escola superior de tecnologia e gestão
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Development of a retractable landing gear for an aircraft

Master's degree in Mechanical Engineering

Rodrigo Gaspar Amorim

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Project Report under the supervision of Professor Maria Leopoldina Mendes Ribeiro de Sousa Alves, and Professor Luís Manuel de Jesus Coelho

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Dedication

“Only those who will risk going too far can possibly find out how far one can go.” – T.S. Eliot.

To all the M’s who shaped who I am and who I will be.

Acknowledgments

With the development of this project finished, several people need to be acknowledged for all the help, inspiration and above all, patience.

My biggest thank you is for all my family, who are always by my side, whenever and wherever, to make sure that I know that nothing is out of reach. To my friends, for the best moments one can wish for and who help me continuously every day.

To both my supervisors, Maria Leopoldina Mendes Ribeiro de Sousa Alves and Luís Manuel de Jesus Coelho, for all the guidance, for keeping me motivated, for all the meetings and calls that made this project real.

To Tekever UAS, and everyone who works there, as well as AERO.NEXT Portugal – Portugal’s Aeronautical Agenda, for the extraordinary opportunity of working in the development of a huge project.

Abstract

The focus of this project is the development of a retractable landing gear system for an aircraft, with the goal of improving overall efficiency, safety and performance. The project emphasizes in dimensioning a realistic solution for an initial draft of an aircraft, with several parameters defined taking into account current market requirements. The project encompasses various critical aspects such as the landing gear arrangement, retraction movements, shock absorption solutions and braking systems while also referring to regulations and guidelines.

In order to dimension an initial solution for the landing gear, a thorough research was conducted regarding the current solutions as well as any up-and-coming alternatives that may be more suitable for the project. With all the information gathered, a set of requirements was then obtained taking into account market demands, which would be further applied to the methodology developed, helping in the development of an initial solution.

As a result, several findings were obtained, regarding the position, movement and requisites for the components of the landing gear structure. For the landing configuration, a tricycle layout was selected and then dimensioned through a series of steps in order to find the best position for both the main and front landing gear, ensuring a reliable maneuverability and safe structure. In regard to the retraction movement, a forward retractable system was suggested as the best option, mainly due to the restrictions in payload areas in the fuselage, with the usage of additional wheel bays as the most suitable solution for storage. For the shock absorption, an oleo-pneumatic solution was deemed the most appropriate, and then dimensioned to have at least a stroke of 8.8 in and a diameter of 0.105 ft. At last, the braking requirements resulted in a brake capable of absorbing at least 98578 ft.lbf of energy and capable of producing more than the minimum value of torque, at 525.95 lbf.in.

These findings and results, serve as an introduction towards the development of a full landing gear structure, with a long series of steps still needed to be taken into account before the final solution is ready.

Keywords: retractable landing gear, aircraft design, shock absorption, braking system, aviation safety, regulation.

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List of Abbreviations and Acronyms

AOA	Angle of Attack
CG	Center of Gravity
EASA	European Union Aviation Safety Agency
ESTG	Escola Superior de Tecnologia e Gestão
IPL	Instituto Politécnico de Leiria
MTOW	Maximum Takeoff Weight
MGC	Mean Geometric Chord
T-O	Take off

1. Introduction

Humanity has always pursued that which seems impossible. From the first time a bird was sighted flying above us, in a dimension that seemed inaccessible to us, to today where we rule the sky, there have been many attempts, dreams, projects, failures and successes to define the path that led us here. The ensuing pursuit of being able to glide through the air started thousands of years ago from as early as stories in Greek mythology about *Icarus* and *Daedalus* who, when attempting to flee from a labyrinth, attached wings to his arms and flew. However, as is widely known, it ended in tragedy, reminding us of the consequences of failure when flying.

Visionaries like *Leonardo Da Vinci* pioneered schematics of mechanical flying machines with engines as a concept, upon realizing humans could never produce the required power to achieve flight. Among *Da Vinci's* sketches are ornithopters, displayed in Figure 1, with flapping wings, proving the innovative power of biomimetics. Despite all the scrupulously drawn sketches, *Da Vinci* never merged both the concepts of engines and flying machines together [1].

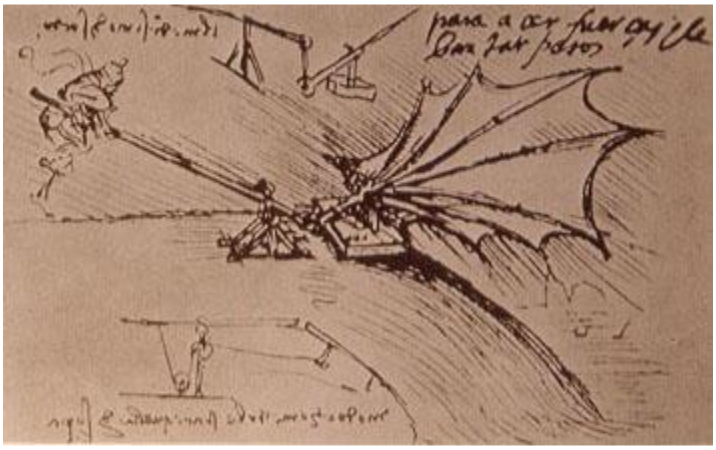

Figure 1 - Ornithopters sketches by *Da Vinci* [1]**.**

In ancient China, toys in the form of kites, balloons filled with gas and rotating-wing tops appeared displaying some alternatives for flight, thus resulting in attempts at constructing giant human-carrying kites, unsuccessfully though. It would not be until 1783 that the *Montgolfier* brothers would design the first human-carrying vehicle, Figure 2, capable of constant flight. A single month later, *De Rozier* and the *Marquis d'Arlandes* would write their names in aviation history by conducting the first free flight in a balloon, traveling around 8 km at 150 meters high before a successful landing [2].

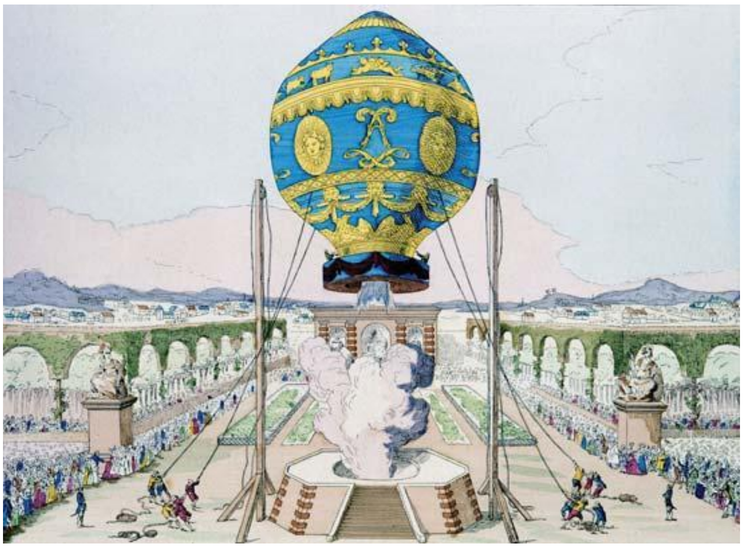

Figure 2 - *Montgolfier* brother's balloon [1]**.**

These attempts proved that what was previously thought of as impossible was already happening, kickstarting a continuous process of innovation and creativity. Names like *Sir George Cayley*, denominated as the “Father of Aviation”, took a pioneering role with major breakthroughs. The first one by identifying the four forces of flight [3]:

- Lift: Upward force created by the wings moving through the air
- Drag: Resistance of the aircraft to forward motion, caused by air resistance
- Thrust: Force exerted by the engine and its propeller(s)
- Weight: Downward force due to the weight and load of the aircraft

A state of equilibrium is reached when the thrust and drag are equal and opposite. In this scenario, an aircraft will continue to move forward at the same speed, however if thrust increases the aircraft will accelerate and the opposite will happen if thrust decreases. The same logic can be applied to lift and weight, if the lift is greater than weight, the aircraft will climb and upon the weight surpassing the lift, the aircraft will descend. The four forces are represented on an aircraft on Figure 3.

