A Computational Fluid Dynamics Study on the Aerodynamic Performance of Ram-Air Parachutes

Angelo A. Fonseca Pazmiño

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A COMPUTATIONAL FLUID DYNAMICS STUDY ON THE AERODYNAMIC
PERFORMANCE OF RAM-AIR PARACHUTES

A Thesis
Submitted to the Faculty
of
Embry-Riddle Aeronautical University
by
Angelo A. Fonseca Pazmiño

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science in Aerospace Engineering

July 2018
Embry-Riddle Aeronautical University
Daytona Beach, Florida
A COMPUTATIONAL FLUID DYNAMICS STUDY ON THE AERODYNAMIC PERFORMANCE OF RAM-AIR PARACHUTES

by

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A Thesis prepared under the direction of the candidate’s committee chairman, Dr. Mark Ricklick, Department of Aerospace Engineering, and has been approved by the members of the thesis committee, Dr. John Leishman and Dr. Richard Anderson. It was submitted to the School of Graduate Studies and Research and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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ACKNOWLEDGMENTS

It is an honor for me to thank the people who made this thesis possible. My upmost gratitude to my father Marcelo and my mother Angelica for teaching me the values that define me today as a person. Thank you for always supporting my dreams. To my sisters Angelica, Stephanie, and Luz Mia, who are my refuge in the hard times, thank you for your unconditional love and motivation.

To my advisor, Dr. Ricklick, thank you for your guidance and support throughout these last three years. While tedious at times, this thesis has been a challenging and rewarding experience I will never forget. Special thanks to my committee members, Dr. Leishman and Dr. Anderson, for taking the time to read this thesis and give me valuable ideas for future improvements. To John Leblanc and the PD staff, thank you for the introduction to the world of ram-air parachutes.

Many thanks to all my friends who have been with me throughout my university career. I share this thesis with my friend and work partner, Christian Guzman, who gave me invaluable knowledge, support, and advice. To my closest friends Diego Garcia, Javier Cisneros, Silvi Ureña, Chirag Jain, Erik Proaño, Juanfer Garcia, Andrea Cevallos, Nathalie Quintero, Carlos Bernaza, Sergio Bacca, and Andres Chavez, thank you for your sincere friendship and the awesome times we shared together as a family.

Finally, I would like to dedicate this thesis to the person who waited the most for my return back home, my grandfather Angel. I will always cherish and honor the great moments I spent with you. When the time comes, I know you will receive me with the same smile and joy as the first time I came home. Gracias por todo mi Capitán!

“Try not to become a man of success, but rather try to become a man of value.”

Albert Einstein
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SYMBOLS

\( C_d \) 2D Drag Coefficient
\( C_l \) 2D Lift Coefficient
\( C_D \) 3D Drag Coefficient
\( C_L \) 3D Lift Coefficient
\( \alpha \) Angle of Attack
\( \beta \) Anhedral Angle
\( b \) Canopy Span
\( S \) Canopy Area
\( C_{LC} \) Circulation Lift Coefficient
\( a_0' \) Corrected Two-Dimensional Lift Curve Slope
\( k_1 \) Correction Factor
\( \rho \) Density
\( S_{Du} \) DuBois Area
\( \mu \) Dynamic Viscosity
\( W \) Exit Weight
\( \gamma \) Glide Angle
\( u \) Horizontal Velocity Component
\( C_{D,i} \) Induced Drag Coefficient
\( k - \epsilon \) K-Epsilon Turbulence Model
\( k - \omega \) K-Omega Turbulence Model
\( a \) Lift Curve Slope
\( L/D \) Lift-to-Drag Ratio
\( C_{Di} \) Line Drag Coefficient
\( \dot{m} \) Mass Flow Rate
\( R \) Mean Line Length
\( f_0 \) Normal Stress
\( n \) Number of Suspension Lines
\( \tau \) Oswald Efficiency Factor
\( H \) Parachutist Height
\( p \) Pressure
\( C_{D0} \) Profile Drag
\( Re \) Reynolds Number
\( c \) Rib Chord
\( d \) Suspension Line Diameter
\( S_{St} \) Store Drag Area
\( C_{DSt} \) Store Drag Coefficient
\( \vec{n} \) Unit Normal Vector
\( V \) Total Velocity
\( w \) Vertical Velocity Component
\( \vec{u} \) Velocity Vector
\( W/S \) Wing Loading
\( \alpha_{ZL} \) Zero Lift Angle
ABBREVIATIONS

2D Two-Dimensional
3D Three-Dimensional
AoA Angle of Attack
AR Aspect Ratio
CPU Central Processing Unit
CFD Computational Fluid Dynamics
CAD Computer-Aided Design
DES Detached Eddy Simulation
DNS Direct Numerical Simulation
FEA Finite Element Analysis
FSI Fluid-Structure Interaction
LES Large Eddy Simulation
LE Leading Edge
PD Performance Designs
PC Personal Computer
RAM Random-Access Memory
RANS Reynolds-Averaged Navier-Stokes
SST Shear-Stress Transport
TE Trailing Edge
W&H Ware & Hassell
ABSTRACT

Fonseca Pazmino, Angelo A. MSAE, Embry-Riddle Aeronautical University, July 2018.
A Computational Fluid Dynamics Study on the Aerodynamic Performance of Ram-Air Parachutes.

The modeling of a ram-air parachute presents challenges in the prediction of the in-flight geometry, as there is a strong interaction between the flow field and parachute structure. This thesis presents the development of a CAD design and CFD methodology to the simulation of ram-air parachutes in steady-state conditions. Starting from a 2D rib drawing, methods were developed to approximate the 3D geometry and efficiently model the parachute as a rigid and impermeable body. The use of distortions was implemented on a 2D, pseudo-2D, and 3D model to enhance their behavior during a real flight. The SST turbulence model was chosen for the modeling of these designs because of its suitability to predict flow separation and reattachment from adverse pressure gradients. The high complexity of the 3D model is handled using appropriate boundary conditions and cleaning geometric tools within the CFD software. Visualization of the fluid flow parameters such as velocity profiles, streamlines, and pressure gradients were made. Furthermore, parameters such as lift and drag coefficients at different angles of attack allow to evaluate aerodynamic performance at the specified flight conditions and provide clear trends for best model shapes. The computational results were compared to other experimental and numerical studies.
1. Introduction

1.1. Introduction to Ram-Air Parachutes

Parachutes have several applications ranging from sports to military guidance delivery missions. The geometric design of the parachute has evolved throughout the past years, making the ram-air type the most efficient in terms of aerodynamic efficiency. The main reason for this is because of the ability of the ram-air type to produce higher gliding and maneuverability characteristics than its predecessors (round-type, rogallo-wing, and annular). These improved characteristics enable the ram-air type design to be ideal for use in precision guided airdrop systems and skydiving competitions (Shute, 1971).

A notable improvement in parachute design came with the invention of the ram-air parachute by Jalbert in 1964 (Jalbert, 1964). The ram-air parachute canopy resembles a flying wing when fully inflated. A typical ram-air parachute design is presented in Figure 1-1.

![Ram-air parachute schematic](image-url)

Figure 1-1: Schematic for a ram-air parachute design (Lingard, 1995).
The canopy is composed of several chambers that are divided by ribs along the spanwise direction. The formation of two chambers is known as a cell. Each cell has opening cuts at the leading edges which allow ram-air to enter the canopy and enable its inflation into a low aspect ratio wing. The inlet openings divide the structure into an upper surface and a lower surface.

Suspension lines are attached to the lower surface at specific locations along the chordwise direction to maintain the canopy shape profile. The suspension lines are divided into an upper and lower section. The upper section has suspension lines arranged in a cascade setup to decrease the drag they produce (Lingard, 1995).

The ribs that have suspension lines attached are known as the loaded ribs, whereas the ribs that do not have suspension lines attached are known as the non-loaded ribs. The non-loaded ribs tend to be tilted at a slightly higher angle along the longitudinal axis compared to the loaded ribs. This angle between the longitudinal direction and the chord pitches the rib to a nose-up position and is known as the angle of incidence. The reason for this change in angle of incidence is because of the tension imposed by the suspension lines on the loaded ribs.

The ribs have small hole cuts along the chordwise direction known as crossports. The purpose of the crossports is to maintain an equal pressure distribution along the canopy cells as a result of ram-air entering the inlets. Usually a rib can have between 2 to 4 crossports cut along its chord.

The fabric material used for the construction of a ram-air canopy is chosen as impermeable as possible to enable a strong wing shape and reduce pressure losses as a result of air leaks in areas beside the openings.
A 2D profile of the ram-air canopy along the chordwise direction gives the shape of an airfoil. The only difference with an airfoil is because of the opening cut section where ram-air enters the structure. An example of a 2D profile is shown in Figure 1-2. Point A corresponds to the airflow traveling at freestream conditions. Point B corresponds to the stagnation region where airflow velocity is zero and the highest static pressure value is achieved. Point B also indicates the spot where the airflow divides into the upper and lower surfaces. Points C and D have both an internal and external pressure value acting on their respective surface. At steady state conditions, the internal pressures acting on the upper surface (Point C) and lower surface (Point D) are equal as a result of stagnant air on the inside of the canopy. However, external pressure values acting on the upper and lower surface are different. These external pressures follow the same aerodynamic pattern as a conventional airfoil where a lower pressure acts on the upper surface and a higher pressure acts on the lower surface (Sobieski, 1994).

Figure 1-2: Airflow distribution across rib sections A, B, C, and D. The arrow indicates the direction where airflow is coming from (Sobieski, 1994).
A ram-air parachute comparison with a normal airplane wing has four main differences. The first and primary difference between a ram-air parachute and a normal airplane wing is flexibility. The ram-air canopy possesses no rigid members and is composed purely on fabric material that expands and compresses easily because of the surrounding fluid conditions.

The second difference is the center of gravity location. In a conventional ram-air parachute system, most of the canopy weight is caused by the jumper or payload. Because most of this weight acts on the bottom end of the suspension lines, the center of gravity will be situated in a point far below the canopy away from the center of lift.

The third difference is how the ram-air parachute operates for its stability and controllability. The canopy changes the shape of its structure by a process called ‘wing warping’ (Sobieski, 1994). Wing warping is accomplished when a separate set of lines, known as the steering lines, are pulled to deform part of the canopy. By doing so, the ram-air parachute can be steered and turned in various directions.

Finally, the fourth difference is the opening section. As mentioned earlier, the opening section enables the air to flow inside the canopy and provide its inflation by ram-air pressure. Figure 1-3 shows an image of the complete parachute system and identifies some of the differences discussed in this paragraph.
Figure 1-3: Schematic of ram-air parachute system with payload (Tweddle, 2006).
1.2. Motivation of Study

The modeling of a ram-air parachute presents challenges in the prediction of the in-flight geometry because is a strong interaction between the flow field and the parachute structure. Over the past 50 years, experimental testing of ram-air parachutes on wind tunnels and drop tests have been used to analyze the aerodynamic performance under simulated flight conditions. The dominance in experimental testing have caused the ram-air parachute design to be a completely empirical process throughout its history. However, with the emerging evolution of computer modeling, new numerical methods are being implemented to design and test parachute models at a lower cost and time effort (Strickland & Higuchi, 1996).

The use of computer modeling and software simulations permit the user to explore different parachute configurations that would be challenging to do at an experimental level (Kalro et al., 1997). Furthermore, the ability to obtain parameters such as velocity flow visualization, pressure field, and deformation areas, make computational techniques a powerful tool to implement in the parachute industry.

The strong interaction between the flow field and the parachute structure makes the use of different computational techniques a challenging process. Computational Fluid Dynamics (CFD) is a modern tool used to determine fluid flow characteristics such as velocity and pressure fields. CFD simulations use a fixed geometry setup in space to gather results at different flow conditions. Finite Element Analysis (FEA) is another computational tool used to determine stress fields and deformations in the geometry structure at selected material properties and force conditions. The combination of both CFD and FEA tools, a computational method known as Fluid-Structure Interaction (FSI), allows a complete simulation of both the structure and fluid flow from deployment to steady flight.
conditions (Stein et al., 2001). The drawbacks from these types of simulations are the long computational time, computer power resources, and the complex model setup for one particular flight condition (Longatte et al., 2009). These disadvantages have led to find alternative ways of simplifying simulations to a faster and less effort consuming process.

Computer-Aided Design (CAD) is a computational tool used to create and optimize a design based on technical and engineering drawings. A CAD software can be used to create the in-flight geometry of a ram-air parachute at steady conditions given key design parameters. Whereas a FSI model is the tool used to get a high fidelity model of a ram-air parachute at both steady and unsteady conditions, a CAD software with CFD modeling can also provide reliable results of the parachute structure at a lower computational time and effort. The latter computational technique has been used in the research reported in this thesis.

This work aims to create a CAD design and CFD simulation methodology to the simulation of a ram-air parachute canopy at steady flight. This process will enable to evaluate the aerodynamic performance of the canopy and provide extra insight to the use of computational methods in ram-air parachute design and investigation.

1.3. Thesis Objectives

The main objective of this thesis is to model a ram-air parachute in steady flight conditions using computational tools. Based on detailed literature review presented in the next chapter, there is a limited understanding of the physics involved in the aerodynamic performance of ram-air parachutes. Furthermore, the impact of various modeling techniques to catch the realistic in-flight operation of a ram-air parachute is not well understood. The thesis hypothesis is that efficient modeling of ram-air parachutes can be achieved by modeling the structure as a rigid surface while sufficiently modeling the in-
flight geometry. This type of modeling will reduce the cost of development and improve computational performance. Consequently, the following objectives were made:

- Develop a CAD design and CFD methodology to the simulation of a ram-air parachute canopy at steady flight conditions.
- Implement the use of distortions on a 2D rib, pseudo-2D, and 3D geometry models.
- Assess impact of distortion effects for all geometry models using CFD.
- Expand the analysis of 3D effects on different ram-air parachute planform shapes at specific angles of attack.
- Evaluate aerodynamic performance (lift, drag, $L/D$) and provide clear trends for best model shapes.
- Verify research findings with experimental and computational studies.

1.4. Thesis Outline

This thesis is divided into the following chapters:

- Chapter 2 gives a literature review study where the design and modeling of ram-air parachutes is analyzed. The challenges that the geometry modeling presents and the effect of distortions within the canopy structure are discussed. Previous experimental and computational studies based on aerodynamic flight performance are also described.
- Chapter 3 discusses the geometry design process adapted for this work. The chapter starts with a brief introduction of the CAD software capabilities and the methodology approach chosen to construct the ram-air canopy. A programming
method to allow a more automated process to build the geometry models is presented. Finally, the final models to be tested with the CFD software are described.

- Chapter 4 discusses the CFD methodology used to simulate the CAD geometry models. The chapter starts with a brief introduction of the CFD software capabilities and the turbulence model chosen for the present simulations. A general model setup with suitable boundary conditions and meshing techniques used are described. Finally, the fluid parameters for each type of simulation are presented.

- Chapter 5 includes the CFD simulation results for each of the geometry models tested. The chapter starts with the results for the 2D model and its aerodynamic analysis based on lift and drag values, inlet opening effect, and rib distortions effect. The pseudo-2D model is analyzed in a similar way to the 2D model and it includes a performance study of the 3D effects expected for the 3D model. The 3D model is analyzed in a similar way and includes a discussion on the planform shape effect. A comparison between the simulated models is included to determine aerodynamic trends and shape optimization. Finally, a comparison of the simulated models with experimental and computational studies is presented.

- Chapter 6 summarizes the main findings of this thesis and gives suggestions for future work.
2. Literature Review

2.1. Design Parameters and Physics of Ram-Air Parachutes

The design of a ram-air parachute can be condensed to three key parameters: wing shape, wing loading, and trim (Burke, 1997). Wing shape relates to the type of rib and the canopy aspect ratio ($AR$). The type of rib is selected according to thickness and camber. Early designs have been carried out using the Clark-Y airfoil, while more modern designs have moved towards the low speed NASA LS (1)-0417 (Lingard, 1995). The Clark-Y airfoil is a thinner airfoil compared to the NASA LS (1)-0417. A thin airfoil flies faster and has less drag compared to a thick airfoil. However, a thin airfoil has left lifting ability and stalls more abruptly than a thick airfoil. Therefore, a typical maximum thickness range for a ram-air parachute rib can be between 10% to 18% of the chord (Burke, 1997).

