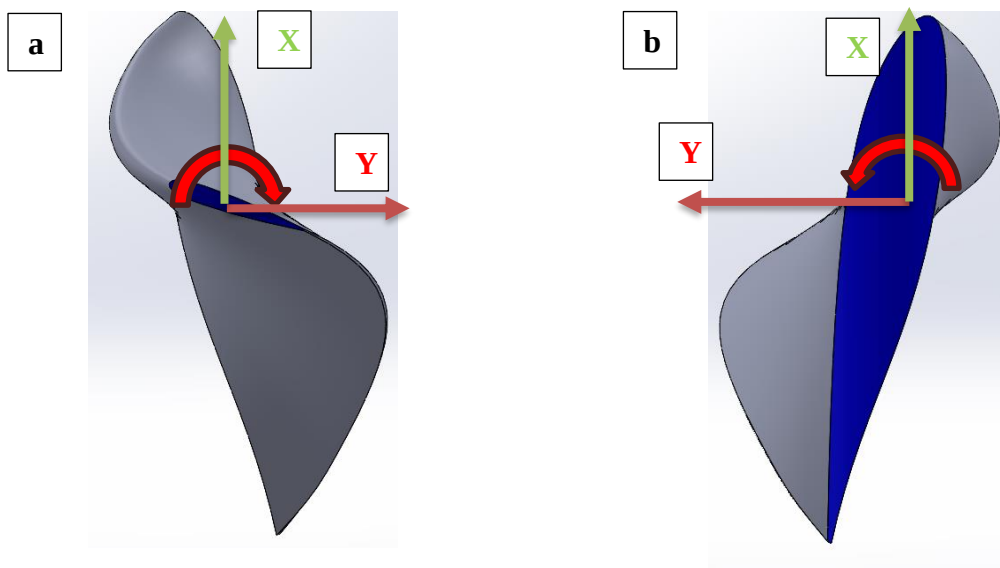


Fig. 2.16. Cruising flight mode geometry twisting directions to achieve maximum speed flight mode geometry: (a) – twisting blade tip; (b) – twisting blade root (prepared by author)

The same method is applied to the blade geometry in the take-off flight mode. But in this case, the angle displacement directions are vice versa compared to the maximum flight speed mode. On the figure below (see Fig. 2.17.) , on the left-hand side (a), the angle displacement of the blade tip applied counterclockwise, and on the right-hand side (b), the angle displacement of the blade root applied clockwise.

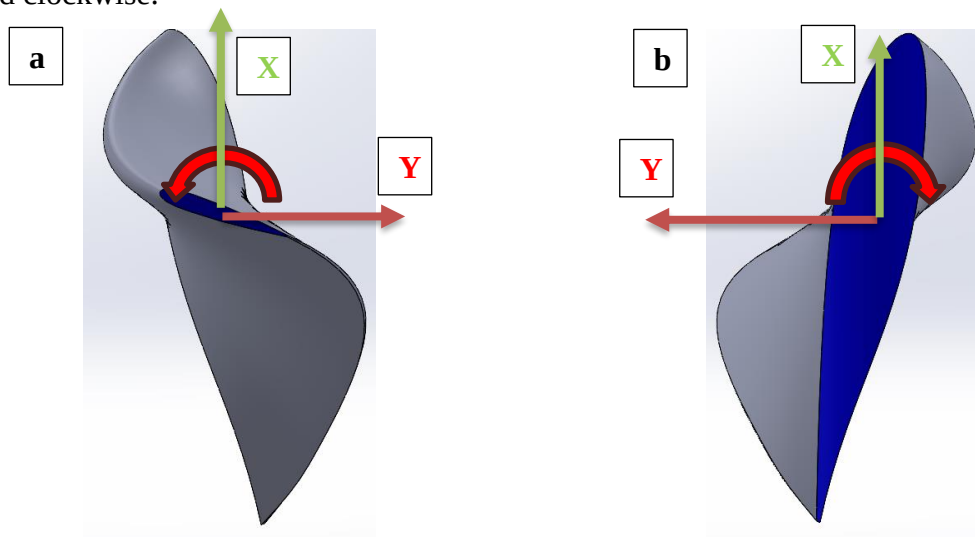


Fig. 2.17. Twisting directions of the cruise flight mode geometry to achieve the take-off flight mode geometry: (a) - tip of the twist blade; (b) - root of the twist blade tip; (b) – twisting blade root (prepared by author)

As a result, from one base geometry, the other two can be achieved when four angle displacements are applied as a boundary condition. The angle displacement boundary conditions for the cruising flight speed blade geometry will try to achieve maximum speed and take-off flight mode blade geometries.

The split line, 2/3 of blade geometry, and 1/3 of blade geometry are respectively indicated in Fig. 2.18. and Fig. 2.19.. This naming and indication will be used in later chapters.

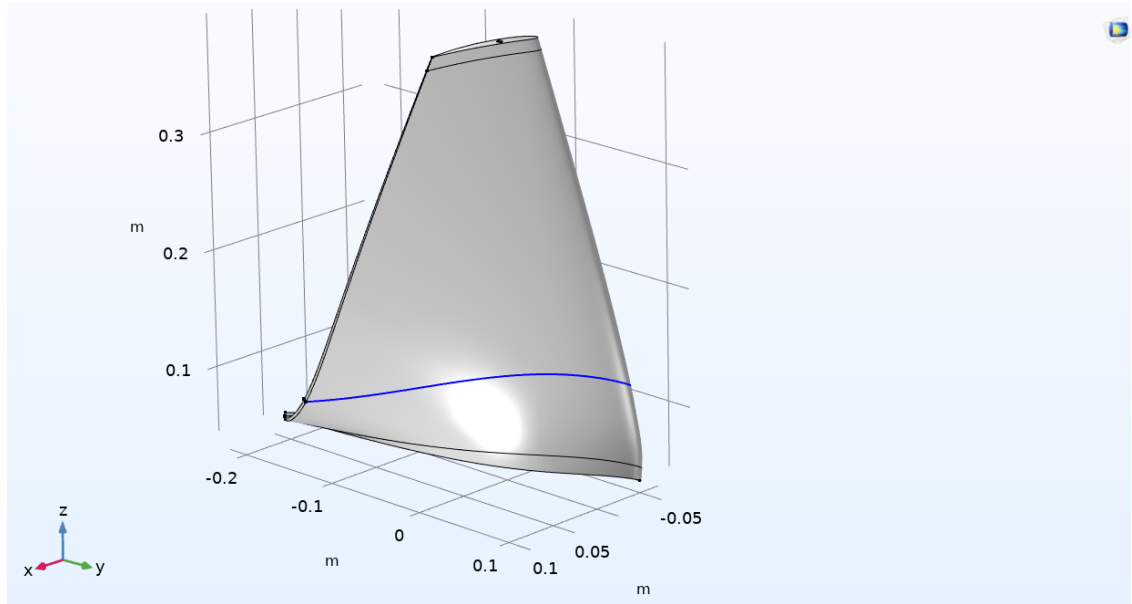


Fig. 2.18. Split line marked with a blue line (prepared by author)

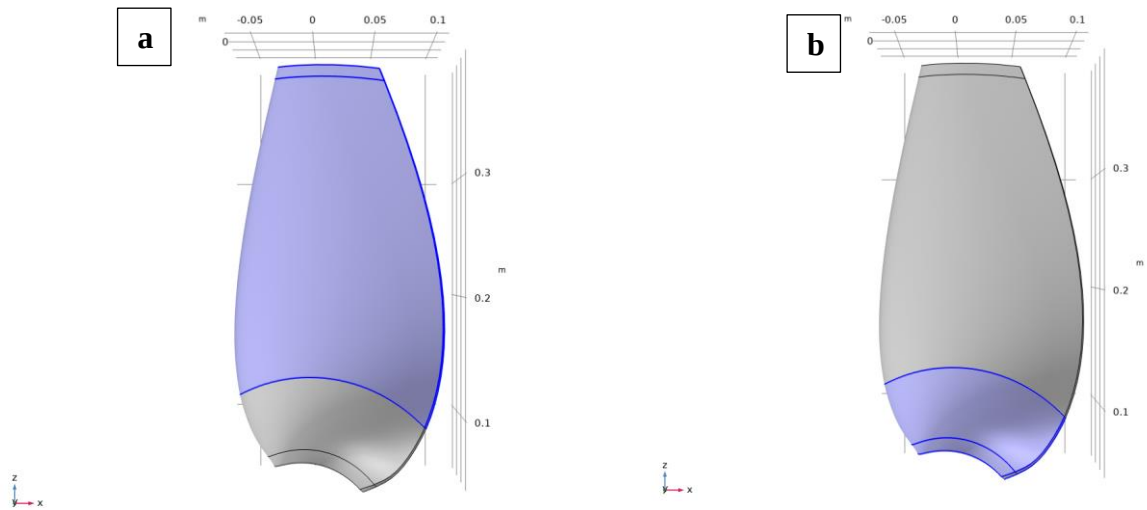


Fig. 2.19. (a) left side - 2/3 of blade, (b) right side – 1/3 blade (prepared by author)

Formula 2.1 shall be used in *COMSOL Multiphysics* to extract the chord angles of the 2/3 blade section. In the other formulas, this formula would be recorded as κ .

$$\left(\text{sys1}.e_{\phi 1} \cdot \frac{u}{\text{sys1}.r} + \text{sys1}.e_{\phi 2} \cdot \frac{v}{\text{sys1}.r} + \text{sys1}.e_{\phi 3} \cdot \frac{w}{\text{sys1}.r} \right) \quad (2.1)$$

Formula 2.1 on *COMSOL Multiphysics* is based on the cylindrical coordinate system, and it is presented below in Fig. 2.20..

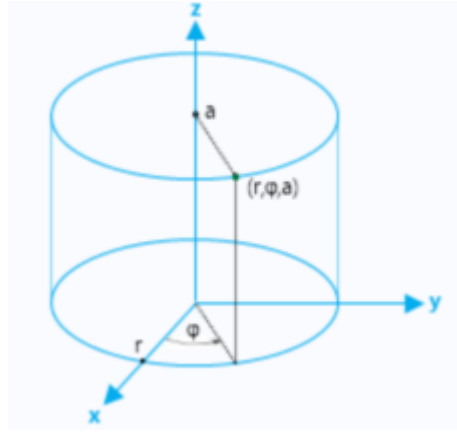


Fig. 2.20. Cylindrical coordinate system (Comsol, 2020)

In the following, the given formula (2.2) extracts the average blade surface error, when the base geometry chord beta angles are twisted to the maximum flight speed geometry or the take-off flight mode geometry. The error evaluation is based on a Cartesian coordinate system. The example is shown in Fig. 2.21. (a).

$$\left(\left((\kappa) - (\beta_1(Z) - \beta(Z)) \right)^2 \right)^{0.5} \quad (2.2)$$

Here: $\beta_1(Z)$ – blade chord pitch angles of take-off or maximum speed flight modes;

$\beta(Z)$ – blade chord pitch angles of the cruising flight mode.

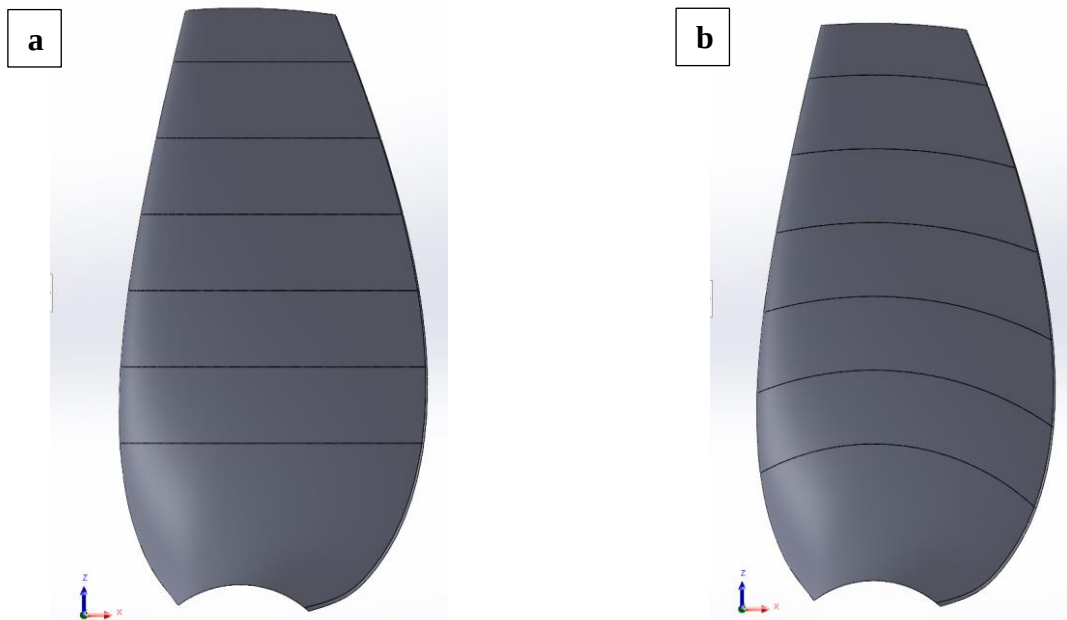


Fig. 2.21. Representative illustration of error evaluation method: (a) left side – blade chords when Cartesian coordinate system used, (b) right side – blade airfoils when cylindrical coordinate system used (prepared by author)

The second blade surface error evaluation formula is based on the cylindrical coordinate system (see Fig. 2.21. (b)). Formula 2.3 is modified from the Cartesian coordinate system to a cylindrical coordinate system. It is given below:

$$\left(\left((\kappa) - \left(\beta_1 \left(((Z^2) + (X^2))^{0.5} \right) - \beta \left(((Z^2) + (X^2))^{0.5} \right) \right) \right)^2 \right)^{0.5} \quad (2.3)$$

The above given formulas will be implemented on the COMSOL Multiphysics software. With four topology analysis simulation runs, the maximum flight speed and the take-off flight speed errors would be evaluated. First, the average surface error shall be evaluated with the Cartesian coordinate system. Second, the average surface error shall be evaluated with a cylindrical coordinate system.

