Bachelor of Engineering
(Mechanical)

PARAMETRIC GEOMETRICAL MODELLING OF WIND TURBINE BLADES & HUB

(Report on Capstone Project II)

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DECLARATION

We hereby declare that this report entitled “Parametric Geometrical Modelling Of Wind Turbine Blades & Hub” is the result of our own project work except for quotations and citations which have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

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ABSTRACT

Wind turbine industry has substantially grown in last decades and is still becoming larger. Hence, effective ways to design wind turbines are needed. In this report, the procedure of parametric design of a wind turbine blade is presented. This is performed with the help of Grasshopper®, an application embedded into Rhinoceros 3D graphical design software. The process involves parametric construction of airfoil sections along the wind turbine blade. The geometry is modeled by taking advantage of Bezier curves, since they can be used to build nonlinear high curvature contours. Main feature curves in an airfoil are the camber, upper and lower sides, which are defined by a set of appropriately selected parameters. The generation of multiple airfoil sections enables us to construct a complete 3D shape with help of the lofting feature in Rhinoceros environment. Results can be further utilized for static or dynamic analysis. The aim of the project is to develop an algorithm that enables us to reconstruct any available wind turbine blade with maximum precision and to establish a verified solution method by reproducing published data for NACA 4412 in the subsonic flow regime. The blade design is described in detail in this report and all the stages are presented with appropriate illustrations.
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LIST OF ABBREVIATIONS, NOTATIONS / GLOSSARY OF TERMS

Measurements and calculations were made in SI Units.

\( C_p \) pressure coefficient

\( c \) airfoil chord

\( c_{ld} \) section profile-drag coefficient

\( c_l \) section lift coefficient

\( c_{m} \) section pitching-moment coefficient about quarter-chord point

\( L. \) lower surface

\( M \) Mach number

\( \max \) maximum (subscript)

\( \text{NREL} \) National Renewable Energy Laboratory

\( R \) Reynolds number based on free-stream conditions and airfoil chord

\( S. \) boundary-layer separation location, \( 1 - s_{sep}/c \)

\( s_{sep} \) arc length along which boundary layer is separated

\( s_{turb} \) arc length along which boundary layer is turbulent including \( s_{sep}' \)

\( T \) transition (subscript)

\( T. \) boundary-layer transition location, \( 1 - s_{turb}/c \)

\( U. \) upper surface

\( x \) airfoil abscissa

\( y \) model span station, \( y = 0 \) at midspan, positive downward

\( z \) airfoil ordinate

\( \alpha \) angle of attack relative to \( x\)-axis

\( \text{HAWT} \) horizontal axis wind turbine

\( \text{VAWT} \) vertical axis wind turbine
1. INTRODUCTION

1.1. Problem Statement

The energy consumption over the world has been constantly growing over the decades from just under 10 000 million tonnes of oil equivalent in 2000 to almost 13,500 in year 2015 as illustrated in Figure 1.1.1[2]. Conventional energy sources have been shown to have detrimental effect on the environment. The exploitation of sustainable energy sources appears to be one of the most feasible solutions to this problem.

![World Energy Consumption 2000-2015](image)

*Figure 1.1.1: World Energy Consumption 2000-2015 year*

Indeed, wind is an abundant, free and clean source of energy. Thus, wind turbines have become one of the most popular tools in sustainable energy exploitation. Wind turbines can be classified as horizontal axis HAWT and vertical axis wind turbines VAWT depending on the orientation of their shaft and rotational axis as shown in Figure 1.1.2 [6]. Currently, HAWT turbines are more widely used comparing to VAWT. Thus, wind turbines are differentiated based on their design. Overall, a typical wind turbine’s design whether it is HAWT or VAWT consists of blades, hub and tower.
Wind turbines are consistently undergoing design alterations to improve their efficiency and reduce cost. The design of blades has an essential role in the development of the wind turbines, as the blades are the part of the wind turbine that capture the wind and generate the energy [3]. It is a scrupulous work that requires tremendous efforts and time. The aim of the project is to contribute to facilitation of this process by developing the methodology and the software tools that allow the automatic generation of 3D surface and mesh models of wind turbine blades and the accompanying hub. The project consists of two parts. The first part delivered this semester focuses on the development of the methodology and design of the blades, while the second part concentrates on the design of the hub and optimization of the results.

1.2. Project Description

In order to automatically generate 3D surfaces of the blades, the number of their cross-sections that is airfoils are considered. Each airfoil based on its geometrical parameters is constructed in Grasshopper software. Geometrical parameters are chosen as the minimum number of parameters that permits the user to create a wide variety of shape instances offering at the same time the maximum flexibility. The only problem
that was encountered during this project was transferring the algorithm of the curve
construction into Grasshopper building blocks, as this software is newly discovered for
all the group members.

The main steps of the project are:

❖ Identification of the parameters that will be used in the generation wind turbine
  blades (number of blades, chord lengths, angles, radii etc / length, camber
  width, trailing edge angle etc)
❖ Generation of a curve grid comprising basic and auxiliary guiding curves that
  are appropriate for the shape description of the wind turbine
❖ Generation of modeling aids (auxiliary curves and/or surfaces), if required
❖ Generation of the 3d surface model of blades by interpolation of control curve
  grid
❖ Modeling of the existing airfoil shapes
❖ ANSYS Fluent simulation
❖ Optimization

The project is accomplished by a group consisting of three mechanical engineering
students: Yerkegali Metey, Saltanat Nazarova and Aidar Kurmantayev. The main duties
of each group member are:

❖ Literature review, data analysis and report editing - Saltanat Nazarova
❖ Generation of curves, ANSYS Fluent simulation, optimization - Yerkegali Matey
  and Aidar Kurmantayev
❖ Identification of parameters – team work.

1.3. Practical Application

This project is vital to any user who is involved in wind turbine development. The
deliverable of the project is a user-friendly tool based on Grasshopper software that
allow designing wind turbine blades based on the geometrical parameters. Hence, any user even from non-engineering field who has parametrical data can obtain the resultant blade once they input their data. Moreover, this tool may be exploited for modeling of existing airfoil shapes. Indeed, this tool is able to design the shape of a specific existing airfoil, thus the geometrical parameters of a specific shape can be obtained. Overall, this project may be used for research purposes, in wind turbine manufacturing field and by the students for educational purposes.

1.4. Airfoil

The lift force is generated due to the shape of the airfoil. It acts perpendicular to the direction of flow and is the net result of the pressure difference. Indeed, low air pressures act on the surface of the airfoil with more curve, while high-pressure air pushes on it’s the other side. The lift force increases, as the blade is located at a greater angle to the wind that is angle of attack. At very large angles of attack the blade “stalls” and the lift decreases again. So there is an optimum angle of attack to generate the maximum lift.

Another force that acts on the airfoil is the drag force. It is parallel to the flow and increases with angle of attack. At an angle slightly less than the maximum lift angle, the blade reaches its maximum lift/drag ratio. The best operating point will be between these two angles [5].
Since the drag is in the downwind direction, it may seem that it wouldn’t matter for a wind turbine as the drag would be parallel to the turbine axis, so wouldn’t slow the rotor down. It would just create “thrust”, the force that acts parallel to the turbine axis hence has no tendency to speed up or slow down the rotor. When the rotor is stationary (e.g. just before start-up), this is indeed the case. However, the blade’s own movement through the air means that, as far as the blade is concerned, the wind is blowing from a different angle. This is called apparent wind. The apparent wind is stronger than the true wind but its angle is less favourable. At this angle drag is increased, while the lifting force acting on the airfoil decreases. Thus, to maintain a good angle of attack, the blade must be turned further from the true wind angle.

Aerodynamics is a science that mainly focuses on the air movement around a solid body. This discipline has been born with the first attempts of humanity to construct airplanes. The theory behind aerodynamics is based on fluid and gas dynamics. Thus, it is a sub category of these disciplines with the difference that it is concerned mainly with air motion. Although formal development of this discipline began in the eighteenth century, the basic concepts, such as aerodynamic drag, had already been observed and understood earlier. One of the earliest experiments in aerodynamics has

Figure 1.4.1: Airfoil
aimed to achieve heavier-than-air flying machines, and was first illustrated in 1903 by Wilbur and Orville Wright. Since then, the science of aerodynamics has been constantly developing with the use of mathematical analysis and scientific experimentation in wind tunnels as well as computer based simulations. Currently it is focused on the study of more sophisticated concepts such as compressible flow, supersonic and subsonic flow, turbulence, boundary layers and has become increasingly computational in nature.

An airfoil is the cross-sectional shape of the wing. It is a fundamental unit in aerodynamics, as it's study clearly demonstrates basic concepts of this science and simulations of the full number of the cross-sections of the wing provide comprehensive data for practical use. The typical shape of the airfoil is illustrated in Figure 1.4.1. As it is clearly shown, this shape is dependent on its chord line, chamber line, leading and trailing edge etc. These terms will be explained later.

An airfoil-shaped body, moving through a fluid, produces an aerodynamic force. The component of this force, perpendicular to the direction of motion, is called lift. The component parallel to the direction of motion is called drag.