Another notable distinction of the Clark-Y airfoil is the flat lower surface from 30% of the chord back. The flat lower surface aids in an easier wing construction but reduces its aerodynamic efficiency as a result of a lower camber profile. This reduction is fixed by increasing the rib thickness to provide better lift and stalling characteristics. Another solution is the rib replacement to the NASA LS (1)-0417, which are thicker airfoils with high glide performance (McGhee & Beasley, 1973). The tradeoff in rib aerodynamic efficiency at higher and lower speeds is what makes the rib selection process an important design consideration.

The canopy $AR$ is another factor that affects the wing shape in a ram-air parachute design. The $AR$ formula corresponds to the ratio of the span ($b$) to the canopy area ($S$) and is expressed as $AR = b^2/S$. For a parachute with rectangular planform, the $AR$ is reduced to $AR = b/c$, where $c$ corresponds to the rib chord. From Prandtl’s lifting line theory, an
expression relating the effect of lift on the drag produced by the wing vortices on a finite wing is given by:

\[ C_{D,i} = \frac{C_L^2}{\pi e AR} \]  

(1)

where \( C_{D,i} \) is the induced drag coefficient, \( C_L \) is the wing lift coefficient, and \( e \) is the span efficiency factor (Anderson, 2010).

Equation (1) indicates an inverse relationship between \( AR \) and induced drag. The problem with increasing \( AR \) on a ram-air parachute is because of internal cell pressurization and larger number of lines and ribs. As the canopy span increases it is harder to maintain good pressurization within the end cells, increasing the risk of cell collapse. In addition, the span increase requires a higher number of lines and ribs that will increase the parasitic drag. As a result of this negative effects, a canopy \( AR \) is maintained within a limit of 3 to 1 for a 7 or 9 cell design (Burke, 1997).

The next design parameter to analyze is wing loading. This parameter is expressed as the ratio between the exit weight (\( W \)) in pounds and the canopy area (\( S \)) in square foot for U.S. standards. The exit weight is defined as the total weight for the jumper and the equipment used. Wing loading typical range of values can be between 0.7 to 1.6 lbft\(^2\) depending on the desired flight speed of the canopy. A higher wing loading translates into faster forward and descent speeds, higher turn rates, and more sensitive controls. A negative impact from a high wing loading starts to appear at around 1.4 lbft\(^2\) where the canopy glide capabilities start to decrease while descent rate continues to increase (Burke, 1997).

The last design parameter to evaluate is canopy trim. This parameter is affected by the angle of incidence, i.e., nose position of the canopy. A nose down trim results in higher
descent rate and increased stability, while a nose up trim increases glide capabilities and collapsing risk (Burke, 1997). The trim position is affected considerably by the steering line input by the jumper when controlling the canopy during maneuvers.

The physics of a ram-air parachute are discussed in a seminar work by Lingard in 1995. The aerodynamic analysis is presented based on the lifting line theory for low AR wings to both 2D and 3D designs. For a ram-air wing, the total lift coefficient can be expressed as:

\[ C_L = a(\alpha - \alpha_{ZL}) + k_1 \sin^2(\alpha - \alpha_{ZL}) \cos(\alpha - \alpha_{ZL}) \]  \hspace{1cm} (2)

where \( a \) is the lift curve slope, \( \alpha \) is the angle of attack, \( \alpha_{ZL} \) is the zero lift angle, and \( k_1 \) is a correction factor that takes into account the non-linearity effect of the wing low AR and the tip edges (Lingard, 1995).

The lift curve slope \( a \) (1/°) is expressed by the following formula:

\[ a = \frac{\pi^2 AR a_0'}{180(\pi AR + a_0'(1+\tau))} \]  \hspace{1cm} (3)

where \( (1 + \tau)^{-1} \) is the Oswald efficiency factor, and \( a_0' \) is the corrected two-dimensional lift curve slope (accounting for small AR wings) given by:

\[ a_0' = 2\pi AR \tanh \left( \frac{a_0}{2\pi AR} \right) \]  \hspace{1cm} (4)

The \( k_1 \) correction factor over the range \( 1.0 < AR < 2.5 \) is expressed by the following formula:

\[ k_1 = 3.33 - 1.33AR \]  \hspace{1cm} (5)

whereas for \( AR > 2.5, k_1 = 0 \) (Hoerner & Borst, 1985).

Continuing with the lifting line theory analysis, the total drag coefficient for a ram-air wing is expressed as:

\[ C_D = C_{D0} + \frac{c_L c^2}{\pi AR(1+\tau)} + k_1 \sin^3(\alpha - \alpha_{ZL}) \]  \hspace{1cm} (6)
where $C_{D0}$ is the profile drag, and $C_{LC}$ is the lift coefficient because of circulation only, i.e. $C_{LC} = a(\alpha - \alpha_{ZL})$. The second term in Equation (6) corresponds to the induced drag $C_{Di}$.

Similar to the lift coefficient, the last term in the drag coefficient formula accounts for the non-linear lift component because of the low wing $AR$ (Lingard, 1995).

The profile drag $C_{D0}$ is a non-lifting value that depends on the basic airfoil shape, surface irregularities and fabric roughness, open airfoil nose, and pennants and stabilizer panels (Ware & Hassell, 1969).

From the previous lift and drag discussion, the wing lift-to-drag ratio ($L/D$) can be evaluated. Figure 2-1 shows a $L/D$ versus $\alpha$ plot from the lifting line analysis for various $AR$ wings. The figure shows the maximum $L/D$ is achieved between the range $5^\circ < \alpha < 10^\circ$ and it increases with $AR$ as expected.

![Figure 2-1: $L/D$ vs $\alpha$ plot for various $AR$ (Lingard, 1995).](image)

The previous lifting line theory analysis only applies to the ram-air wing. To determine the aerodynamic effect of the remaining parachute components, Lingard expanded his analysis to include the anhedral effect, suspension lines, and store drag
contribution to the lift and drag of the complete system. Each of these components are discussed next.

The anhedral effect decreases the lift value of the total system. This reduction is because of the extra lift component created in the spanwise direction at the canopy lateral edges. Despite the decrease in lift efficiency, the anhedral effect aids in faster turning performance as the angle increases (Tweddle, 2006). The anhedral effect is added to the lift formula by the following equation:

\[ C_L = C_{L\beta=0} \cos^2 \beta \]  

where \( \beta \) is the anhedral angle, and \( C_{L\beta=0} \) is the lift coefficient given by Equation (2) (Lingard, 1995).

The suspension lines are components that increase substantially the total drag of the parachute system. The line drag coefficient is given by:

\[ C_{DL} = \frac{nRd\cos^3 \alpha}{S} \]  

where \( n \) is the number of lines, \( R \) is the mean line length, \( d \) is the line diameter, and \( S \) is the canopy area (Lingard, 1995).

It is important to note the tradeoff between \( AR \) and line drag from Equation (8). An increasing \( AR \) will produce a more efficient wing by increasing lift coefficient and decreasing induced drag from Equations (2) and (6). However, a higher \( AR \) wing will need more lines and a larger length, increasing the line drag coefficient of the complete system. Therefore, the best aerodynamic efficiency of the total system will be achieved at the wing \( AR \) that causes the largest reduction in induced drag and the lowest increase in line drag (Lingard, 1995).
The last component to analyze is the store drag $C_{DSt}$. The canopy store corresponds to the total weight added from the parachutist and the equipment. Lingard takes the store drag coefficient as a constant value given by:

$$C_{DSt/S} = \frac{(C_{DSt}S_{St})}{S} \quad (9)$$

where $S_{St}$ corresponds to the store drag area. The equation is non-dimensionalized with respect to the canopy area $S$ to add its value with the remaining components of the parachute system. An important note to consider is that the payload used to determine the store drag corresponds to one used for precision aerial delivery system missions.

An analytical approach to determine the store drag coefficient for a parachutist is presented in a research work from Mkrtchyan & Johari (Mkrtchyan & Johari, 2011). The authors determine the store drag area based on the DuBois area $S_{Du}$, which is expressed as:

$$S_{Du} = 0.0769W^{0.425}H^{0.725} \quad (10)$$

where $W$ is the weight (N), and $H$ is the height (m).

In other research from Penwarden et al., the estimated frontal area based on the DuBois area is expressed as:

$$S_{St} = 0.35S_{Du} \quad (11)$$

The frontal area is required to determine the store drag coefficient $C_{DSt}$. Wind tunnel analysis from this research suggests a $C_{DSt}$ value of 1.17 for a male person (Penwarden et al., 1978). Consequently, the store drag area $C_{DSt}S_{St}$ can be found and non-dimensionalized with respect to the canopy area using Equation (9) to obtain $C_{DSt/S}$.

Summarizing Lingard’s lifting line analysis for the total parachute system (canopy + anhedral effect + suspension lines + store drag), the final lift and drag formulas are given by:
\[
C_L = a(\alpha - \alpha_{ZL}) \cos^2 \beta + k_1 \sin^2(\alpha - \alpha_{ZL}) \cos(\alpha - \alpha_{ZL}) \tag{12}
\]
\[
C_D = C_{D0} + C_{Dl} + C_{DSt} + \frac{C_{Lc}^2}{\pi dR(1+r)} + k_1 \sin^3(\alpha - \alpha_{ZL}) \tag{13}
\]

Based on the total parachute system analysis, the flight performance at steady descent is determined by the glide angle \( \gamma \) and the velocity components \( u \) and \( w \). The glide angle is given by:

\[
\frac{L}{D} = \frac{1}{\tan \gamma} \tag{14}
\]

Equation (14) shows that a smaller glide angle will require a greater \( L/D \) value and a greater distance travel for a given height loss (Lingard, 1995).

The velocity components \( u \) and \( w \) correspond to the horizontal and vertical components of the total velocity \( V \). These are expressed in the following three equations.

\[
V = \left( \frac{2 W}{\rho S (C_L^2 + C_D^2)^{0.5}} \right)^{0.5}
\]

\[
u = V \cos \gamma \tag{16}
\]

\[
w = V \sin \gamma \tag{17}
\]

where \( \rho \) is the air density, and \( \frac{W}{S} \) is the wing loading. These three equations show the gliding velocity depends on the flying altitude and wing loading. Flying higher and increasing wing loading will cause a faster descent velocity along the glide path (Lingard, 1995).

### 2.2. Effect of Distortions on Ram-Air Parachutes

Distortions can affect considerably the geometry and performance of a ram-air parachute. The structure flexibility creates deformations along the span and chordwise directions, as shown in Figure 2-2. These deformations can be further enhanced by the effect of ram-air pressure and parachutist input on the risers.
Figure 2-2: Ram-air parachute bottom surface during flight (Adapted from Airborne Systems, from https://airborne-sys.com/product/intruder-ra-1-military-ram-air-parachute/).

Figure 2-2 shows surface deformations at the LE openings and lateral tip sides (red arrows). The parachutist is pulling the risers to give high tension to the suspension lines at the tip sides. This is noted by the greater deformation at the end ribs, which causes a larger anhedral angle. From the previous Lingard analysis, a larger anhedral angle translates into less lift and lower performance from the canopy.

The LE deformations in Figure 2-2 are mainly because of ram-air impact that compresses the nose aft in the chordwise direction. Inflation of the canopy also causes parabolic shapes between the ribs that form compound curves in the spanwise direction at the bottom surfaces. In addition, the canopy inflation leads to an increase in airfoil thickness that would cause a reduction in the span of the canopy. This span reduction is also attributed to the greater upward lifting force exerted on the non-load ribs as a result of the lack of suspension lines to maintain their rigidity. The large lifting force is what also contributes to the greater angle of incidence for the non-load ribs compared to the load ribs.
The span reduction and airfoil thickness increase can vary between 15-20% and 30-40%, respectively (J. Leblanc, personal communication, 2016).

Figure 2-3: Ram-air parachute top surface during flight (Adapted from Airborne Systems, from https://airborne-sys.com/product/multi-mission-system-ram-air-parachute/).

Figure 2-3 shows how inflation causes the same parabolic curvatures between the load and non-load ribs in the top surface (red arrows). From this figure, it is expected the maximum cell thickness is located at the middle section between two ribs. Looking at one cell, it can be seen that the non-load rib is pushed more aft than the load rib (yellow arrows). This effect is caused by the lack of suspension lines at the non-load rib. Because the load ribs have a suspension line attached to the lower LE opening, it exerts enough tension to maintain its location within the canopy. The non-load rib, alternatively, is not able to withstand the ram-air pressure and is pushed farther aft in the chordwise direction. Therefore, the compound curve that joins the leading edges of both ribs is in such a way the inlet opening is tilted more vertical and raised up compared to the design rib (J. Leblanc, personal communication, 2016).

Another important deformation to consider from Figure 2-2 and Figure 2-3 comes from small bumps present at the top and bottom surfaces as a result of the outward
ballooning where the crossport holes are located. This type of deformation appears at the crossport locations because of the inability of the material fibers to resist the large internal ram-air pressure. The breaking of the material fibers at these crossport locations causes both top and bottom rib surfaces to expand slightly in thickness, leaving small bumps present in the exterior surfaces. (J. Leblanc, personal communication, 2016).

Figure 2-4: Ram-air parachute back side during flight (Adapted from Airborne Systems, from https://airborne-sys.com/product/hi-5-military-ram-air-parachute/).

Figure 2-4 shows the back side deformation and the TE configuration during flight. The TE comprises the joint of the top and bottom surfaces and has a rounding section because of cell pressurization. The maximum thickness at this point can range between 3 to 5 inches between ribs (J. Leblanc, personal communication, 2016). The rounding TE leads to a blunt shape that has a negative effect on the rib efficiency because the flow leaving the top and bottom surfaces will create more pressure drag (Anderson, 2010).

The last type of deformation comes from the loading of the suspension lines on the canopy load ribs. As shown in Figure 2-2 and Figure 2-4, each load rib is attached to suspension lines at 5 points. Starting from the LE towards the TE, these 5 attachment points correspond to the A, B, C, D, and control lines. The loading imposed by the line tension
on these points cause chordwise compression of the rib that is balanced with the ram-air internal pressurization. The thicker area of the wing (attachment points A and B) manages to withstand the tension load. However, as the wing becomes thinner towards the TE, points C and D have not enough internal pressurization to balance the tension load. In consequence, the higher tension load leads to localized buckling and crushing of the rib near the TE (J. Leblanc, personal communication, 2016).

2.3. Experimental Studies

Wind tunnel testing provides a good understanding of the flowfield around a canopy that helps significantly to assess the preliminary design and performance of new models (Johari & Desabrais, 2003). Full-scale and scale models have been tested in research work by Ware & Hassell, Nicolaides, Sanger & Ware, and Belloc. All these experiments were focused on determining the aerodynamic performance parameters such as lift, drag, and moment coefficients, at specific range of velocities, aspect ratios, and angles of attack.

The first experimental models to analyze correspond to rectangular canopies in the study from Ware & Hassell (Ware & Hassell, 1969). The scale models tested in this experiment at NASA Langley varied in AR between 1.0 and 3.0, and were divided into two sets: constant area and constant chord series. The full-scale model corresponded to an AR of 1.5. The testing flight velocities were in a range from 30 to 60 ft/s and covered an angle of attack range from the lowest possible to near stall conditions. Some drawbacks from these tests came from the increased number of lines used to hold the bottom surfaces straight to keep a similar inflated shape between all tested cases. As a consequence, the model rigging caused difficulties in the measurement of the angle of attack. In addition, a
drag correction analysis from the suspension lines was taken into consideration because not all the lines were exposed to the airstream in the wind tunnel. The experiment results showed an increase in the maximum wing alone $L/D$, ranged from 2.7 to 4.4, as the $AR$ increased from 1.0 to 3.0 for both constant area and constant chord models. The full-scale model gave a maximum wing alone $L/D$ of 3.7, which was larger than the value from the constant area and constant chord model. The larger $L/D$ value was attributed to a less distorted wing along the LE upper surface or error drag estimation. The distorted models presented in this thesis had the canopy modeled in this research as the baseline geometry.

The research from Nicolaides and Sanger & Ware present a similar test setup than the one by Ware & Hassell described previously. The wind-tunnel models tested by Nicolaides also present flow visualization techniques using smoke and wool tufts at the upper surface. From these observations, flow attachment from LE to TE was achieved until an angle of attack about 7.5°, with latter angles starting to present detachment until the half point of the upper surface. Unfortunately, the tufts were only used in the upper surface, with no flow insight on the lower surface. In addition, the rigging problems and inflation distortions on the canopies presented difficulties in obtaining unique performance value for each angle of attack tested (Nicolaides, 1971). Sanger & Ware analyzed three low $AR$ models with an $L/D$ range of 1.9 to 2.7 and lift coefficient range of 0.9 to 1.1 as final results.