In summary, *COMSOL Multiphysics* software during the optimization compares the airfoil beta chord angles of the twisted blade of the cruising flight mode between the *XRotor* outputs. As an example, in the cruising flight mode, the root and tip of the blade are twisted to achieve the geometry of the maximum speed of flight. The chord beta angles output data from the *XRotor* software shall be used in *COMSOL Multiphysics* to evaluate the average surface error of a twisted blade from the cruising flight mode. It indicates what is the difference between required geometry and resultant geometry from the simulations (see Fig. 2.1).

2.5. Topology optimization method

The lay-out problem that shall be defined in the following combines several features of the traditional problems in structural design optimization. The purpose of topology optimization is to find the optimal lay-out of a structure within a specified region. The only known quantities in the problem are the applied loads, the possible support conditions, the volume of the structure to be constructed, and possibly some additional design restrictions such as location and size of prescribed holes or solid areas. In this problem the physical size and the shape and connectivity of the structure are unknown (Bendsøe & Sigmund, 2004).

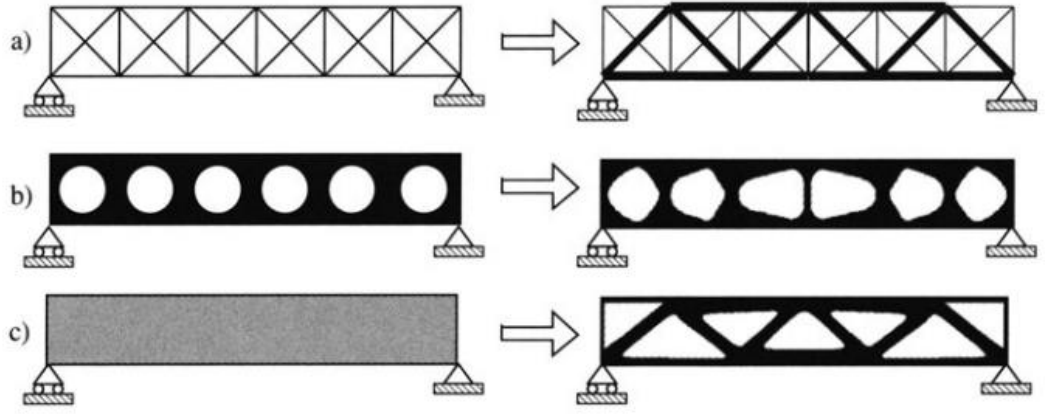


Fig. 2.22. Three categories of structural optimization (Bendsøe & Sigmund, 2004)

The topology, shape, and size of the structure are not represented by standard parametric functions but by a set of distributed functions defined on fixed design domain. These functions in turn represented a parametrization of a the stiffness tensor of the continuum and it the suitable choice of this parametrization which leads to the proper design formulation for topology optimization (Bendsøe & Sigmund, 2004)

The density method involves the definition of a control variable field, θ_c , which is bounded between 0 and 1. In solid mechanics, $\theta_c = 1$ corresponds to the material from which the structure is to be built, while $\theta_c = 0$ corresponds to a very soft material. By default, the void Young's modulus is 0.1 % of the solid Young's modulus. In fluid mechanics, convention dictates that $\theta_c = 1$ corresponds to fluid, while, $\theta_c = 0$ is a (slightly) permeable material with an inverse permeability factor, α (Jensen, 2019). For example a damping term is added to the Navier-Stokes equation:

$$\rho \frac{Dv}{Dt} = -\nabla p + \eta \nabla^2 v - \alpha(\theta_c)v \quad (2.4)$$

The *Density Model* feature supports regularization via a Helmholtz equation. This introduces a minimum length scale using the filter radius, R_{min} (Jensen, 2019):

$$\theta_f = R_{min}^2 \nabla^2 \theta_f + \theta_c \quad (2.5)$$

Here, θ_c is the raw control variable, which is modified by the optimizer, and θ_f is the filtered variable. The mesh edge size is the default value for the filter radius. While this works well in terms of regularizing the optimization problem, it's important to set a fixed length (larger than the mesh edge size) to get mesh-independent results (Jensen, 2019).

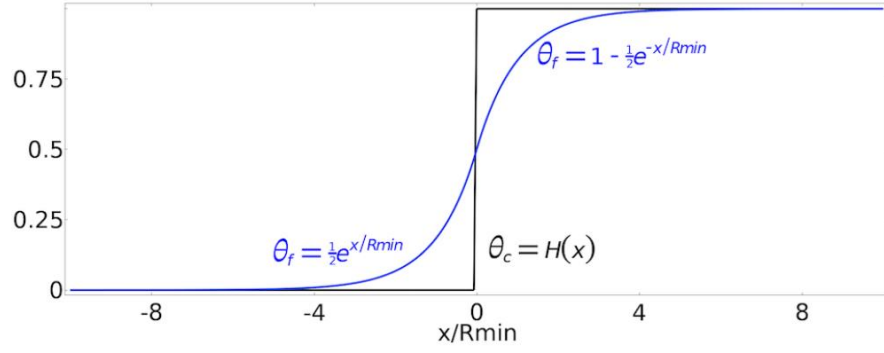


Fig. 2.23. The equation for the Helmholtz filter can be solved analytically for a 1D Heaviside function (Jensen, 2019)

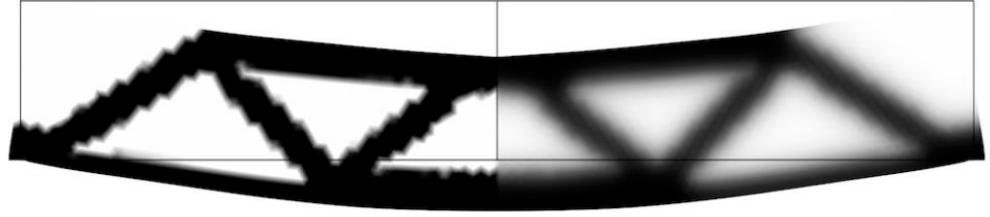


Fig. 2.24. The raw control variables to the left and the filtered version to the right (Jensen, 2019)

The Helmholtz filter gives rise to significant grayscale, which does not have a clear physical interpretation. The grayscale can be reduced by applying a smooth step function in what is referred to as projection in topology optimization. Projection reduces grayscale, but it also makes it more difficult for the optimizer to converge. The density topology feature supports projection based on the hyperbolic tangent function, and the amount of projection can be controlled with the projection steepness, β (Jensen, 2019).

$$\theta = \frac{\tanh(\beta(\theta_f - \theta_\beta)) + \tanh(\beta\theta_\beta)}{\tanh(\beta(1 - \theta_\beta)) + \tanh(\beta\theta_\beta)} \quad (2.6)$$

Here: θ_β is the projection point.

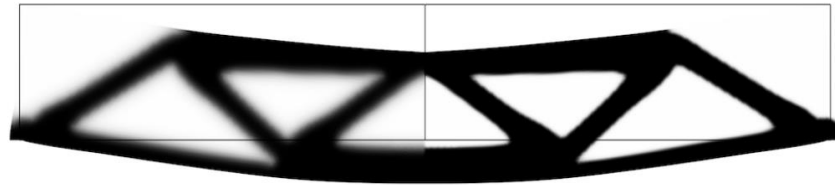


Fig. 2.25. Plot showing the filtered field to the left and the projected field to the right. (Jensen, 2019)

Projection makes it possible to avoid grayscale, but grayscale can still appear if the optimization problem favors it. If the same interpolation function is used for the mass and the stiffness, grayscale is optimal in volume-constrained minimum compliance problems. It is thus common to use interpolation functions that cause intermediate values to be associated with little stiffness relative to their cost (compared to the fully solid value). You can think of this as

a *penalization* of intermediate values for the material volume factor, and the *Density Model* interface (shown below) supports two such interpolation schemes for solid mechanics: solid isotropic material with penalization (SIMP) and rational approximation of material properties method (RAMP) interpolation. Darcy interpolation is provided for fluid mechanics. The interpolated variable is called the penalized material volume factor, θ_p , and is used for interpolating the material parameters, e.g., for SIMP interpolation, the p_{SIMP} exponent can be increased to reduce the stiffness of intermediate values, so that grayscale becomes less favorable. (Jensen, 2019).

$$\theta_p = \theta_{min} + (1 - \theta_{min})\theta^{p_{SIMP}} \quad (2.7)$$

$$E_p = E\theta_p \quad (2.8)$$

Here, E is Young's modulus of the solid material and E_p is the penalized Young's modulus to be used throughout all optimized domains. (Jensen, 2019)

Since p_{SIMP} controls the greyscale of the system, it is assumed that it controls distributions of two different stiffness filaments along the blade. If the p_{SIMP} coefficient is greater than 1, it is assumed that mixed materials will be used to manufacture the blade. If the p_{SIMP} coefficient is equal to 1 or less, it is assumed that two separate filaments would be used for blade printing.

In summary, two different printing methods should reveal whether it affects the surface average error results.

2.6. Trial and error, approach methods

Trial and error, approach methods are required to obtain the required increasement coefficient at the blade root. The formula below is applied to the *COMSOL Multiphysics* software to twist the blade root for both the maximum speed and the take-off speed flight modes.

$$sys1.r \cdot (\beta_1(Z) - \beta(Z)) \cdot c \quad (2.9)$$

Here: $sys1.r$ – coordinate system;

$\beta_1(Z)$ – airfoil angle at split line, applicable for maximum speed and take-off speed flight modes;

$\beta(Z)$ – airfoil angle at split line, applicable for cruising flight mode;

c – coefficient to increase the twist angle for both flight modes.

The trial and error method is a problem-solving technique that involves trying different approaches or solutions until you find the one that works best. This method can be an effective way to solve complex problems, especially when there is obvious solution (Benayan, 2023).

The *COMSOL Multiphysics* software does not allow to execute the parametric sweep analysis with topology analysis optimization. It means that it is not possible to obtain the required increasement coefficients which would increase the twisting angle at the root of the blade to obtain

the required angles at the split line for maximum flight speed and take-off flight modes. To solve this problem, the trial and error method shall be applied. The analysis method is shown below in Fig. 2.26.

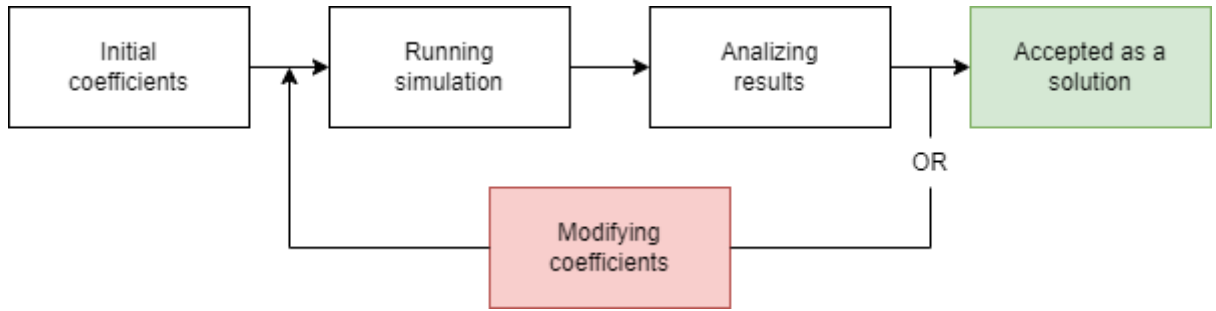


Fig. 2.26. Trial and error method application to analysis (prepared by author)

The approach method shall be applied after the first topology optimization analysis with initial increasement coefficient results post-processing. It means that if the twist angles for maximum flight speed and take-off flight mode at the split line are higher than the required angle, it would be an indication that the coefficients at the blade root should be reduced. The vice versa approach method would apply if the angles at the split line were lower than the target angles.

The limited approaches will be performed to obtain required angles at split line for maximum flight speed and take-off flight modes. The method application is presented in Fig. 2.27.

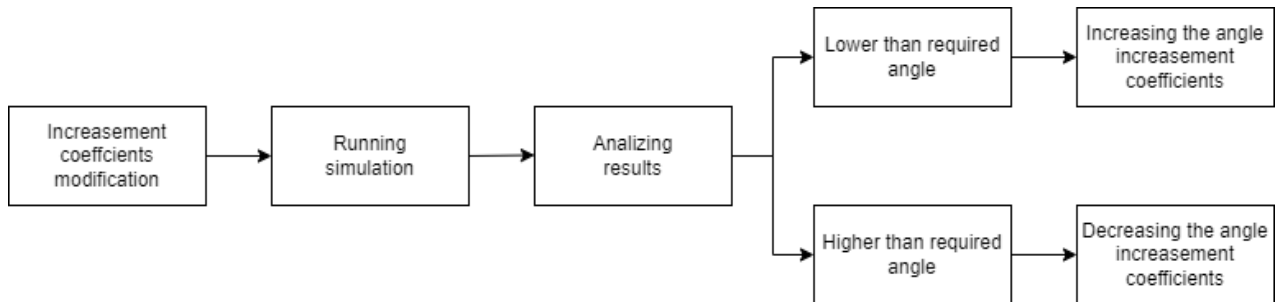


Fig. 2.27. Approach method application to analysis (prepared by author)

The approach method which is pictured above shall help to choose if the increasement coefficients should be increased or decreased.

2.7. Conclusions from analysis of research methods

1. To control the filament distribution, the SIMP coefficient shall be modified. If the SIMP coefficient is greater than 1, it is assumed that two mixed filaments will be used to manufacture the blade. If the SIMP coefficient is equal to 1 or less, it is assumed that two separate filaments would be used for blade manufacturing.

2. The required methods are analyzed to investigate the average error value along the blade. The first one is the Cartesian coordinate system error evaluation method, and the second one is the cylindrical coordinate system error evaluation method. Both methods shall be used to compare the deformation accuracy of the blade.