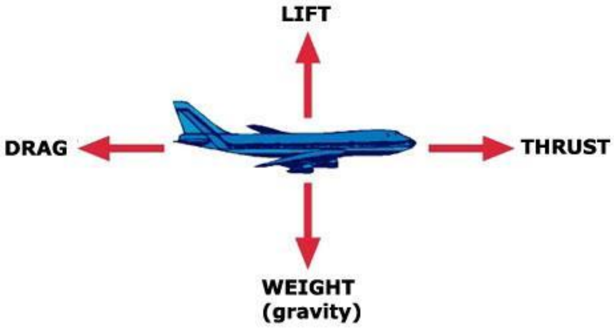

Figure 3 - Four forces of flight [3]**.**

By coming up with these four forces, *Cayley* proved that the propulsion system used should only focus on thrust, opposing the views of previous researchers, who thought that the propulsion system should generate both lift and forward motion, as can be seen in ornithopters. By noticing that the geometry of the wing could be designed and shaped to produce lift, an enormous step was taken towards the development of aircraft as we know it today. In 1799, *Cayley* designed an aircraft composed of a fixed main wing, a fuselage, a tail with control surfaces for horizontal and vertical control, a cockpit, and a rudimentary propulsion system. The sketch of this design can be seen in Figure 4.

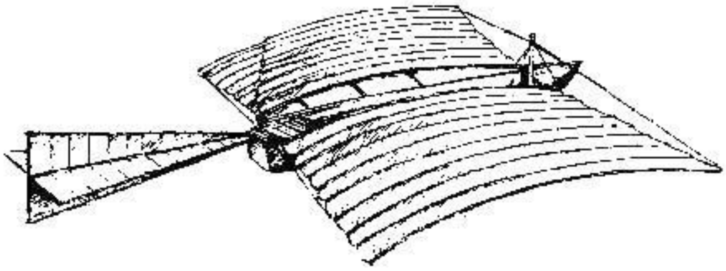

Figure 4 - ***George Cayley*** **1799 design** [4]**.**

Cayley would spend his long career searching and recognizing the solutions for the basis of flight, from ratios of lift to wing area, airfoil design, wheeled undercarriage, and the need for a lightweight power source, which at the time was not an option, thus preventing the biggest breakthrough in aviation history, for the time being. He however predicted that, without a lightweight power source, aircraft would never make it to the sky by themselves, an event that only took place in 1903 [4].

Dressed for the occasion, on a December morning on a sandy beach, the Wright brothers made history by breaking our bond to the earth. Despite a flight time of under 12 seconds and a distance of only 36 meters covered, all the work idealized throughout history was proved as, for the first time, a machine heavier than air, in Figure 5, left the ground by itself, moved forward under control, and landed on a point as high as the starting one. Within two generations we had taken to the air for routine travel, seen several aircraft break the sound barrier and watched humanity walking on the moon [5].

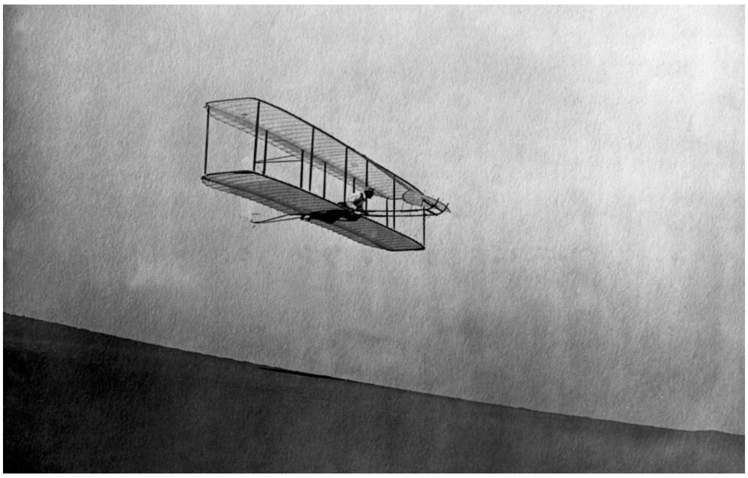

Figure 5 - Kitty Hawk Flyer[6].

1.1.Research aims

"It is not the destination, it is the journey", a quote commonly used to express the importance of appreciating everything one goes through, not just the ending. Despite the truth behind this statement, flight was developed with the goal of starting and ending in the same conditions, on the ground. "The essential intermediary between the aircraft and catastrophe" is an accurate description of the role of the landing gear [7].

As one of the key factors differentiating a successful flight from an unsuccessful one, landing gear, whether retractable or not, must be extensively researched and tested, to ensure that no single mishap or failure happens. Throughout the last years, several accidents have occurred in commercial aviation due to issues related to landing gears, with varied problems, such as landing gears not locking down due to a broken spring and immediate landing gear cylinder failures upon touchdown, both caused by fatigue. Another accident occurred due to ruptured tires on take-off, which upon landing spun with the ground producing similar natural frequencies of the main landing gear, eventually leading to a full collapse of the right main landing gear [8], [9], [10], [11].

These accidents serve as a reminder of the consequences of a final error, of a fatigued component, of a missed check or evaluation, reminding us of the importance of the landing gear and its purpose. For these reasons, a thorough project is required for the development of a landing gear for an aircraft, from a design standpoint to an engineering analysis, to an extensive testing procedure and constant maintenance.

Due to the systematic need for longer flight times, heavier payloads and better aerodynamics, a retractable landing gear is seen as the ultimate solution for aircraft. The overall efficiency of the aircraft is improved with the use of retractable landing gear systems, enabling the reduction of drag throughout the flight, resulting in less fuel used and better performance [12].

The main purpose of this project is to develop a functioning retractable landing gear suitable for an aircraft while ensuring that the solution is compact, lightweight, and sturdy. One of the main goals is to ensure the minimization of the occupied space when the landing gear is stowed while still meeting the requirements defined regarding structural integrity. Additionally, some more aspects need to be considered regarding the landing gear, for instance the need for a braking and damping system.

1.2. Research objectives

When designing the landing gear several aspects must be considered, and this is further compounded when the gear is retractable. Both the kinematics of the landing gear mechanism and space-claims inside the airframe must be accounted for, so the following issues must be defined before progressing:

- Landing gear arrangement
    - In this section, the general layout and position of the wheels will be defined, taking into account the most advantageous configuration as well as the requirements of the project
- Type of retraction
    - The main objective here is to define what the retraction movement should be, with all the restrictions clearly defined, in order to ensure a safe and consistent retraction
- Shock absorption
    - For the shock absorption, the goal is to identify the best solution available as well as dimensioning the minimum requirements in order to research a suitable option

- Braking system
    - At last, for the braking system, the main purpose is to ensure a safe braking, through the dimensioning of prerequisites for the brakes, taking into account several factors such as the speed and weight of the aircraft.