To provide a more realistic flight behavior, Belloc (Belloc, 2015) presented wind tunnel data for an arched wing with elliptical planform shape and more severe anhedral effect. His experiment used a scale model of a paraglider using a NACA 23015 as ribs. The focus of his work was on the external flow and on the effect of the arched shape on the
longitudinal and lateral aerodynamic parameters. Therefore, his scale model maintained rigidity and was filled in the inside. Experimental results showed a lift curve slope of about 0.0525 deg\(^{-1}\) (3.01 rad\(^{-1}\)) between an AoA range between \(-5^\circ \leq \alpha \leq 5^\circ\). In addition, the arched shape presented a strong lateral force that affected the pitching, yawing, and rolling moment coefficients in a different manner compared to a rectangular shape.

As shown in this section discussion, wind-tunnel experiments have provided a good insight on how to determine the aerodynamic parameters of a ram-air parachute. However, the flow visualization techniques are very limited to only catch effects on the external surface. In addition, keeping the canopy from complete inflation results in a lack of certainty for the effects that distortions might produce on the canopy surfaces and their effect on aerodynamic performance overall. These difficulties are some of the reasons why computational studies have been of recent interest in the last years, as will be discussed in the next section.

2.4. **Computational Studies**

Over the past two decades, several computational studies have been performed to evaluate the aerodynamic performance of ram-air parachutes based on specific geometry modifications. CFD techniques have been applied to both 2D and 3D models solving the RANS equations using turbulence models such as the Spalart-Allmaras or SST. Simulation results allow to analyze the flow field characteristics around both internal and external surfaces of the canopies. Furthermore, the ability to assess how the flow behavior affects the aerodynamic efficiency at specific locations have provided better design approaches for future models.
One of the earliest computational studies was performed by Mittal et al. (Mittal et al., 2001). This research investigated the effect of the LE cut for a two-dimensional rib (Clark-Y type) of a ram-air parachute. Main focus was established on the size and location of the LE cut along the rib. The study resolved the RANS equations for incompressible flow using the Baldwin-Lomax turbulence model. To evaluate flow characteristics at different $Re$, both laminar and turbulent flows are presented. All simulations presented unsteady flow behavior and a strong influence of the LE cut on the rib performance. Results from these simulations show the flow separation over the lower surface decreased as the LE cut becomes smaller, with a $L/D$ range increase from 3.4 to 5.8. Furthermore, the flow over the upper surface was insensitive to the configuration of the cut.

A similar 2D study was performed by Mohammad & Johari on a high-performance parafoil. The physics study solved the RANS incompressible flow equations for steady flow using the Spalart-Allmaras turbulence model. Assuming impermeable, rigid, and smooth parafoil surfaces, the simulations determined lift and drag values at three freestream velocities (31, 49, and 68 ft/s) and an angle of attack range between $-3.5^\circ \leq \alpha \leq 14.5^\circ$. The performance results were compared with a closed baseline model not specified by the authors. The results showed the parafoil lift curve slope decreased 8% compared to the baseline model, whereas the drag coefficient almost doubled for the parafoil model. The smallest drag values were achieved at an angle of attack range between $2.5^\circ \leq \alpha \leq 7^\circ$, with the highest $L/D$ value attained at $\alpha = 7^\circ$. Flow visualization identified the presence of a separation bubble on the lower LE and a vortex inside the cell opening that diverted the flow around both external surfaces (Mohammad & Johari, 2009). Figure 2-5 shows a vorticity contour plot to show the flow behavior obtained for the parafoil.
As shown in Figure 2-5, the flow separates significantly at the lower LE until reattachment is restored about a quarter distance towards the TE. Alternatively, the upper surface shows increasing flow separation after it passes the thickest rib section and moves towards the TE.

The previously described 2D study was expanded into a 3D flow field visualization for a full-scale model of a MC-4 ram-air military canopy. The model geometry was extracted from close-up images of the canopy in flight. Using the same physics as the 2D study, the 3D simulation determined lift and drag values at a freestream velocity of 40 ft/s and an angle of attack range between $-4^\circ \leq \alpha \leq 14^\circ$. The results showed a linear lift increase until $\alpha = 12^\circ$, with the minimum drag achieved at $\alpha = 2^\circ$. In addition, the maximum $L/D$ value corresponded to 5.7 and was attained at $\alpha = 10^\circ$. Flow visualization identified a thick boundary layer at the lower surface without reattachment, a result which disagreed with the observation from the 2D study described earlier. Finally, using finite wing expressions based on lifting line theory, the MC-4 rib was analyzed from a 2D to 3D study to compare against the CFD simulated results. Figure 2-6 shows an image detailing the comparison between the $L/D$ values for the two cases (Eslambochi & Johari, 2013).
As shown in Figure 2-6, the maximum $L/D$ for the 2D extension was obtained at $\alpha = 6^\circ$ instead of the 3D CFD at $\alpha = 10^\circ$. Furthermore, the finite wing theory predicted a $L/D$ ratio that was 36% greater than the CFD simulated results (Eslambochi & Johari, 2013).

Another computational study on 3D models was performed by Cao & Zhu (Cao & Zhu, 2013). Their work presents how geometric parameters, i.e., anhedral arc, planform geometry, airfoil shape, and LE opening, affect the aerodynamic performance of the parachute. The baseline model for their study was chosen from Nicolaides experimental work. The RANS equations were solved using the SST turbulence model. The cases examined corresponded to a flight velocity of 40 ft/s and an angle of attack range between $-5^\circ \leq \alpha \leq 20^\circ$. Results from this study showed the following: an inverse relationship between lift and anhedral arc, an elliptical planform produces the least drag, the airfoil shape with the thickest part located at the middle chord (smaller LE radius) is the most efficient in $L/D$ value, and the smaller LE cut provides the least amount of drag.

Ghoreyshi et al. (Ghoreyshi et al., 2016) presented 2D and 3D simulations of ram-air parachutes using both steady and unsteady solvers of the RANS equations. The 2D
models corresponded to rigid airfoils with/without an inlet opening, TE deflections or bleed air spoilers. The 3D model corresponded to experimental models with/without inlet openings tested at a wind tunnel in Japan. Simulation results recommended the use of unsteady solvers for open airfoil/ wing simulations as a result of initial high oscillations of the forces and moments compared to the close models. The 2D performance analysis of the open inlet geometries compared against the closed geometry concluded the following: larger drag values, minimum drag attained at a greater angle, lift slightly smaller, and sooner stall. Flow visualization showed an eddy at the lower surface LE that decreased in size as the angle of attack increased. In addition, as the angle of attack increased, an eddy started to form at the upper surface LE that caused flow separation earlier than the closed inlet geometry. The 3D performance analysis of the open wings compared against the 2D airfoils concluded the following: stall reached at higher angles of attack, smaller lift, larger drag, and smaller $L/D$ values. Flow visualization showed presence of eddies at the lower surface that became stronger at the wingtips.

To predict the inflated geometry more effectively, FSI simulation studies have been also studied over the last years. Fogell (Fogell, 2014) developed a loosely coupled FSI approach to predict the equilibrium shape of a single-cell model during steady glide. The rib cross-section was taken from the work by Ware & Hassell (Ware & Hassell, 1969), which was described in the earlier section. The physics solved the incompressible RANS equations using an adjusted $\kappa$-$\epsilon$ turbulence model. Assuming impermeable and zero thickness surfaces, the model was simulated at a freestream velocity of 108 ft/s and $\alpha = 5^\circ$. The 2D simulations were performed on open and closed models, while the 3D single-cell simulation neglected the end-cell effects. Results from the 2D analysis concluded the
drag force created by the internal pressure on the upper surface is the largest component of overall drag. Furthermore, the analysis presented a reduction in lift about 7% for the open case compared against the closed one. Results from the 3D analysis showed good drag comparison with experimental cases, but 50% under-prediction in lift values. The great lift reduction was attributed to the high suction pressure on the lower surface because of the chosen turbulence model. The disadvantage of this study was the long computational expense of the simulations. A typical CFD simulation took 15-25 hours in 16 CPUs, while a FSI simulation with 10 iterations took two weeks to complete.

Another recent FSI study was performed by Burnett (Burnett, 2016). In this research, the simulation of a single-cell square parafoil was performed using ANSYS Multiphysics. The simulation was compared against an experimental test carried out by the same author. Results from this study showed the FSI model underpredicted the canopy deformations by 25%. The drawback, similar to Fogell, was in the high computational time required to run the FSI model. A complete FSI cycle took 4 days using a standard 16 GB RAM, 8 cores, 3 GHz processor.

As shown in the previous computational studies, there has been a considerable progress and understanding of the physics of ram-air parachutes from a 2D to 3D perspective based on design characteristics. However, most of these studies assume an undistorted canopy. Therefore, the implementation of distortions on the canopy surfaces and their effect on aerodynamic performance is a topic that has not been reported on past research to the author’s knowledge.
3. Geometry Creation

3.1. CATIA Introduction

The CAD software used for this study is CATIA V5. A leading program in the aerospace industry, CATIA was chosen because of its automatic updates in the engineering design phase that save modeling time considerably (Haines, 2015). In addition, as a ram-air parachute is a high complex structure, the ability to intersect, sweep, and trim complex surfaces is very well handled by the Generative Shape Design tool included in the software. Finally, the software enables the use of parametric variables and Visual Basic scripting, which are useful tools to make the design process more automated based on adjusting geometric characteristics of the parachute.

3.2. Methodology Approach

The design process starts from the 2D model. For this thesis, AutoCAD rib drawings that correspond to the undistorted and distorted cases from a rectangular canopy were supplied by Performance Designs Inc. Figure 3-1 shows an image of the undistorted rib in AutoCAD.

Figure 3-1: AutoCAD undistorted rib (Performance Designs Inc.).

As shown in Figure 3-1, the middle straight line (blue arrow) corresponds to the maximum chordwise distance from LE to TE. The rib has a flat bottom surface, which resembles the Clark-Y airfoil profile (easy construction, lower efficiency). The straight line coming down
from the LE nose corresponds to the rib opening length where air enters the canopy (red arrow). To compare with past research studies, the rib was assumed a chord value of 1 m. With this assumption, the maximum thickness value resulted in 14.5% located at 0.2 m from the LE. Finally, a 10% chord length value was assigned for the rib opening length. Table 3-1 summarizes the geometry characteristics of the undistorted rib.

Table 3-1: Undistorted rib geometry characteristics.

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<table>
<thead>
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<tbody>
<tr>
<td>Chord Length $c$ (m)</td>
<td>1</td>
</tr>
<tr>
<td>Maximum Thickness ($% c$)</td>
<td>14.5</td>
</tr>
<tr>
<td>Maximum Thickness Location ($% c$)</td>
<td>20</td>
</tr>
<tr>
<td>Opening Length ($% c$)</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 3-2 shows an image of the distorted rib in AutoCAD. This rib accounts for the distortions discussed in Section 2.2.

Figure 3-2: AutoCAD distorted rib (Performance Designs Inc.).

As shown in Figure 3-2, there are clear geometric differences compared to the undistorted case. The LE nose has a blunter shape coming from the distortion of the ram-air impact effect. This effect also causes the curved profile of the rib opening length. Looking at the bottom surface, the rib seems to expand slightly in thickness, especially towards the TE. This expansion is likely as a result of the distortion effect from the suspension lines tension load imposed on the lower surface, which becomes larger moving towards the TE. Looking
at the upper surface, the rib seems to also expand in thickness at certain positions as it goes from LE to TE. The increase in thickness from this region is because of the distortion effect of the outward ballooning at the crossport locations.

Each of the AutoCAD rib drawings were digitized to extract the surfaces coordinate points (X, Y) as a .txt file. Figure 3-3 shows an image of the digitized distorted rib.

![Digitized distorted rib](image)

**Figure 3-3: Digitized distorted rib.**

From Figure 3-3, the green points around the rib surfaces correspond to the coordinate points extracted from AutoCAD.

An Excel Macro was used to transfer the rib coordinate points from the .txt format to CATIA V5. The macro works with CATIA V5 open in the Part Design workbench, and exports the points in mm units. Therefore, the proper unit conversion was made in Excel before running the macro. Figure 3-4 shows an image of CATIA V5 with all the coordinate points extracted from the macro.

![CATIA V5 distorted rib](image)

**Figure 3-4: CATIA V5 distorted rib.**
The rib coordinate points in CATIA V5 allowed to start using the Generative Shape Design tool to create splines and surfaces. The splines were divided into three sections: upper, lower, and opening. The opening length was designed by taking the first point from the flat section of the lower surface as the initial point. Therefore, this point would correspond to the lower surface LE. From this point moving towards the nose LE, the upper surface LE point was selected according to the point that matched closer the geometric value of the opening length (10 % c). Figure 3-5 shows the spline corresponding to the rib opening length.

After creating the rib opening spline, the next two splines for both upper and lower surfaces are built to enclose the rib. Once the rib is closed, a surface is created using the Fill command. Finally, the surface is exported from CATIA V5 as a drawing file in *.dxf format to import into COMSOL. The procedure described until now was used to test the undistorted and distorted (inlet open/closed) rib cases. Figure 3-6 shows the three ribs designed for the 2D CFD analysis.

Figure 3-5: Distorted rib opening length.
Looking at Figure 3-6, the distorted open rib corresponds to the splines for both upper and lower surfaces only.
The next step in the design process continues with the pseudo-2D model. This geometry corresponds to a single-cell model, which neglects the 3D effects (tip vortices) in the CFD analysis. A single-cell comprises 3 ribs: 1 non-loaded, and 2 loaded. Therefore, two ribs created from the 2D design are offset by a half span value. Splines across the spanwise direction are used for both upper and lower sections to create the surfaces. For the undistorted case, the splines correspond to flat lines in the spanwise direction. Alternatively, the distorted case presents splines that are curved to give the parabolic shape between ribs. The parabolas were built by inserting points at the middle location between the load and non-load ribs. The coordinates of these points were manually adjusted to give an approximate maximum thickness value of 30% and a TE radius of 5 inches between the load and non-load rib. In addition, the non-load rib coordinate points were rotated and translated vertically to take into account the incidence angle and the compound curves connecting the ribs LE at both upper and lower surfaces. Figure 3-7 shows images of the undistorted and distorted pseudo 2D models.
b) Distorted pseudo-2D

Figure 3-7: CATIA pseudo-2D models (isometric, front, side, and bottom views).

The geometric characteristics of the pseudo-2D models are summarized in Table 3-2.

Table 3-2: Pseudo-2D geometric characteristics.

<table>
<thead>
<tr>
<th>Pseudo Model</th>
<th>Undistorted</th>
<th>Distorted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord Length $c$ (ft)</td>
<td>7.35</td>
<td>7.35</td>
</tr>
<tr>
<td>Span (ft)</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Incidence Angle ($^\circ$)</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Vertical Translation (in)</td>
<td>0</td>
<td>$\frac{3}{4}$</td>
</tr>
<tr>
<td>Opening Length (% $c$)</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

As shown in Table 3-2, the chord length corresponds to a different value compared to the 2D case. This value was determined from a rectangular 3D canopy ($AR = 2.1$) by Performance Designs Inc. The span for the distorted rib is about 15% less than the undistorted case to account for the shrinkage distortion as a result of cell inflation. In
addition, the 1.5° incidence angle allows to consider the upward lifting force exerted on the non-load rib. The vertical translation value considers the upward shift of the non-load rib to form the compound curves between the ribs. To compare this model against past research, the dihedral angle and the use of crossports were neglected.

The final step in the design process ends with the 3D model. The construction of the 3D model started from the pseudo-2D single cell and mirrored the remaining cells based on the total number desired for the complete canopy. The dihedral angle is taken into consideration by partitioning the total angle value by the total number of cells in the canopy. The remaining geometry characteristics from the pseudo model are kept within the same values for the distorted 3D model. The final CAD model is exported in *.igs format to import in the CFD software. Table 3-3 summarizes the geometric characteristics and Figure 3-8 shows an image of the complete 3D distorted model.