3. Since the *COMSOL Multiphysics* software does not perform the density topology optimization and parametric sweep analysis at the same time, it was decided to use trial and error approach methods.

3. RESULTS AND ANALYSIS

The analysis and results evaluation were performed using *COMSOL Multiphysics* computer aided engineering (CAE) software. The Comsol (2020) 'The Optimization Modulus User Guide' is used to investigate and understand the software optimization module of the topology. The chapter contains of:

- Error results and analysis;
- Materials distribution results;
- Stress analysis.

3.1. Error results and analysis

3.1.1. Two separate filaments

Since the topology optimization does not perform analysis with parametric sweep analysis, it was decided to apply the trial and error, approach methods. Initial coefficients were chosen to apply on the tip and the root of the blade to increase the twist angle and reach the required angle at the split line. For the initial coefficients, it was chosen to apply 1.4 for maximum speed flight mode and 1.3 for take-off flight speed mode. The target angle for the split line position 9.466° during the maximum flight speed mode and -5.002° for the take-off flight mode. The target angle for blade tip for the maximum speed flight is equal to 5.954° and for take-off flight mode -2.564° The Table 3.1. below presents the applied coefficients and resultant angles at the split line position.

Table 3.1. Results of different blade twist coefficients (prepared by author)

Attempt number	Coefficient 1, maximum flight mode	Coefficient 2, take-off flight mode	Maximum flight mode, resultant angle, $^\circ$	Take-off flight mode, resultant angle, $^\circ$
1	1.40	1.30	10.682	-5.071
2	1.30	1.20	10.479	-4.959
3	1.10	1.25	10.220	-5.453
4	1.15	1.15	10.257	-5.025
5	1.10	1.10	10.138	-4.960
6	1.05	1.10	9.990	-5.030
7	1.04	1.10	9.943	-5.042
8	1.03	1.10	9.892	-5.057
9	1.02	1.08	9.859	-5.012

It is indicated in the Table 3.1. above that the initial coefficients were too high. Consequently, it was decided to lower the coefficients and reduce the resulting angle on the split line for both flight modes. However, the twist angle for the maximum speed and the take-off flight mode at the tip of the blade are identical to the target angle.

The difference between the resultant angle and the output angles is presented in Table 3.2. below.

Table 3.2. Difference between the resultant and target angles at the blade splitting line (prepared by author)

Attempt number	Coefficient 1, maximum flight mode	Coefficient 2, take-off flight mode	Maximum flight mode, difference between target angle °	Take-off flight mode, difference between target angle °
1	1.40	1.30	1.216	-0.069
2	1.30	1.20	1.013	0.043
3	1.10	1.25	0.754	-0.451
4	1.15	1.15	0.791	-0.023
5	1.10	1.10	0.672	0.042
6	1.05	1.10	0.524	-0.028
7	1.04	1.10	0.477	-0.040
8	1.03	1.10	0.426	-0.055
9	1.02	1.08	0.393	-0.010

The Table 3.2. reveal that the outputs of the attempt number 9 coefficient 1 and coefficient 2 are the closest results to the target angle, respectively, for the maximum flight mode and the take-off flight mode.

The Table 3.3. below indicate the maximum flight speed and take-off flight mode 2/3 blade surface average error values according to applied coefficients. The error evaluation method is based on the Cartesian coordinate system.

Table 3.3. Results of 2/3 blade surface error (prepared by author)

Attempt number	Coefficient 1, maximum flight mode	Coefficient 2, take-off flight mode	Maximum flight mode, 2/3 blade surface average error value, °	Take-off flight mode, 2/3 blade surface average error value, °
1	1.4	1.3	0.286	0.174
2	1.3	1.2	0.272	0.170
3	1.1	1.25	0.285	0.249
4	1.1	1.1	0.229	0.147
5	1.15	1.15	0.244	0.155
6	1.05	1.1	0.218	0.145
7	1.04	1.1	0.212	0.147
8	1.03	1.1	0.209	0.150
9	1.02	1.08	0.205	0.142

The optimal 2/3 blade surface error shall be the lowest or closest to zero. Attempt number 9 demonstrates the lowest average errors (see Table 3.3.).

The results in the above hint that the optimal coefficient for the maximum speed flight mode is equal to 1.02 and for the take-off flight mode is 1.08. First, the difference between the target angle and the resultant angle is the lowest. Second, the average error of 2/3 of the blade surface is the lowest

compared on both flight modes with the other attempts. As a result, a further topology optimization analysis is performed with the coefficients 1.02 and 1.08 coefficients.

The Fig. 3.1. presents the difference of the twist angle at the split line when Cartesian coordinate system and cylindrical coordinate system error evaluation methods are used.

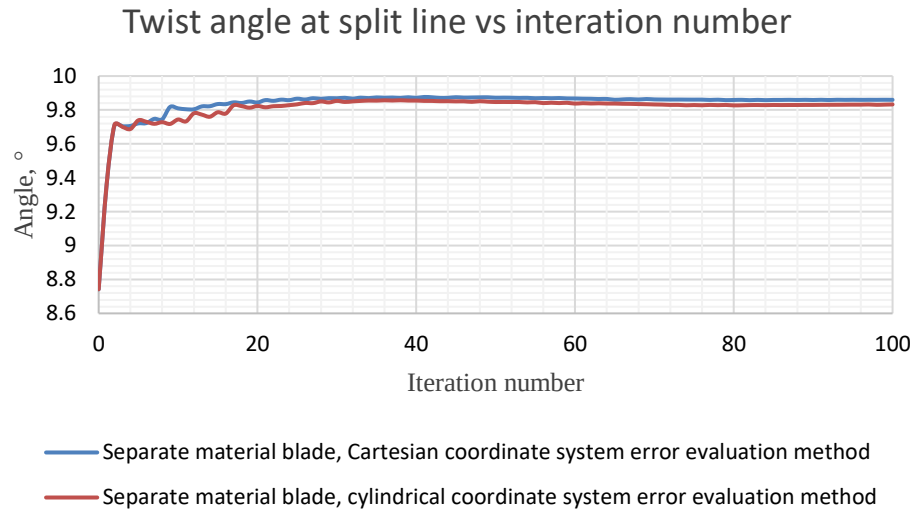


Fig. 3.1. Maximum speed flight mode, two separate materials, twist angles at split line
(prepared by author)

The resultant angle with Cartesian coordinate system error evaluation method is equal to 9.859° and with cylindrical coordinate system error evaluation method is equal to 9.831° (see Fig. 3.1).

The Fig. 3.2 presents the difference of 2/3 blade surface average error when Cartesian coordinate system and cylindrical coordinate system error evaluation methods are used.

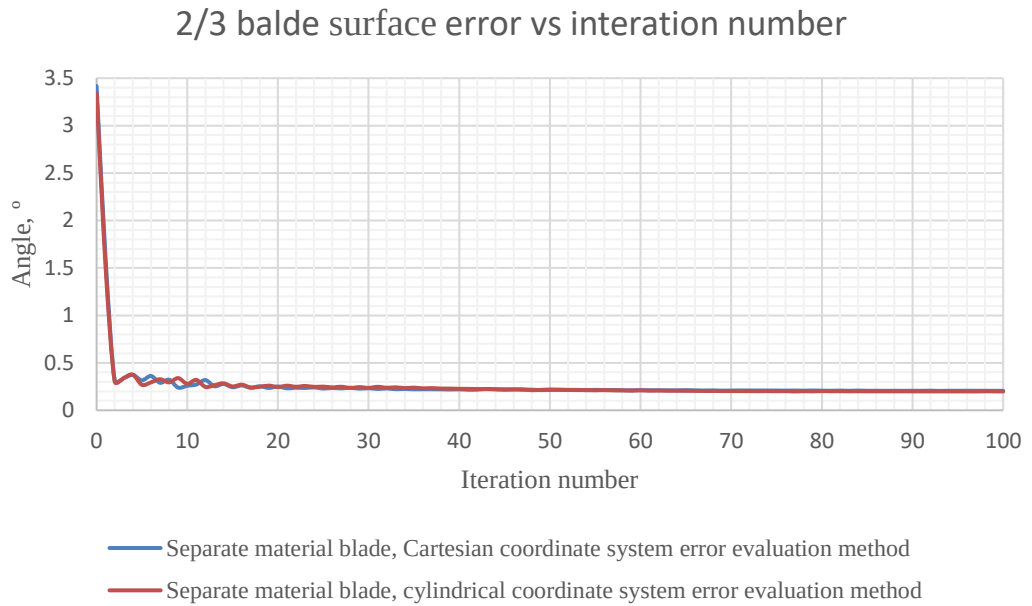


Fig. 3.2. Maximum speed flight mode, two separate materials, 2/3 blade surface section average error (prepared by author)

The difference between results is not significant (see Fig. 3.2.). The average 2/3 blade surface error with the Cartesian coordinate system error evaluation method is equal to 0.205° and with cylindrical coordinate system error evaluation method is equal to 0.198° .

The comparison between the Cartesian coordinate system and the cylindrical coordinate system error evaluation methods for the maximum flight speed mode is presented in Table 3.4.

Table 3.4. Maximum speed flight mode, two separate filaments blade geometry results overview (prepared by author)

	Twist angle at split line	2/3 blade surface average error
Cartesian coordinate system error evaluation method	9.856°	0.205°
Cylindrical coordinate system error evaluation method	9.834°	0.198°
Difference	0.263 %	3.414 %

From Table 3.4. it can be seen that the difference in the twist angle on the split line is not significant. However, the difference in 2/3 blade surface average error is around 3.4% more accurate if the cylindrical coordinate system error evaluation method is used.

The Fig. 3.3. below presents the isometric view 1 of the 2/3 blade surface error when Cartesian and cylindrical coordinate systems error evaluation methods are used.

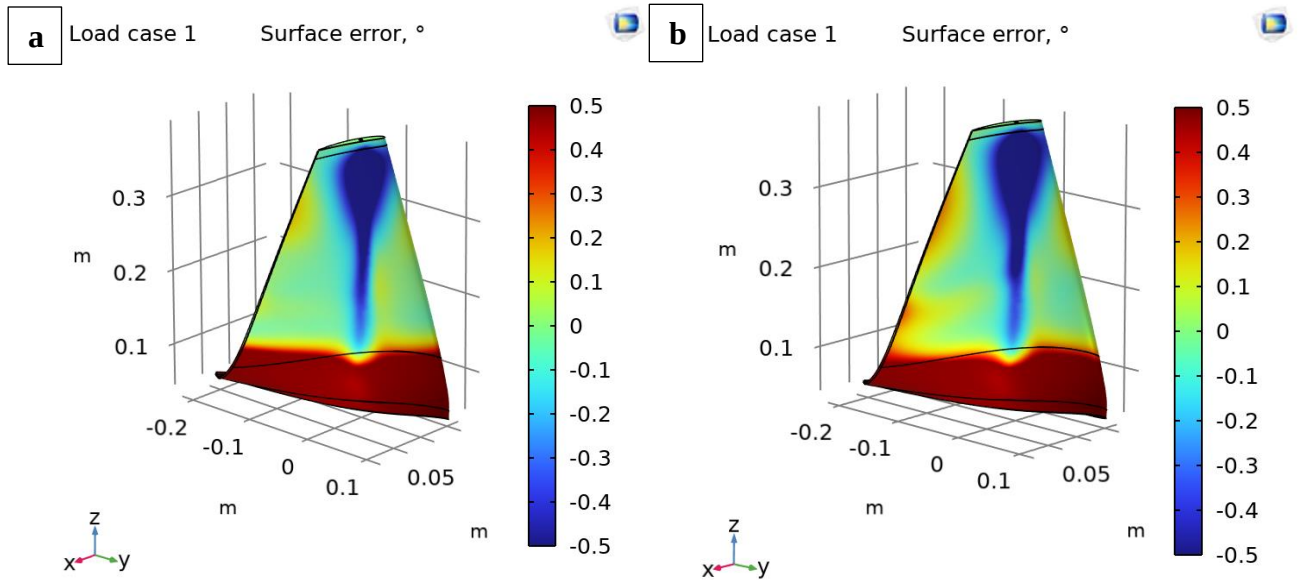


Fig. 3.3. Maximum speed flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two separate filaments, isometric view 1 (prepared by author)

The Fig. 3.4. below presents isometric view 2 of the 2/3 blade surface errors when Cartesian and cylindrical coordinate system error evaluation methods are used.

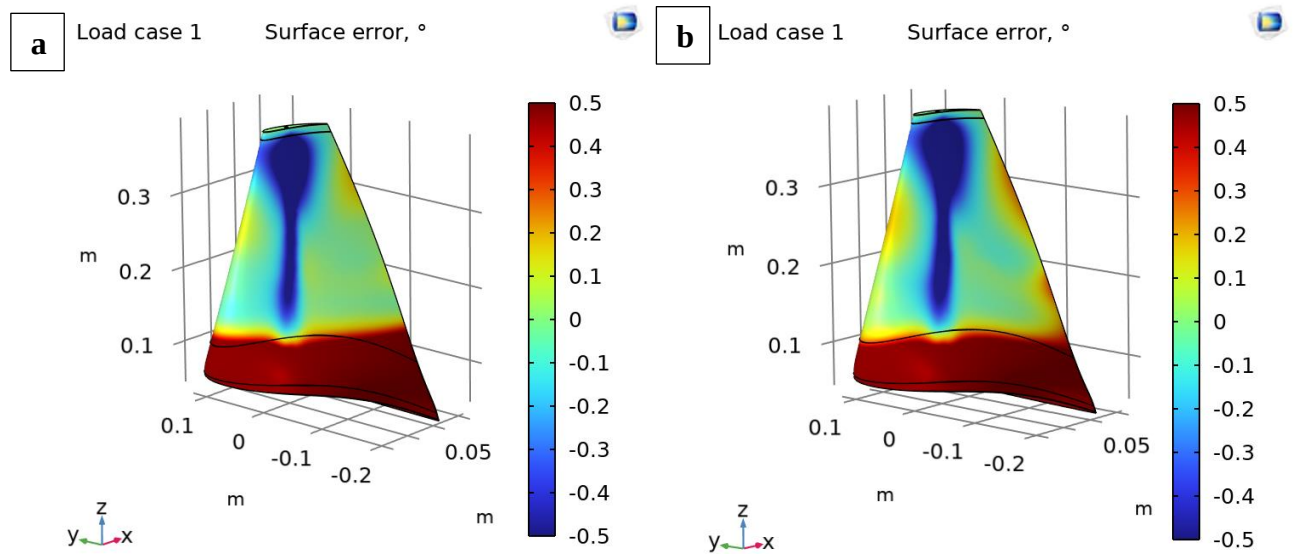


Fig. 3.4. Maximum speed flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two separate filaments, isometric view 2 (prepared by author)

The difference between two different error evaluation methods can be observed (see Fig. 3.3. and Fig. 3.4.). When the cylindrical coordinate system error evaluation method is used, a few error increasement areas are identified at the trailing edge of the blade. However, it is more accurate method compared to a Cartesian coordinate system error evaluation method.