The lift of an airfoil is mainly the result of its angle of attack and shape. When oriented at a suitable angle, the airfoil deflects the oncoming air, resulting in a force on the airfoil in the direction opposite to the deflection. This force is known as aerodynamic force and can be resolved into two components: lift and drag. Most foil shapes require a positive angle of attack to generate lift, but cambered airfoils can generate lift at zero angle of attack. This "turning" of the air near the airfoil creates curved streamlines, resulting in lower pressure on one side and higher pressure on the other. This pressure difference is accompanied by a velocity difference, as described by Bernoulli's principle, so the resulting flowfield about the airfoil has a higher average velocity on the upper surface than on the lower surface.
Terms related to the geometry of an airfoil:

❖ The leading edge is the foremost point of the airfoil. For a zero angle of attack, it coincides with the stagnation point.
❖ The trailing edge is the point at the end of the airfoil where the flow rejoins.
❖ The chord line is the straight line connecting leading and trailing edges.
❖ Angle of attack is the angle between the chord line and the direction of the oncoming flow.
❖ Camber line is the locus of points midway between the upper and lower surfaces. It may or may not be a straight line.
❖ Lift coefficient is a dimensionless coefficient that relates the lift force on the body to a reference area and to fluid's velocity and density.
❖ Drag coefficient is a dimensionless coefficient that relates the dragging force on the body to a reference area and to fluid's velocity and density.
❖ Stall angle of attack is the angle of attack at which the lift coefficient is maximum and after which the lift coefficient starts to decrease.

1.5. Bezier Curve

The algorithm of construction of airfoils in Grasshopper is based on Bezier curves. It is the curves that are developed with the use of control polygons that are comprised of control points. Figure 1.5.1 shows the examples of Bezier curves. Bezier curve passes through its first and last control points, and is tangent to the control polygon at those endpoints. Complicated shapes can be designed by using a number of Bezier curves. Since Bezier curves are tangent to their control polygons, it is easy to join together two Bezier curves such that they are tangent continuous. Bezier curves of any degree can be defined. Figure 1.5.2 shows Bezier curves of various degrees [7]. A degree n Bezier curve has n + 1 control points. In this project degree n=2 and n=3 are used. A mathematical equation that is used for Bezier curve construction has a form of:

\[ P(t) = m_0(t)P_0 + m_1(t)P_1 + m_2(t)P_2 + m_3(t)P_3. \] [1.5.1]
Figure 1.5.1: Examples of Bezier Curves

Figure 1.5.2: Bezier curves of various degrees


2. LITERATURE REVIEW

Various methods are currently being developed in the field of detailed wind turbine modeling. Different views and approaches on how to design each crucial shape are employed, such as taking advantage of B-spline curves and inserting parameters for such curves or constructing outer shape by generating points on a 2D plane etc. are implemented to achieve that objective. In following literature review some of these methods will be presented.

2.1. Design And Analysis Of A Bladed Vertical Axis Wind Turbine Blade Using Analytical And Numerical Techniques

Hameed and Afaq [4] focused on design and optimization of the Vertical Axis Wind Turbine (VAWT) using analytical and numerical techniques. This type of turbine has the advantage of allowing separate placement of the wind capturing component and the generator, which can be installed on the ground. In addition, VAWT is able to handle wind coming from any direction without yawing. The blades are straight, untwisted and uniform sectioned, therefore are easy to fabricate. However, though the benefits of this turbine are motivating, there are still risks involved. Comparing to the width of a blade, it length is very big, hence the aspect ratio is substantially large and when high values of bending moments appear in its weakest points, the result can be a failure of that blade. The solution proposed was a three-blade design, which will alleviate the stresses at the connection between the blade and a tower. The blade model specifications were calculated analytically, the model was justified numerically and the optimum value of the wall thickness was determined for highest values of bending stresses and deflections.

There is a substantial number of design parameters incorporated in this research. Following is the table describing each of them.
### Table 2.1.1: Parameters for Modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design velocity, $V$</td>
<td>The average operational wind speed was taken as 8 m/s</td>
</tr>
<tr>
<td>No. of blades, $n$</td>
<td>Three or more blades can reduce the torque ripple</td>
</tr>
<tr>
<td>Tip speed ratio, TSR</td>
<td>Ratio between rotational speed of the blade tip and wind velocity</td>
</tr>
<tr>
<td>Solidity</td>
<td>The ratio of blade area and rotor area</td>
</tr>
<tr>
<td>Power coefficient, $C_P$</td>
<td>For TSR=4.1, solidity=0.24, $C_P=0.43$</td>
</tr>
<tr>
<td>Diameter of turbine, $D$</td>
<td>For 900 W output and density of air as 1.23 Kg/m$^3$, $D=2.578$m</td>
</tr>
<tr>
<td>Span length of the blade, $b$</td>
<td>Span was also taken as 2.578m</td>
</tr>
<tr>
<td>Aspect ratio, AR</td>
<td>For straight bladed VAWT, AR=12.5</td>
</tr>
<tr>
<td>Chord length of the blade, $c$</td>
<td>Calculated value for chord length was 0.2062m</td>
</tr>
<tr>
<td>Selection of airfoil</td>
<td>NACA 0015 was chosen as most suitable because of desired aerodynamic performance</td>
</tr>
</tbody>
</table>

First thing the researchers did was finding the relation between angle of attack and a pitching angle. The various values of angles and their relations were tabulated and plotted versus each other. After that lift and drag coefficients were calculated utilizing commercial DESFOL software. They were also inserted in a table sorting them accordingly to a pitch angle. Next was evaluating maximum tangential blade velocity $R_w$, which was equal to 32.8 m/s. Relative velocity as a vector solution of maximum blade tip velocity and velocity $V$ was calculated for various angles inside velocity triangle. Normal and axial forces were determined in complete rotation of a blade. Then locations of strut attachment with the blade and cross sectional parameters were identified. The design material was selected to be aluminum with $E=70$ GPa, $\rho=2700$ Kg/m$^3$ and $\nu=0.33$. After calculating the centrifugal forces, finally, maximum deflections and stresses were evaluated and recorded.

Numerical evaluations involved subjecting the model under the same boundary conditions, and altering the wall thicknesses and element type specifications in ANSYS 11.0 library. The difference between numerical and analytical models is represented in following pictures. Solid45 and Beam3 are element types chosen from ANSYS library in order to compare the convergence of solutions to analytical ones.
Figures indicate after specifying the element type to Beam3, the analytical and numerical solutions become similar. This purpose of this part of literature review was to illustrate one type of wind turbine blade modeling. The geometry was optimized firstly basing on the beam theory, and after that it was numerically modeled.

2.2. Computer-Aided Design Of Horizontal Axis Turbine Blades

Next research employs a distinct approach in designing a wind turbine blade. Specifically, Perez and Vargas present a method that utilizes B-spline surfaces realized in computer environment [6]. They have done their work in QBLADE, the platform for wind turbine blade design and aerodynamic simulation [11]. A horizontal axis rotor is made of several twisted blades uniformly placed around a hub. A series of airfoil sections define the surface of those blades, alternating from a circular shape near the hub up to sharp streamlined surfaces at the tip of the blade. The 3D model of blade is constructed via interpolation between multiple curves in 3D space, which are indeed cross sections of a blade. In order to build these curves it is required to accurately represent the shape of an airfoil in the software. Standard approaches require working with large amount of data in turn, because more than hundred discrete points are needed to capture airfoil shape. The reason behind this is the leading edge of the airfoil,
which has high curvature, compared to its rear part, and this leading edge possesses most aerodynamic properties of the turbine.

The method comprises the following: the geometric parameters of the blade are recorded firstly, being the position, skew, rake, and twist distribution and the sectors, which were defined discretely. Next, curve-fitting scheme is implemented and B-spline curves emerge as a result. Finally, a lofting procedure is applied and the 3D exterior surface is generated. The crucial point here is that all mentioned parameters help to define coordinates of a curve relative to an origin. The derived equation is following:

\[ Q_j = (r_i \sin(\alpha_i + \text{Sk}_i), R \sin(\theta + \text{Tw}_i) + \text{Rk}_i, r_i \cos(\alpha_i + \text{Sk}_i)) \]  

[2.2.1]

Where \( r_i \) is the coordinate vector radius

- \( \text{Tw}_i \) – twist angle
- \( \text{Sk}_i \) – skew angle
- \( \text{Rk}_i \) – rake angle

Several points are obtained, and a least squares approximation method is applied, so that the number of control points is not large. An iterative process is employed for acquiring the required shape accuracy for the resulting description.

Finally, the lofting process is curve interpolation process where the solution to systems of parameterized equations will provide the shape of the airfoil.

### 2.3. Optimization Design, Modeling and Dynamic Analysis for Composite Wind Turbine Blade

Song et al claim that it is difficult to evaluate the most important features of wind turbine blades such as axial and circumferential factors [9]. The shape of blade is complex, and moreover, the materials of which modern turbine blades are made of (fiber glass and other composites) require accurate and precise modeling of their shape. The purpose of their research was to develop software that enables to aerodynamically
optimize and precisely reconstruct the blade in CAD program for further static and dynamical analysis.