Table 3-3: 3D distorted model geometric characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord Length c (ft)</td>
<td>7.35</td>
</tr>
<tr>
<td>Span (ft)</td>
<td>15.4</td>
</tr>
<tr>
<td>Planform Area (ft²)</td>
<td>112.93</td>
</tr>
<tr>
<td>AR</td>
<td>2.1</td>
</tr>
<tr>
<td>Incidence Angle (°)</td>
<td>1.5</td>
</tr>
<tr>
<td>Vertical Translation (in)</td>
<td>3/4</td>
</tr>
<tr>
<td>Opening Length (% c)</td>
<td>10</td>
</tr>
<tr>
<td>Anhedral Angle (°)</td>
<td>20</td>
</tr>
</tbody>
</table>

As shown in Table 3-3, the calculated AR for the complete parachute is 2.1, which corresponds to the canopy by Performance Designs Inc. This value allows to compare the performance results against available data from past experimental and numerical studies.
As shown in Figure 3-8, the complete model corresponds to a seven cell canopy, which is a typical total cell value for a real canopy.

To allow for a more automated process that saves modeling time, some geometric characteristics (i.e., span, incidence angle, translation, anhedral, parabolic mid points, and reduction percentages) were used as variable parameters in CATIA V5. With this feature, changing the value of one parameter could be used to design a new 3D model within seconds. The drawbacks from this method were the limited creation of only parachutes with rectangular planform shapes, specific total cell number (7 cells), and constant parameter values for all ribs. These issues were addressed in the programming method discussed in the following section.

### 3.3. Programming Method

A Visual Basic code developed by Guzman enhanced the automated process of creating 3D models in CATIA V5 from AutoCAD drawings. The code uses the same methodology approach described in the previous section, but considers ribs with a larger number of coordinate points at the upper and lower surfaces. The extra rib coordinates allow to higher sensitivity models to account for canopy distortions. Another advantage is
the creation of ribs with different chord lengths across the spanwise direction. This extra feature allows the design of elliptical planform shapes. Finally, the code also enables the user to alter geometric variables i.e. incidence angle, translation, and opening length values, between each rib. This feature provides a better user control of the whole canopy design overall (C. Guzman, personal communication, 2016).

3.4. **Geometry Results**

This section summarizes the geometries designed for the CFD analysis. The geometries described in Section 3.2 (2D, pseudo-2D, and 3D) correspond to a canopy supplied from AutoCAD drawings from Performance Designs Inc. This model consisted of a seven cell canopy with rectangular planform shape. The 2D and pseudo-2D CFD analysis is based on this model. Figure 3-9 shows an image of the final 3D canopy.

![Figure 3-9: PD 3D distorted model (isometric, front, side, top views).](image)

The 3D analysis is carried out using several canopy models. The first model is taken from Ware & Hassell and corresponds to an undistorted rectangular canopy. To assess the impact of distortions individually, three distorted models were developed from the
undistorted canopy: a span shrinkage model, an incidence and upward translation model, and a maximum thickness model. These canopies were designed by the programming method using the rib coordinates from the experimental research by Ware & Hassell.

Figure 3-10 shows the different 3D models (distorted cases) to be analyzed in the CFD. Finally, the geometric characteristics for the baseline model (undistorted case) are summarized in Table 3-4.

a) 15% Span shrinkage model

b) 1.5° Incidence angle and ¾” upward translation model
c) 30% Maximum thickness model

Figure 3-10: Ware & Hassell 3D distorted models.

Table 3-4: Ware & Hassell 3D baseline model geometric characteristics.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length (ft)</td>
<td>8.57</td>
</tr>
<tr>
<td>Span (ft)</td>
<td>17.15</td>
</tr>
<tr>
<td>Rib maximum thickness (%)</td>
<td>17.9</td>
</tr>
<tr>
<td>AR</td>
<td>2</td>
</tr>
<tr>
<td>Total cell number</td>
<td>16</td>
</tr>
<tr>
<td>Curvature angle</td>
<td>38.2°</td>
</tr>
</tbody>
</table>

The last 3D model was designed based on an elliptical canopy from Performance Designs Inc. As the other 3D models, this canopy was designed using the programming method from Section 3.3. This model was built to compare the planform shape effect against the rectangular model presented in Figure 3-9. Table 3-5 summarizes the geometric characteristics, and Figure 3-11 shows an image of the elliptical model.

Table 3-5: PD elliptical model geometric characteristics.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length Center Rib (ft)</td>
<td>7.76</td>
</tr>
<tr>
<td>Span (ft)</td>
<td>20.04</td>
</tr>
<tr>
<td>Planform Area (ft²)</td>
<td>150</td>
</tr>
<tr>
<td>AR</td>
<td>2.68</td>
</tr>
<tr>
<td>Total cell number</td>
<td>9</td>
</tr>
</tbody>
</table>
Figure 3-11: Elliptical PD model
4. CFD Methodology

4.1. COMSOL Multiphysics Introduction

The CFD software used for this study is COMSOL Multiphysics. The program was chosen because of its user-friendly interface for setting models and its cheaper cost compared to other industry leaders such as ANSYS and STAR CCM+. For this thesis, two modules are used in the modeling setup within COMSOL: CAD, and CFD Modules. The CAD Module allows the import of CATIA files from *.dxf and *.igs format for 2D and 3D geometries, respectively. Alternatively, the CFD Module carries out the fluid flow physics and solves the governing equations using different turbulence models. Finally, the software has also easy multiphysics modeling, which is a useful tool to setup FSI simulations if more complex work is required for these geometries.

4.2. Turbulence Modeling

The turbulence model selected for this study is the Shear Stress Transport (SST). The SST turbulence model combines the standard $k - \epsilon$ in the free shear layers and boundary layer wake region, and the $k - \omega$ at the near-wall region (sub- and log-layer) of the boundary layer. This two-equation eddy-viscosity model is more suited to flows involving high separation regions as a result of adverse pressure gradients, which describes the flow behavior expected for a ram-air parachute system. Several flow applications, including a NACA airflow model, are presented in Menter’s research to validate the use of the SST turbulence model on aerodynamic applications (Menter, 1994).
4.3. General Model Setup

The flow behavior is described by the continuity and momentum Navier-Stokes equations, which are expressed in Equations (18) and (19) for a steady, incompressible Newtonian fluid in three dimensions with body forces neglected.

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  
(18)

\[
\rho \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]  
(19a)

\[
\rho \left( u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)
\]  
(20b)

\[
\rho \left( u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\]  
(21c)

where \( \rho \) is the density, \( u, v, w \) are the velocity components, \( p \) is the pressure, and \( \mu \) is the dynamic viscosity (Houghton & Carpenter, 2003).

The RANS equations are chosen for this study because of the low computational expense compared to other numerical approaches such as LES or DNS. These time-averaged equations are solved for turbulent flows by decomposing the flow properties into their mean and fluctuating values. The non-linearity from the velocity fluctuations, known as the Reynolds stresses, in the Navier-Stokes equations are handled by the use of turbulence models to close the RANS equations (Pope, 2000).

The 2D computational domain is shown in Figure 4-1. The domain is composed of a D-shaped inlet with the model located 10 chord lengths from the upstream, top, and bottom boundaries, and 20 chord lengths from the downstream boundary. The length dimensions were chosen according to the study by Mohammadi & Johari (Mohammad & Johari, 2010) where they suggested a 16x10 domain (11 chord lengths in flow direction, 10 chord lengths in transverse direction) was large enough to avoid boundary effects.
Figure 4-1: 2D computational CFD domain.

The 3D fluid computational domain is presented in Figure 4-2. The domain has the same length dimensions for top, bottom, upstream, and downstream boundaries, as the 2D domain. For the pseudo-2D model, the lateral boundaries in the spanwise direction are aligned with the end ribs. For the 3D model, the lateral boundaries are located 10 chord lengths (per side) from the center rib TE.

Figure 4-2: 3D computational CFD domain.

As shown in Figure 4-2, the inlet boundary for this domain corresponds to a cubic shape. A scaled domain closer to the model was built for better mesh resolution.
4.4. **Boundary Conditions**

The boundary conditions are described as follows:

- **Upstream Boundary:** Inlet with velocity field \((x, y, z)\) as function of angle of attack \(\alpha\).
  \[
  x = V \cos \alpha \\
  y = V \sin \alpha \\
  z = 0
  \]
  where \(V\) is the free-stream velocity.

- **Downstream Boundary:** Open boundary with normal stress \(f_0 = 0\).

- **Top/Bottom Boundary:** Wall free-slip boundary with \(\vec{u} \cdot \vec{n} = 0\). (\(\vec{u}\) is velocity vector, \(\vec{n}\) is a unit normal vector to the boundary)

- **Side Boundary:** Symmetry boundary for pseudo-2D model with \(\vec{u} \cdot \vec{n} = 0\). Open boundary for 3D model with normal stress \(f_0 = 0\).

- **Rib/Parachute Boundary:** Interior wall no-slip condition with \(\vec{u} = 0\) (impermeable, rigid walls with zero thickness).

4.5. **Mesh Resolution**

For the 2D model, an unstructured triangular mesh was applied to most of the computational domain, including the interior of the rib in the opening case. The exception of the unstructured mesh fell in the vicinity of the external and internal upper and lower rib surfaces where a boundary layer mesh (structured rectangular) was implemented. Figure 4-3 shows an image with the mesh used for the 2D cases.
As shown in Figure 4-3, the mesh resolution starts with the finest resolution of elements in the close area where the rib is located. Moving towards the computational boundaries, the mesh element size gradually increases. Figure 4-4 shows a close-up view of the boundary layer mesh.
The boundary layer mesh from Figure 4-4 consists of 35 layers (per side) with a first layer height value of 3E-5 (ft). A stretching factor of 1.2 is applied to the subsequent layers, resulting in a total boundary layer thickness of 0.0885 (ft). The total thickness is estimated based on turbulent flat-plate theory, which is dependent on the flow conditions described in the next section. The first layer height value ensures the first node attains a non-dimensional distance to cell center around 1. This parameter is an equivalent of the \( y^+ \) value denoted for other CFD software. A value close to or lower than 1 is necessary with the SST model to ensure the boundary layer is well resolved from the wall.

A total number of elements of 90,000 (closed cases) and 150,000 (open case) is used for the 2D simulations. The cases were run on a 6 core PC with 128 GB of RAM. The total simulation time ranged from 1 hour (undistorted case) to 3.5 – 6 hours (distorted cases) for eight (closed cases) and five (open case) angle of attack values.

For the pseudo-2D and 3D model, an unstructured tetrahedral mesh was applied to most of the computational domain, including the interior of the canopy cells. The exception of the unstructured mesh fell in the vicinity of the external upper and lower rib surfaces.
where a boundary layer mesh (structured prism) was implemented. Figure 4-5 shows an image with the mesh used for the pseudo-2D and 3D cases.

Figure 4-5: Pseudo-2D and 3D meshes.
As shown in Figure 4-5, the pseudo 2D starts from the finest mesh resolution at the close area near the model. Progressing towards the computational boundaries, the mesh resolution starts decreasing gradually by increasing the element size. The local meshing in the scaled domain is visible by the area enclosed by the red rectangle. For the 3D case, the parachute is shown in the enclosed red circle. The element size moving toward the computational boundaries was increased to a higher growth rate than the pseudo-2D.

In addition, the 3D mesh shown in Figure 4-5 corresponds to a scaled mesh (approximately 1.5 bigger) from the baseline mesh to save simulation time. Figure 4-6 shows an image of the boundary layer mesh for these simulations.

![Figure 4-6: Pseudo-2D boundary layer mesh.](image)

The boundary layer mesh from Figure 4-6 has the same characteristics as the 2D case. The only exception for the pseudo-2D and 3D case is the exclusion of the boundary layer mesh for the interior surfaces of the canopy cells. From the 2D analysis (described in the next chapter), the author found that the velocity gradients present in the interior rib are small enough to neglect the use of a boundary layer mesh in this area.

A total number of elements of approximately 800,000 is used for the pseudo-2D simulations. For the 3D models, the total number of elements increased to approximately 5 – 6 million for the baseline mesh. The scaled mesh (as shown in Figure 4-5) reduced the
The total number of elements to approximately 2 million. The cases were run on a 6 core PC with 128 GB of RAM. The total simulation time took approximately 15 hours for the pseudo-2D model at one angle of attack case. Alternatively, the total simulation took between 22 (1 angle of attack) to 36 hours (3 angles of attack) to run for the 3D models. A sufficient number of iterations were carried out to ensure the lift and drag values achieved a stable value at the end of each tested case.

### 4.6. Flow Parameters

To validate the results from the 2D simulations, a LS (1)0417 airfoil was tested first in the CFD using the same meshing as the 2D undistorted/distorted cases. The airfoil results from the CFD were compared against available experimental data from NASA. The chord for this airfoil was given a value of 3.28 ft. For this simulation, the flow parameters are presented in Table 4-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Angle of Attack $\alpha$ ($^\circ$)</td>
<td>$-8^\circ \leq \alpha \leq 16^\circ$</td>
</tr>
<tr>
<td>Freestream Velocity $V$ (ft s$^{-1}$)</td>
<td>103.7</td>
</tr>
<tr>
<td>Density $\rho$ (slugs ft$^{-3}$)</td>
<td>0.002377</td>
</tr>
<tr>
<td>Dynamic viscosity $\mu$ [slug/(ft s)]</td>
<td>3.737E-7</td>
</tr>
<tr>
<td>Reynolds Number $Re$</td>
<td>2.1E6</td>
</tr>
</tbody>
</table>

The 2D simulations (undistorted/distorted) are run with the flow parameters described in Table 4-2. The angle of attack $\alpha$, in parachute terminology, is measured as the angle between the freestream and the lower surface of the canopy. This same convention is used for this study.
Table 4-2: 2D simulation flow parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Angle of Attack $\alpha$ ($^\circ$)</td>
<td>$-6^\circ \leq \alpha \leq 8^\circ$</td>
</tr>
<tr>
<td>Freestream Velocity $V$ (ft s$^{-1}$)</td>
<td>115</td>
</tr>
<tr>
<td>Density $\rho$ (slugs ft$^{-3}$)</td>
<td>0.002377</td>
</tr>
<tr>
<td>Dynamic viscosity $\mu$ [slug/(ft s)]</td>
<td>3.737E-7</td>
</tr>
<tr>
<td>Reynolds Number $Re$</td>
<td>2.33E6</td>
</tr>
</tbody>
</table>

For the distorted open case, the simulation was run with an angle of attack range that only takes into account the positive values from Table 4-2. Notice that the chord length for all the tested 2D cases has a value of 3.28 ft (same as airfoil case).

The pseudo-2D simulations maintain the same $Re$ value as the 2D cases to compare results at one angle of attack setting. The freestream velocity is adjusted to 50 ft/s because of the change in chord length for this model (7.35 ft). A summary of the flow parameters for the pseudo-2D simulations is presented in Table 4-3.

Table 4-3: Pseudo-2D simulation flow parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Angle of Attack $\alpha$ ($^\circ$)</td>
<td>0$^\circ$</td>
</tr>
<tr>
<td>Freestream Velocity $V$ (ft s$^{-1}$)</td>
<td>50</td>
</tr>
<tr>
<td>Density $\rho$ (slugs ft$^{-3}$)</td>
<td>0.002377</td>
</tr>
<tr>
<td>Dynamic viscosity $\mu$ [slug/(ft s)]</td>
<td>3.737E-7</td>
</tr>
<tr>
<td>Reynolds Number $Re$</td>
<td>2.33E6</td>
</tr>
</tbody>
</table>

To validate the results from the 3D simulations, the Ware & Hassell undistorted model was tested first in the CFD. The baseline model results from the CFD were compared against available experimental data from their research work. The next 3D distorted models
carried on with the same meshing settings as the baseline model to compare results. The chord length for these models corresponded to 8.57 ft. For these simulations, the flow parameters are presented in Table 4-4.

Table 4-4: 3D Ware & Hassell simulation flow parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Angle of Attack α (°)</td>
<td>4°, 5°, 8°</td>
</tr>
<tr>
<td>Freestream Velocity V (ft s⁻¹)</td>
<td>50</td>
</tr>
<tr>
<td>Density ρ (slugs ft⁻³)</td>
<td>0.002377</td>
</tr>
<tr>
<td>Dynamic viscosity μ [slug/(ft s)]</td>
<td>3.737E-7</td>
</tr>
<tr>
<td>Reynolds Number Re</td>
<td>2.73E6</td>
</tr>
</tbody>
</table>

Finally, the 3D distorted model expanded from the pseudo-2D uses the same flow parameters in Table 4-3 to compare results. The elliptical model also uses the same flow parameters as the pseudo-2D case, with the only exception coming from a slightly larger $Re$ (2.47E6) because of the larger chord length value of 7.76 ft. These two 3D cases are used to compare results against the 2D and pseudo-2D cases which are run at the same $Re$. 
### 4.7. Test Matrix

A summary of the test cases analyzed for this thesis is shown in Table 4-5.