The Fig. 3.5. presents the angle twist results at the blade split line with respect to iteration number when blade geometry is set for take-off flight mode.

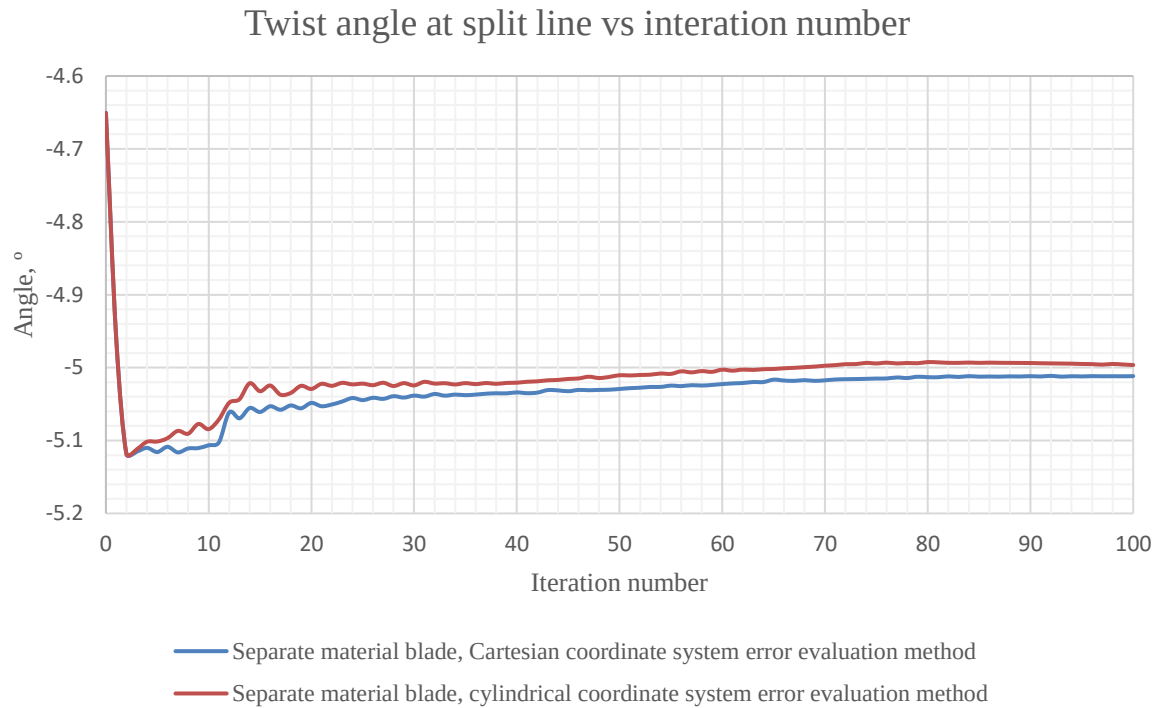


Fig. 3.5. Take-off flight mode, two separate filaments, twist angles at split line (prepared by author)

The topology analysis with cylindrical coordinate system error evaluation method outputs an angle with higher accuracy than Cartesian coordinate system (see Fig. 3.5.). The angle at the twist line with Cartesian coordinate system error evaluation method is equal to -5.012° and cylindrical coordinate system error evaluation formula is equal to -4.996° . The difference between target angle and angle at the twist line with the cylindrical coordinate system error evaluation method is equal to 0.0055° and with the Cartesian coordinate system error evaluation method is equal to -0.0097° .

The Fig. 3.6. presents the 2/3 blade surface average error value with respect to iteration number.

2/3 blade surface error vs iteration number

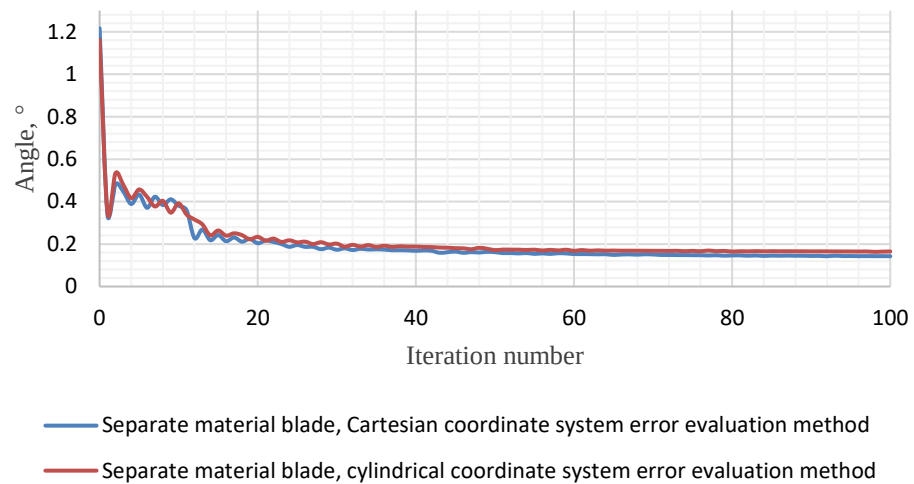


Fig. 3.6. Take-off flight mode, two separate filaments, 2/3 blade surface section average error (prepared by author)

Here, the difference between Cartesian coordinate system error evaluation method and cylindrical coordinate system error evaluation method is more evident. The 2/3 blade surface average error with Cartesian coordinate system error evaluation method is equal to 0.143° and with coordinate system error evaluation method it is equal to 0.165° .

The Table 3.5. presents the twist angle at the split line and the 2/3 blade surface average error results.

Table 3.5. Take-off flight mode, two mixed filaments blade geometry results overview (prepared by author)

	Twist angle at the split line	2/3 blade surface average error
Cartesian coordinate system error evaluation method	-5.011°	0.143°
Cylindrical coordinate system error evaluation method	-4.996°	0.165°
Difference	0.3 %	15.6 %

In Table 3.5. the Cartesian coordinate system and cylindrical coordinate error evaluation methods are compared. As can be seen, the Cartesian coordinate system error evaluation method is a more accurate method than the cylindrical coordinate system error evaluation method. The difference between the results is equal to 15.6 %.

The Fig. 3.7. presents isometric view 1 of the Cartesian coordinate system error evaluation and cylindrical coordinate system error evaluation methods difference at 2/3 blade surface error.

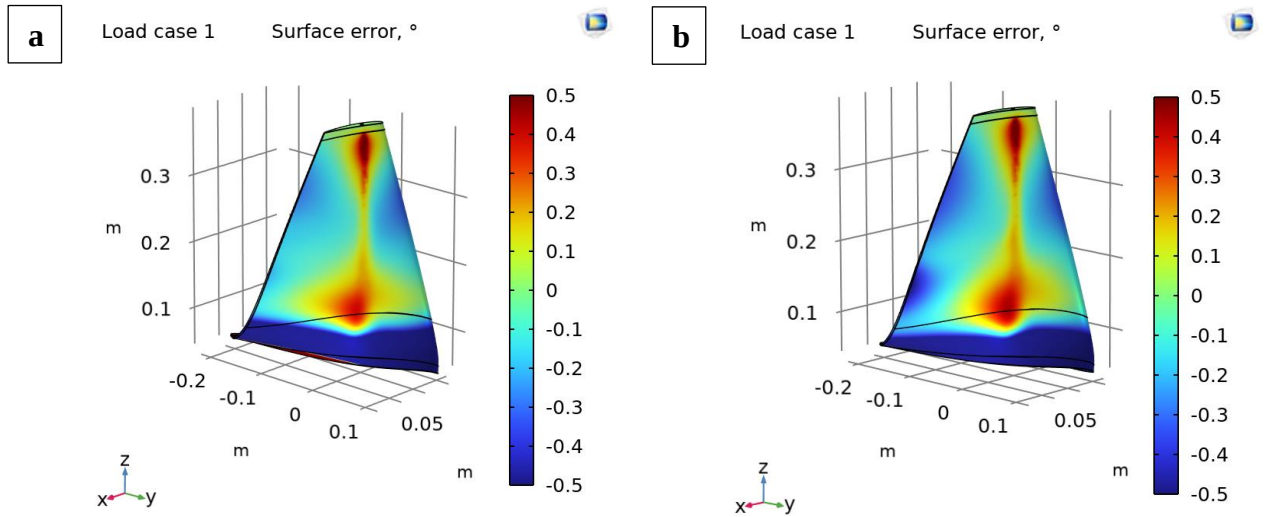


Fig. 3.7. Take-off flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two separate filaments, isometric view 1 (prepared by author)

The Fig. 3.8. presents isometric view 2 of the Cartesian coordinate system error evaluation and cylindrical coordinate system error evaluation methods difference at 2/3 blade surface error.

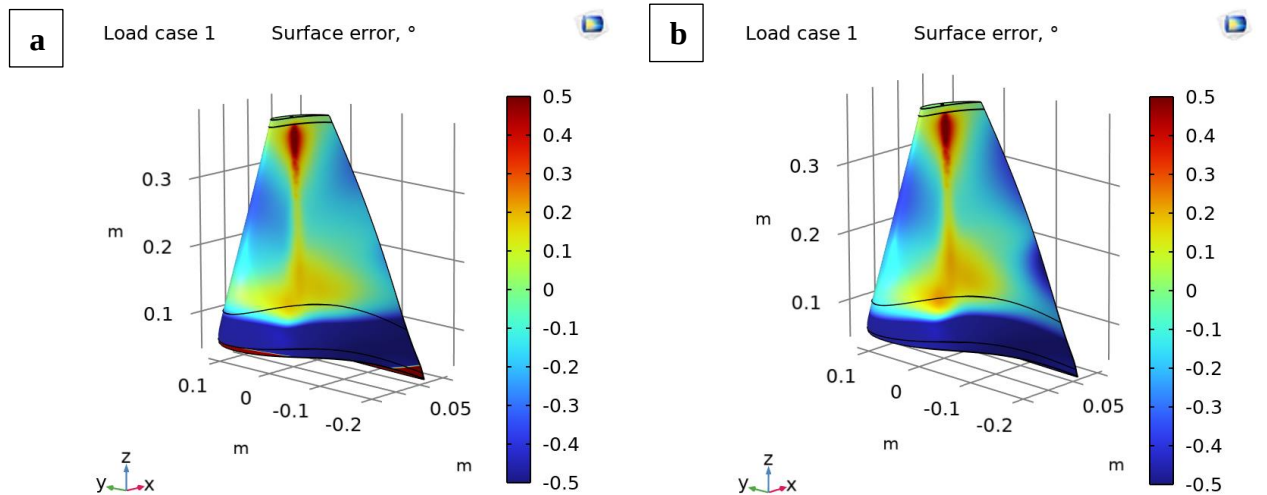


Fig. 3.8. Take-off flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two separate filaments, isometric view 2 (prepared by author)

The Cartesian coordinate system surface error evaluation method is more accurate than the cylindrical coordinate system surface error evaluation method. Since the difference between both error evaluation methods is greater compared to the maximum flight mode, the difference in results is noticeable. The cylindrical coordinate system error evaluation method indicates areas where the error is greater. These are noted on the trailing edge of the blade (see Fig. 3.7 and Fig. 3.8.).

3.1.2. Two mixed filaments

As was mentioned in the previous chapter, it was decided to continue the analysis with the coefficients of the last attempt. These coefficients were applied to the analysis of two mixed filaments. For the maximum flight speed mode, the root twist angle increasement coefficient is equal to 1.02 and for the take-off mode it is equal to 1.08.

The Fig. 3.9. below presents the twist angle at the split line, referring to the iteration number. The difference between the Cartesian coordinate system error evaluation method and the cylindrical coordinate system error evaluation method results is notable. Furthermore, the cylindrical coordinate system error evaluation method shows the result, which is closer to the target angle and equal to 9.743° . However, with the Cartesian coordinate system error evaluation method, the result is equal to 9.782° .