The optimization process started from specifying standard parameters such as choosing the existing turbine model, its rotor diameter, and angle of attack at the blade, aiming to obtain to maximum wind energy utilization coefficient. It was based on Blade Element - Momentum Theory, and adopted for optimization by Wilson method [9]. The optimization algorithm was coded in MATLAB designed to obtain chord length and twist angle as utilization coefficient variables. The iterative loop was used and identified the most suitable needed values.

The geometrical blade modeling was performed by means of coordinate transformation. Taking the tailing edge as origin, the two and three-dimensional translation was applied. The example of such an equation is presented below

\[
\begin{align*}
X &= -\frac{C}{100} \times \sqrt{X^2 + Y^2} \times \cos(\arctan \frac{Y}{X} + \theta) \\
Y &= -\frac{C}{100} \times \sqrt{X^2 + Y^2} \times \sin(\arctan \frac{Y}{X} + \theta) \\
Z &= r
\end{align*}
\]

[2.3.1]

The coordinates were inserted and cross section profiles defined by set of dots were obtained. Following pictures illustrate charts resulting from transformation.

*Figure 2.3.1: Cross-section charts of blade elements*
To sum up, the authors applied MATLAB programming to shape the contour of wind turbine blades. Integrating data in SolidWorks and ANSYS allowed constructing 3D models to observe what the actual blade would look like.

2.4. T4T (Tools for Turbomachinery) software.

Strofylas et al. (2014) have developed a tool named “T4T” (Tools for Turbomachinery) for the parametric design of turbomachinery and wind turbine blades. The authors claim that precise and efficient geometry representation is a crucial point in either construction of new airfoils or in optimizing existing models. They developed a program in QT C++ which has some specific features such as the methodology to calculate the mean camber line, leading edge, chord for any arbitrary blade section, or ability to modify trailing edge and add thickness to it and others.

Two ways of constructing the blade profile are reported in their work. In the first the design procedure starts with a definition of the mean camber line, after which “thicknesses” are distributed along the airfoil and the profile is created. The second method involves importing points provided in a text file and fitting a curve higher than second degree to ensure continuity of 2\(^{nd}\) derivatives. After outer curve is constructed, the mean camber line, leading edge and chord line computations are performed. However, to construct the mean camber line, a slightly complex procedure is carried out, because leading edge is usually unknown. The bisector line between upper and lower sides is approximated with help of circles inscribed in the profile. The centers of each circle are connected to form a curve and finally, the curve is extended along its tangent vector and its intersection with the profile curve defines the leading edge.
To produce the 3D model, the blade profiles are distributed perpendicularly to the stacking line which is usually a straight line. They can be oriented with respect to their center of gravity or the leading edge, or some specific points such as aerodynamic center. After that the profiles are distributed in following manner.
Final step of outer 3D surface construction is the interpolation along the span of the turbine blade. The important note is that all profiles must have same number of interpolation points. The necessary points are computed using a cosine distribution and interpolation is performed. Strofylas et al. (2014) claim that this methodology ensures continuity of the surface, while some commercial software fail to carry out proper lofting procedure leaving inaccurate trailing and edge geometries.

Another research presented by Charalampous et al. (2015) demonstrates the methodology for the parametric design of wind turbine blades in Grasshopper 3D. The methodology is similar to what is done in our capstone except for the profile is again constructed from set of points fitted to a curve like mentioned above. The motivation behind is in the freedom provided by the Grasshopper 3D and Rhinoceros 3D in constructing various types of curves and shapes, while most of commercial software are limited in the complex shape definitions which in turn make it difficult to finalize the model. Authors claim that Grasshopper 3D not only overcomes the problem, but also enables them to construct parametric models for the geometric design specifications of wind turbine blades.

3. METHODOLOGY
3.1. Construction of The Model

The blade is designed in Rhinoceros-3D with the aid of the Grasshopper® visual programming software package. This software was chosen as it has user-friendly interface. Eight parameters are employed for the design of an airfoil: camber curve parameters are angle at leading edge, angle at trailing angle, maximum camber width Y, and longitudinal position of maximum camber width X; upper side curve parameters are angle at trailing edge, maximum width Y, longitudinal position of maximum width X, and shape fullness at leading edge. An airfoil consists of upper, camber and lower curves. First, the camber curve is set up, then it is followed by upper curve the construction definition of which will be presented afterwards, and finally lower curve is constructed by mirroring selected points from upper curve about the camber curve and joining them in order to get lines between points. Consequently, these lines are mirrored about camber curve. End points of each line are interpolated to get lower
curve. Bezier curves are used to model curves. Especially, second and third-degree Bezier curves were utilized.

Table 3.1.1: Components used in Grasshopper® software

<table>
<thead>
<tr>
<th>Components</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Point" /></td>
<td><em>Point</em> - contains a collection of three-dimensional points</td>
</tr>
<tr>
<td><img src="image" alt="Slider" /></td>
<td><em>Number slider</em> - numeric slider for single values</td>
</tr>
<tr>
<td><img src="image" alt="Read File" /></td>
<td><em>Read File</em> - read the contents of a file</td>
</tr>
<tr>
<td><img src="image" alt="Remap Numbers" /></td>
<td><em>Remap Numbers</em> - remap numbers into a new numeric domain</td>
</tr>
<tr>
<td><img src="image" alt="Set Union" /></td>
<td><em>Set Union</em> - creates the union of two sets (the collection of unique objects present in either set)</td>
</tr>
<tr>
<td><img src="image" alt="Nurbs Curve" /></td>
<td><em>Nurbs Curve</em> - construct a nurbs curve from control points</td>
</tr>
<tr>
<td><img src="image" alt="Move" /></td>
<td><em>Move</em> - translate (move) an object along a vector</td>
</tr>
<tr>
<td><img src="image" alt="Mirror Curve" /></td>
<td><em>Mirror Curve</em> - mirror a shape in a freedom curve</td>
</tr>
<tr>
<td><img src="image" alt="Loft" /></td>
<td><em>Loft</em> - create a lofted surface through a set of section curves</td>
</tr>
<tr>
<td><img src="image" alt="Line" /></td>
<td><em>Line</em> - create a line between two points</td>
</tr>
<tr>
<td><img src="image" alt="Join Curves" /></td>
<td><em>Join Curves</em> - join as many curves as possible</td>
</tr>
</tbody>
</table>
### 3.1.1. Camber Curve

The starting and end points of the curve are fixed and shown in the program as point 1 and point 5 in Grasshopper® model of camber curve. Their coordinates are (0,0) and (1,0) respectively. However, the length of the airfoil is set to (1,0) by default, so it can be set to any number and hence the last point could be noted as (L,0). Four parameters are allowed to be changed with the help of *Number Slider* component: leading edge angle, trailing edge angle and the coordinates of the max width of the curve, which are \( x_{\text{max}} \) and \( y_{\text{max}} \).
Figure 3.1.1.1: Airfoil parameters

Table 3.1.1.1: Parameters of camber curve and its abbreviations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading edge angle</td>
<td>$c_{a_l}$</td>
</tr>
<tr>
<td>Trailing edge angle</td>
<td>$c_{a_t}$</td>
</tr>
<tr>
<td>Maximum camber width</td>
<td>$c_{max}$</td>
</tr>
<tr>
<td>Longitudinal position of maximum camber width</td>
<td>$x_{c_{max}}$</td>
</tr>
</tbody>
</table>

The camber curve construction is divided into two parts for simplicity in network construction and airfoil parameters are represented in Figure 3.1.1.1.

Its first part is built using point 1, point 2 and point 3. To give a clear explanation, components of Grasshopper® will be introduced step by step. Component **Point** is used here to define the points in X, Y and Z coordinates. However, airfoil shape only needs X and Y coordinates. Point 3 indicates the coordinates of the max width of the curve, $(x_{\text{max}}, y_{\text{max}})$. The values of $x_{\text{max}}$ and $y_{\text{max}}$ are set using component **Number Slider**. Component **Number Slider** has numeric upper and lower limit. Then it goes to **Remap Numbers** component in order to remap numbers. For $x_{\text{max}}$, the target domain is from 0.2 to 0.8. For $y_{\text{max}}$, it is from 0.01 to 0.15. Remap Numbers component is used to define angles and points directly. Point 2 is located at $(x, y_{\text{max}})$, where $y_{\text{max}}$ is set by user using **Numeric Slider**, $x$ is expressed as $y_{\text{max}}/\tan(\text{leading edge angle})$. The intermediate control point needs to be at the intersection of two lines: a horizontal line passing through point 3 and the line passing through point 1 with an angle equal to the leading-edge angle. Here, the leading-edge angle is defined by **Numeric Slider** with numeric domain from 0 to 1. Then, it also goes to **Remap Numbers** component with target domain calculated via **Expression**: $\tan(y_{\text{max}}/x_{\text{max}})$. Therefore, leading edge angle directly depends on the values of $x_{\text{max}}$ and $y_{\text{max}}$. As a result, model is
constructed. Few manipulations with the building blocks and its connections allows us to establish such relationships that when any of the parameters are changed the control points 2 and 3 change accordingly.