1.3.Document organization

The present document will be divided into the following chapters:

- Literature review, in which a concise research takes place to identify the current available solutions and understand what the advantages and disadvantages are of each one
- Methodology, where the approach to be followed throughout the project will be presented, ensuring that the method used can be easily identified and applied to other projects or parameters if needed
- Results, presenting what was obtained by following the methodology and applying the required variables, obtained from market requirements.
- Conclusion, a summary of the results obtained
- Future works, the last chapter, where all the work to be done will be identified, ensuring that the project can be carried through

In order to better organize the document, a decision was made to divide some of the chapters into four sub-chapters, corresponding to the four research objectives.

2. Literature review

By doing a literature review before the development of the project in question, research is done by gathering existing literature thus serving as an explanation as to why certain aspects and characteristics were addressed and their importance and implications.

In this chapter, an initial benchmark analysis will be presented, in which the focus is to set the existing solutions and alternatives to the variety of configurations possible for a landing gear. To facilitate the organization and presentation of said benchmark, the following chapter was divided into four sub-chapters.

- Landing gear arrangement
- Type of retraction
- Shock absorption
- Braking system

In each of these four sub-chapters, different alternatives will be discussed, with the goal of presenting the advantages and disadvantages of each one to then establish which of the configurations and options were selected for the present development.

Additionally, a chapter focused on all the required regulations is also presented, with the aim of providing all the required information about the EASA (European Union Aviation Safety Agency) norms regarding the current project. As with every other component of an aircraft, for it to be airworthy, several conditions must be met. From weights limits and maximum dimensions to load tests, every single one of these requirements is necessary and mandatory.

The present chapter focuses on exploring the key elements around the design and performance of a retractable landing gear system, with a critical evaluation focused on differentiating several options available on the present day. As previously mentioned, the chapter is divided into four different chapters, addressing the pivotal elements behind the decisions regarding the design of an efficient and advanced solution.

By considering this benchmark, the current options are considered but also evaluated on whether they are suitable for improvement. With the current demands behind modern aviation, no consideration must be left behind when picking which solution to follow through with, so by unraveling the intricacies of the alternatives for landing gear optimization, the stage for the development of a new landing gear is set.

2.1. Landing gear arrangement

As the landing gear represents one of key components of the aircraft, several features must be taken into consideration upon the initial design, such as the positioning and ground clearance of the landing gear. The former must be paid crucial attention to as the main and auxiliary landing gears must be positioned respectively to the center of gravity thus reducing the risk of certain problems like ground looping, overturning, crosswind canting and to enable the aircraft to maneuver as needed during take-off and landing procedures. The latter is also of huge importance as a constant clearance is needed between the ground and all the aircraft components, even during worst case scenarios like flat tires or shock absorber abnormalities.

The landing gear positioning is the first decision that must be made regarding the development. A huge variety of configurations have been used throughout history, but the four most common arrangements are displayed in Figure 6. These four arrangements cover around 99% of all aircraft ever built.

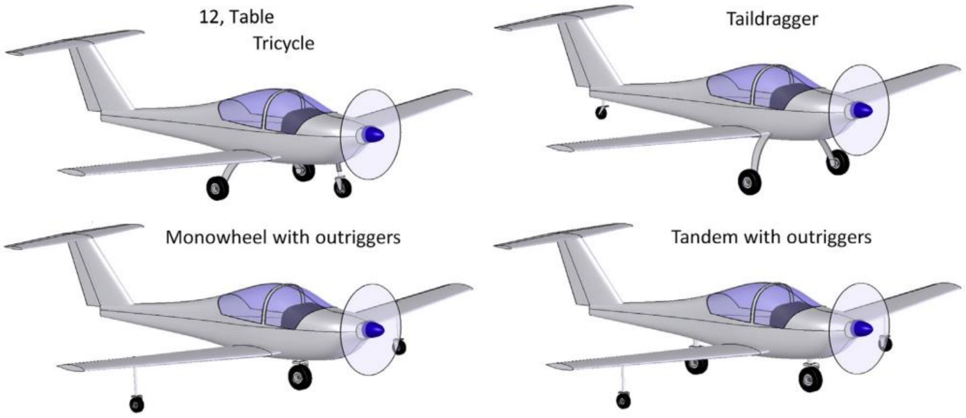

Figure 6 - Landing gear arrangement [13].

For the project, the Tricycle arrangement was selected after evaluating the most common arrangements due to the significant advantages it presents compared to the other options, which some of them are presented below on Table 1 as well as some disadvantages.

Table 1 - Tricycle arrangement advantages and disadvantages [13]**.**

Advantages	Disadvantages
Easy ground maneuverability	Higher structural weight
Better propeller protection	More costly
Less bounce on touch-down	Higher cruise drag
Tighter turning radius	Steering mechanism more complex
Plane does not nose over when braking	Skidding on heavier brakes
Easier to land	Nosewheel retraction challenging
Lower AOA needed for T-O	More braking effort during landing

In addition to the landing gear arrangement selection, the exact position of the wheels must also be predefined as they have an immediate impact on the maneuverability on the ground as well as on the impact during take-offs and landings. Figure 7 presents some of the geometric dimensions related to the landing gear:

- Wheelbase – Defined as "the distance between the front and back wheels of a motor vehicle" [14].
- Wheel track – Shortest distance between the center of the tire threads on the same axle
- Turning angle – Angle between the axis of the main landing gear and front landing gear [15].
- Turning radius – Distance between the intersection of the axis of the front and main landing gear relative to the front landing gear.

The consequence of different values for some of these dimensions can be seen in the Figure 7. The turning radius is crucial for ground maneuvering, mainly on narrow or unprepared runways. The variable θ is the turning angle and the value "h" below denotes the location of the center of turn. The turning radius can be calculated by knowing the wheelbase and turning angle of the nose gear, in which a higher turning angle directly results in a lower turning radius.

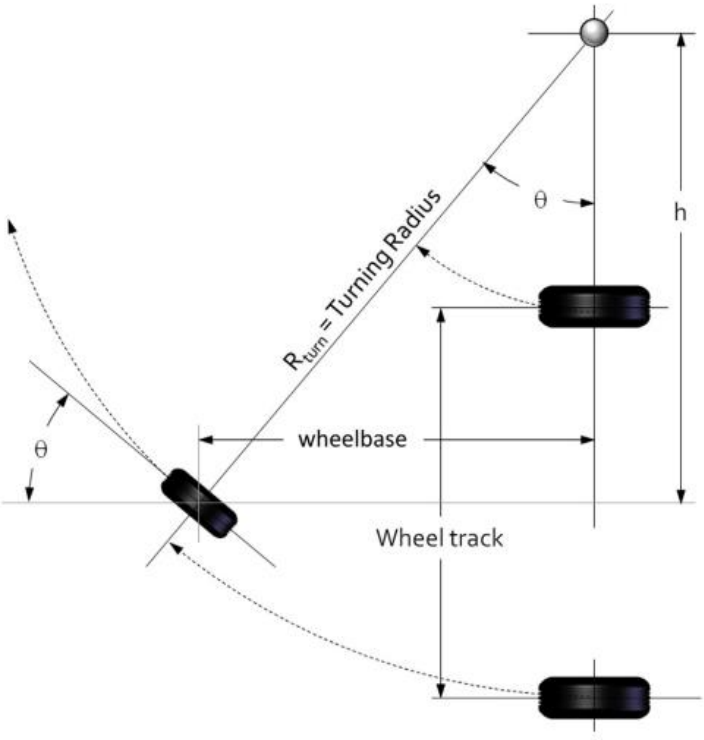

Figure 7 - Geometric definitions to determine turning radius [13]**.**

2.2.Type of retraction

The topic in the present chapter plays a major role in the efficiency and aerodynamics of the aircraft as opting to use a retractable landing gear has several advantages to the aircraft, with the main benefit being the added efficiency, as long as the system is correctly dimensioned and the structure accounted for, as a retractable solution is always heavier and more complex than a stationary one. The goal is to determine the best retraction system and orientation, considering several parameters, as well as some restrictions in the fuselage. Some existing solutions of different retraction systems are presented below, as well as the main advantages and disadvantages of each.