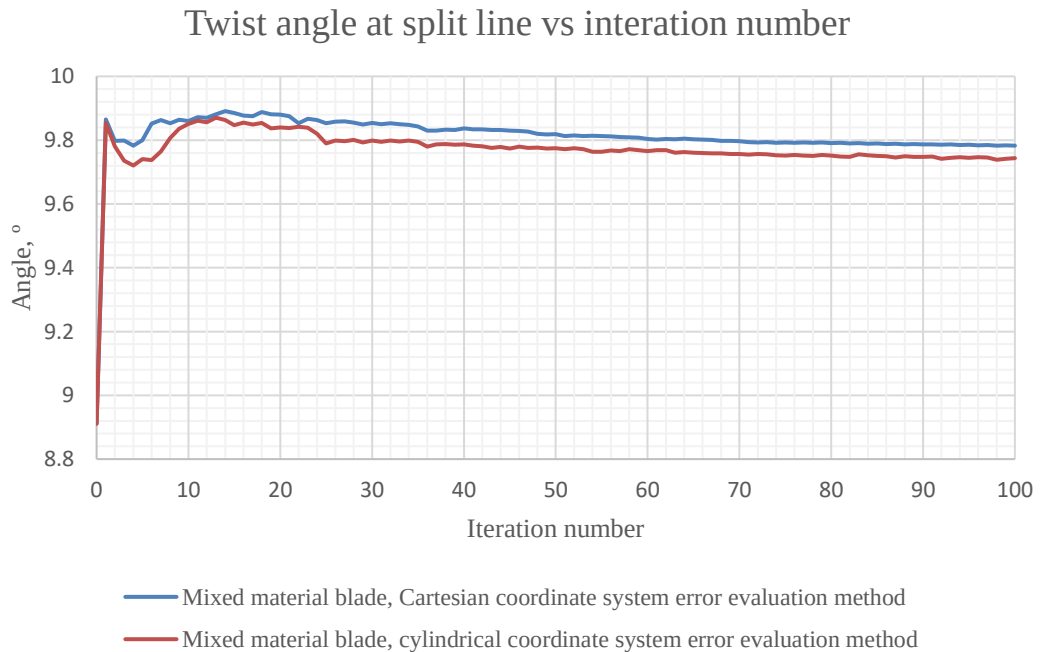


Fig. 3.9. Maximum speed flight mode, two mixed filaments, twist angles at split line
(prepared by author)

The Fig. 3.10. below presents the 2/3 blade surface average error. The difference between the Cartesian coordinate system error evaluation method and the cylindrical coordinate system error evaluation method is equal to 0.026° . The formula for the cylindrical coordinate system error

evaluation method is optimal in comparison to the Cartesian coordinate system error evaluation method formula.

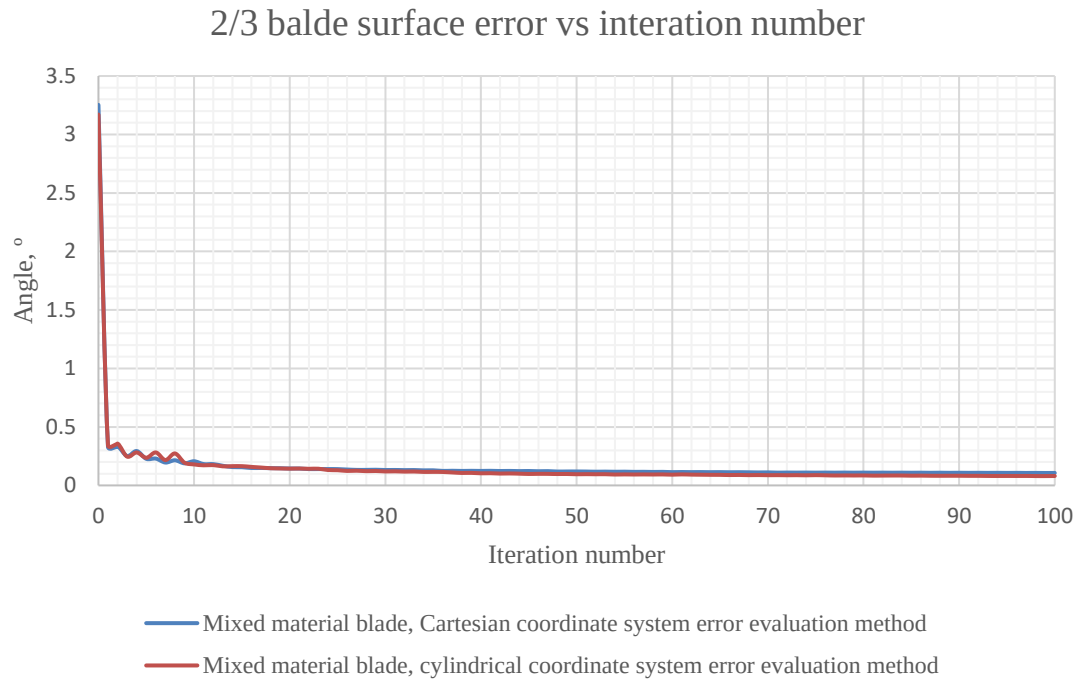


Fig. 3.10. Maximum speed flight mode, 2/3 blade surface section average error (prepared by author)

The Table 3.6. presents a comparison of the Cartesian coordinate system error evaluation method and the cylindrical coordinate system error evaluation method. The difference in twist angles at the split line is not high and equals 0.4 %. Meanwhile, the 2/3 blade surface average error results indicate a higher difference, which is almost equal to 25 %. However, this difference is hardly noticeable on Fig. 3.11. and Fig. 3.12..

Table 3.6. Maximum speed flight mode, mixed filaments blade geometry results overview (prepared by author)

	Twist angle at the split line	2/3 blade surface average error
Cartesian coordinate system error evaluation method	9.782°	0.106°
Cylindrical coordinate system error evaluation method	9.743°	0.080°
Difference	0.40 %	24.58 %

The Fig. 3.11. presents isometric view 1 of the Cartesian coordinate system error evaluation and cylindrical coordinate system error evaluation methods difference at 2/3 blade surface error. The blade is assumed to be printed with two mixed 3D printing filaments, and the achievable geometry is for the maximum speed flight mode.

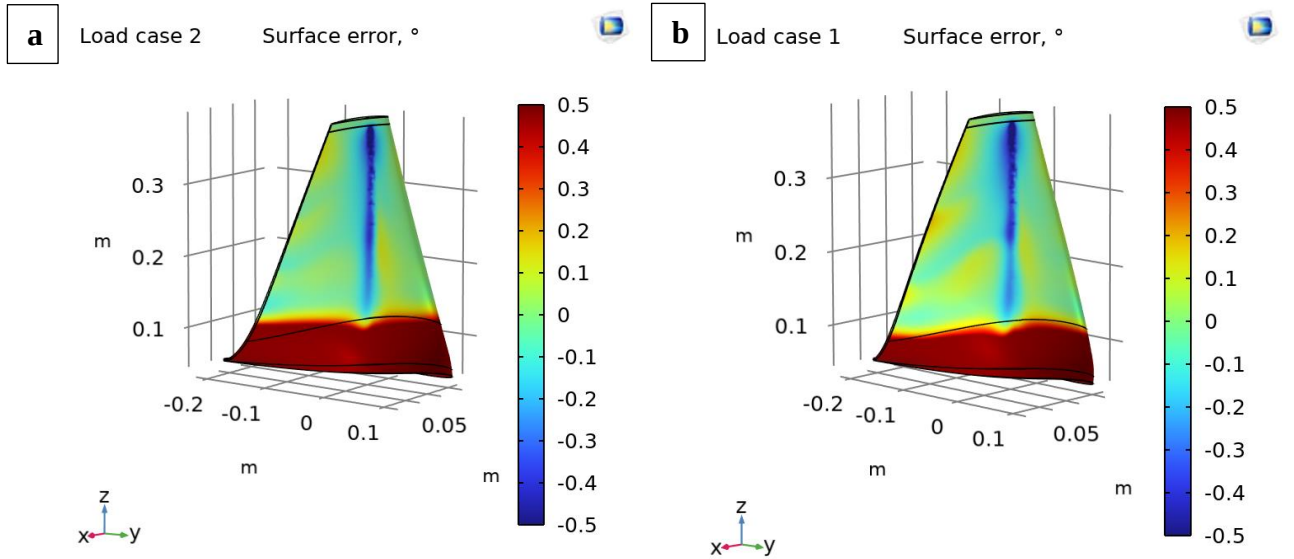


Fig. 3.11. Maximum speed flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two mixed filaments, isometric view 1 (prepared by author)

The Fig. 3.12. presents isometric view 2 of the Cartesian coordinate system error evaluation and cylindrical coordinate system error evaluation methods difference at 2/3 blade surface error.

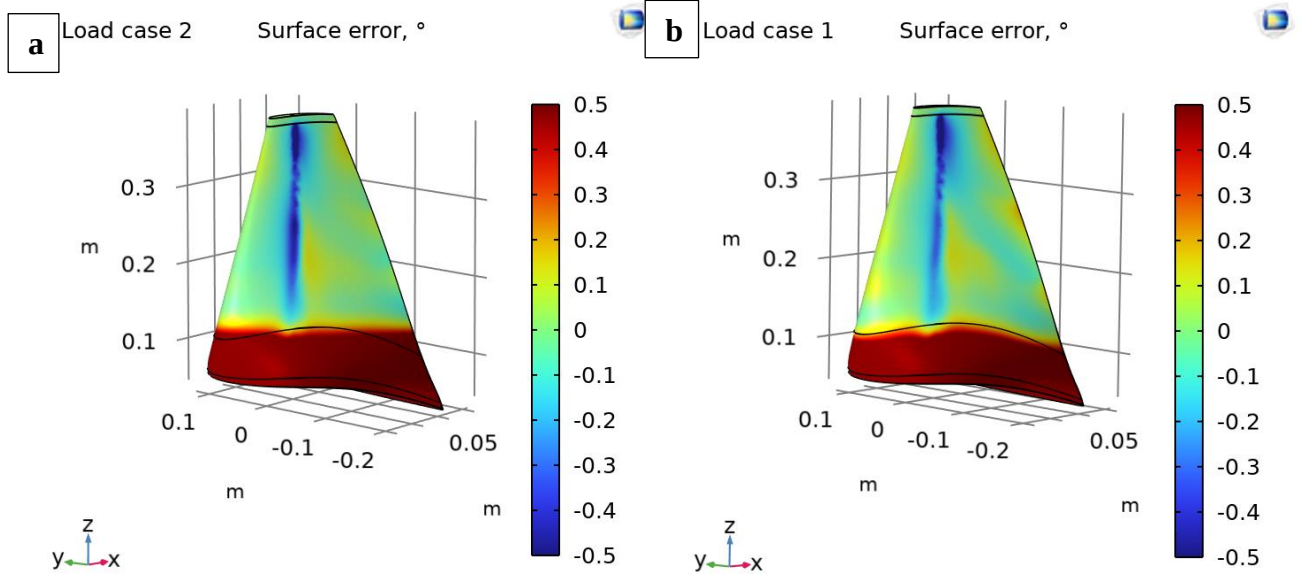


Fig. 3.12. Maximum speed flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two mixed filaments, isometric view 2 (prepared by author)

The Fig. 3.13. below presents the twist angle at the split line, referring to the iteration number. The difference between the Cartesian coordinate system error evaluation method and the cylindrical coordinate system error evaluation method result is notable. The Cartesian coordinate system error evaluation method shows the result, which is closer to the target angle and equal to -5.004° . However, with the cylindrical coordinate system error evaluation method, the result is equal to -4.978° .

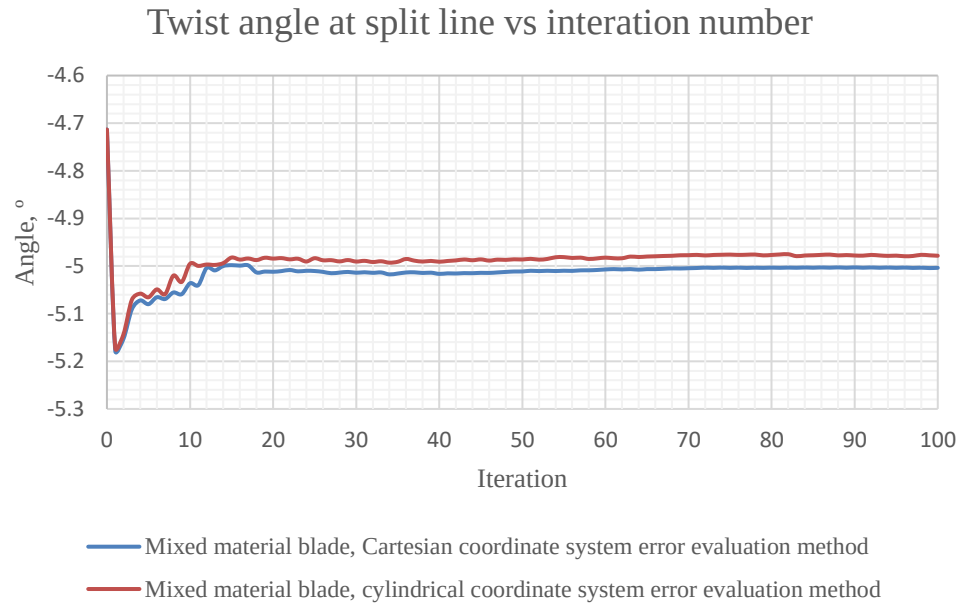


Fig. 3.13. Take-off flight mode, twist angles at split line (prepared by author)

The Fig. 3.14. below presents the 2/3 blade surface average error. The difference between the Cartesian coordinate system error evaluation method and the cylindrical coordinate system error evaluation method is equal to 0.075° . The Cartesian coordinate system error evaluation method is more accurate than the cylindrical coordinate system error evaluation method.

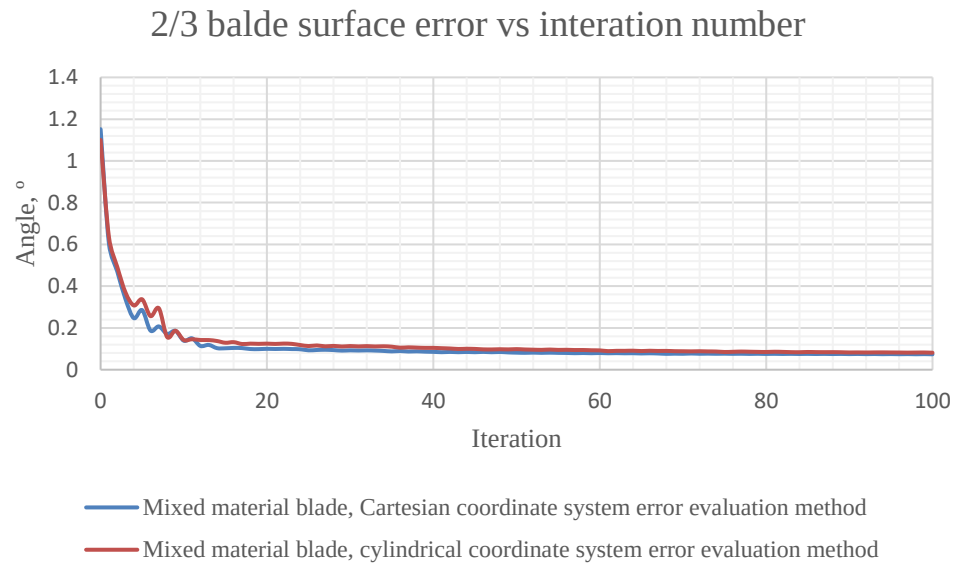


Fig. 3.14. Take-off flight mode, 2/3 blade surface section average error (prepared by author)

The Fig. 3.15. presents isometric view 1 of the Cartesian coordinate system error evaluation and cylindrical coordinate system error evaluation methods difference at 2/3 blade surface error. The blade is printed with two mixed 3D printing filaments and achievable geometry is for take-off flight mode.