The second part of the camber curve is modeled with the aid of 3 control points: point 3, point 4 and point 5. While point 3 and 5 are already defined, point 4 is defined as the point 2. It is located at \((x, y_{\text{max}})\) where point \(x\) can be found as \(1-y_{\text{max}}/\tan(\text{trailing\_edge\_angle})\). Because, this point is located in the second part of the curve. The intermediate control point needs to be at the intersection of two lines: a horizontal line passing through point 3 and the line passing through point 5 with an angle equal to the trailing edge angle. Trailing edge angle is determined by method similar to leading edge angle determination. However, when it is remapped into a new numeric domain, its target domain calculated using another Expression: \(\tan(-y_{\text{max}}/(x_{\text{max}}-1))\). Set Union component is used to create a union of defined control points. For the first part of camber curve, point 1, point 2 and point 3 are set together. For the second part, point 3, point 4 and point 5 are joined. Hence, two parts of camber curve are constructed using component Nurbs Curve that requires curve degree insertion. In our case, it is set to two degrees, because there are 3 control points for each curve. Finally, Join Curves component is used to join two curves and get camber curve. Figure 3.1.1.2 illustrates the camber curve construction algorithm in Grasshopper. Figure 3.1.1.3 illustrates the curve itself in Rhinoceros because of constructed model.

![Figure 3.1.1.2: Construction algorithm of camber curve in Grasshopper® software](image-url)
3.1.2. Upper Curve

The design construction of upper curve is similar to camber curve. Upper side is also divided into two parts for simplicity. Second part is designed as the tail of the camber curve, while the first part has some alterations. Tail part of upper curve is also two-degree curve, while the first part of the curve is different. It is modeled with the aid of 4 points; therefore, it is a third-degree curve. It can be observed from Figure 3.1.1.1.

Table 3.1.2.1: Parameters of upper curve and its abbreviations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading edge angle</td>
<td>( l_s )</td>
</tr>
<tr>
<td>Trailing edge angle</td>
<td>( a_t )</td>
</tr>
<tr>
<td>Maximum camber width</td>
<td>( z_{\text{max}} )</td>
</tr>
<tr>
<td>Longitudinal position of maximum camber width</td>
<td>( x_{z_{\text{max}}} )</td>
</tr>
</tbody>
</table>

Point 1 (0,0) and point 6 (L,0) are fixed. Point 4 define the coordinates of the max width of the curve, \((x_{\text{max}}, y_{\text{max}})\). Points 2 and 3 are used to designate the nose of upper curve. Numeric Slider component expressed as \( l_s \_\text{parameter} \) helps to change the position of points in conjunction. Moreover, the leading edge of upper curve is 90 degrees at starting point 1. Point 2 is defined as \((0, y)\), where \( y \) is calculated via
Expression $ls\_parameter\ast y\_max$. Point 3 coordinates are $(x, y\_max)$, where $x$ is expressed through $(1-\ast ls\_parameter)\ast x\_max$.

For the second part, point 5 is located at $(x, y\_max)$, where $y\_max$ is set by utilizing Numeric Slider, while $x$ is denoted as $1-y\_max/\tan(\text{trailing\_edge\_angle})$. Here, the trailing edge angle is defined by Numeric Slider. Then, it is remapped by Remap Numbers component using Expression: $\tan(-y\_max/(x\_max-1))$ for the target domain calculation. Consequently, control points 1, 2, 3 and 4 are united together in order to obtain first part of the upper curve (Nurbs Curve component with third-degree curve). Another union is produced by control points 4, 5 and 6 (Set Union component) to construct second part of the upper curve (Nurbs Curve component with two-degree curve). Join Curves component is used to define upper curve as one curve. Figure 3.1.2.1 interprets the upper curve Grasshopper® algorithm. Upper curve is represented in Figure 3.1.2.2.

![Figure 3.1.2.1: Construction algorithm of upper curve in Grasshopper® software](image-url)
The construction of lower curve is based on the upper and camber curves. The main principle is to select specific number of points on the upper curve and mirror it about camber curve. Initially, Divide Curve component is used to divide a curve into equal length segments, thereby new points are appeared. Totally, 10 equal line segments are taken. Consequently, points on camber curve are detected through Curve Closest Point component. As a result, there is the same number of points on camber curve as on upper curve that are connected with those points identified on upper curve respectively using Line component. Afterwards, Mirror component is used which requires geometry to be mirrorred and mirror curve. In our case, geometry and mirror curve are above-mentioned lines and camber curve respectively. In order to construct lower curve, end points of that mirrorred lines are needed. End Points component helps to identify corresponding end points. As a result, new set of points defined which is used to construct lower curve of the airfoil using Interpolate (t) component. Here, the importance of constructing camber curve is characterized. Also, the leading edge angle of lower curve is 90 degrees, which can be directly set through limits of the component Interpolate (t) (Tangent at start of curve {0.0, -1.0, 0.0}). Finally, joining upper, camber and lower curves constructs 2D airfoil shape that is represented in Figure 3.1.2.2 below.
3.1.4. Airfoil Algorithm

Finally, the combination of camber, upper and lower curves algorithms compose the whole airfoil algorithm, which is illustrated in Figure 3.1.4.1. 2D shape of airfoil can be seen from Figure 3.1.3.2.
3.1.5. Read File component

The aim of Read File component is to read corresponding parameters from external sources such as notepad text editor, wordpad and so on. Hence, this component can be used instead of above-mentioned sliders in order to simplify the insertion procedure of parameters. Parameters are taken from internet or reliable sources can be further transported into some text editor. Then, using Read File component instead of Numeric Slider component to read the file, shape and surface construction can be developed in an automated manner.

3.2. Blade Surface Definition

In the proposed philosophy, the blade surface definition depends on progressive 2D airfoil profiles. The relating blade cross-sections (airfoil shapes) are determined by a direct interpolation process through a set of points, utilizing the curve fitting technique. The derived curves are distributed in perpendicular planes along a line, which establishes the pitch axis of the blade. The twist of the blade depends on twist angle of each cross-section. By applying the appropriate translational and rotational motions the section curves are accordingly positioned in the 3D space.
Once the airfoils are properly arranged, the construction of blade surface can be performed by using the built cross-sections. Grasshopper® gives the ability to make surfaces through different methods; in the present work, the surface is described using the lofting method. To succeed this, each cross-section is formed as single NURBS curves to avoid discontinuity issues in the resulting surface. An illustration plan of a 3D surface is displayed in Figure 4.1.1.

3.3. Geometry Description

The geometrical coordinates for NREL’s S809 Airfoil 150-400 kW wind turbine was used to show the flexibility of introduced methodology. The geometrical data of airfoil used are taken from the work of Somers [8]. S809 Airfoil shape is shown in Figure 4.2.1. S809 Airfoil coordinates, namely upper curve and lower curve points are represented in table 1.

These points are utilized to show the performance of generated methodology. The main aim is to import S809 Airfoil points of upper and lower curves into Rhinoceros program. Then using airfoil algorithm, airfoil shape should be manipulated so that it
corresponds to S809 Airfoil shape by changing different parameters in Grasshopper® using sliders. This process is illustrated in Figure 4.2.2.

![Figure 4.2.1: S809 Airfoil shape](image1)

![Figure 4.2.2: S809 Airfoil points and produced airfoil](image2)

### 4. ANSYS FLUENT SIMULATION

#### 4.1. Description of Tool

This research utilizes the software FLUENT by ANSYS to analyze the flow. This flow modeling software provides expansive modeling abilities necessary to model flow, turbulence, heat transfers and range of reactions for practical applications ranging from the air flow around the wing to combustion in a heater. Its technology enables quick and accurate CFD results, adaptable meshes and unrivaled parallel scalability. Besides,
ANSYS allows import of meshes from other softwares. Utilizing the functionality, offered 2D airfoils and 3D blades can be efficiently analyzed. Progresses and innovations in modern technology and software developments have revolutionized the whole engineering design process of products. There is a substantial number of qualitative CFD packages that can be used to model flow over solid objects. The modeling procedure consists of few steps. Initially, the geometry and meshes are created. After the development of the mesh or grid, a solver is utilized to solve the governing equations of the problem. FLUENT has been chosen as our main solver during this research. The results of the analysis were compared with the available data on NACA 4412 airfoil.

4.2. Inputs and Constraints

The mesh that will be created prior to the calculations will be on a structured domain. In Fluent, standard sea level values will be assumed for the freestream properties. Hence, Pressure = 101,325 Pa, Density = 1.176674 kg/m$^3$. Temperature = 300 K Kinematic viscosity = 1.407e-5 m$^2$/s. Chord length = 1m. Re=1000000. The freestream velocity will be 15.2 m/s and the angle of attacks analyzed are 0°, 1°, 3°, 5°.