- Electro-Mechanical Systems:

  One of the most common retraction solutions is based on the use of an electric motor serving as an actuator to both retract and deploy the landing gear. This solution is highlighted by its reliability, simplicity, and weight efficiency [16]. However, depending on the aircraft dimensions, this solution may require a higher power consumption than desired, especially when compared to the other solutions presented, which may end up having an overall negative impact on the aircraft energy efficiency.

- Hydraulic Systems:

  Already established as one of the main solutions for landing gear retractions, their precise control and quick response make it a perfect solution for a variety of aircraft configurations [17]. Mainly applied to heavier aircraft due to their power requirements and load capacity. Another offset of the hydraulic system is the complexity behind the components, requiring a huge number of additional parts like pumps, valves, and fluid lines, which not only increases the weight but also provides a challenge for maintenance purposes.

- Pneumatic Systems:

  Despite being less common, pneumatic alternatives have been studied mainly due to their reduced complexity and weight compared to the previous solutions. However, due to their reduced precision and low power density, it ends up being a solution only appropriate to small aircraft with low landing gear loads [18].

There are several solutions and orientations for the retraction system, with some possibilities presented in Figure 8 and Figure 9.

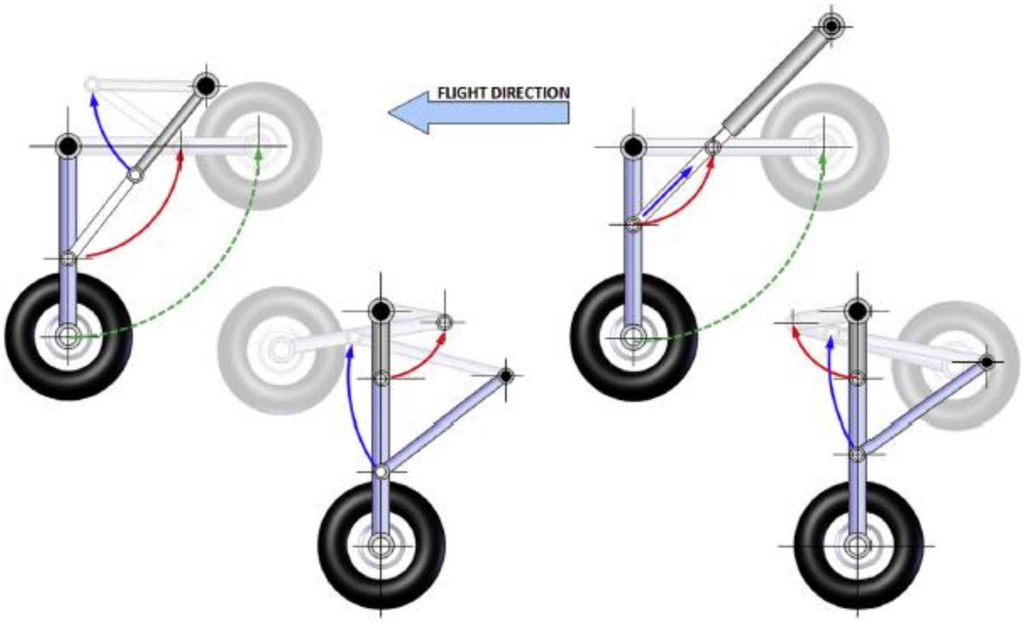

Figure 8 - Side view retraction solutions [13].

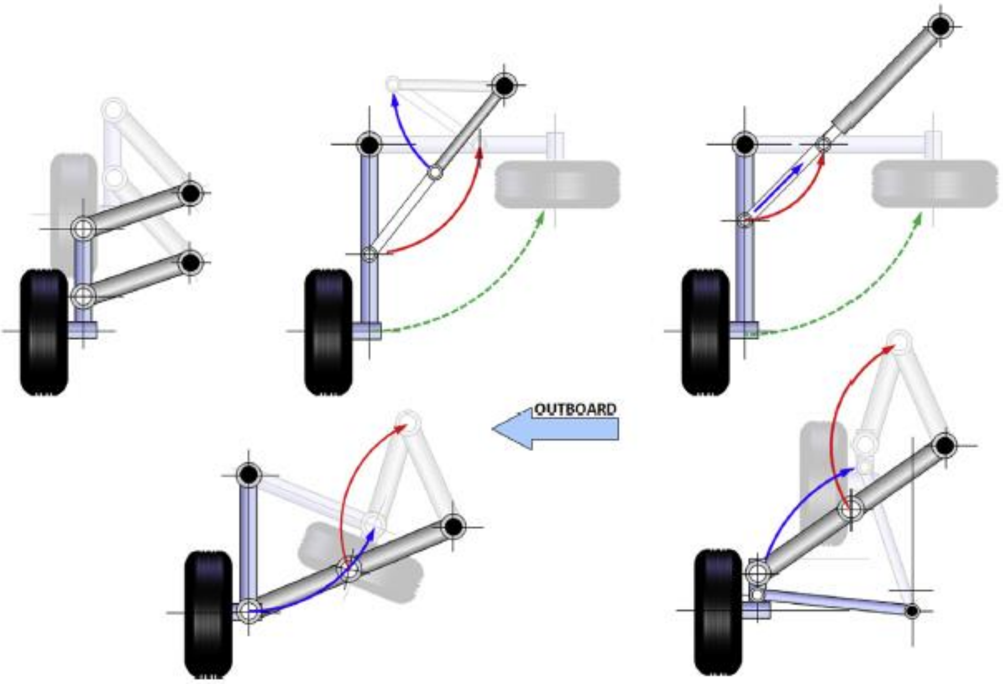

Figure 9 - Front view retraction solutions [13].

2.3. Shock absorption

The main purpose of a shock absorber is to minimize the impact of a quick deceleration on the aircraft [19]. On an ideal scenario, the deceleration happens through the force acting on the absorber, changing the applied force from zero to a maximum load just as the rate-of-descent approaches zero. Ideally, this deceleration would take place over a long struct length, to provide a soft landing, void of any shock. However, due to the size constraints, a solution must be engineered to solve this problem in only a few inches. The answer relies on a spring action that is neither too flexible nor too stiff to enable the reduction of the vertical speed to 0 comfortably. Figure 10 displays the relation between deflection and load, defined by the variable Ks, while also providing some examples of varied types of absorption systems and their efficiency. If a value of Ks = 1 is achieved, the entire load is absorbed in zero distance, which despite efficient ends up not being exactly comfortable. As seen in the Figure 10, the Oleo-Pneumatic presents one of the most efficient solutions of slowing down the aircraft vertically. The graph shows that it absorbs most of the landing load over a short distance and the remainder is absorbed throughout, providing a more comfortable experience.