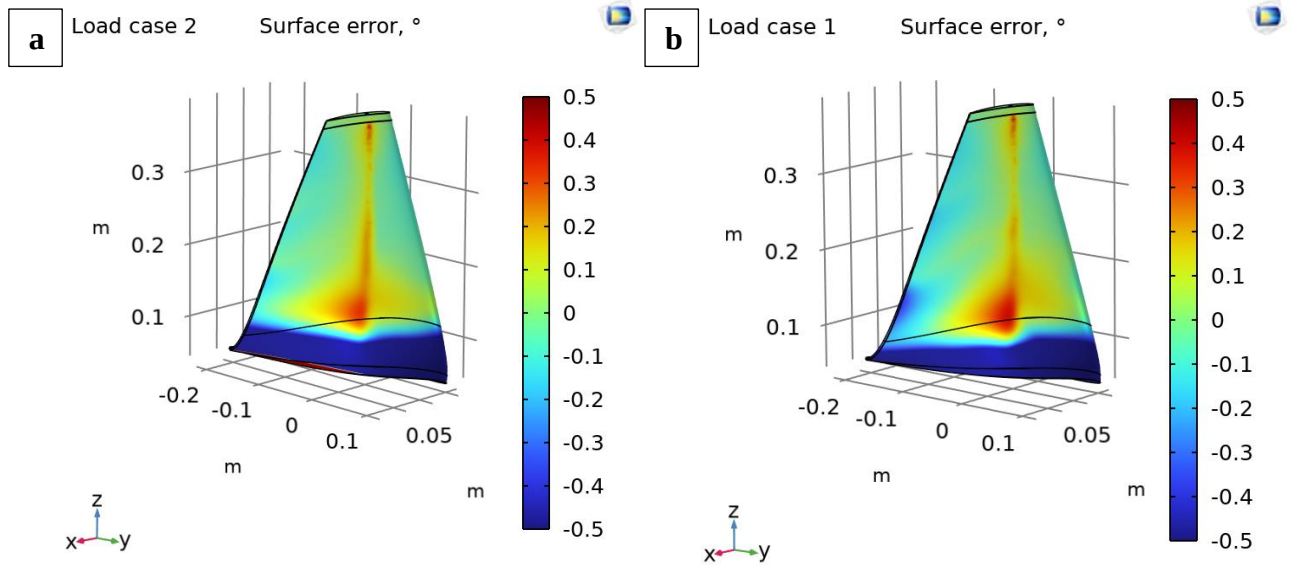


Fig. 3.15. Take-off flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two mixed filaments, isometric view 1 (prepared by author)

The Fig. 3.16. presents isometric view 2 of the Cartesian coordinate system error evaluation and cylindrical coordinate system error evaluation methods difference at 2/3 blade surface error.

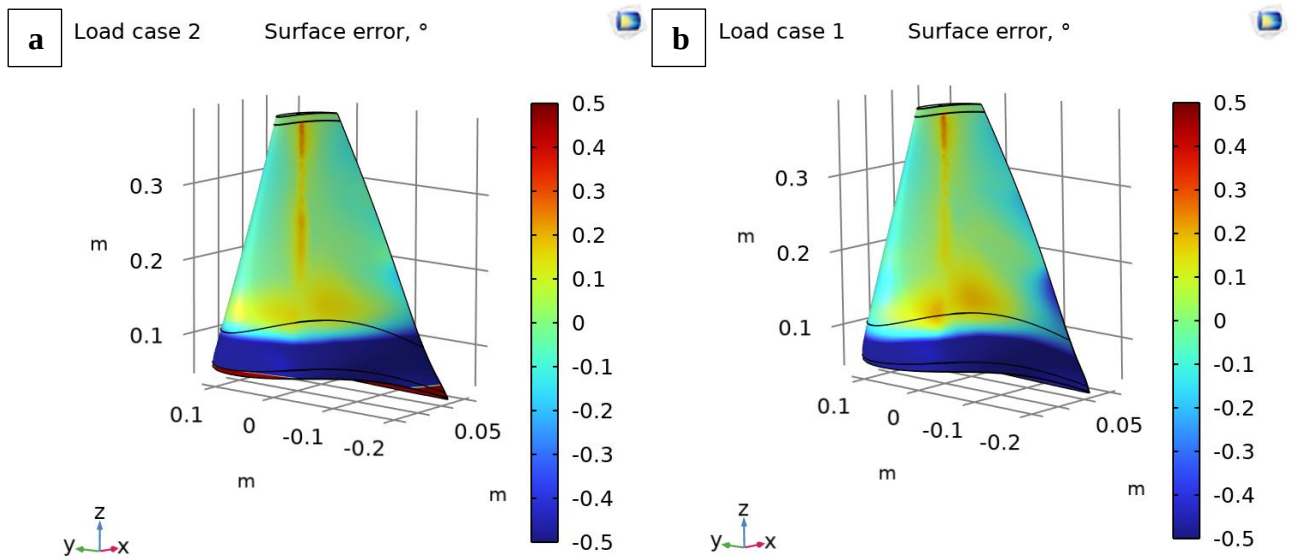


Fig. 3.16. Take-off flight mode, 2/3 blade surface error: left side (a) – Cartesian coordinate system; right side (b) – cylindrical coordinate system. Two mixed filaments, isometric view 2 (prepared by author)

The Table 3.7 presents the comparison of Cartesian coordinate system error evaluation method and cylindrical coordinate system error evaluation method.

Table 3.7. Take-off flight mode, mixed filaments blade geometry results overview (prepared by author)

	Twist angle at the split line	2/3 blade surface average error
Cartesian coordinate system error evaluation method	-5.004°	0.074°
Cylindrical coordinate system error evaluation method	-4.978°	0.081°
Difference	0.51 %	10.19 %

The difference in the twist angles at the split line is not high and is equal to 0.51 %. Meanwhile, the results of the 2/3 blade surface average error indicate a higher difference, which is equal to 10.19 %. However, this difference is noticeable on the blade trailing edge, near the split line (see Fig. 3.15. and Fig. 3.16).

3.1.3. Summary

The Table 3.8. presents the overall separate filaments and mixed filaments printing approaches of 2/3 blade surface average error outputs.

Table 3.8. Separate material and mixed filaments 2/3 blade surface average errors comparison (prepared by author)

	Separate material 2/3 blade surface average error, °		Mixed material 2/3 blade surface average error, °	
Flight mode	Maximum speed	Take-off	Maximum speed	Take-off
Cartesian coordinate system error evaluation method	0.205	0.142	0.106	0.073
Cylindrical coordinate system error evaluation method	0.198	0.165	0.080	0.081

The Table 3.8. indicates that the Cartesian coordinate system error evaluation method is optimal when two separate filaments are used for 3D printing. However, with two mixed filaments, the cylindrical coordinate system error evaluation method is more accurate and optimal.

For further results analysis, two separate filaments blade is going to be presented when the Cartesian coordinate system is used and two mixed filaments blade when the cylindrical coordinate system is used.

3.2. Filament distribution results

In this chapter results of two-filament distribution is evaluated. The blue color indicated the distribution of *NinjaFlex* material. This filament has lower Youngs modulus and is more flexible compared with the second filament. The second material distribution is marked by a red colour and indicates *Volcano PLA* material. This material has a higher Youngs modulus and is not as flexible as

NinjaFlex material. This evaluation of results is applicable only for the separate filament printing method. Since the mechanical properties of two mixed filaments changed, the same material identification approach is not correct.

The Fig. 3.17. indicates two different filaments distribution along the blade, the first isometric view.

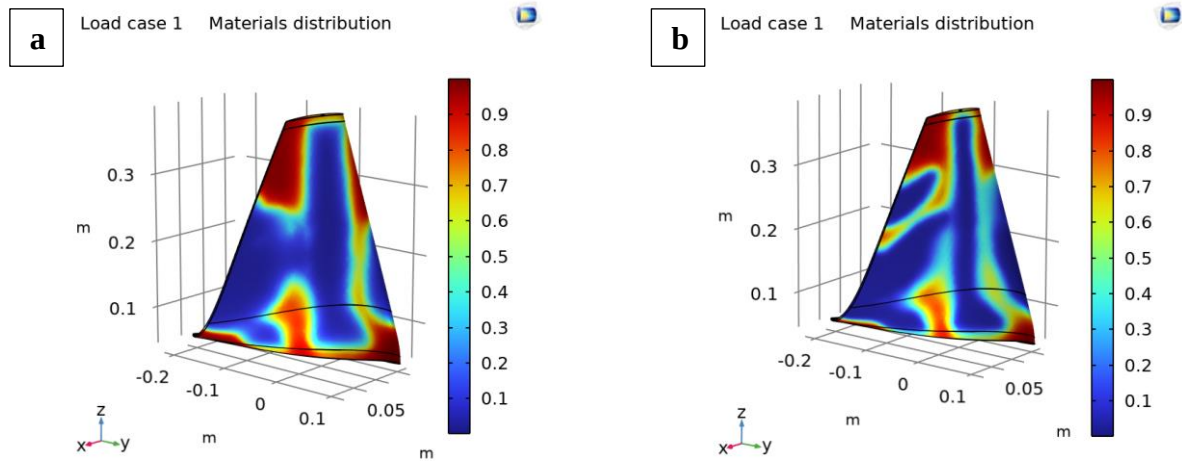


Fig. 3.17. Two different printing methods filaments distribution along the blade: left side (a) – two separate filaments, Cartesian coordinate system error evaluation method; right side (b) – mixed filaments, cylindrical coordinate system error evaluation method.

Isometric view 1 (prepared by author)

The Fig. 3.18. presents the material distribution along the blade on the other side.

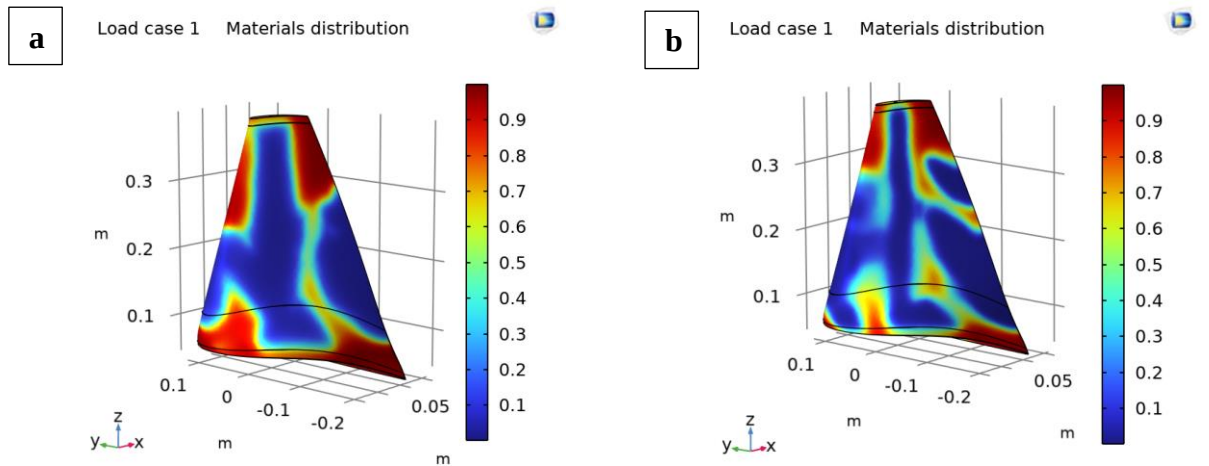


Fig. 3.18. Two different printing methods filaments distribution along the blade: left side (a) – two separate filaments, Cartesian coordinate system error evaluation method; right side (b) – mixed filaments, cylindrical coordinate system error evaluation method.

Isometric view 2 (prepared by author)

The distribution difference between the two filaments is noticeable and varies at the tip, leading edge, and trailing edge of the blade (see Fig. 3.17. and Fig. 3.18.).

The Fig. 3.19. presents the isometric view 1 of *Volcano PLA* and *NinjaFlex* material distribution along the blade when the Cartesian coordinate system error evaluation method is applied and the printing method is two separate filaments.