4.3. Simulation Procedure

For the simulation procedure, the geometry of NACA 4412 airfoil was generated by our methodology using Grasshopper and Rhinoceros. Afterwards it was imported to ANSYS Workbench. The procedure of Fluent simulation is presented step by step in the next sections.
The two-dimensional version of ANSYS Fluent was utilized, introducing the steady implicit coupled solver. It provides with the direct solution of continuity, momentum and energy equations at once. Pressure far-field boundary conditions were gauge pressure of 101,325 Pa and temperature of 300 K. In the turbulence model, default settings were utilized, with only change of turbulent viscosity ratio to 1 and turbulent intensity to 10%. For the solver, the modified turbulent viscosity was set to a second-order upwind discretization scheme.

4.3.1. Turbulence Model

Inviscid flow analyses can be used when the effect of viscosity is negligible. For example, it is applied for high-Reynolds-number cases where inertial forces tend to dominate viscous forces. In case of an aerodynamic analysis of some high-speed projectile, the pressure forces on the body dominate the viscous forces. Therefore, an inviscid analysis provides a quite adequate estimate of the primary forces acting on the body. Once the shape of the body is improved to maximize the lift forces and minimize
the drag forces, a proper viscous analysis can be used to include the effects of the fluid and turbulent viscosity on the lift and drag forces[4].

Additional example when inviscid flow analysis can be performed is to obtain an adequate initial solution for problems involving complicated flow physics and/or complicated flow geometry. In this case, viscous forces are ignored at the initial stages in complicated momentum equations. But once the calculation has begun and the residuals are diminishing, the viscous terms are to be turned on by enabling laminar or turbulent flow and the solution to be progressed to converge. This is quite common method for complicated flows analysis.

4.3.2. Geometry

Firstly, we import the NACA 4412 airfoil shape to ANSYS Workbench Design Modeler from Rhinoceros. Afterwards, wind tunnel geometry was prepared appropriately as shown in figure. To get more accurate meshing, circle was drawn around an airfoil geometry. Moreover, rectangle was used to represent the path after wind passes the airfoil shape. It also increases the quality of mesh. The Split Edges feature was used, which allows for the splitting of edges into two or more pieces. In our case, it was divided into two parts. The last procedure in Design Modeler is to identify boundary conditions by creating named selections. They are: inlet, outlet, free, part1-airfoil, part2-airfoil.
Meshing is the process in which the geometry is discretized into elements and nodes in space. The mathematical representation of the stiffness and mass distribution of the structure is done through meshing and material properties specification.

In ANSYS, the mesh can be set by default at a solve time, depending on several factors such as model size, the closeness of other topologies, curvature of the body, and complexity of the function. The fineness of the mesh can be varied to get more accurate results, or any can refine the mesh in the proximity of geometry where it is more important and leave the rest unchanged.
The mesh can be previewed before solving. Mesh controls like Global Mesh Controls, Local Mesh Controls, Virtual Topology are available in ANSYS to help the user in mesh adjustment [1].

Figure 4.3.3.1: Wind tunnel at an angle of 0°

Figure 4.3.3.2: Mesh of a wind tunnel at an angle of 0°
Figure 4.3.3.3: Scaled mesh of an airfoil at an angle of 0°

Considering a 3D body, we start by choosing the body in which the inflation mesh will be created, and then recognise the faces that we want to inflate from.

For a swept body, we start by choosing the source face, and afterward the boundaries or edges from which it will be inflated. This is an alternate approach from other 3D bodies as the source face is meshed first individually, which is then swept through the body.

Once we have determined the boundaries of inflation, other parameters such as number of inflation layers, inflation growth rate can be managed easily by using different methods. They are Total Thickness, First Layer Thickness, First layer Aspect Ratio, Last Layer Aspect Ratio or the Smooth Transition option. In our case, Total Thickness option was used, which allows to set the exact number of inflation layers and growth rate. Inflation results are shown in figure 4.3.3.4.
Edge Sizing controls can be given to any edge and use bias factors, whereby the mesh size can be changed along the edge. Edge Sizing was used in two edges of airfoil. Furthermore, Edge Sizing has several options: specified element size, a number of divisions along the edge and sphere of influence. Number of divisions option was utilized by setting the division number to 250 for every edge.
4.3.4. Set Up Procedure
5. OPTIMIZATION EXAMPLE

A maximization problem was setup where the optimization goal was to maximize the ratio of lift coefficient to drag coefficient ($\frac{C_L}{C_D}$) under a specific area constraint. In the optimization loop, an inviscid potential flow solver, employed with one way-coupled boundary corrections, was used [16]. Our developed parametric model was used in the generation of different shapes as described in the corresponding section. The airfoil area was set to be equal to that of NACA 4412 airfoil area. The optimization algorithm employed was an evolutionary one (MATLAB’s Genetic Algorithm implementation)
and the airfoil shape depicted in Fig. 5.1 was the resulting shape after around 6500 iterations. The same profile was also simulated in ANSYS Fluent using the same methods, options and set up procedure as in the simulation process of NACA 4412 airfoil we have previously mentioned. The primary purpose of this was to verify the optimization results by comparing them with ANSYS output.

### Table 5.1: Inviscid solver and ANSYS Fluent results

<table>
<thead>
<tr>
<th></th>
<th>Inviscid solver</th>
<th>ANSYS Fluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;L&lt;/sub&gt;</td>
<td>2.138465</td>
<td>1.995200</td>
</tr>
<tr>
<td>C&lt;sub&gt;D&lt;/sub&gt;</td>
<td>0.014859</td>
<td>0.010635</td>
</tr>
<tr>
<td>C&lt;sub&gt;L&lt;/sub&gt;/C&lt;sub&gt;D&lt;/sub&gt;</td>
<td>~ 144</td>
<td>~ 187</td>
</tr>
</tbody>
</table>

The results from ANSYS are giving a higher lift over drag ratio but qualitatively and judging from the resulting shape and the good agreement in lift estimation we feel that we have a good indication that the optimizing framework works quite well.

Obviously, future work should include further experimentation with ANSYS simulations and realization of an optimization loop having ANSYS as the main flow solver.

### 6. RESULTS

Table 6.1: Results of ANSYS FLUENT simulation

<table>
<thead>
<tr>
<th>Angle of attack (AOA)</th>
<th>C&lt;sub&gt;L&lt;/sub&gt;</th>
<th>C&lt;sub&gt;D&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>5.1021e-01</td>
<td>7.9353e-03</td>
</tr>
<tr>
<td>1°</td>
<td>6.3709e-01</td>
<td>6.4180e-03</td>
</tr>
<tr>
<td>3°</td>
<td>8.6788e-01</td>
<td>6.3324e-03</td>
</tr>
<tr>
<td>5°</td>
<td>9.6436e-01</td>
<td>8.5923e-03</td>
</tr>
</tbody>
</table>

Following the simulation procedure, finally we got the results which are shown in table 6.1. All data provided are computed with a help of convergence study, so that it provides more accurate results. For 0° angle of attack, the lift coefficient is 0.51021, while the drag coefficient is 0.0079353. For the rest of AOA, the simulation procedure was
changed with adding Rotate option in Design Modeler. Consequently, the desired angle of attack was achieved by rotating whole airfoil. For 1° angle of attack, the lift coefficient is 0.63709, while the drag coefficient is 0.006418. For 3° angle of attack, the lift and drag coefficients are 0.86788 and 0.0063324 respectively. The lift and drag coefficients are 0.96436 and 0.0085923 respectively for the 5° angle of attack.

7. CONCLUSION AND DISCUSSION

The aim of the work displayed in this report was to portray the advancement of an alternative model for the parametric geometry definition of wind turbine blade surface, utilizing the Grasshopper® graphical algorithm editor. The blade surface can be characterized in a direct and computerized way, by simply reading the parameters from external text files. 2D blade cross-sections are utilized for the development of the 3D NURBS surface through a lofting method. The utilization of introduced methodology demonstrated its effectiveness in description of blade surface and the procedure is comprehensible, which can be automatically re-shaped by simply changing their parameters, within pre-indicated limits.