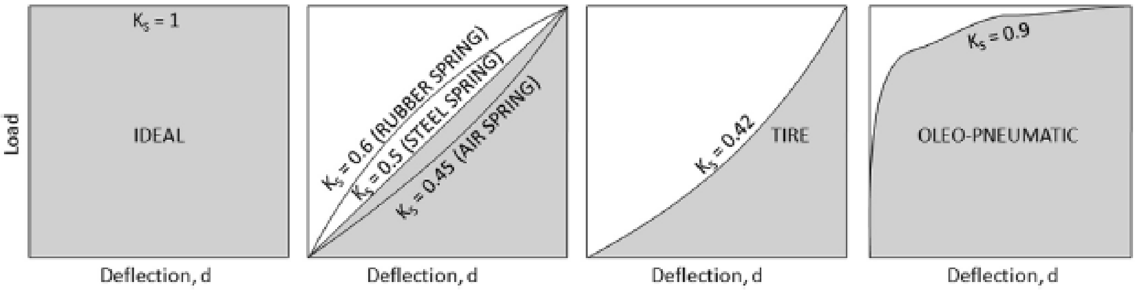

Figure 10 - Relation between deflection and load [13]**.**

To decide which solution to integrate in the system, an initial analysis must be done regarding some key parameters, such as:

- Weight of the aircraft
- Landing speed
- Landing strip conditions
- Touchdown rate
- Available landing gear space

The main types of landing gear shock absorption solutions are:

- Rigid axle
- Solid spring
- Oleo-Pneumatic Strut

Due to the weight and landing speed assigned to the aircraft, with the former set at 600 kg and the latter at 58 knots or 107.4 km/h, with these values being set considering current market demands, the solution regarding using only a rigid axle is disregarded, leaving as the only feasible solutions a solid spring system or an oleo-pneumatic strut. To better evaluate the advantages of each of the mentioned solutions, a more in-depth comparison will be presented below.

2.3.1. Solid Spring

The solid spring, illustrated in Figure 11, is made of a solid but flexible strut, connecting the fuselage to the wheel arrangement. The strut is attached to the fuselage at an angle enabling some vertical displacement by bending the structure which results in some shock absorption. This system, however, suffers from a flaw due to the lack of damping from the vibration caused by the shock, causing the aircraft to reverberate up and down during harsher landings.

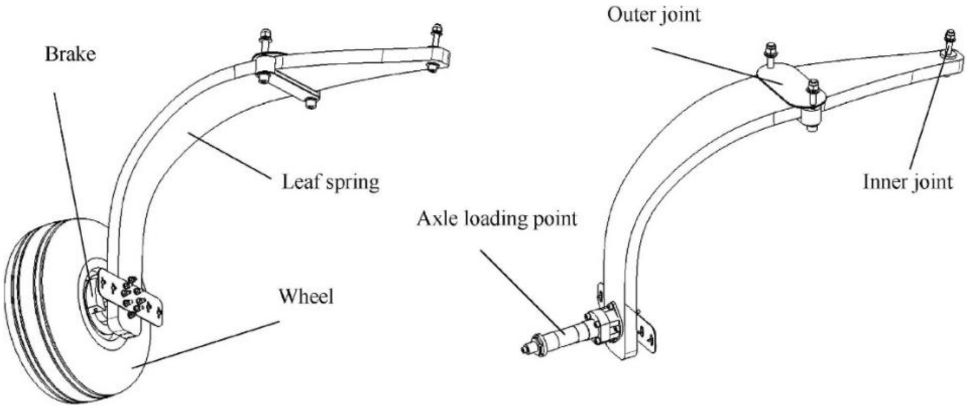

Figure 11 - Solid Spring Arrangement [20].

This solution finds itself as the preferred solution for light aircraft with a small touchdown rate by serving as a simple and low-cost solution, an example of this solution applied to existing aircraft is present in Figure 12.

Figure 12 - Tekever AR5 with a solid spring landing gear [21].

2.3.2. Oleo-Pneumatic

The oleo-pneumatic shock absorption system is currently the most common solution used in medium to large aircraft due to providing excellent shock absorption and damping. A typical pneumatic shock strut uses compressed air or nitrogen combined with a hydraulic fluid to absorb and dissipate shock loads. Composed of two telescoping cylinders with the upper one fixed to the aircraft and without any movement and the lower one, the piston, sliding in and out of the upper cylinder. The shock absorber comprises two chambers, with the top one always filled with compressed air or nitrogen and the bottom one with hydraulic fluid, with an orifice or a metering tube to provide passage for the fluid from the bottom chamber to the top cylinder when compressed. The metering tube has the purpose of controlling the flow of hydraulic fluid to the upper chamber, further converting impact energy into heat [22]. A shock absorber with a metering tube is represented in Figure 13.

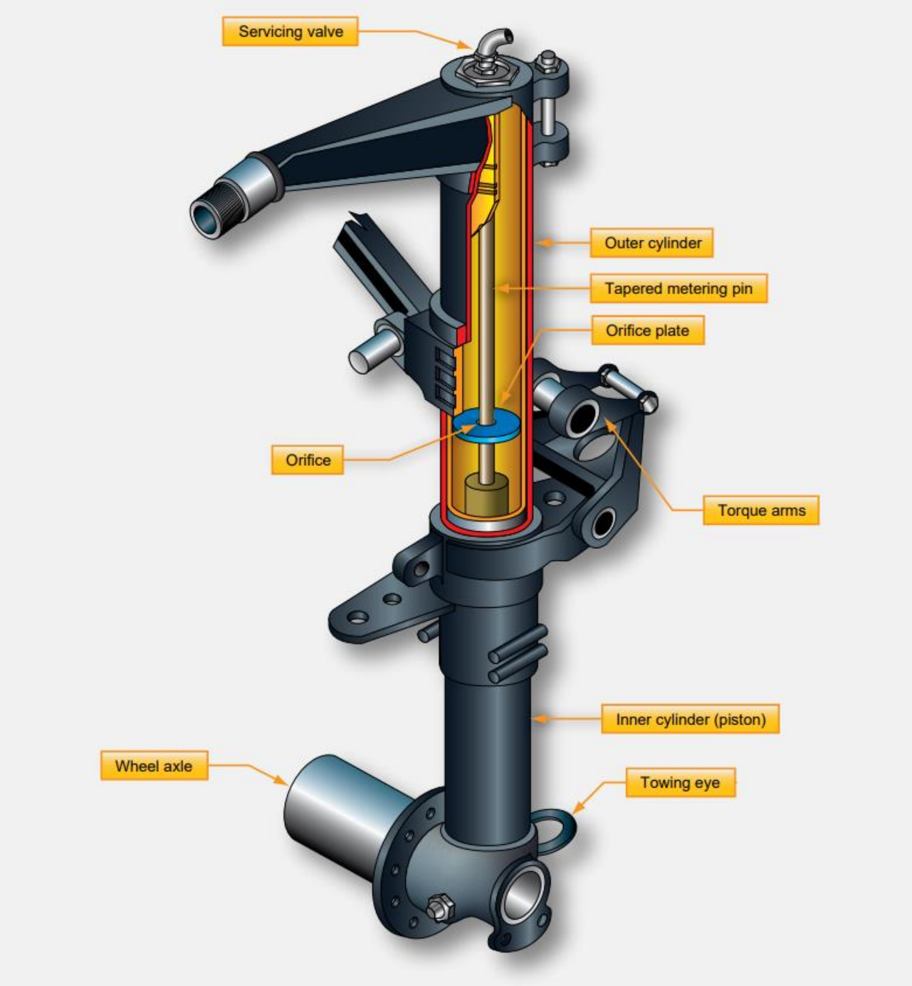

Figure 13 - Landing gear shock strut [22].