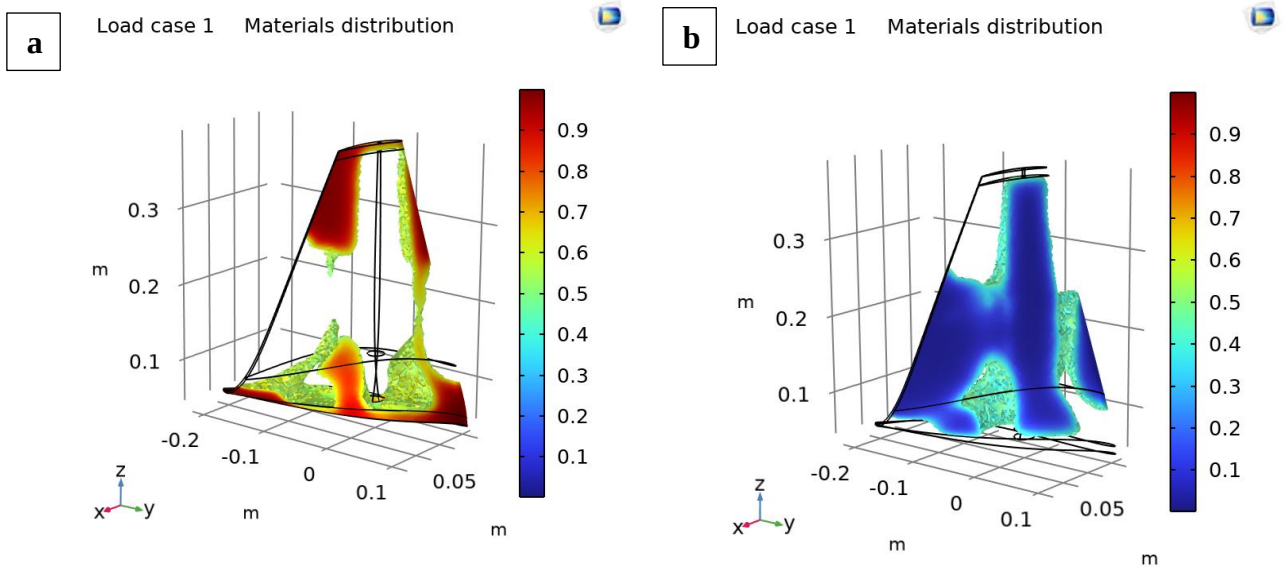


Fig. 3.19. Two separate filaments distribution along the blade: (a) left side – Volcano PLA filament, (b) right side – NinjaFlex. Isometric view 1 (prepared by author)

The Fig. 3.20. presents isometric view 2, *Volcano PLA* and *NinjaFlex* material distribution along the blade when the Cartesian coordinate system error evaluation method is applied and the printing method is two separate filaments.

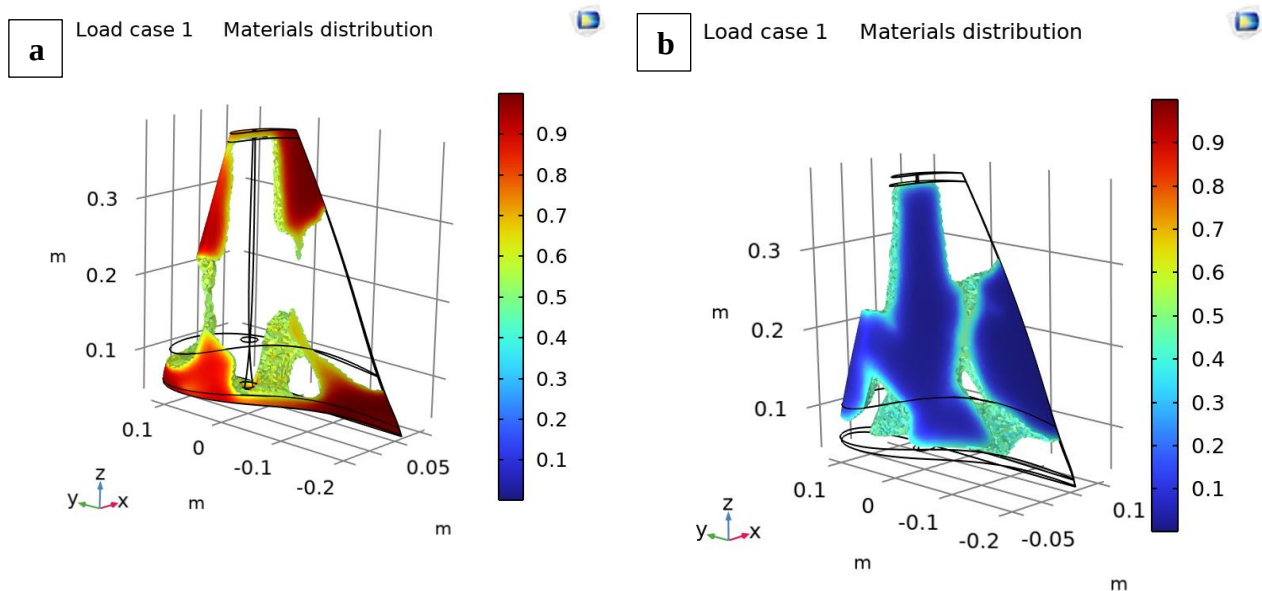


Fig. 3.20. Two separate filaments distribution along the blade: (a) left side – Volcano PLA filament, (b) right side – NinjaFlex. Isometric view 2 (prepared by author)

In the Fig. 3.19. and Fig. 3.20. compares the distribution of the *Volcano PLA* and *NinjaFlex* material along the blade. The view on the left hand side (a) presents the *Volcano PLA* filament distribution, and on the right hand side (b) presents the *NinjaFlex* filament distribution.

It should be taken into account that the material distribution does not vary between different flight modes.

3.3. Stress analysis

The figures below present the stresses along the surface of the blade. It should be taken into account that this stress occurs when the blade is twisted to the maximum flight speed configuration or the take-off flight mode configuration. Centrifugal, thrust, and aerodynamic forces are not taken into account.

The Fig. 3.21. presents two separate filaments printing method blade von Mises stress when maximum flight speed geometry is obtained. Here, the maximum stress scale is set to 40 MPa.

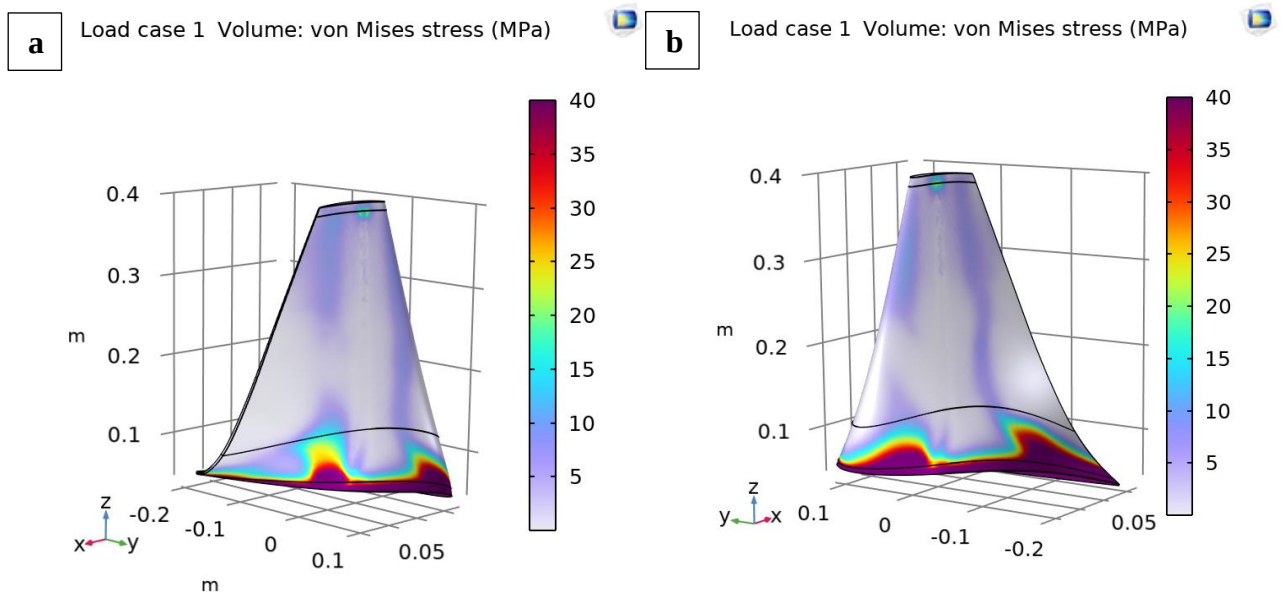


Fig. 3.21. Maximum speed flight mode, two separate filaments with Cartesian coordinate system: (a) left side, isometric view 1, (b) left side, isometric view 2. Scale up to 40 MPa (prepared by author)

The Fig. 3.22. presents two separate filaments printing method blade von Mises stress when take-off flight mode geometry is obtained. The maximum stress scale is set to 40 MPa.

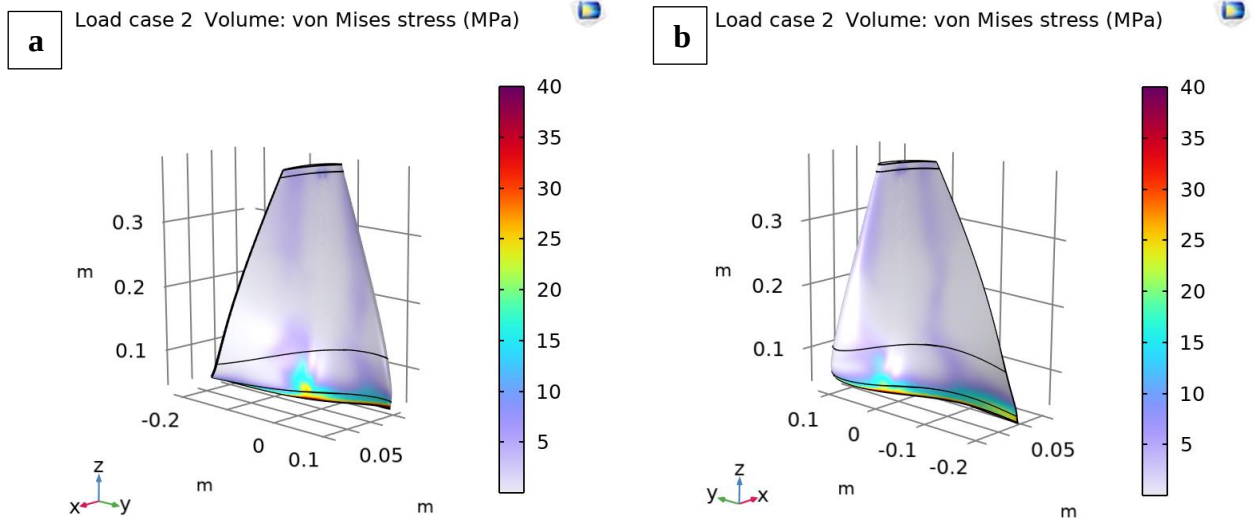


Fig. 3.22. Take-off flight mode, two separate filaments with Cartesian coordinate system: (a) left side, isometric view 1, (b) left side, isometric view 2. Scale up to 40 MPa (prepared by author)

It can be observable from Fig. 3.21. that the highest stress appears at the root of the blade and it is around 40 MPa. The stress of 40 MPa appears in the areas where Volcano PLA material is distributed (see Fig. 3.19. and Fig. 3.20.).

The Fig. 3.23. presents two separate filaments printing method blade von Mises stress when maximum flight speed geometry is obtained. Here, the maximum stress scale is set to 5 MPa.

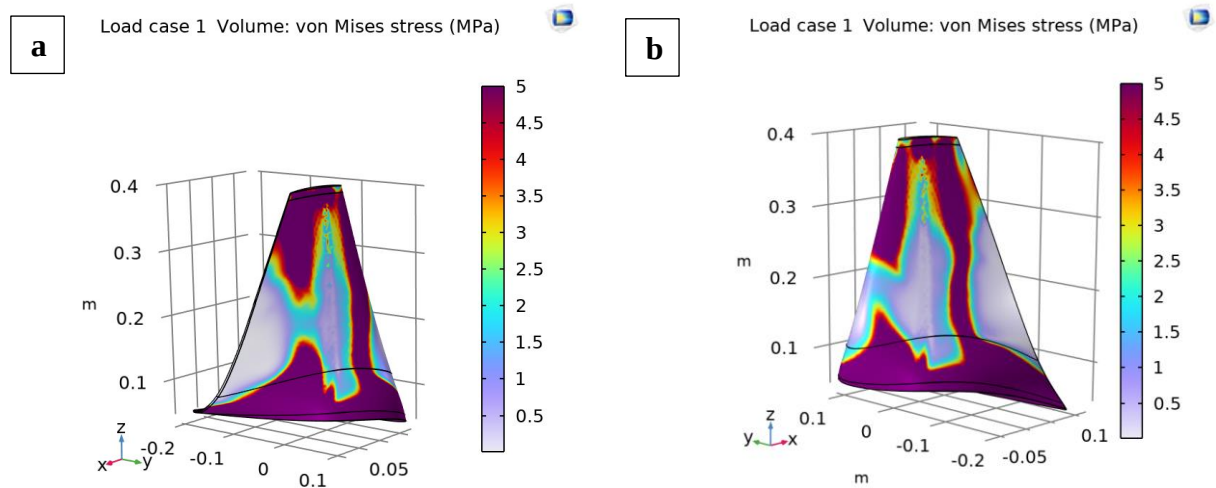


Fig. 3.23. Maximum speed flight mode, two separate filaments with Cartesian coordinate system: (a) left side, isometric view 1, (b) left side, isometric view 2. Scale up to 5 MPa (prepared by author)

The Fig. 3.24. presents two separate filaments printing method blade von Mises stress when take-off flight mode geometry is obtained. Here, the maximum stress scale is set to 5 MPa.