**Table 4-5: Test matrix.**

<table>
<thead>
<tr>
<th>Case #</th>
<th>Test Cases</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2D Ribs</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>LS(1)0417 Airfoil</td>
<td>Validation (NASA)</td>
</tr>
<tr>
<td>2</td>
<td>Undistorted Closed</td>
<td>Distorted Closed</td>
</tr>
<tr>
<td></td>
<td>Pseudo 2D Cells</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Undistorted Single</td>
<td>Distorted Single</td>
</tr>
<tr>
<td></td>
<td>3D Canopies</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Undistorted Rectangular</td>
<td>Validation (W &amp; H)</td>
</tr>
<tr>
<td>5</td>
<td>Span Shrink</td>
<td>Incident &amp; Translation</td>
</tr>
<tr>
<td>6</td>
<td>Distorted Open 2D Rib</td>
<td>Distorted Single Cell Pseudo 2D</td>
</tr>
<tr>
<td>7</td>
<td>Distorted Rectangular</td>
<td>Distorted Elliptical</td>
</tr>
</tbody>
</table>

*PD = Performance Designs  
*W & H = Ware & Hassell
5. CFD Results

5.1. 2D Model Analysis

The main focus of the 2D study was to evaluate the distortion effect on the aerodynamics of the rib. In addition, the analysis will serve to give an initial insight of the flow behavior around these surfaces. With this, an estimated performance of the 3D model can be assessed. Two cases were tested: a validation analysis of the LS (1)0417 airfoil, and a comparison analysis between an undistorted closed, distorted closed, and distorted open rib. These analyses serve two objectives: the correct physics and meshing settings of the model, and 2) the opening cut and the rib distortions effect on the aerodynamics of the flow, i.e. the rib performance.

The first case corresponds to the CFD validation analysis of the LS (1)0417 airfoil with available experimental data from NASA (McGhee & Beasley, 1973). As a refresher, the flow parameters for this simulation are presented in Table 4-1. Figure 5-1 shows an image of the non-dimensional distance to cell center around the rib contour for two angle of attack values. As a recall from chapter 4, simulations using the SST turbulence model recommend a value close to or lower than 1 to ensure a good boundary layer resolution.
Figure 5-1: LS (1)0417 non-dimensional distance to cell center.

As shown in Figure 5-1, the non-dimensional distance to cell center parameter presents a lower value than 1 in most of the rib contour, with the higher values reached around the airfoil nose. The reason for the higher value can be expected because of the location of the stagnation point around this region. Comparing the two angles of attack, it is seen that the higher the angle of attack, the higher the non-dimensional distance values. This proportional effect might be attributed to the higher flow separation experienced by the airfoil as the angle of attack increases.

Figure 5-2 shows the lift and drag comparison between the CFD and the experimental data extracted from McGhee & Beasley. As shown in the two plots, there is a good agreement between the numerical and experimental data sets for all simulated angles of attack. The maximum error percentage between experimental and numerical data sets was estimated to be approximately 10%. With this airfoil analysis, the physics and mesh settings used in this case are justified for similar appliance to the second case from Table 4-5.
The second 2D case corresponds to the comparison analysis between the undistorted closed, distorted closed, and distorted open rib. As a refresher, the designed geometries and characteristics are presented in Figure 3-6 and Table 3-1, respectively. Furthermore, the flow parameters for these simulations are shown in Table 4-2. Figure 5-3 shows a velocity streamline plot for the three cases at a zero angle of attack.
Figure 5-3: 2D rib velocity streamlines (0° AoA).
Figure 5-3a shows the undistorted closed rib with smooth streamlines transitioning from LE to TE in close proximity to the rib profile. The streamlines of orange/yellow color over the upper surface indicate flow acceleration occurs at this region. Based on Bernoulli’s principle, this flow acceleration will be equivalent to a higher suction i.e. low pressure region. The streamlines of light blue color over the lower surface indicate the free-stream velocity value (115 ft/s). However, there exists a slight flow acceleration (red circle) as soon as the fluid passes the start point of the lower surface. This acceleration is caused by the linear shape of the inlet section (opening length) that begins from the rib nose to the lower surface. The difference in flow velocities from the upper and lower surfaces causes a pressure differential region, with the higher pressure acting on the lower side, creating lift. In addition, the location of the stagnation point seems to fall right at the upper LE.

Figure 5-3b shows a similar streamline flow behavior to the undistorted case, with exceptions appearing as a result of the curved inlet shape and blunter nose. At the upper surface, the flow accelerates faster than the undistorted rib. This effect can be attributed to the blunter nose profile and the small upper surface peaks along the maximum thickness section. The curved inlet shape seems to divert the flow more abruptly towards the lower surface, resulting in a larger velocity (light green color streamline) increase compared to the undistorted case. The larger velocity translates into a lower pressure region that would decrease the pressure differential on this rib, expecting a lower lift value i.e. rib performance. Furthermore, the inlet shape appears to shift the location of the stagnation point slightly downward towards the region where the opening is.

Figure 5-3c shows a similar streamline flow behavior to the distorted closed case, with exceptions clearly visualized at the lower surface. The removal of the opening surface
causes sharp leading edges to appear at both upper and lower surfaces. The upper surface seems to be unaffected by the sharp LE with streamlines still following the rib contour closely towards the TE. Alternatively, the sharp LE at the lower surface causes a larger flow disruption than the closed case, leading to a larger flow separation until reattachment is achieved past the middle section. From this observation, it can be expected to have a further reduction in rib performance compared to the previous cases. Another important flow feature comes from the lack of streamlines noticed within the rib interior. Finally, the removal of the opening length confirms the stagnation point location falls within this region, close to the upper LE.

To corroborate the streamlines behavior from the preceding discussion, Figure 5-4 and Figure 5-5 show the velocity surface and pressure contour plots for the three cases.
Figure 5-4 confirms the presence of flow acceleration at the lower surface LE for all three cases (red circles). Additionally, the stagnation point indeed moves slightly downward towards the inlet opening by comparing the undistorted and distorted closed cases. New observations can be noticed by the presence of the boundary layer extending from the upper and lower surfaces. The distorted open model clearly has the largest flow separation shown by the large blue region below the bottom surface. The distortion peaks at the upper surface (red color) present two acceleration peaks, with the distorted closed
case enclosing a slightly larger acceleration area than the distorted open case at the maximum thickness location. This reduced acceleration can be attributed to a small flow separation because of the sharp LE created from the removal of the opening section.

Finally, the distorted open case shows the rib interior consists mostly of stationary flow (blue color) i.e. stagnant pressure. The high pressure on the interior maintains the rib inflation and prevents the streamlines from going past the opening region, which explains the behavior shown in Figure 5-3c.
The pressure contours from Figure 5-5 confirm the trends analyzed from the velocity streamlines and surface plots. The undistorted rib presents a uniform suction region (blue color) over the upper surface, whereas the distorted cases show an irregular pattern comprised of three suction points. In addition, the contours show smaller pressure values acting over a larger region of the lower surface for the distorted cases. The high pressure acting on the rib interior is clearly identified by the dark red color in Figure 5-5c. Finally, the stagnation point region is larger for the distorted cases compared to the undistorted case. This effect would be attributed to the blunter shape of the distorted ribs.

The boundary layer behavior for the three cases is analyzed by the vorticity plots from Figure 5-6. At the upper surface, the undistorted case starts developing an increasing boundary layer past the maximum thickness point towards the TE. A similar behavior is followed in the lower surface starting from the lower LE. The distorted cases show a considerable increase in the boundary layer thickness at the lower surface, confirming the presence of flow separation regions. The distorted open case starts to develop the boundary layer from the upper LE, achieving a larger thickness compared to the other cases. Finally,
the presence of small vortices in the rib interior is identified by the curved vortex joining the upper and lower LE past the opening section in Figure 5-6c.

Figure 5-6: 2D rib vorticity magnitude (0° AoA).
The previous analysis evaluated flow characteristics of the three 2D cases at one particular angle of attack value (0°). To compare the effect of angle of attack on the flow behavior, Figure 5-7, Figure 5-8, Figure 5-9, and Figure 5-10 show the velocity streamlines, velocity surface, pressure contours, and vorticity magnitude at a 4° angle of attack, respectively.
The 4° angle of attack from Figure 5-7 show a similar flow behavior compared to Figure 5-3. At the upper surface of the undistorted case, the streamlines are more condensed for the larger angle of attack, indicating higher flow acceleration i.e. lower pressure region. Alternatively, the acceleration peak at the start point of the lower surface has reduced for the larger angle of attack, providing a more uniform freestream velocity along its contour. This same streamline pattern can be visualized in the distorted closed case from Figure 5-7b. One difference compared to Figure 5-3b can be noticed by the larger enclosed region where the flow accelerates (red streamlines).

A clear visualization of the less separated flow at the lower surface is seen in Figure 5-7c. In addition, the stationary flow is identified by the low (nearly zero) velocity magnitude of the vortex streamlines observed in the rib interior. Finally, the larger angle of attack has shifted the stagnation point further downward towards the middle point of the opening section for the three cases, with the distorted open rib case showing the location even closer to the lower LE.
Figure 5-8: 2D rib velocity surface (4° AoA).
The velocity surface plots from Figure 5-8 confirm the presence of a larger boundary layer growth over the upper surface compared to the 0° angle of attack. At the lower surface, the flow shows less separation (red circles). The two acceleration peaks at the upper surface have moved slightly towards the LE, indicating the flow starts accelerating faster for the larger angle of attack.

![Undistorted closed rib](image1)

![Distorted closed rib](image2)
The pressure contour plots from Figure 5-9 confirm the smaller pressure values present at the upper surface i.e. larger suction. Furthermore, the third acceleration peak observed in the 0° angle of attack case has vanished for the 4° angle of attack. This effect is likely caused by an earlier flow separation experienced at the upper surface. Finally, the lower surface shows a more uniform and larger pressure distribution, proving the flow is reattached to the contour faster than the 0° angle of attack cases.
The vorticity magnitude plots from Figure 5-10 corroborate the boundary layer thickness at the upper surface is larger than the 0° angle of attack cases, which corresponds to earlier flow separation. In the same manner, the lower surface presents a smaller boundary layer thickness, indicating less separated flow than the 0° angle of attack cases. The reduction in boundary layer thickness at the lower surface appears to be more significant than the increment in thickness at the upper surface, suggesting a higher rib performance is achieved by the larger angle of attack case.
5.1.1. Lift and Drag

The flow observations explained in the previous section provide valuable insight in how the flow differs between an undistorted and a distorted rib. The lift and drag analysis shown in this section serves to expand the flow characteristics at the tested AoA values. Figure 5-11 presents the lift and drag comparison plots for all three rib cases.

Figure 5-11: 2D ribs lift and drag plots.
As shown in Figure 5-11a, there is a similar lift coefficient distribution for all three cases until the stall conditions. Interestingly, the distorted closed rib provided slightly larger (about 10%) lift coefficient values than the other two cases. This $C_l$ increase is supported by the larger acceleration experienced by this rib as a result of the surface peaks positioned near the maximum thickness location. Even though there is a small flow separation at the lower surface, the larger acceleration at the upper surface overcomes this lift deficit by increasing the pressure difference between the two surfaces. The distorted open rib presents $C_l$ values between the other two cases. Because this model lacks the lift contribution from the opening length section, it is expected to have a lower $C_l$ value than the distorted closed case. The $C_l$ difference between the three models starts decreasing as the models reach stall conditions, with the distorted models coming first (approximately around $6^\circ$ AoA). This condition can be explained by the larger levels of flow separation experienced by the distorted models at both upper and lower surfaces. Overall, the lift coefficient values are not significantly affected by the rib distortions and opening length characteristics while operating away from the stall conditions.

Alternatively, the drag polar shown in Figure 5-11b points out significant differences in the drag values for the three models. The distorted cases clearly possess the larger $C_d$ values. Most of the larger drag is expected from the increase in pressure drag because of the flow separation seen at both surfaces, especially the lower one. Other drag contributions can be expected from the rib surface roughness and the inlet drag (for the open case). In addition, the faster stalling behavior reached by the distorted models provides a narrower drag bucket region, with the minimum drag values obtained at an AoA value of $2^\circ$ for both distorted cases. Overall, the drag coefficient values are considerably
affected (in a larger proportion) by the rib distortions and opening length characteristics.

As a final comparison, Figure 5-12 presents the $L/D$ values for all three models.

![L/D vs AoA plot](image)

Figure 5-12: 2D ribs $L/D$ plot.

As shown in Figure 5-12, the distorted cases have the lower $L/D$ values as a result of the larger drag contributors discussed earlier. The maximum $L/D$ value is obtained at an angle of attack of $4^\circ$ for all three cases. At this AoA, the $L/D$ value corresponds to 65.4, 54.4, and 36.2 for the undistorted, distorted closed, and distorted open cases, respectively. This represents a 17% reduction in $L/D$ performance solely by the effect of distortions between the undistorted and distorted closed cases. Adding the effect of the opening length, there is a 45% reduction in $L/D$ performance for the distorted open case compared to the undistorted one. Because this AoA value corresponds to the largest $L/D$ attained for the three cases, the 45% reduction is a good indicator on how impactful the consideration of the rib distortions and opening length are on the flow characteristics and canopy performance.
5.1.2. Effect of Distortions

To appreciate the distortion effect on the rib upper and lower surfaces, Figure 5-13 shows the pressure coefficient distribution for the rib three cases at a $4^\circ$ angle of attack.

Figure 5-13: 2D ribs pressure distribution ($4^\circ$ AoA).
Comparing the three cases, the undistorted model presents a smooth pressure distribution, whereas the distorted models show a chaotic pattern with several peaks at both upper and lower surfaces. For the undistorted case, the opening length region is represented by the decrease in pressure values at the lower surface. The small bump (red line) indicates the acceleration portion as the flow curves past the lower surface LE. For the distorted cases, the upper surface peaks represent the acceleration portions (lowest pressure areas) seen from the velocity and pressure plots in Figure 5-8 and Figure 5-9, respectively. The lower surface also presents some pressure peaks along its contour which indicate flow acceleration regions. The line discontinuity in the distorted open case represents clearly the opening length region. The upper surface pressure values (note the axis values) compared to the undistorted case prove the larger suction regions experienced by the distorted ribs.

5.1.3. Comparison with Literature

The performance analysis described in the preceding sections is compared against available literature studies in Table 5-1. All studies were simulated at a \( Re \) in the million (1 to 6 E6) range. A 5° angle of attack was chosen to compare against the past studies.

Table 5-1: 2D rib lift and drag comparison.

<table>
<thead>
<tr>
<th>Study</th>
<th>Baseline Airfoil</th>
<th>( C_l )</th>
<th>( C_d )</th>
<th>L/D</th>
<th>L/D % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mohammadi &amp; Johari</td>
<td>N/A</td>
<td>0.5742</td>
<td>0.04</td>
<td>14.36</td>
<td>-56.86</td>
</tr>
<tr>
<td>Fogell</td>
<td>Ware &amp; Hassell</td>
<td>1.074</td>
<td>0.047</td>
<td>22.9</td>
<td>-31.19</td>
</tr>
<tr>
<td>Ghoreyshi et al.</td>
<td>NSRDEC</td>
<td>1.050</td>
<td>0.030</td>
<td>35</td>
<td>+5.15</td>
</tr>
<tr>
<td>Current</td>
<td>PD</td>
<td>1.115</td>
<td>0.0335</td>
<td>33.28</td>
<td>---</td>
</tr>
</tbody>
</table>
As shown in Table 5-1, the performance values obtained in this study fall within an acceptable range compared to previous studies. The highest results discrepancy is presented against the study of Mohammadi & Johari, especially in the lift coefficient value. A possible explanation can be because of the type of airfoil used, which is not specified by their study. The lower lift coefficient value can be attributed to larger flow separation regions at both surfaces. The next study by Fogell gives a similar lift coefficient but a larger drag coefficient. The airfoil used in Fogell’s study resembles a modified version of the Clark-Y. However, the airfoil is much thicker (18% c) than the typical Clark-Y and the airfoil used in this study. This increase in thickness can be one factor for the larger drag presented in his study, with the other factor being a larger inlet drag in consequence of a bigger opening length. Finally, the performance results from Ghoreyshi et al. fall within the closest margin to the ones presented in this study. Ghoreyshi et al. specifies its airfoil as a low-speed, flat lower surface with 17% max thickness and 0.1 m inlet length, which are similar geometric characteristics to the airfoil used in this study. Overall, the 2D study served to show how the distorted airfoil shape would deteriorate the aerodynamic performance compared to a smooth closed airfoil shape.