The oleo-pneumatic can be divided into 3 different configurations:

- Telescopic Strut
- Articulated Strut
- Semi-Articulated Strut

The main difference between each of the mentioned configurations relies on the positioning of the landing gear strut relative to the wheel and whether the shock absorber is rigid with respect to the fuselage.

2.3.2.1. Telescopic Struct

In this configuration, represented in Figure 14, the oleo-pneumatic system is positioned in line with the strut of the landing gear, with the shock absorber housed within the strut. Upon landing, the wheel deflects in the same line as the shock absorber, which poses a problem due to the necessity of a lengthy shock strut to absorb the energy. Additionally, when requiring maintenance, this solution requires the entire landing gear system to be removed as the shock absorption solution is housed within. The Figure 14 displays the main components as well while also aiding to visualize the aforementioned problem.

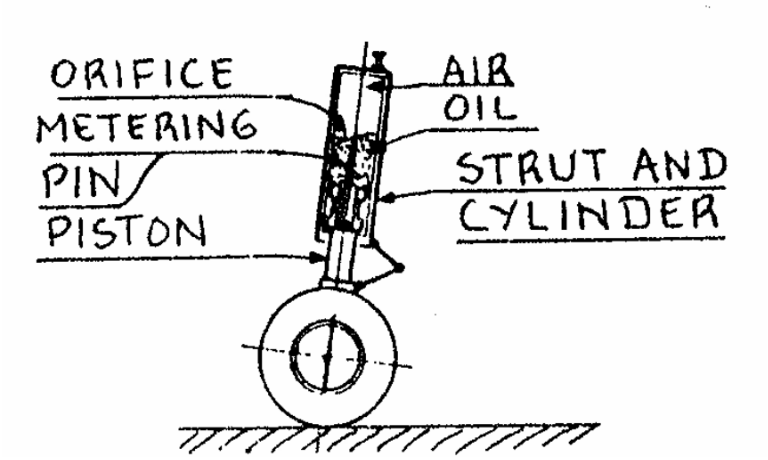

Figure 14 - Oleo-Pneumatic telescopic configuration [23]**.**

2.3.2.2. Articulated Strut

In this configuration the shock absorber serves as the link between a support strut and a linkage to the wheel. In this system, presented in Figure 15, the wheel deflects in a circular arc around the axis set at the intersection between the strut and the linkage. The main advantage of this solution results from the increased wheel stroke length when compared to the shock absorber stroke due to the linkage interface.

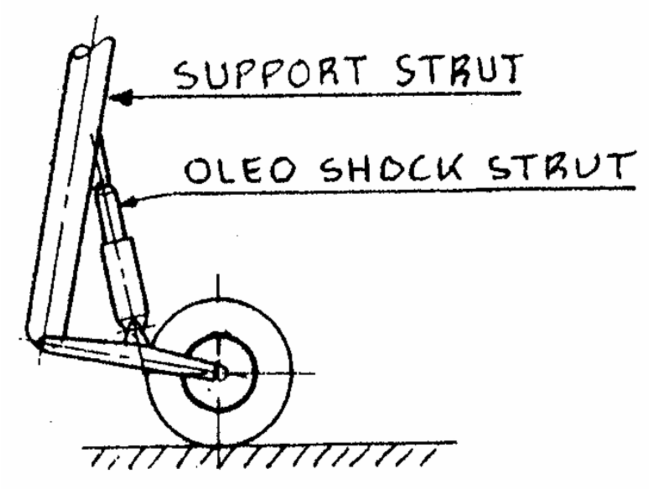

Figure 15 - Articulated strut [23].

2.3.2.3. Semi-Articulated Strut

The last configuration for an oleo-pneumatic system is the semi-articulated solution, Figure 16, in which the shock absorber is placed in the support strut of the landing gear system with an additional linkage between the shock absorber and the wheel. This solution can be seen as a middle ground between the telescopic and articulated configurations, without the drawbacks of the telescopic solution.

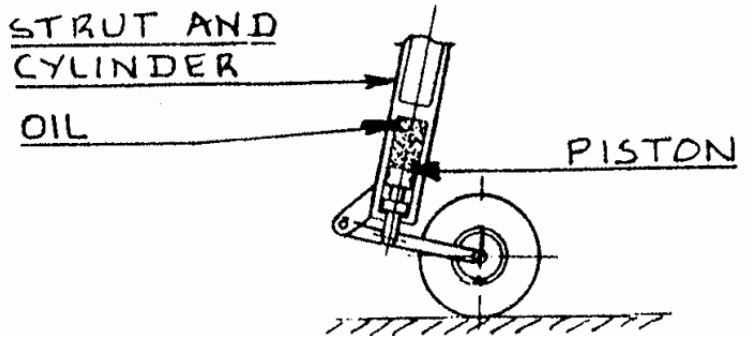

Figure 16 - Semi-articulated strut [23].

2.3.3. Shock absorption comparison

With the advantages and disadvantages listed above, the best option for shock absorption tends to be the oleo-pneumatic strut. Not only are these solutions more efficient at dampening and shock absorption but they are also lightweight and compact, thus being greatly desired for retractable landing gears. As an additional form of comparison between the solutions, Figure 17 relates the efficiency of each of the systems to their average weight further confirming the choice towards oleo pneumatic.

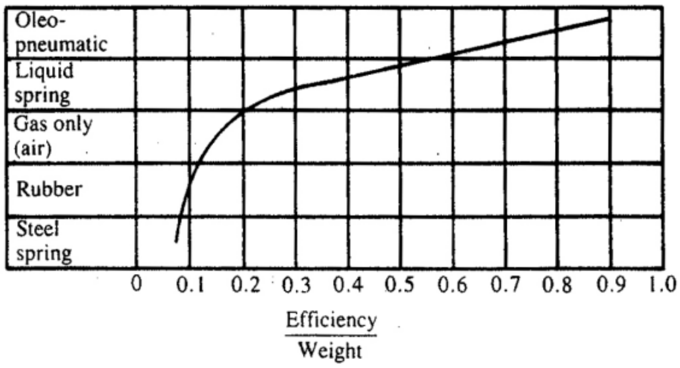

Figure 17 - Efficiency to weight ratio for shock absorption solutions [23].

2.4. Braking system

Behind every good flight is a good landing, however the landing is not finished until the aircraft is at full stop. Despite this, in the beginning, aircraft brakes were not a necessity, however with the increase of weight and speed of the aircraft, the need for them became a necessity and as such, braking solutions were developed to meet the newfound requirements [24].

The main goal in this chapter is to set the requirements for a braking system, taking into account the market requirements set. By defining certain necessary characteristics, such as a certain torque or stopping distance, available solutions in the market can be compared and evaluated to decide which one is more suitable.

Three additional aspects will also be addressed, all of which are relevant towards the final decision regarding the available braking solutions. The different options are as follows:

- Anti-skid systems
- Brakes materials
- Air brakes

As can be seen, not only the different alternatives to braking will be addressed as well as the best material for the aircraft class in question, with the final decision being made regarding which parameter is deemed more important.

2.4.1. Anti-skid system

The system activates automatically upon the initial wheel spin up on landing and only disables under a certain minimum speed. The main advantages of this system are the minimization of aquaplaning and tire damage by preventing locked wheels while improving stopping distance on substandard surfaces, either affected by gravel, grass, or ice, by maximizing effective braking. The decision to whether to implement an anti-skid system comes down to the mass, as other solutions could be implemented instead, like air brakes or brake flaps and thrust reversal [25].