<table>
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<tr>
<th>Alpha</th>
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<th>Cd</th>
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<th>Bot_Xtr</th>
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</thead>
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<tr>
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<td>0.574</td>
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<tr>
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<td>0.9842</td>
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<td>0.8941</td>
<td>0.00709</td>
<td>0.4646</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.1: Data taken from airfoiltool.com
In this study lift and drag performances of NACA 4412 airfoil were performed. A FLUENT program was used to numerical calculations. Computational results presented in section 6 was compared with available data on NACA 4412 airfoil which is represented in table 7.1. The difference in percentage was given as follows:

- For 0° angle of attack: 5.57% for lift coefficient, 17.04% for drag coefficient
- For 1° angle of attack: 13.32% for lift coefficient, 8.05% for drag coefficient
- For 3° angle of attack: 6.68% for lift coefficient, 6.88% for drag coefficient
- For 5° angle of attack: 5.95% for lift coefficient, 7.81% for drag coefficient

By this method, the computational results agreed very well with corresponding experimental data.
REFERENCE LIST


## APPENDICES

*Table 1. S809 Airfoil Coordinates*

<table>
<thead>
<tr>
<th>Upper Surface</th>
<th>Lower Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x/c )</td>
<td>( z/c )</td>
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Table 2. Model Orifice Locations

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Table 2. Model Orifice Locations (Concluded)

<table>
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<tr>
<th>x/c</th>
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<th>Lower Surface</th>
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<td>y, mm</td>
<td>x, mm</td>
<td>y, mm</td>
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\(c = 600.00 \text{ mm (23.622 in.)}\)
Table 3. Airfoil Design Specifications (S809)

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<tr>
<th>Specification</th>
<th>Value</th>
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<td>Minimum lift coefficient</td>
<td>-</td>
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<tr>
<td>Maximum lift coefficient</td>
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<tr>
<td>«Design» lift coefficient</td>
<td>0.5</td>
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<tr>
<td>Lower limit of laminar bucket</td>
<td>0.2</td>
</tr>
<tr>
<td>Upper limit of laminar bucket</td>
<td>0.8</td>
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<tr>
<td>Zero-lift pitching-moment coefficient</td>
<td>≥ -0.05</td>
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<tr>
<td>Reynolds number</td>
<td>$2.0 \times 10^6$</td>
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<tr>
<td>Thickness</td>
<td>0.21c</td>
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</table>

Table 4. Roughness Size and Location

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<th>Reynolds Number</th>
<th>Grit Number</th>
<th>Nominal Size, mm/in.</th>
<th>x/c</th>
<th>Grit Number</th>
<th>Nominal Size, mm/in.</th>
<th>x/c</th>
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<td>$1.0 \times 10^6$</td>
<td>80</td>
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<td>0.02</td>
<td>46</td>
<td>0.419/0.0165</td>
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<tr>
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<td>120</td>
<td>0.124/0.0049</td>
<td>0.02</td>
<td>70</td>
<td>0.249/0.0098</td>
<td>0.05</td>
</tr>
<tr>
<td>$2.0 \times 10^6$</td>
<td>120</td>
<td>0.124/0.0049</td>
<td>0.02</td>
<td>70</td>
<td>0.249/0.0098</td>
<td>0.05</td>
</tr>
<tr>
<td>$2.5 \times 10^6$</td>
<td>120</td>
<td>0.124/0.0049</td>
<td>0.02</td>
<td>70</td>
<td>0.249/0.0098</td>
<td>0.05</td>
</tr>
<tr>
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<td>0.124/0.0049</td>
<td>0.02</td>
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<td>0.249/0.0098</td>
<td>0.05</td>
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Table 5. AOA1 > Geometry

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<th>Object Name</th>
<th>Geometry</th>
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<tbody>
<tr>
<td>State</td>
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</tbody>
</table>

**Definition**
- **Source**: C:\Users\User\Desktop\2D simulation Fluent\2D Fluent_files\dp0\Geom-2\DM\Geom-2.agdb
- **Type**: DesignModeler

**Bounding Box**
- **Length X**: 21.721 m
- **Length Y**: 14. m
- **Length Z**: 0. m

**Properties**
- **Volume**: 0. m³
- **Scale Factor Value**: 1.

**Statistics**
- **Bodies**: 4
- **Active Bodies**: 4
- **Nodes**: 157895
- **Elements**: 157585
- **Mesh Metric**: None

**Basic Geometry Options**
| Solid Bodies | Yes |
| Surface Bodies | Yes |
| Line Bodies | Yes |
| Parameters | Independent |
| Parameter Key | Attributes | Yes |
| Attribute Key | Yes |
| Named Selections | Yes |
| Named Selection Key | Yes |
| Material Properties | Yes |

**Advanced Geometry Options**

| Use Associativity | Yes |
| Coordinate Systems | Yes |
| Coordinate System Key | Yes |
| Reader Mode Saves | No |
| Updated File | No |
| Use Instances | Yes |
| Smart CAD Update | Yes |
| Compare Parts On Update | No |
| Attach File Via Temp File | Yes |
| Temporary Directory | C:\Users\User\AppData\Local\Temp |
| Analysis Type | 3-D |
| Mixed Import Resolution | None |
| Decompose Disjoint Geometry | Yes |
| Enclosure and Symmetry Processing | Yes |

**Table 6. AOA1 > Geometry > Parts**

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<thead>
<tr>
<th>Object Name</th>
<th>Line Body</th>
<th>Surface Body</th>
<th>Surface Body</th>
<th>Surface Body</th>
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<tbody>
<tr>
<td>State</td>
<td>Hidden</td>
<td>Meshed</td>
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</table>

**Graphics Properties**

| Visible | No | Yes |
| Transparency | 1 |

**Definition**

| Suppressed | No |
| Coordinate System | Default Coordinate System |
| Offset Mode | Refresh on Update |
| Offset Type | Centroid | Middle |
| Model Type | Beam |
| Reference Frame | Lagrangian |
| Thickness | 0. m |
| Thickness Mode | Refresh on Update |
| Behavior | None |
| Body of Influence | Yes |

**Material**

| Fluid/Solid | Defined By Geometry (Solid) |

**Bounding Box**

| Length X | 1.0101 m | 21. m |
| Length Y | 0.12421 m | 14. m |
| Length Z | 0. m |

**Properties**

| Volume | 0. m³ |
| Length | 2.0679 m |
| Cross Section | 0 |
### Cross Section Area
- **Cross Section IYY**
- **Cross Section IZZ**

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<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
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<tr>
<td>Centroid Y</td>
<td>4.0005e-002 m</td>
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<tr>
<td>Centroid Z</td>
<td>0. m</td>
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<tr>
<td>Surface Area (approx.)</td>
<td>272.89 m²</td>
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</table>

### Statistics

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<td>Elements</td>
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<td>Mesh Metric</td>
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### CAD Attributes
- DMSheetThickness: 0

### Table 7. AOA1 > Connections

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</table>

#### Auto Detection
- Generate Automatic Connection On Refresh: Yes

#### Transparency
- Enabled: Yes

### Table 8. AOA1 > Mesh

<table>
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<th>Object Name</th>
<th>Mesh</th>
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<td>Solved</td>
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#### Display
- Display Style: Body Color

#### Defaults
- Physics Preference: CFD
- Solver Preference: Fluent
- Relevance: 0
- Export Format: Standard
- Shape Checking: CFD
- Element Midside Nodes: Dropped

#### Sizing
- Size Function: Proximity and Curvature
- Use Uniform Size Function For Sheets: No
- Relevance Center: Fine
- Initial Size Seed: Active Assembly
- Smoothing: High
- Span Angle Center: Fine
- Curvature Normal Angle: Default (18.0 °)
- Num Cells Across Gap: Default (3)
- Proximity Size Function Sources: Faces and Edges
- Min Size: Default (3.7725e-003 m)
- Proximity Min Size: Default (3.7725e-003 m)
- Max Face Size: 0.10 m
- Max Tet Size: 0.10 m
- Growth Rate: Default (1.20 )
- Automatic Mesh Based Defeaturing: On
- Defeaturing Tolerance: Default (1.8863e-003 m)
- Minimum Edge Length: 4.906e-003 m

#### Inflation
- Use Automatic Inflation: None
<table>
<thead>
<tr>
<th>Inflation Option</th>
<th>Smooth Transition</th>
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<tr>
<td>Transition Ratio</td>
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<tr>
<td>Maximum Layers</td>
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<td>Growth Rate</td>
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<tr>
<td>Inflation Algorithm</td>
<td>Pre</td>
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<tr>
<td>View Advanced Options</td>
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</tbody>
</table>

**Assembly Meshing**

- Method: None

**Advanced**

- Number of CPUs for Parallel Part Meshing: Program Controlled
- Straight Sided Elements: Program Controlled
- Number of Retries: 0
- Rigid Body Behavior: Dimensionally Reduced
- Mesh Morphing: Disabled
- Triangle Surface Meshing: Program Controlled
- Topology Checking: No
- Use Sheet Thickness for Pinch: No
- Pinch Tolerance: Default (3.3953e-003 m)
- Generate Pinch on Refresh: No
- Sheet Loop Removal: No

**Statistics**

- Nodes: 157895
- Elements: 157585
- Mesh Metric: None

### Table 9. AOA1 > Mesh > Mesh Controls

<table>
<thead>
<tr>
<th>Object Name</th>
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<th>Edge Sizing</th>
<th>Edge Sizing 2</th>
<th>Inflation</th>
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<td>Fully Defined</td>
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</tr>
</tbody>
</table>

**Scope**

- Scoping Method: Geometry Selection
- Geometry: 1 Body, 2 Edges, 1 Face

**Definition**

- Suppressed: No
- Type: Body of Influence
- Number of Divisions: 2 Bodies
- Element Size: 2.e-002 m
- Growth Rate: 1.2
- Local Min Size: Default (3.7725e-003 m)
- Number of Divisions: 250
- Behavior: Hard
- Bias Type: No Bias
- Boundary Scoping Method: Geometry Selection
- Boundary: 4 Edges
- Inflation Option: First Layer Thickness
- First Layer Height: 1.e-006 m
- Maximum Layers: 100
- Inflation Algorithm: Pre