5.2. Pseudo 2D Model Analysis

The main focus of the pseudo-2D study is to expand the findings of the 2D analysis to a 3D flow visualization (without end-cell effects) of a single-cell design. Furthermore, the distortion effect is assessed by evaluating the aerodynamic performance of two separate designs. The two tested cases correspond to an undistorted and distorted single-cell composed of two load ribs and one non-load rib. As a reminder, the end-cell vortices are neglected by constraining the lateral sides of the computational domain to match exactly
with the position of the load ribs, hence the pseudo-2D terminology. The geometric characteristics of both models are presented in Table 3-2, whereas the flow parameters are shown in Table 4-3. Figure 5-14 shows a velocity streamline plot for the undistorted case.

Figure 5-14: Undistorted pseudo-2D velocity streamlines (0° AoA).
Figure 5-14a shows an isometric view with the velocity streamlines following both upper and lower surfaces from LE to TE. The upper surface presents a smooth and symmetric velocity pattern across the spanwise direction. Similar to the 2D case, the red color streamlines at the upper surface indicate flow acceleration is occurring around the region of cell maximum thickness. As the flow directs towards the TE, there is a slight flow separation starting to develop approximately at the cell mid-section, as shown in Figure 5-14b and Figure 5-14c.

The flow over the lower surface presents the same separation region as the 2D case because of the sharp LE. However, the separation region for this single-cell seems to be larger, with the flow not fully reattaching to the lower surface as it continues towards the TE. The larger flow separation at this lower region will contribute to a larger pressure drag, i.e. decrease in overall performance. In addition, as in the 2D case, the stagnation point region seems to fall closely to the upper LE location. Finally, the flow directed towards the lower surface experience the same behavior as the 2D case, with the high pressure inside of the cell acting as a blockage wall for streamlines to move past the opening region. This effect is corroborated by the internal pressure surface plots presented in Figure 5-15.

![Internal Pressure](image)

a) Upper surface view
As shown in Figure 5-15, the internal pressure values correspond to a positive value (red color) over the upper and lower surfaces, indicating stationary flow and cell inflation. There are two small regions located at the start of the lower surface and the opening of the non-load rib (pointed by the blue arrows in Figure 5-15b) where the pressure values are slightly smaller than the rest of the surfaces. The lower surface regions would correspond to possible collapsing-risk areas if the external pressure is larger than the inside pressure value. The smaller pressure region at the opening of the non-load rib give an extent of how far the streamlines travel into the cell interior before diverting towards the lower surface section.

Figure 5-16 shows the external pressure acting on both upper and lower surfaces. The upper surface experiences the highest suction (lowest pressure) over an area just before the cell maximum thickness. After the flow passes this region, the pressure starts to increase gradually towards the TE. In addition, there is a small high pressure region acting just past the upper LE point, indicated by the black arrow in Figure 5-16a. This region would correspond to a collapsing-risk area in the same way as the start of the lower surface observed from Figure 5-15b.
Looking at the lower side in Figure 5-16b, there is a negative pressure region (light green color) acting over the surface as the flow passes by the LE. This region likely corresponds to the flow separation area experienced by the sharp LE. Around the mid-section of the surface towards the TE, the pressure values start to increase. The flow over this region starts to reattach to the lower surface, decreasing the amount of separation (pressure drag) and increasing the aerodynamic efficiency of the cell. The collapsing-risk region observed from Figure 5-15b is shown by the black circle in Figure 5-16c. The flow disruption towards the lower surface causes acceleration to happen as it curves around the LE, noted by the decrease in pressure values enclosed by the black circle.

To check whether the cell is able to maintain inflation at steady conditions, Figure 5-17 presents the pressure differential plot between the internal and external pressure values.
As shown in Figure 5-17, the pressure differential results in a positive pressure value around both upper and lower surfaces. Thus, inflation is achieved by maintaining a larger internal pressure. The negative pressure values seen at the legend bar (dark blue color) come from the side ribs, which are stationary as a result of the imposed boundary conditions on this simulation.
Figure 5-17: Undistorted pseudo-2D pressure differential surface (0° AoA).

As a final observation, Figure 5-18 present a 2D velocity and pressure plot from a slice cut located at the middle section between the load and non-load rib of the single-cell. The velocity plot shows a smooth contour with acceleration present at the area around the maximum thickness. The acceleration is corroborated by the low pressure region (blue color) seen in Figure 5-18b. After acceleration, a boundary layer starts to develop increasingly towards the TE.

At the lower surface, the flow separates as it passes the LE, indicated by the blue
bubble region. As the flow continues moving towards the TE, the separation decreases. This behavior is also shown in the pressure contour plot, where the negative pressure region points out to the separation region, until reattachment (positive pressure values) is achieved past the middle section of the rib. Finally, the opening region in both plots identifies clearer the distance traveled by the streamlines as they try to enter the cell.

![Figure 5-18: Undistorted pseudo-2D middle rib cut (0° AoA).](image)
Figure 5-19 shows a velocity streamline plot for the distorted case. Over the upper surface, the streamlines start accelerating at four different locations (black arrows). The first location is right after the flow passes by the upper LE, indicated by the red color of the streamlines. Afterwards, the flow decelerates slightly before increasing again to its largest value (darkest red) at the maximum thickness region. The same pattern continues for the third and fourth location, with the fourth peak situated around the cell mid chord. These acceleration points occur as a result of the rib distortions across the chordwise direction. Despite of the chaotic velocity pattern, the flow seems to remain attached to approximately half section of the upper surface.

Over the lower surface, the flow presents the same separation region as the undistorted case, with acceleration happening as the flow deviates past the LE. However, the streamlines at the non-load rib seem to divert less downward than the ones at the load ribs. This effect translates into a higher efficiency for the non-load rib because of less flow separation present at the lower surface. In addition, the blockage effect as a result of the high pressure acting on the cell inside is also present in this distorted model. Figure 5-20 shows the cell internal pressure plot for better visualization.

![Streamlines: Velocity Field](image)

**a) Isometric view**
b) Side view 1

Figure 5-19: Distorted pseudo-2D velocity streamlines (0° AoA).

As shown in Figure 5-20, the internal pressure values over both upper and lower surfaces resemble a similar contour as the undistorted case. One difference can be noted in the collapsing-risk area of the lower surface as the flow encounters the LE. The region has a lower pressure value than the undistorted case, indicating a higher probability of collapse.
Figure 5-20: Distorted pseudo-2D internal pressure surface (0° AoA).

Figure 5-21 shows the external pressure plot for the upper and lower surfaces. The upper surface has several low pressure areas (blue color) which confirm the acceleration regions previously seen in the streamline plot from Figure 5-19.

Looking at the color intensity, there seems to be a larger suction region (lower pressure) acting closer to both types of ribs, as marked by the black arrows on Figure 5-21a. Such effect can be associated to the change in cell thickness, with the region closer to the ribs providing the larger flow acceleration.
The lower surface presents a similar pressure contour as the undistorted case, with negative pressure acting approximately in the first half portion of the cell. After this region, the flow starts reattaching to the surface as shown in the increase in pressure values. However, there exists a slight decrease in pressure marked by the black arrow in Figure 5-21b. This pressure decrement is likely correlated to the localized rib distortion at this chordwise station.

Figure 5-21: Distorted pseudo-2D external pressure surface (0° AoA).
Figure 5-22: Distorted pseudo-2D pressure differential surface (0° AoA).

Figure 5-22 shows the pressure differential plot between the internal and external pressures acting on both upper and lower surfaces. As shown in this plot, the distorted model is maintaining inflation (positive values) from the larger internal pressure. A difference from the undistorted cell can be seen at the upper surface, with the larger pressure values (red color) present as soon as the flow passes the LE. In addition, the rib distorted profile causes a non-uniform pressure distribution across the top surface, which is clearly identified by the back and forth change in colors across the cell chordwise direction.
As a final observation, Figure 5-23 shows the velocity surface and pressure contour plots for a slice cut located at the middle section between the load and non-load rib. The velocity plot confirms the acceleration peaks (red color) at the chordwise direction as the flow passes the upper LE region. This behavior is also shown by the larger suction regions (blue color) at the upper surface from the pressure contour plot. After passing the rib
maximum thickness section, the flow seems to start separating from the surface at a faster pace compared to the undistorted model.

At the lower surface, the same separation bubble (blue region) from the previous model is seen. However, the size of separation looks to be slightly smaller compared to the undistorted case. This effect can be attributed to the lightly curved shape of the lower surface LE, with the distorted model providing a smoother flow transition towards the lower section. Looking at the pressure contour plot, the flow starts reattaching to the lower surface approximately after the rib half chord, which is similar to the undistorted case. Finally, the rounded TE in the velocity plot shows a larger wake region (light blue color) produced by this model, suggesting a lower decrease in cell aerodynamic efficiency because of a larger flow separation i.e. increased pressure drag.

5.2.1. Lift and Drag

To assess the flow behavior observed from the previous section, Table 5-2 shows the lift and drag values obtained for both undistorted and distorted single cell models. As a reminder, the performance values correspond to a 0° angle of attack case and a same $Re$ as the 2D case.

<table>
<thead>
<tr>
<th>Single-Cell Model</th>
<th>Baseline Airfoil</th>
<th>$C_l$</th>
<th>$C_d$</th>
<th>$L/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undistorted</td>
<td>PD</td>
<td>0.5805</td>
<td>0.03531</td>
<td>16.44</td>
</tr>
<tr>
<td>Distorted</td>
<td>PD</td>
<td>0.5562</td>
<td>0.06541</td>
<td>8.50</td>
</tr>
</tbody>
</table>

As shown in Table 5-2, there is a 4% difference in $C_l$ values between the undistorted and distorted models. The slight lift coefficient difference is likely because of the surface
roughness presented for the distorted rib, with the chaotic pressure and velocity patterns present along the chordwise and spanwise direction as observed from the previous section plots.

Alternatively, the drag coefficient shows a 46% difference between the two models. This effect can be mostly attributed to the larger pressure and inlet drag of the cell. In terms of pressure drag, the distorted model presents larger flow separation regions at the upper surface and wake sections. In addition, the change in thickness section along the spanwise direction can contribute as well to different flow separation regions at the lower surface, which could further increment the drag of the cell. This behavior is seen when comparing the slice cut plots for the two models in Figure 5-18 (undistorted) and Figure 5-23 (distorted), with the distorted model (thicker rib) providing the least separation at the lower surface. In terms of inlet drag, although not seen directly from flow observations, it can be intuitive that an increase in opening length associated with the thickness change along the spanwise direction is proportional to an increment in drag as more air is entering the cell.

The considerable drag variation leads to a 48% \( L/D \) difference comparing the two models, which is a similar trend to the one observed from the 2D case results (45% \( L/D \) reduction). This comparison gives more credibility to the modeling of these pseudo-2D models (and pure 2D cases) and reinforces the negative impact of distortions on the canopy performance.

5.2.2. 3D Effects & Distortions

This sub-section entails the limitations in the pseudo-2D single-cell models previously discussed. In terms of lift, the single-cell neglects the use of anhedral angle. The reason for avoiding this design parameter into the single-cell modeling was to simplify the
boundary matching between the computational domain and the cell end ribs. However, the
3D model analyzed in the following section considers the use of anhedral angle, which is
expected to cause a negative effect on the canopy lift as shown in the research in the
literature review section. Another lift reduction will arise from the lift slope decrease as a
result of the presence of downwash created by the tip vortices of the 3D model.

In terms of drag, the single-cell neglects the induced drag by the boundary
constraint imposed at the cell end ribs. The inclusion of induced drag in the 3D model is
expected to cause a larger total drag coefficient compared to the previous 2D models.
Nevertheless, the induced drag is directly proportional to the square of the canopy lift. As
such, a small reduction in lift will be joined by a large decrease in induced drag.
Alternatively, additional drag from the suspension lines (line drag) and payload (store drag)
will be considered to give an estimate of the total drag for the complete 3D parachute
system (canopy + lines + payload).

The distorted shape shown by the pseudo-2D model gives a preliminary insight on
how significant the distortions can affect the cell performance. Because the single-cell
incorporated all types of distortions in its modeling, it is not possible to check which types
are the most critical in decreasing the performance. Therefore, the 3D model will also serve
to identify more precisely which type of distortions have the larger/less impact on the
aerodynamic performance overall.

5.3. 3D Model Analysis

The main focus of the 3D study was to complete the 2D and pseudo-2D analyses
with the introduction of the 3D effects, additional design parameters (anhedral angle +
planform shape change), and the remaining parachute system components i.e. suspension
lines and payload. The incorporation of these system components was done analytically based on the research formulas presented in the literature review Section 2.1. In addition, isolating each distortion separately helped to identify which ones affected most the canopy performance. Four cases are tested: a validation analysis of the Ware & Hassell canopy design, a comparison analysis between three distorted models based on the Ware & Hassell geometry, a comparison analysis between the 2D, pseudo-2D, and 3D model based on the PD geometry, and a comparison analysis between two different planform shapes based on PD canopy models.

The first 3D model analyzed corresponds to a validation case based on the geometry design from Ware & Hassell. As a reminder, the geometric characteristics and flow parameters for this simulation are presented in Table 3-4 and Table 4-4, respectively. Figure 5-24 shows a plot of the distance to cell center in viscous units for the external and internal surfaces at a 5° angle of attack. This parameter is an equivalent to the non-dimensional distance to cell center parameter seen from the 2D analysis. The parameter name change for the 3D model was a consequence of an updated version of the software.

![Distance to cell center in viscous units, internal](image)

a) Internal surface
As shown in Figure 5-24a, the distance to cell center parameter presents a lower value than 1 in all the canopy internal surface, with the larger values reached at the ribs opening sections. This behavior is expected because the opening region has a slightly stronger velocity gradient compared to the inside of the cells where mostly stationary air is contained.

Alternatively, the presence of stronger velocity gradients at the external surface causes the distance to cell center parameter to increase, as shown in Figure 5-24b. Checking the legend bar, most of the external surface consists of values closer to 1. However, larger parameter values are located at the end ribs LE and TE, as marked by the black arrows. The reason for this increase is likely associated with the canopy vortices. Even though the parameter values are much larger than 1 in these regions, the area enclosed (red circles) is very small compared to the rest of the external surface. Therefore, their effect on the simulation results can be neglected. With this conclusion, the modeling and meshing techniques used on these 3D models ensure a good boundary layer resolution is achieved.

Figure 5-25 shows the lift and drag comparison between the CFD and the experimental data extracted from Ware & Hassell. The lift plot has a good agreement
between the numerical and experimental data sets for the three AoA tested, with a maximum error percentage estimate of 3%. The drag polar, however, shows a significant deviation between numerical and experimental data sets. From this plot, the maximum error percentage was estimated to be 23%. Despite the drag under-prediction, all three AoA cases present almost the same 23% percentage value. This suggests there might be either modeling features not properly addressed in the CFD or errors present in the obtainment of the experimental data.

Based on the process followed to design and simulate the 3D model, there are four possible reasons to support the drag discrepancy values. The first reason comes from variations in the profile drag analysis of the experimental model. The research from Ware & Hassell performs the profile drag analysis basing on an average thickness rib, a parameter which disagrees from the thickness of the original rib with given coordinate points. A second reason can be measuring equipment errors in the data acquisition. These errors can be caused by the gustiness of the wind tunnel, or the instability of the model attached to the rigid mount (Ware & Hassell, 1969).