2.4.2. Brakes material

The material most commonly used for a disk brake is steel or even iron. However, on larger and heavier aircraft, the brakes are subject to high levels of kinetic energy and its resulting heat, which translates into an efficiency loss as the temperature increases for both iron and steel. In addition to this, the materials high density results in heavy weight solutions, making developing a new material suitable for the brakes a priority.

A switch to carbon fiber brakes appeared as a possible alternative, with a solution that not only reduced weight but also improved high-heat performance with the drawback of a price increase. On average, carbon fiber brakes are roughly 40% lighter than standard iron or steel disc brakes, which on a large aircraft represents several hundred pounds of weight savings. The Table 2 presents the weight savings on some airliners, displaying the difference between the two materials [26].

Regarding thermal benefits the results are also impressive with the carbon fiber brakes handling 2 to 3 times as much heat as steel while also being able to dissipate residual heat more quickly than their counterpart.

Their longevity and maintenance are also key benefits, as they tend to last 20 % to 50 % longer than conventional alternatives.

The only drawback is their cost, which often ends up being a big enough argument for the final choice to revert towards steel brakes, but with an ever-evolving technology, cheaper carbon brakes are bound to appear, wide spreading their usage in aviation.

Table 2 - Weight savings between steel and carbon brakes [27].

Aircraft	Steel brake [kg]	Carbon brake [kg]
B757	101	60
B767	141	89
A300	145	75
A310	132	74

2.4.3. Air brakes

Air brakes, also known as spoilers, serve as crucial aerodynamic devices that aircraft can benefit from. By providing a means to manage and control airspeed during various phases of flight, these control surfaces enable a better maneuverability of the aircraft. The focus of this solution is aimed towards the landing phase.

By providing the aircraft with different means of slowing down, spoilers enable the reduction of airspeed on approach, reducing the need for extensive and heavy brakes usage, avoiding overheating problems. By increasing the drag of the aircraft, a lower speed and an enhanced descent rate can be achieved, which results in an improved landing precision as the aircraft approaches the ground slower and more stable [28].

The drawback of these control surfaces comes down to their added weight and complexity, with the need for additional components that require maintenance and that increase the risk of system failures.

Despite this, most of the aircraft currently operating utilize some sort of spoiler solution, due to the benefits far outweighing the problems. In the Figure 18, the spoilers can be seen on an airliner.

Figure 18 - Airbrakes on an airliner [28]**.**

2.5. EASA regulation

The European Union Aviation Safety Agency, logo presented in Figure 19, stands as the central authority in establishing and enforcing the regulation behind the design, production, and operation of all the aircraft within the European Union. Due to this, their guidelines and standardizations must be carefully studied to ensure that airworthiness of an aircraft is achieved [29].

Figure 19 - EASA logo [30].

The required EASA regulations for the aircraft in this project will be presented as well as the requisites needed to validate a landing gear system, from the redundancies needed to the simulations that must be passed before a maiden flight.

The aircraft portrayed for this project is classified as a “Light Sport Aircraft” (CS-LSA), with the precise category of a Small Rotorcraft (CS-27) due to the type of engine used.

For the CS-LSA category, the following criteria is defined [31]:

- A maximum take-off mass of no more than 600 kg.
- A maximum stalling speed of no more than 83 km/h when the aircraft is at its maximum take-off mass and most critical CG.
- A single, non-turbine engine or electric propulsion unit fitted with a propeller.
- A non-pressurized cabin.

In the interest of this project, a chapter of the EASA regulation is of critical importance, from the CS-27 category, which are as follows [32]:

- CS 27.723 – Shock absorption tests

For the shock absorption to be validated, the following tests must be passed, CS 27.725 and 27.727. The testing conditions involve the complete rotorcraft or on units made of the wheel, tire, and shock absorber in their proper relation.

- CS 27.725 – Limit drop test

The limit drop test follows the following rules:

a) The drop height must be at least 0.33 m from the lowest point of the landing gear to the ground.
b) If considered, the rotor lift must be introduced into the drop test by appropriate energy absorbing devices or using an effective mass.
c) Each landing gear unit must be tested in an attitude that simulates the landing conditions in the most critical conditions.

- CS 27.727 – Reserve energy absorption drop test

The reserve energy absorption drop test must be conducted as follows:

a) A drop height 1.5 times taller than the one used in CS 27.725 a).
b) The rotor lift, where considered in a manner similar to that prescribed in CS 27.725 b), must not exceed 1.5 times the lift allowed under that paragraph.
c) The landing gear must withstand the test without collapsing. If a single member of the nose, main gear or tail does not support the aircraft, resulting in part of the aircraft other than the landing gear and external accessories impacting the landing surface, the landing gear is considered to have collapsed.

- CS 27.729 – Retracting mechanism

For aircraft with a retractable landing gear, the following applies:

a) *Loads*. The landing gear, retracting mechanism, wheel-well doors, and supporting structure must be designed for all the loads that may occur during any maneuver with the gear retracted, the combined friction, inertia and air loads during the retraction and extension at any airspeed and all the flight loads sustained, including when the gear is extended.
b) *Landing gear lock*. A solution must be engineered to keep the gear extended.
c) *Emergency operation*. Emergency means must be provided for extending the gear in the event of any failure in the normal retraction system or in the failure of any single source of hydraulic, electric, or equivalent energy used.
d) *Operation tests*. Tests must be conducted to demonstrate the proper functioning of the retracting mechanism.
e) *Position indicator*. There must be an indication on whether the landing gear is secured in extreme positions.
f) *Landing gear warning*. A warning, either aural or visual, must be issued when the aircraft is in a landing and the landing gear is not fully extended. This warning

must have a manual shut-off capability and must automatically reset when the aircraft is no longer in landing mode.

- CS 27.731 – Wheels
    a) All landing gear wheels must be approved,
    b) The maximum static load rating of each wheel must be above the static ground reactions with the maximum weight and the critical center of gravity.
    c) The maximum limit load rating of each wheel must equal or pass the maximum radial limit load determined under the applicable ground load requirements of this CS-27.
- CS 27.733 – Tires
    a) Each landing gear wheel must have a tire that properly fits the rim of the wheel and of the proper rating.
    b) The maximum static load rating of each tire must equal or surpass the static ground reaction at its wheel at the design maximum weight and the most unfavorable center of gravity.
    c) All the tires installed on a retractable landing gear system must have a clearance to the surrounding structure that prevents contact between the tire and any part of the structure or system.
- CS 27.735 – Brakes

For aircraft with wheel-type landing gear, a braking device must be installed that is:

a) Controllable by the pilot.
b) Operable during power-off landing.
c) Adequate to counteract any typical unbalanced torque when starting and stopping the engine and must hold the aircraft when parked on a 10” slope on a dry and smooth pavement.

For the project, the rules presented above are the principal guidelines when designing and determining which solution to integrate. Failure to follow the steps mentioned will result in a failure to certify an aircraft design, which will undoubtedly be a major step-back. With this very reasoning in mind, all the decisions and choices made throughout the project will be heavily influenced by protocols hereby established.

3. Methodology

By explaining how a project is expected to be carried out, the development becomes logical and systematic, ensuring that the aims and objectives previously defined are properly met. In this chapter, the methods, techniques, and tools used for the selection of each component will be explained, offering several benefits such as [33]:

- If a need surges to replicate the project, enough information is provided on how the tests and choices were made
- Previously researching all the possible procedures for a specific task tends to result in a more precise development
- In case of any problem or mistake, a rapid verification can be executed by addressing the methodology applied

The chapter will be divided into four sub-chapters, addressing each of the major factors to be decided.