### Table 10. AOA3 > Geometry

<table>
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<th>Object Name</th>
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<th>Geometry</th>
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</thead>
<tbody>
<tr>
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<td>Fully Defined</td>
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</tbody>
</table>

**Definition**

- Source: C:\Users\User\Desktop\2D simulation Fluent\2D Fluent_files\dp0\Geom-
Type: DesignModeler
Length Unit: Meters

**Bounding Box**
- Length X: 21.721 m
- Length Y: 14. m
- Length Z: 0. m

**Properties**
- Volume: 0. m³
- Scale Factor Value: 1.

**Statistics**
- Bodies: 4
- Active Bodies: 4
- Nodes: 133542
- Elements: 133197
- Mesh Metric: None

**Basic Geometry Options**
- Solid Bodies: Yes
- Surface Bodies: Yes
- Line Bodies: Yes
- Parameters: Independent
- Parameter Key: Attributes
- Attribute Key: Yes
- Named Selections: Yes
- Named Selection Key: Material Properties: Yes

**Advanced Geometry Options**
- Use Associativity: Yes
- Coordinate Systems: Yes
- Coordinate System Key: Reader Mode Saves
- Updated File: No
- Use Instances: Yes
- Smart CAD Update: Yes
- Compare Parts On Update: No
- Attach File Via Temp File: Yes
- Temporary Directory: C:\Users\User\AppData\Local\Temp
- Analysis Type: 3-D
- Mixed Import Resolution: None
- Decompose Disjoint Geometry: Yes
- Enclosure and Symmetry Processing: Yes

**Table 11. AOA3 > Geometry > Parts**

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Line Body</th>
<th>Surface Body</th>
<th>Surface Body</th>
<th>Surface Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Hidden</td>
<td>Meshed</td>
<td>Fully Defined</td>
<td></td>
</tr>
</tbody>
</table>

**Graphics Properties**
- Visible: No
- Transparency: 1

**Definition**
- Suppressed: No
- Coordinate System: Default Coordinate System
- Offset Mode: Refresh on Update
<table>
<thead>
<tr>
<th>Offset Type</th>
<th>Centroid</th>
<th>Middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Type</td>
<td>Beam</td>
<td></td>
</tr>
<tr>
<td>Reference Frame</td>
<td>Lagrangian</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>0. m</td>
<td></td>
</tr>
<tr>
<td>Thickness Mode</td>
<td>Refresh on Update</td>
<td></td>
</tr>
<tr>
<td>Behavior</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Body of Influence</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Fluid/Solid Defined By Geometry (Solid)</td>
<td></td>
</tr>
</tbody>
</table>

**Bounding Box**

<table>
<thead>
<tr>
<th>Length X</th>
<th>1.0087 m</th>
<th>21. m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Y</td>
<td>0.13615 m</td>
<td>14. m</td>
</tr>
<tr>
<td>Length Z</td>
<td>0. m</td>
<td></td>
</tr>
</tbody>
</table>

**Properties**

<table>
<thead>
<tr>
<th>Volume</th>
<th>0. m³</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>2.0679 m</td>
<td></td>
</tr>
<tr>
<td>Cross Section</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Cross Section Area**

**Cross Section IYY**

**Cross Section IZZ**

<table>
<thead>
<tr>
<th>Centroid X</th>
<th>4.5988 m</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Centroid Y</td>
<td>4.0009e-002 m</td>
<td></td>
</tr>
<tr>
<td>Centroid Z</td>
<td>0. m</td>
<td></td>
</tr>
</tbody>
</table>

**Surface Area (approx.)**

272.89 m²

**Statistics**

<table>
<thead>
<tr>
<th>Nodes</th>
<th>88</th>
<th>133454</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td>44</td>
<td>133153</td>
</tr>
<tr>
<td>Mesh Metric</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

**CAD Attributes**

| DMSheetThickness | 0 |        |

**Table 12. AOA3 > Connections**

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Connections</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fully Defined</td>
<td></td>
</tr>
</tbody>
</table>

**Auto Detection**

Generate Automatic Connection On Refresh | Yes |

**Transparency**

Enabled | Yes |

**Table 13. AOA3 > Mesh**

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Solved</td>
</tr>
</tbody>
</table>

**Display**

<table>
<thead>
<tr>
<th>Display Style</th>
<th>Body Color</th>
</tr>
</thead>
</table>

**Defaults**

<table>
<thead>
<tr>
<th>Physics Preference</th>
<th>CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solver Preference</td>
<td>Fluent</td>
</tr>
<tr>
<td>Relevance</td>
<td>0</td>
</tr>
<tr>
<td>Export Format</td>
<td>Standard</td>
</tr>
<tr>
<td>Shape Checking</td>
<td>CFD</td>
</tr>
<tr>
<td>Element Midside Nodes</td>
<td>Dropped</td>
</tr>
</tbody>
</table>

**Sizing**

<table>
<thead>
<tr>
<th>Size Function</th>
<th>Proximity and Curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use Uniform Size Function For Sheets</td>
<td>No</td>
</tr>
<tr>
<td>Parameter</td>
<td>Setting</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>Relevance Center</td>
<td>Fine</td>
</tr>
<tr>
<td>Initial Size Seed</td>
<td>Active Assembly</td>
</tr>
<tr>
<td>Smoothing</td>
<td>High</td>
</tr>
<tr>
<td>Span Angle Center</td>
<td>Fine</td>
</tr>
<tr>
<td>Curvature Normal Angle</td>
<td>Default (18.0 °)</td>
</tr>
<tr>
<td>Num Cells Across Gap</td>
<td>Default (3)</td>
</tr>
<tr>
<td>Proximity Size Function Sources</td>
<td>Faces and Edges</td>
</tr>
<tr>
<td>Min Size</td>
<td>Default (3.7725e-003 m)</td>
</tr>
<tr>
<td>Proximity Min Size</td>
<td>Default (3.7725e-003 m)</td>
</tr>
<tr>
<td>Max Face Size</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Max Tet Size</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Growth Rate</td>
<td>Default (1.20 )</td>
</tr>
<tr>
<td>Automatic Mesh Based Defeaturing</td>
<td>On</td>
</tr>
<tr>
<td>Defeaturing Tolerance</td>
<td>Default (1.8863e-003 m)</td>
</tr>
<tr>
<td>Minimum Edge Length</td>
<td>4.906e-003 m</td>
</tr>
<tr>
<td><strong>Inflation</strong></td>
<td></td>
</tr>
<tr>
<td>Use Automatic Inflation</td>
<td>None</td>
</tr>
<tr>
<td>Inflation Option</td>
<td>Smooth Transition</td>
</tr>
<tr>
<td>Transition Ratio</td>
<td>0.272</td>
</tr>
<tr>
<td>Maximum Layers</td>
<td>2</td>
</tr>
<tr>
<td>Growth Rate</td>
<td>1.2</td>
</tr>
<tr>
<td>Inflation Algorithm</td>
<td>Pre</td>
</tr>
<tr>
<td>View Advanced Options</td>
<td>No</td>
</tr>
<tr>
<td><strong>Assembly Meshing</strong></td>
<td></td>
</tr>
<tr>
<td>Method</td>
<td>None</td>
</tr>
<tr>
<td><strong>Advanced</strong></td>
<td></td>
</tr>
<tr>
<td>Number of CPUs for Parallel Part Meshing</td>
<td>Program Controlled</td>
</tr>
<tr>
<td>Straight Sided Elements</td>
<td></td>
</tr>
<tr>
<td>Number of Retries</td>
<td>0</td>
</tr>
<tr>
<td>Rigid Body Behavior</td>
<td>Dimensionally Reduced</td>
</tr>
<tr>
<td>Mesh Morphing</td>
<td>Disabled</td>
</tr>
<tr>
<td>Triangle Surface Mesher</td>
<td>Program Controlled</td>
</tr>
<tr>
<td>Topology Checking</td>
<td>No</td>
</tr>
<tr>
<td>Use Sheet Thickness for Pinch</td>
<td>No</td>
</tr>
<tr>
<td>Pinch Tolerance</td>
<td>Default (3.3953e-003 m)</td>
</tr>
<tr>
<td>Generate Pinch on Refresh</td>
<td>No</td>
</tr>
<tr>
<td>Sheet Loop Removal</td>
<td>No</td>
</tr>
<tr>
<td><strong>Statistics</strong></td>
<td></td>
</tr>
<tr>
<td>Nodes</td>
<td>133542</td>
</tr>
<tr>
<td>Elements</td>
<td>133197</td>
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<tr>
<td>Mesh Metric</td>
<td>None</td>
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<table>
<thead>
<tr>
<th>Table 14. AOA3 &gt; Mesh &gt; Mesh Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object Name</strong></td>
</tr>
<tr>
<td><strong>State</strong></td>
</tr>
<tr>
<td><strong>Scope</strong></td>
</tr>
<tr>
<td><strong>Geometry</strong></td>
</tr>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td><strong>Suppressed</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td><strong>Bodies of Influence</strong></td>
</tr>
<tr>
<td><strong>Element Size</strong></td>
</tr>
<tr>
<td><strong>Growth Rate</strong></td>
</tr>
<tr>
<td>Property</td>
</tr>
<tr>
<td>----------------------------------</td>
</tr>
<tr>
<td>Local Min Size</td>
</tr>
<tr>
<td>Number of Divisions</td>
</tr>
<tr>
<td>Behavior</td>
</tr>
<tr>
<td>Bias Type</td>
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<tr>
<td>Boundary Scoping Method</td>
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<td>Boundary</td>
</tr>
<tr>
<td>Inflation Option</td>
</tr>
<tr>
<td>Number of Layers</td>
</tr>
<tr>
<td>Maximum Thickness</td>
</tr>
<tr>
<td>Inflation Algorithm</td>
</tr>
</tbody>
</table>