The third reason arises from the experimental model additional surface irregularities coming from the fabric. This effect translates into an increment in the profile drag of the canopy. Finally, the fourth reason comes from the turbulence model selected for the physics of the CFD simulation. Because turbulence models predict flow separation in different ways, a study of different types (K-epsilon, Spalart-Allmaras) could give valuable information on which are more suitable to match closer the experimental drag of this 3D model. Taking into account these observations, the modeling and physics settings applied to this baseline model were justified for similar use in the next 3D case.
The second 3D case corresponds to the comparison analysis between three distorted models based on the previous baseline model from Ware & Hassell. These three models consist of a 15% span shrinkage model, a 1.5° incidence angle and 0.75in upward translation model, and a 30% maximum thickness model. As a reminder, Figure 3-10 shows the three distorted geometries, while Table 4-4 presents the flow parameters for the CFD simulations. Figure 5-26 shows the pressure differential plot between the internal and external pressure for the baseline model and the three distorted models at a 5° AoA.
a) Baseline model top view

b) Span shrinkage model top view

c) Incidence and translation model top view
d) Inflation model top view

Figure 5-26: 3D W&H models pressure differential surface (5° AoA).

As shown in Figure 5-26, the four 3D models present different pressure differentials across the spanwise direction. All models present the largest pressure values (red color) at the mid cell. Moving towards the adjacent cells to the end sides, the pressure starts decreasing. Thus, most of the lift is produced by the mid-section of the parachute. This effect is likely attributed to the anhedral angle which creates a lift component in the spanwise direction. As the end cells are the ones that produce the less lift, they run with the higher risk of collapse. This explains why most of the end cells present a larger number of crossports at the ribs to ensure a larger internal pressure is achieved to overcome the external pressure.

Comparing the three distorted models to the baseline model, there are slight differences to point out. The span shrinkage model shows a similar pressure distribution than the baseline model but with smaller pressure values. A possible explanation of this pressure reduction comes from the decrease in $AR$.

Alternatively, the incidence and translation model present a different pressure distribution than the baseline model, with the larger pressure values located towards the
load ribs. Figure 5-27 shows an isometric view for a better visualization at the load and non-load rib pressure values. The result of a larger pressure acting on the side of the load ribs is unexpected because the non-load ribs are tilted at a larger angle of attack. However, a look at the streamline plot from Figure 5-28 gives an insight of how the flow behaves towards these load ribs (marked by the black arrows). From this plot, there seems to be a larger density of lines enclosing towards the load ribs i.e. larger mass flow rate. From the equation $\dot{m} = \rho VA$, density $\rho$ and area $A$ are constant. Therefore, an increase in the mass flow rate $\dot{m}$ would be accompanied by an increase in velocity $V$. A larger velocity in these regions is equal to a lower external pressure (suction). As the internal pressure is almost equal within a cell, there exists a larger pressure differential on the side of the load ribs, which explains the effect seen in Figure 5-27.

Another interesting flow behavior from Figure 5-28 is visualized at the end cells, where the streamlines start to tilt outward towards the canopy center. This effect is clearly caused by the pressure difference between the upper and lower surfaces which create the trailing vortices seen at the tips for a finite wing.

Taking a look at the lower surface in Figure 5-29, the streamlines show an opposite effect as the upper surface, where the largest density is closer to the non-load ribs (marked by the black arrows). Thus, the effect of increasing the incidence angle and upward translation creates a larger acceleration i.e. lower pressure area closer to the load and non-load ribs at the upper and lower surface, respectively. This effect starts decreasing from the canopy center cell toward the end cells because of the increase in anhedral angle.
Figure 5-27: Incidence and translation model pressure differential surface (isometric view).

Figure 5-28: Incidence and translation model streamlines upper surface (5° AoA).

Figure 5-29: Incidence and translation model streamlines lower surface (5° AoA).
Finally, the inflation model in Figure 5-26d also presents a different pressure distribution compared to the baseline model. The increase in cell thickness causes the larger pressure values to be allocated near the ribs (either load or non-load). This effect was also seen in the pseudo-2D single-cell model from Figure 5-21, where the larger suction regions were present near the ribs.

Looking at the streamline plot from Figure 5-30, a similar explanation as the incidence and translation model applies to this inflation model as well. However, the inflation model seems to pack a larger number of streamlines at the rib locations, which would further increase the velocity (lower pressure) acting on these regions. This explains why the largest pressure values in Figure 5-26 correspond to the inflation model (refer to the legend bar). An analysis of the lower surface streamlines shows a similar behavior as the upper surface, with the larger density located closer to the ribs position.

Figure 5-30: Inflation model streamlines.

A lift and drag analysis of the four models is presented in Figure 5-31. In addition, a summary of the final performance values at the three tested angles of attack is shown in Table 5-3.
Figure 5-31: 3D W&H models lift and drag comparison.

Table 5-3: 3D W&H lift and drag comparison.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Characteristics</th>
<th>AoA = 4°</th>
<th>AoA = 5°</th>
<th>AoA = 8°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$C_L$</td>
<td>$C_D$</td>
<td>$C_L$</td>
</tr>
<tr>
<td>Baseline Model</td>
<td>Built from experimental wind tunnel data</td>
<td>0.445</td>
<td>0.09691</td>
<td>0.487</td>
</tr>
<tr>
<td>Span Shrinkage Model</td>
<td>15% span reduction</td>
<td>0.398</td>
<td>0.09762</td>
<td>0.436</td>
</tr>
<tr>
<td>Incidence and Translation Model</td>
<td>1.5° incidence, 3/4 in upward translation</td>
<td>0.470</td>
<td>0.1006</td>
<td>0.512</td>
</tr>
<tr>
<td>Inflation Model</td>
<td>30% max thickness inflation between ribs</td>
<td>0.428</td>
<td>0.1505</td>
<td>0.467</td>
</tr>
</tbody>
</table>
As shown in Figure 5-31, the incidence and translation model is the only one that produces the larger $C_L$ values compared to the baseline model. This positive effect on the incidence and translation model is likely attributed to a larger suction region experienced by the upper surface compared to the lower surface.

Alternatively, the inflation model and the span shrinkage model affect negatively the lift coefficient in relation to the baseline case. The span shrinkage model reduced $AR$ is mainly the factor of a decrease in the lift coefficient. For the inflation model, however, a decrement in the lift coefficient is unexpected because the pressure distribution is somewhat similar to the incidence and the translation model, as explained in the previous paragraphs. A look at the pressure contour plots for both models in Figure 5-32 and Figure 5-33 point out extra flow differences in the upper and lower surface. The slice cuts correspond to two planes: the load rib, and the middle section between the load and non-load rib. Comparing the two cases, there is a larger suction region experienced by the inflation model at the lower surface (note the negative pressure values from the legend bar). The larger suction contributes to an increase in flow separation that decreases the pressure differential between the upper and lower surfaces i.e. the lift. This lift reduction is the factor that contributes to the decrease in $C_L$ compared to the baseline model.

Another observation can be made by comparing the two slice cuts per model. In the case of the incidence and translation model, the slice cut at the middle section seems to present a slightly larger flow separation (suction) at the lower surface. In addition, the suction area (blue color) at the upper surface near the rib maximum thickness covers a larger contour for the load rib case. These suction differences at the upper and lower surface
corroborate the trends previously observed for this model in Figure 5-28 and Figure 5-29.

In the case of the inflation model, the flow at the load rib lower surface presents a larger flow separation (suction) than the middle section (thickest region). At the upper surface, the thickest section covers a larger suction contour (blue color) than the load rib. However, looking at the maximum negative pressure values at these suction areas confirm the largest values are present at the load rib. This flow effect explains the streamlines behavior from Figure 5-30 in packing closer to the ribs than to the thickest section of the cell.

The drag polar presented in Figure 5-31b shows the inflation model as the one producing the largest amount of drag. This result is expected as a result of a larger inlet drag from the increase in opening area, and a larger pressure drag from the blunter shape at the TE and from the increase in flow separation at the lower surface. Alternatively, the incidence and translation model also presents a small increase in drag that is likely a consequence of the increment in lift coefficient. Finally, the span shrinkage model shows as well a barely increase in drag attributed to the effect of the reduced AR. Refer to Table 5-3 for a clear view of the numerical performance values for these 4 models.
Figure 5-32: Incidence and translation model pressure contour (5° AoA).

Figure 5-33: Inflation model pressure contour (5° AoA).
As a final remark, Table 5-5 and Table 5-5 present the $L/D$ values and error percentage between the four Ware & Hassell models. The error percentage is determined between the baseline model and each distorted model.

Table 5-4: 3D W&H $L/D$ comparison.

<table>
<thead>
<tr>
<th>3D Model</th>
<th>AoA = 4°</th>
<th>AoA = 5°</th>
<th>AoA = 8°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Model</td>
<td>4.59</td>
<td>4.73</td>
<td>4.78</td>
</tr>
<tr>
<td>Span Shrinkage Model</td>
<td>4.07</td>
<td>4.22</td>
<td>4.42</td>
</tr>
<tr>
<td>Incidence and Translation Model</td>
<td>4.68</td>
<td>4.70</td>
<td>4.75</td>
</tr>
<tr>
<td>Inflation Model</td>
<td>2.84</td>
<td>3.01</td>
<td>3.10</td>
</tr>
</tbody>
</table>

Table 5-5: 3D W&H lift and drag error percentage.

<table>
<thead>
<tr>
<th>Percentage Difference Against Baseline Model (%)</th>
<th>AoA = 4°</th>
<th>AoA = 5°</th>
<th>AoA = 8°</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Model</td>
<td>$C_L$</td>
<td>$C_D$</td>
<td>$C_L$</td>
</tr>
<tr>
<td>Span Shrinkage Model</td>
<td>-10.58</td>
<td>+0.733</td>
<td>-10.37</td>
</tr>
<tr>
<td>Incidence and Translation Model</td>
<td>+5.78</td>
<td>+3.76</td>
<td>+5.24</td>
</tr>
<tr>
<td>Inflation Model</td>
<td>-3.83</td>
<td>+55.25</td>
<td>-4.18</td>
</tr>
</tbody>
</table>

As shown in Table 5-4, the largest reduction in $L/D$ performance comes from the inflation model. Checking the individual lift and drag percentage values from Table 5-5, the main contributor to the $L/D$ reduction is the drag. Between the three angles of attack, an estimate of 50% additional drag is developed for the inflated model. The next model that follows the largest reduction is the span shrinkage model. The performance decrease in this model is caused primarily because of the lift reduction from the smaller aspect ratio. Finally, the model that causes the least change in performance is the incidence and translation model. The increase in both lift and drag values for this model compensate each other and maintains the $L/D$ ratio similar to the baseline model.
The third 3D case corresponds to the analysis of the distorted model based on the PD geometry. This model is the final 3D design that started from the 2D rib and then expanded to the pseudo-2D single-cell model. As a refresher, Table 3-3 and Table 4-3 detail the geometric characteristics and the simulation flow parameters, respectively. Figure 5-34 shows a velocity streamline plot.
e) Front view

Figure 5-34: 3D PD distorted model velocity streamlines (0° AoA).
Figure 5-34a presents an isometric view of the flow passing by the upper surface of the model. As shown in this view, the same acceleration region present in the pseudo-2D model exists within this 3D model, with the flow velocity increasing just past the upper LE region. This velocity effect, as shown in the previous Ware & Hassell models, gradually decreases towards the end cells because of the anhedral angle effect. In addition, the 3D effects from a finite wing are clearly expressed by the tilting of the streamlines at the canopy end cells.

Looking at the lower surface from Figure 5-34b, a flow deceleration region exists as the fluid encounters the opening region. After this, the flow diverts and accelerates past the lower LE around the lower surface. The formation of the trailing vortices at the end cells is also present in this figure.

Figure 5-34c shows a top view of the flow passing by the upper surface. In this figure, the black arrows correspond to load ribs regions. A similar behavior as the Ware & Hassell models occurs in this 3D model, with the larger density of streamlines present closer to the load ribs. As explained in the precedent Ware & Hassell case, the larger density is followed by an increase in velocity i.e. lower pressure (suction) at these rib locations.

The lower surface view from Figure 5-34d shows the opposite behavior as the upper surface, with the larger density of lines closer to the non-load ribs (pointed by the black arrows). Like the upper surface comparison, the flow interaction at the lower surface is identical to the previous Ware & Hassell models.

Finally, Figure 5-34e shows a front view image of the upper surface flow distribution in the spanwise direction of the canopy. In this view, it is clearly identified
how this rectangular model corresponds to a non-elliptic lift distribution as the flow extends past the canopy TE (marked by the black arrow). Overall, this distorted model shows similar flow trends observed from the pseudo-2D and Ware & Hassell 3D models.

Figure 5-35 shows the canopy internal pressure. As shown in the upper and lower surface views, most of the internal pressure values is attained by the center cells (darkest red color). The pressure starts decreasing towards the end cells (orange color), indicating a higher collapsing-risk region. Nevertheless, it is worth to remember that this model lacks the use of crossports in the ribs, a design feature that would cause a more uniform internal pressure distribution across the cells in the spanwise direction.

At the lower surface view, note the area with lower pressure values (yellow color) at the bottom opening region. As explained in the pseudo-2D model, these areas have a higher possibility of collapse than the rest of the surface. This effect is also manifested at the end ribs of the canopy, corroborating the fact that the end cells are the regions of highest collapse.
b) Lower surface view

Figure 5-35: 3D PD distorted model internal pressure surface (0° AoA).

Figure 5-36 shows the canopy external pressure on both upper and lower surfaces. The upper surface presents several low pressure areas (blue color) along the chordwise direction. The color intensity along this direction is non-uniform, which identifies the distorted behavior of the canopy. The suction regions start to diminish in intensity along the spanwise direction as well, noting once again the effect of the anhedral angle. Finally, the streamlines behavior seen from Figure 5-34c is confirmed by the larger suction regions present near the load ribs (black arrows).

At the lower surface, the negative pressure regions are present around half portion of the canopy, indicating possible flow separation. Like the upper surface, the anhedral angle effect reduces the suction regions towards the end cells. Finally, the same pressure decrease seen from the pseudo-2D model is present in this model (marked by black arrow).
Figure 5-36: 3D PD distorted model external pressure surface (0° AoA).

Figure 5-37 shows the canopy pressure differential plot for both upper and lower surfaces. The pressure differential shows resemblance to the pseudo-2D case, with the majority of the canopy maintaining inflation from the positive pressure values. The critical parts are seen at the start of the upper and lower LE regions where slight negative pressure differential (blue color) is obtained.

Another important highlight is visualized at the lower surface where the larger pressure values are attained closer to the non-load ribs (marked by black arrows), suggesting a larger suction exists within these ribs. This effect confirms the streamlines behavior seen from Figure 5-34d.
Finally, Figure 5-38 shows the velocity surface and pressure contour plots for the slice cut located at the middle section between the load and non-load rib of the center cell. The velocity shows a considerable amount of flow separation develops as the air passes by the rib maximum thickness region. The distortions present at the upper side are identified by the larger suction regions (darkest blue color) in the pressure contour plot.

At the lower side, a flow separation region is seen just past the LE (suction peak). Note the inside of the cell has a slight different pressure value at approximately half chord, with the aft region achieving a larger internal pressure. Finally, the large wake region produced by the rounded TE is seen clearly in the velocity plot.
Figure 5-38: 3D PD distorted model middle rib cut (0° AoA).

Table 5-6 presents the lift and drag comparison between the distorted 2D rib, pseudo-2D single-cell, and 3D PD models. As a reminder, the performance values correspond to a 0° angle of attack case.

Table 5-6: PD distorted 2D, pseudo-2D, and 3D lift and drag comparison.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>C_L</th>
<th>C_D</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>0.630</td>
<td>0.0336</td>
<td>18.78</td>
</tr>
<tr>
<td>Pseudo-2D</td>
<td>0.556</td>
<td>0.0654</td>
<td>8.50</td>
</tr>
<tr>
<td>3D</td>
<td>0.192</td>
<td>0.0625</td>
<td>3.08</td>
</tr>
</tbody>
</table>

As shown in Table 5-6, there is an approximately 60% reduction in the lift coefficient $C_L$ values between the pseudo-2D and 3D models. As discussed in the pseudo-
2D section, the lift reduction for the 3D model is expected from the incorporation of the anhedral angle effect and the downwash created by the tip vortices. However, the large percentage discrepancy between these two distorted models seems a bit questionable. A possible additional component in the lift reduction for the 3D model can be larger areas of flow separation experienced across both spanwise and chordwise directions.

Alternatively, the drag coefficient $C_D$ shows only a 4% difference between the pseudo-2D and the 3D model. This slight $C_D$ difference is mainly as a result of the smaller $C_L$ values produced by the 3D model. Despite the large lift coefficient reduction, it is important to note how the drag coefficient still maintains a high value. This effect mainly attributes to the flow being affected by the 3D effects (induced drag) plus extra surface distortions from the larger number of cells.