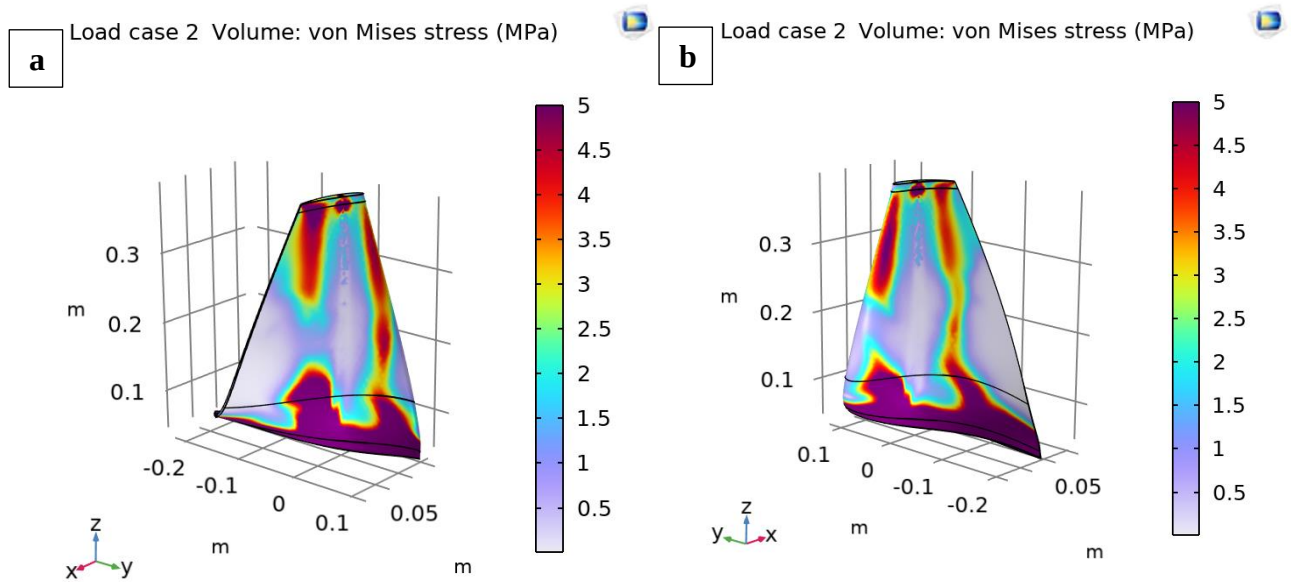


Fig. 3.24. Take-off flight mode, two separate filaments with Cartesian coordinate system: (a) left side, isometric view 1, (b) left side, isometric view 2. Scale up to 5 MPa (prepared by author)

The Fig. 3.23. and Fig. 3.24. highlights the stresses where the *Volcano PLA* and *NinjaFlex* filaments are distributed. The maximum scale stress (5 MPa) appears where *Volcano PLA* is distributed (see Fig. 3.19. and Fig. 3.20.). The stress around 1-2 MPa is visible where *NinjaFlex* material is distributed.

In summation, the stress of 40 MPa at the root of the blade exceeds the ultimate tensile strength of *Volcano PLA* which is equal to 39 MPa. However, the stress on *NinjaFlex* is lower than the tensile strength (1-2 MPa < 4 MPa).

3.4. Conclusions from the analysis of results

1. The Cartesian coordinate system error evaluation method is optimal when two separate filaments are used for 3D printing manufacturing. However, with two mixed filaments, the cylindrical coordinate system error evaluation method is more accurate and optimal.

2. The distribution of two different filaments along the blade is evaluated. The first case is the blade printed from two separate filaments, and the second case is the blade printed from two mixed filaments. The first case is based on the Cartesian coordinate system error evaluation method, and the second case is based on the cylindrical coordinate system error evaluation method. The reason is that these methods indicated the lowest average error values along the 2/3 surface of the blade.

3. The stress analysis showed that the ultimate tensile strength of the *Volcano PLA* material is not feasible. Stress at the root of the blade exceeds the ultimate tensile strength of the filament (40 MPa > 39 MPa).

CONCLUSIONS

1. Investigation of angle displacement error values along the blade between the cruising flight speed geometry, the maximum flight speed, and the take-off flight mode is performed. Two different error evaluation methods were introduced. The first one is the Cartesian coordinate system error evaluation method. The second is the cylindrical coordinate system error. The more accurate results indicated the Cartesian coordinate system error evaluation method when the blade is printed with two separate filaments. The cylindrical coordinate system error evaluation method is more accurate when two filaments are mixed for blade printing.

2. The cylindrical coordinate system error evaluation method with the option of two mixed filaments indicated the lowest surface average error. During the maximum flight speed, the average surface error is equal to 0.080° and during the take-off flight mode it is equal to 0.081° . However, the angle in the split line with the maximum flight speed geometry demonstrated the closest result to the target angle (9.743°). But, the angle at the split line for the take-off flight mode was not the closest result to the target angle.

3. A material distribution analysis was performed. The filaments distribution for the cruising flight mode, the maximum flight speed and the take-off flight mode did not separate as it was aimed at. The analysis showed that it is possible to apply four boundary conditions to the base geometry and extract an optimal distribution of filaments along the blade.

4. The results of the stress of the twisting blade indicated that the *Volcano PLA* material is not suitable. Stress when the blade is twisted (40 MPa) exceeds the ultimate tensile strength value of the *Volcano PLA* filament (39 MPa). It is recommended to use another PLA filament with a higher yield or a maximum tensile strength value.

5. Unfortunately, *COMSOL Multiphysics* software does not perform optimization tasks with topology optimization and parametric sweep. In addition, density topology optimization requires a powerful computer to perform this analysis. For this reason, the number of elements and the accuracy of the results are limited.

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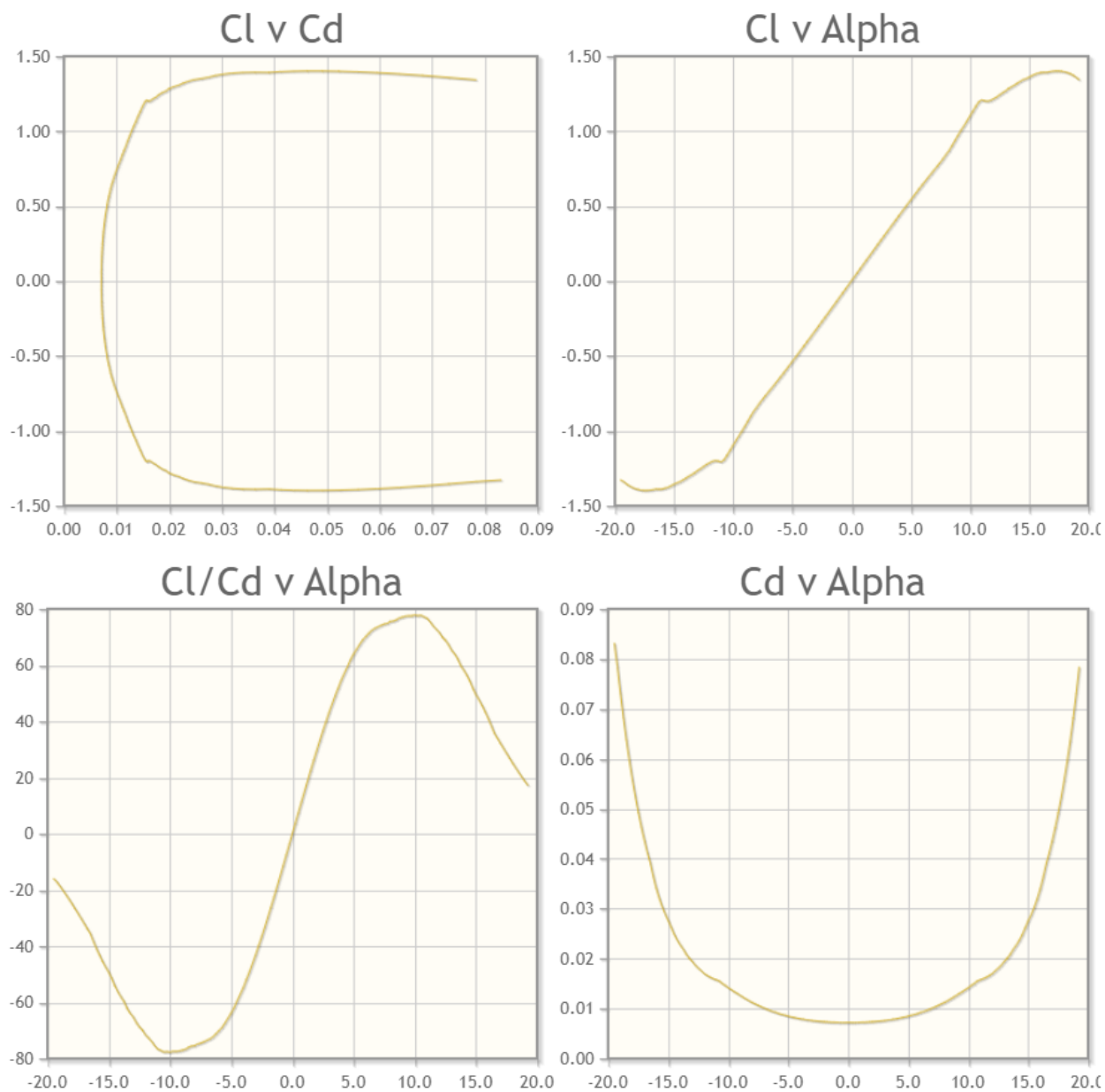
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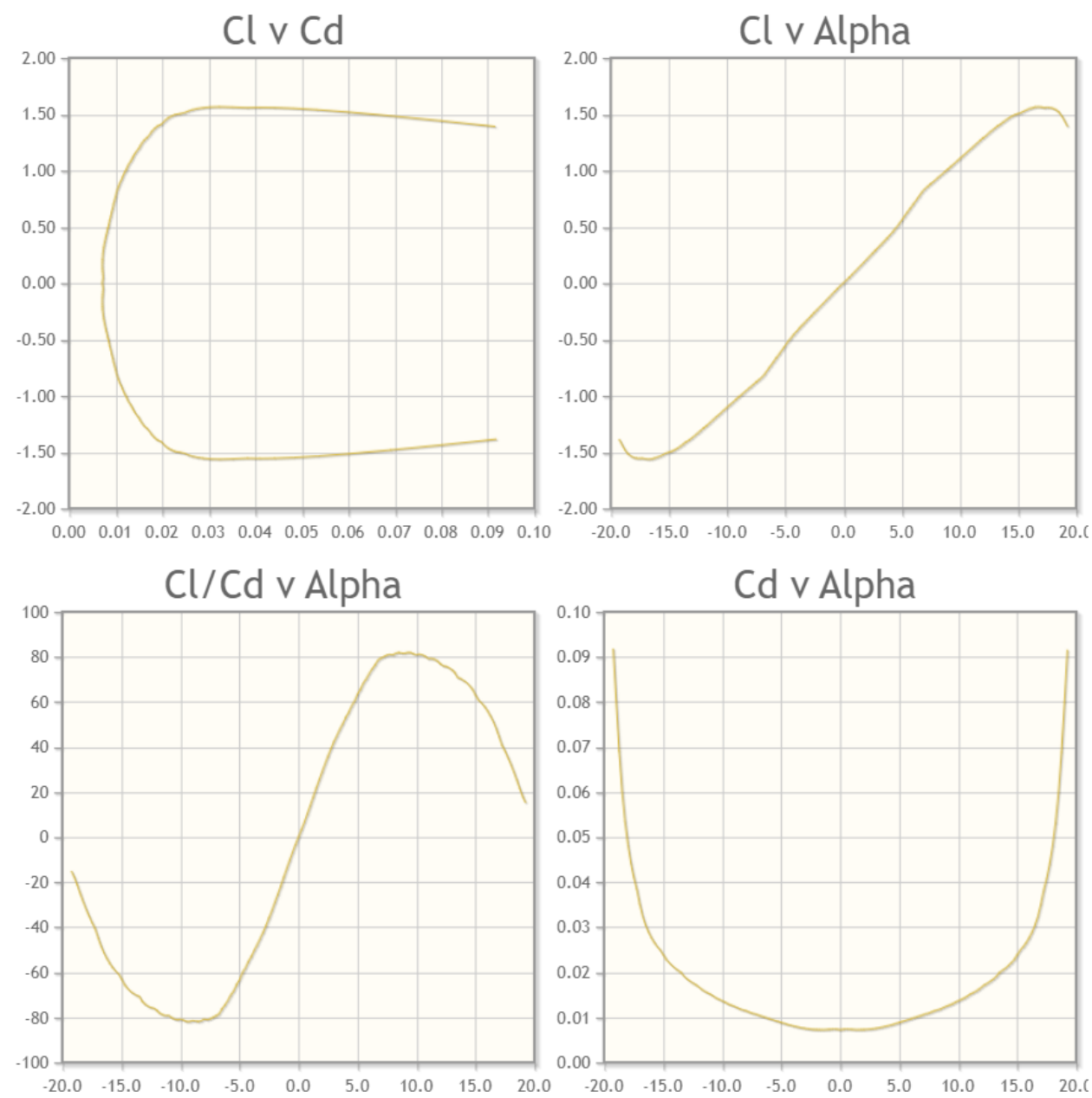
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THE ANNEXES

Annex 1. NACA 0018 aerodynamic properties (Airfoil Tools, 2024)



Annex 2. NACA0012 aerodynamics properties (Airfoil Tools, 2024)



Annex 3. Beta chord angles from the *XRotor* software (prepared by author)

Airfoil section, m	Cruising flight mode beta angles, °	Maximum speed flight mode beta angles, °	Take-off flight mode beta angles, °
0.062	75.405	78.226	74.810
0.068	71.179	75.414	69.421
0.080	64.734	70.889	61.524
0.094	57.990	65.787	53.722
0.110	51.889	60.773	47.067
0.127	46.680	56.146	41.678
0.145	42.330	52.006	37.367
0.163	38.171	48.361	33.905
0.180	35.708	45.174	31.096
0.198	33.188	42.397	28.790
0.215	31.064	39.977	26.877
0.232	29.260	37.867	25.272
0.248	27.718	36.024	23.914
0.264	26.392	34.410	22.755
0.279	25.247	32.995	21.76
0.293	24.253	31.752	20.902
0.307	23.389	30.660	20.157
0.319	22.636	29.700	19.511
0.331	21.979	28.857	18.948
0.342	21.406	28.118	18.459
0.353	20.909	27.473	18.035
0.362	20.479	26.914	17.669
0.370	20.110	26.432	17.355
0.377	19.797	26.021	17.089
0.384	19.535	25.678	16.867
0.389	19.322	25.397	16.685
0.393	19.154	25.176	16.543
0.397	19.030	25.013	16.437
0.399	18.948	24.905	16.368
0.400	18.907	24.851	16.333