<p>| Table 15. AOA5 &gt; Geometry       |
|----------------------------------|------------------------------|
| <strong>Object Name</strong>                  | Geometry                     |
| State                            | Fully Defined                |
| <strong>Definition</strong>                   |                              |
| Source                           | C:\Users\User\Desktop\2D simulation Fluent\2D Fluent_files\dp0\Geom-1\DM\Geom-1.agdb |
| Type                             | DesignModeler                |
| Length Unit                      | Meters                       |
| <strong>Bounding Box</strong>                 |                              |
| Length X                        | 21.721 m                     |
| Length Y                        | 14. m                        |
| Length Z                        | 0. m                         |
| <strong>Properties</strong>                   |                              |
| Volume                           | 0. m³                        |
| Scale Factor Value               | 1.                           |
| <strong>Statistics</strong>                   |                              |
| Bodies                           | 4                            |
| Active Bodies                    | 4                            |
| Nodes                            | 137495                       |
| Elements                         | 137141                       |
| Mesh Metric                      | None                         |
| <strong>Basic Geometry Options</strong>       |                              |
| Solid Bodies                     | Yes                          |
| Surface Bodies                   | Yes                          |
| Line Bodies                      | Yes                          |
| Parameters                       | Independent                  |
| Parameter Key                    |                              |
| Attributes                       | Yes                          |
| Attribute Key                    |                              |
| Named Selections                 | Yes                          |
| Named Selection Key              |                              |
| Material Properties              | Yes                          |
| <strong>Advanced Geometry Options</strong>    |                              |
| Use Associativity                | Yes                          |
| Coordinate Systems               | Yes                          |
| Coordinate System Key            |                              |
| Reader Mode Saves Updated File   | No                           |
| Use Instances                    | Yes                          |
| Smart CAD Update                 | Yes                          |
| Compare Parts On Update          | No                           |
| Attach File Via Temp File        | Yes                          |
| Temporary Directory              | C:\Users\User\AppData\Local\Temp |</p>
<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>3-D</th>
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<tbody>
<tr>
<td>Mixed Import Resolution</td>
<td>None</td>
</tr>
<tr>
<td>Decompose Disjoint Geometry</td>
<td>Yes</td>
</tr>
<tr>
<td>Enclosure and Symmetry</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Object Name</strong></th>
<th><strong>Line Body</strong></th>
<th><strong>Surface Body</strong></th>
<th><strong>Surface Body</strong></th>
<th><strong>Surface Body</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State</strong></td>
<td>Meshed</td>
<td>Fully Defined</td>
<td></td>
<td></td>
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<td><strong>Graphics Properties</strong></td>
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<td></td>
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<tr>
<td>Visible</td>
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<td></td>
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<tr>
<td>Transparency</td>
<td>1</td>
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<tr>
<td><strong>Definition</strong></td>
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<td></td>
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<tr>
<td>Suppressed</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordinate System</td>
<td>Default Coordinate System</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Offset Mode</td>
<td>Refresh on Update</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset Type</td>
<td>Centroid</td>
<td>Middle</td>
<td></td>
<td></td>
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<tr>
<td>Model Type</td>
<td>Beam</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Reference Frame</td>
<td>Lagrangian</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>0. m</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Thickness Mode</td>
<td>Refresh on Update</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Behavior</td>
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<td></td>
<td></td>
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<tr>
<td>Body of Influence</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Material</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid/Solid</td>
<td>Defined By Geometry (Solid)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bounding Box</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length X</td>
<td>1.0061 m</td>
<td>21. m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length Y</td>
<td>0.1615 m</td>
<td>14. m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length Z</td>
<td>0. m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Properties</strong></td>
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<td></td>
</tr>
<tr>
<td>Volume</td>
<td>0. m³</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Length</td>
<td>2.0679 m</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cross Section</td>
<td>0</td>
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<tr>
<td>Cross Section Area</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cross Section IYY</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cross Section IZZ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centroid X</td>
<td>4.5988 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centroid Y</td>
<td>4.0013e-002 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centroid Z</td>
<td>0. m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Area(approx.)</td>
<td>272.89 m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Statistics</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Nodes</td>
<td>166</td>
<td>137329</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elements</td>
<td>83</td>
<td>137058</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesh Metric</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DMSheetThickness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>CAD Attributes</strong></th>
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</thead>
<tbody>
<tr>
<td>DMSheetThickness</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 17. AOA5 > Connections**

<table>
<thead>
<tr>
<th><strong>Object Name</strong></th>
<th><strong>Connections</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>State</strong></td>
<td>Fully Defined</td>
</tr>
<tr>
<td><strong>Auto Detection</strong></td>
<td></td>
</tr>
<tr>
<td>Generate Automatic Connection On Refresh</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Transparency</strong></td>
<td></td>
</tr>
</tbody>
</table>

L
<table>
<thead>
<tr>
<th>Object Name</th>
<th>Mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Solved</td>
</tr>
</tbody>
</table>

### Display
- **Display Style**: Body Color

### Defaults
- **Physics Preference**: CFD
- **Solver Preference**: Fluent
- **Relevance**: 0
- **Export Format**: Standard
- **Shape Checking**: CFD
- **Element Midside Nodes**: Dropped

### Sizing
- **Size Function**: Proximity and Curvature
- **Use Uniform Size Function For Sheets**: No
- **Relevance Center**: Fine
- **Initial Size Seed**: Active Assembly
- **Smoothing**: High
- **Span Angle Center**: Fine
- **Curvature Normal Angle**: Default (18.0 °)
- **Num Cells Across Gap**: Default (3)
- **Proximity Size Function Sources**: Faces and Edges
- **Min Size**: Default (3.7725e-003 m)
- **Proximity Min Size**: Default (3.7725e-003 m)
- **Max Face Size**: 0.10 m
- **Max Tet Size**: 0.10 m
- **Growth Rate**: Default (1.20)

### Inflation
- **Use Automatic Inflation**: None
- **Inflation Option**: Smooth Transition
- **Transition Ratio**: 0.272
- **Maximum Layers**: 2
- **Growth Rate**: 1.2
- **Inflation Algorithm**: Pre
- **View Advanced Options**: No

### Assembly Meshing
- **Method**: None

### Advanced
- **Number of CPUs for Parallel Part Meshing**: Program Controlled
- **Straight Sided Elements**: Program Controlled
- **Number of Retries**: 0
- **Rigid Body Behavior**: Dimensionally Reduced
- **Mesh Morphing**: Disabled
- **Triangle Surface Mesher**: Program Controlled
- **Topology Checking**: No
- **Use Sheet Thickness for Pinch**: No
- **Pinch Tolerance**: Default (3.3953e-003 m)
- **Generate Pinch on Refresh**: No
- **Sheet Loop Removal**: No
### Table 19. AOA5 > Mesh > Mesh Controls

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Body Sizing</th>
<th>Inflation</th>
<th>Edge Sizing</th>
<th>Edge Sizing 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Fully Defined</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Scope

- **Scoping Method**: Geometry Selection
- **Geometry**: 1 Body, 1 Face, 2 Edges, 1 Edge

#### Definition

- **Suppressed**: No
- **Type**: Body of Influence, Number of Divisions
  - **Bodies of Influence**: 2 Bodies
  - **Element Size**: 2.e-002 m
  - **Growth Rate**: 1.20
  - **Local Min Size**: Default (3.7725e-003 m)

- **Boundary Scoping Method**: Geometry Selection
  - **Boundary**: 4 Edges
  - **Inflation Option**: Total Thickness
  - **Number of Layers**: 50
  - **Maximum Thickness**: 1.e-002 m
  - **Inflation Algorithm**: Pre
  - **Number of Divisions**: 250, 5
  - **Behavior**: Hard
  - **Bias Type**: No Bias

---

*Figure 1. Scaled mesh of an airfoil at an angle of 1°*
Figure 2. Scaled mesh of an airfoil at an angle of 3°

Figure 3. Inflation of an airfoil mesh at an angle of 1°
Figure 4. Inflation of an airfoil mesh at an angle of 3°.

Figure 5. Inflation of an airfoil mesh at an angle of 5°.