The two coefficient values of the 3D model result in an approximately 60% $L/D$ reduction compared to the pseudo-2D case. To give confidence in the obtained 3D results, Figure 5-39 shows a theoretical plot of $L/D$ versus AoA for a range of $AR$ between 2.0 and 4.0 for ram-air wings.

![Theoretical L/D vs α plot for various AR](image)

Figure 5-39: Theoretical $L/D$ vs $α$ plot for various $AR$ (Lingard, 1995).
The red arrow in Figure 5-39 corresponds to a 3D ram-air wing with a 2.0 $AR$ value. The theoretical $L/D$ value for this model at a zero AoA is 3.1. This result compares very close with the simulated value of 3.08 for the PD model. However, it is important to note that the theoretical value correlates to a non-distorted shape, whereas the simulated value correlates to a distorted shape. In addition, the theoretical case does not specify the total number of cells nor the inclusion of anhedral angle within its design. Plus, the $AR$ of both models is slightly different (2.0 versus 2.1).

Despite the lack of specifications and small design differences, it is noteworthy to see that the trend of the simulated 3D model falls closely within the range of $L/D$ values of a typical ram-air wing. This ensures an acceptable credibility in the overall performance trend of the 3D model results regardless of the large percentage change compared with the 2D and pseudo-2D models.

Finally, Table 5-7 presents a performance analysis of the 3D PD model against available literature studies. The studies correspond to numerical simulations at a 0° angle of attack case.

<table>
<thead>
<tr>
<th>Study</th>
<th>Baseline Airfoil</th>
<th>$Re$</th>
<th>$C_L$</th>
<th>$C_D$</th>
<th>$L/D$</th>
<th>$L/D$ % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eslambochi &amp; Johari</td>
<td>MC-4 (7 cell)</td>
<td>3.2E6</td>
<td>0.130</td>
<td>0.059</td>
<td>2.20</td>
<td>-28.57</td>
</tr>
<tr>
<td>Cao &amp; Zhu</td>
<td>Nicolaides (12 cell)</td>
<td>1.8E6</td>
<td>0.390</td>
<td>0.100</td>
<td>3.90</td>
<td>+26.62</td>
</tr>
<tr>
<td>Ghoreyshi et al.</td>
<td>Clark Y-M15 (8 cell + 1 individual)</td>
<td>2.0E5</td>
<td>0.240</td>
<td>0.050</td>
<td>4.80</td>
<td>+55.84</td>
</tr>
<tr>
<td>Current</td>
<td>PD (7 cell)</td>
<td>2.3E6</td>
<td>0.192</td>
<td>0.0625</td>
<td>3.08</td>
<td>---</td>
</tr>
</tbody>
</table>
As shown in Table 5-7, the performance values obtained for the 3D study are within a satisfactory range compared to past studies. The first study from Eslambochi & Johari presents a lower range of performance values compared to the ones in this simulation. A possible explanation can be attributed to a different type of rib and anhedral angle used in the canopy design, which are features not specified by the authors. In addition, the use of the Spalart-Allmaras turbulence model instead of the SST model can also be account as a factor in the discrepancy of results.

The next study of Cao & Zhu presents a similar $L/D$ value than the PD model but at a larger lift and drag coefficient values. The model used in their study corresponds to the canopy tested by Nicolaides in his experimental work. This canopy ($AR = 3.0$) consisted in a larger number of cells compared to the PD model (12 versus 7 cells). A larger number of cells is accompanied by a larger lift and drag values, a reason that would justify the larger performance values compared to the PD model.

Finally, the model from Ghoreyshi et al. presents the largest performance results disagreement. This canopy also uses a slightly larger number of cells, hence the increase in lift coefficient. The drag coefficient, however, records a smaller magnitude value than the PD model. This effect can be attributed to the smaller $Re$ (1E5) used for the simulation, where the flow transitions from laminar to turbulent flow and achieves a smaller drag coefficient (from a thinner wake) compared to the case of a larger $Re$ (1E6). This leads to the larger $L/D$ value (4.80) reported for this model. Overall, the 3D study served to show the decrease in aerodynamic performance compared to a 2D model.

The fourth and final 3D case corresponds to a comparison analysis between two PD designs with different planform shapes: rectangular and elliptical. As a reminder, the
geometric characteristic of the rectangular and elliptical canopies are summarized in Table 3-3 and Table 3-5, respectively. In addition, the simulation flow parameters are presented in Table 4-3. Figure 5-40 shows a velocity streamline plot of both canopies.

![Velocity Streamline Plot](image)

**a) Rectangular canopy**

**b) Elliptical canopy**

Figure 5-40: Velocity streamlines front view comparison (0° AoA).

As shown in Figure 5-40, the two canopies present a different velocity distribution. Clearly, the elliptical planform model presents a closer elliptic lift distribution compared to the rectangular planform model. According to Prandtl’s lifting line theory, the elliptic lift distribution across a wingspan produces the less amount of induced drag i.e. a more efficient wing. Therefore, it is expected that the elliptical canopy outperforms the
rectangular canopy. This effect is further analyzed in Figure 5-41 by looking at a comparison plot of the velocity vortices as flow passes by the TE of the two models. Two planes are visualized per model: the closest one to the model which is located 5ft downstream of the TE, and the farthest one which is located 25ft downstream of the TE.

Figure 5-41: Velocity vortices comparison (0° AoA).

Figure 5-41 points out flow differences between the two models. Looking at the closest plane from the TE, the rectangular model has a larger velocity difference compared to the elliptical model (refer to the legend bar colors). This effect translates into a larger downwash produced by the rectangular canopy i.e. stronger tip vortices. In consequence,
the rectangular model generates more induced drag than the elliptical model. The planes located farthest of the TE confirm this behavior, as the elliptical model presents a more uniform velocity distribution than the rectangular model.

Finally, Table 5-8 presents the performance values of the two PD models at a 0° angle of attack case.

Table 5-8: 3D planform shape performance comparison.

<table>
<thead>
<tr>
<th>3D PD Model</th>
<th>CL</th>
<th>CD</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>0.192</td>
<td>0.0625</td>
<td>3.08</td>
</tr>
<tr>
<td>Elliptical</td>
<td>0.199</td>
<td>0.0313</td>
<td>6.35</td>
</tr>
</tbody>
</table>

From Table 5-8, the elliptical model records a lower drag coefficient value (approx. 50%) than the rectangular model. Aside from the lower induced drag produced by this model, the inlet opening size and the rib profile are also factors that might contribute to the drag decrease. Alternatively, the lift coefficient is slightly larger than the rectangular model. This effect is likely attributed to the two extra cells used in the elliptical design (9 cell total). The lift increase and drag decrease causes an overall 51% \( L/D \) increase for the elliptical model. Therefore, it is concluded that an elliptical planform shape leads to a considerable performance increase in a parachute design.

5.3.1. Suspension Lines & Payload Analysis

The previous section analyzed the aerodynamic performance of several canopy models focusing only on the ram-air wing. In this section, a brief analysis of the suspension lines and payload is considered to estimate an overall performance of the complete parachute system. The research formulas used on this analysis are based on Lingard’s, Mkrtchyan’s, and Penwarden’s work (see Section 2.1).
The AutoCAD files for each PD model (rectangular and elliptical) offered an overall view of the total system with suspension lines included. Figure 5-42 shows an image of the rectangular model in AutoCAD.

![AutoCAD PD rectangular model](image)

Figure 5-42: AutoCAD PD rectangular model.

Lingard’s formula for line drag given in Equation (8) require additional geometry characteristics such as the mean line length $R$ and line diameter $d$. To find the total number of suspension lines $n$, the canopy was divided into three sections: front, middle, and back sides. As a result of the lines cascading effect, each of the sections was further divided into two subsections: upper and lower. This division was made to have a better estimate of the lengths for both upper and lower lines.
The line drag formula was applied to both upper and lower lines by taking an average of all the lengths from both subsections, respectively. The line diameter was taken as 2.5 mm (0.00820 ft). To simplify the calculations, all lines were assumed to be facing the same freestream velocity, i.e. $\alpha = 0^\circ$. Table 5-9 shows the final results for the line drag coefficient of both rectangular and elliptical canopies.

Table 5-9: Line drag results.

<table>
<thead>
<tr>
<th>3D PD Model</th>
<th>Total # Lines</th>
<th>Mean Line Length (ft)</th>
<th>$C_{DL}$</th>
<th>$C_{Dwl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular (7 cell)</td>
<td>58</td>
<td>9.23</td>
<td>0.0171</td>
<td>0.0796</td>
</tr>
<tr>
<td>Elliptical (9 cell)</td>
<td>74</td>
<td>10.96</td>
<td>0.0219</td>
<td>0.0532</td>
</tr>
</tbody>
</table>

As shown in Table 5-9, the line drag $C_{DL}$ for the elliptical model is approximately 20% larger than the value of the rectangular model. The larger line drag is attributed to the bigger number of lines and line length used in its design because of the extra 2 cells. Taking into account the total drag produced by the canopies and the suspension lines $C_{Dwl}$, the line drag contributes to a 20% and 40% increase for the rectangular and elliptical models, respectively. The significant drag increase of the two models remarks why the parachute industry seeks the design of smaller $AR$ canopies with the less number of lines possible.

For the payload analysis, formulas given by Equation (9), Equation (10), and Equation (11) are used. A person with 180 lbs (800 N) and 5.83 ft (1.78m) is assumed to obtain the DuBois area. To simplify the analysis, a $C_{DSt}$ of 1 is assumed for the calculations (instead of 1.17). Table 5-10 shows the results for the payload drag coefficient of both PD models. As a reminder, the payload drag coefficient $C_{DSt/S}$ is non-dimensionalized with respect to the canopy area (same as the line drag).
Table 5-10: Payload/store drag results.

<table>
<thead>
<tr>
<th>3D PD Model</th>
<th>DuBois Area (ft²)</th>
<th>Frontal Area (ft²)</th>
<th>Canopy Area (ft²)</th>
<th>$C_{DSt/S}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular (7 cell)</td>
<td>21.54</td>
<td>7.54</td>
<td>112.93</td>
<td>0.0668</td>
</tr>
<tr>
<td>Elliptical (9 cell)</td>
<td>21.54</td>
<td>7.54</td>
<td>150</td>
<td>0.0503</td>
</tr>
</tbody>
</table>

As shown in Table 5-10, the payload incorporation adds another considerable amount of drag to the overall parachute system. The final performance values of the complete system (canopy, suspension lines, and payload) are summarized in Table 5-11.

Table 5-11: 3D PD parachute complete system performance results.

<table>
<thead>
<tr>
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Table 5-11 presents a reduction in $L/D$ performance compared to the results presented in Table 5-8. Therefore, the consideration of suspension lines and payload affect negatively the overall aerodynamic performance because they only contribute to an increase in drag. As there is not much control of the payload used in the system, the other two components (canopy and suspension lines) are the areas where designers focus the most to construct more efficient parachutes.
6. Conclusion and Recommendations

6.1. Conclusion

This thesis has presented the computational modeling of a ram-air parachute in steady flight conditions. A CAD design methodology was implemented to build a 2D, pseudo-2D, and 3D model based on key geometric parameters. Furthermore, the use of distortions was incorporated in the designs by inputs from a parachute designer and canopy photos taken during flight. The CFD study was performed by solving the RANS equations for incompressible and steady flow using the SST turbulence model. The SST model was chosen because of its good suitability for flows experiencing significant separation regions and strong adverse pressure gradients. Boundary conditions were applied to both the computational domain and the parachute 2D and 3D geometries to ensure a realistic flight environment. Finally, meshing techniques were appropriately used to guarantee a good resolution of the boundary layer near the models edges and surfaces.

A test matrix of seven cases was analyzed to validate the modeling within the software, and compare aerodynamic performance results to assess the impact of distortions. The performance results obtained from these studies was compared against available experimental and numerical results from past research work. In addition, the use of different planform models provided a clear trend for best model shapes. Finally, a brief analysis of the suspension lines and payload effect presented an overall look at the performance of the complete parachute system (canopy, suspension lines, and payload).

The main results achieved from the test cases in this study were:

- 2D Validation Case ($-8^\circ \leq \text{AoA} \leq 16^\circ$): comparison of lift and drag against NASA experimental data showed a maximum 10% error deviation in all the tested AoA.
• 2D PD Comparison Case (-6° ≤ AoA ≤ 8°): rib distortions and opening length characteristics had a minor impact on lift coefficient values. Drag coefficient values, alternatively, showed larger values for the distorted cases. Maximum $L/D$ performance for all models attained at 4° AoA. A 45% $L/D$ reduction was obtained for the distorted open model, where 17% corresponded to the effect of distortions and the remaining 28% to the effect of the inlet opening length. Comparison against past research work resulted in 5.15% $L/D$ deviation for the closer similar model to the one built in this thesis study.

• Pseudo-2D PD Comparison Case (0° AoA): the 3D effects neglected in this model were the use of anhedral angle, and the presence of downwash created by the tip vortices, i.e., induced drag. A 4% difference in lift coefficient values was attained for the undistorted and distorted models. In terms of drag coefficient, a 46% difference resulted between the two models. The distorted model drag increase was attributed to a larger pressure and inlet drag of the cell. Lift and drag results led to a 48% $L/D$ difference between the two models, a similar trend observed in the 2D case.

• 3D Validation Case (4°, 5°, 8° AoA): compared against available experimental data, the lift plot showed good agreement with a maximum error percentage of 3%. The drag plot, alternatively, was underpredicted by approximately 23% for all three AoA. This drag discrepancy was attributed to different rib thickness, measuring equipment errors, additional surface irregularities, and turbulence model selection.

• 3D W&H Comparison Case (4°, 5°, 8° AoA): the incidence and translation model produced a larger $C_L$ value than the baseline model, whereas the inflation and span
shrinkage model resulted in smaller $C_L$ values. The inflation model produced the largest amount of drag. The remaining two distorted models presented lower drag coefficient values as well but in smaller proportions than the inflation model. Lift and drag results led to the inflation model being the model with the largest decrease in overall $L/D$ performance, followed by the span shrinkage model, and lastly the incidence and translation model.

- **3D PD Comparison Case (0° AoA):** the 3D model had a 60% lift coefficient reduction compared to the pseudo-2D model. Possible reasons of the large lift reduction are caused by the anhedral angle effect, the downwash created by the tip vortices, and larger flow separation areas. The drag coefficient $C_D$ showed a 4% difference with respect to the pseudo-2D model, leading to an overall reduction in $L/D$ performance of 60%. Comparison of this study $L/D$ results against experimental data and past numerical studies showed good agreement, ensuring acceptable credibility in the performance trends observed for the 3D model.

- **3D Planform Comparison Case (0° AoA):** the elliptical model recorded a 50% drag coefficient reduction compared to the rectangular model. Lift coefficient slightly increased because of the two extra cells used in the elliptical design, which led to an overall 51% $L/D$ increase i.e. better performance than rectangular model.
6.2. Recommendations and Future Work

The first recommendation would be to obtain experimental data from a test model similar in construction to the one performed in this study. The comparison with numerical and experimental data from past research work had some differences either in the geometry modeling or the flow parameters used for the simulations and experiments. Therefore, an experimental test would propose a better and more direct comparison of results to validate the cases performed in this numerical study.

A second recommendation would be to verify the numerical values of the parachute lift and drag forces obtained in this study by using the mass, momentum, and energy balance equations. The use of these conservation equations would be able to give a more physical explanation of the flow behavior around the parachute surfaces.

A third recommendation would be to explore other types of turbulence models that predict more accurately the regions of flow separation such as LES or DES. By doing this, the RANS turbulence model used in the modeling of this study, and also on past work studies, can be assessed. A tradeoff in obtaining more accurate results at the expense of larger computational power and time would be required.

Finally, a fourth recommendation would be to implement additional features to the design of a more complex ram-air parachute. These extra features can include the use of crossports at the ribs, the use of stabilizers at the end cell ribs, the use of suspension lines, the use of seams, and the use of sliders. With these design features, a more thorough analysis of aerodynamic performance can be achieved. Furthermore, the introduction of sideslip conditions and stability variables to the simulation modeling can provide a more complete picture of the behavior of ram-air parachute systems at other flight conditions.
REFERENCES


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