3.1. Landing gear arrangement

To further define the layout of the landing gear geometry, some aspects must be previously set, with the arrangement definition requiring the following:

- Aircraft side view in a cruise attitude with the mean geometric chord on the side view
- Top or bottom view of the aircraft
- Completed CG envelope

After obtaining the mentioned requirements, a series of steps must be taken to accurately lay out the landing gear for a tricycle configuration. With the Mean geometric chord (MGC) established, representing an imaginary line between the leading and trailing edge of the wing, the Figure 20 can be used for the first and second step, which involves defining on the side view, the forward and aft CG limits. The forward and aft CG represent the interval in which the aircraft CG must be to fly. The CG location heavily depends on the payloads chosen and the type of mission required. A brief explanation of the difference between both CG limits is as follows:

- Forward CG: more stable flight, higher stall speed and good stall recovery.

- Aft CG: more fuel efficient, which ends up being the focus during flight [34].

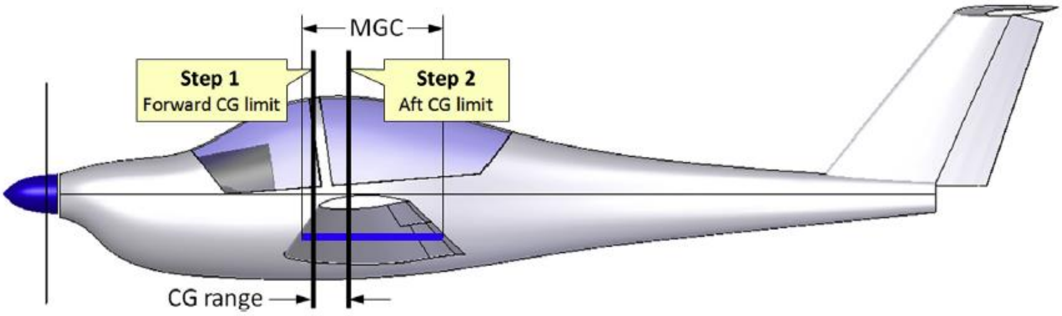

Figure 20 - Steps 1 and 2 of the landing gear geometry definition [13]**.**

The next step is to determine the highest vertical location of the CG at the aft limit, which can be done following the guidelines present in Figure 21.This point is critical as if crossed, the plane will fall on its tail. Step 4 requires drawing the prop-strike limit, evaluating how close to the ground the propeller should get, even when under adverse conditions, like a flat tire [35]. The limit is defined at 7 inches or 177.8 mm. For step 5 the tail-strike line is drawn as shown, ensuring the angle applied matches the stall angle of the aircraft, up to a maximum recommended value of 15º. The following step is to draw a line perpendicular to the previous one, passing through the aft CG. The intersection is where the tire will contact the runway, at 1g load. When flying, the landing gear will drop below the line drawn on step 5, the tail-strike line. To finish this section, a vertical line must be drawn at the intersection point. The mentioned steps are displayed in Figure 21.

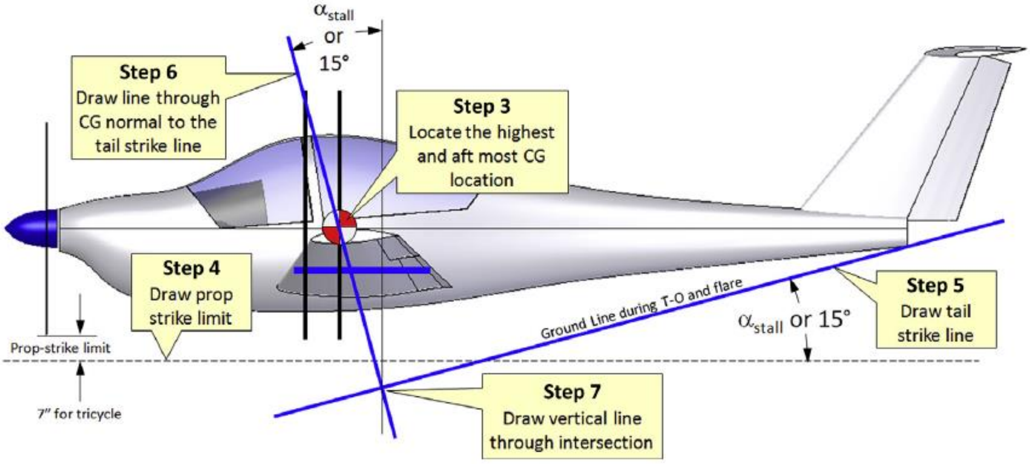

Figure 21 - Steps 3 to 7 of the landing gear geometry definition [13]**.**

The steps 8 and 9, in Figure 22, involve positioning both the main and nose landing gears. The main landing gear must be positioned at the point of intersection previously defined and for the nose landing gear its position must ensure that the gear does not carry more than 20%

of the aircraft weight when the CG is at the forward limit. In Figure 22, h_{cg}, corresponding to the height of the center of gravity in relation to the ground, is also displayed, which will be used in the next step.

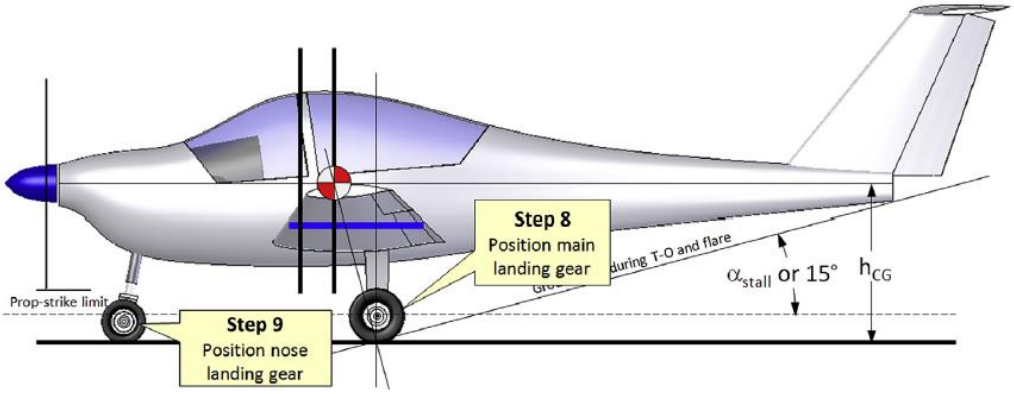

Figure 22 - Steps 8 and 9 of the landing gear geometry definition [13].

These steps defined the landing gear position from a side view, however, sequential steps must be taken to also position from a top view, to ensure that the wheel track remains wide enough to provide lateral stability when taxiing and turning a corner. Steps 10 through 14 will ensure that the required layout will function as intended, depending on the mission of the aircraft. As seen on Figure 23, step 10 refers to drawing a line through the nose and main wheel, passing in the center point of each. For step 11 a line must be drawn, parallel to the previous one, but placed so that it meets the forward CG location. After this, for step 12 a line perpendicular to line 10 and 11 is drawn and for step 13 a parallel to line 12 is sketched distanced with the same value of the distance by the hcg value mentioned previously. To finish, a line is positioned extending from the intersection of the lines from step 10 and 12 to the intersection of the lines from step 11 and 13. This line represents the overturn angle which should be lower than 63º for ground-based aircraft, meaning aircraft that do not have a need to operate on board of aircraft carriers. However, if the angle is higher than the limit defined, some actions must be taken to ensure that it meets the restriction:

- Increasing the wheel-track
- Reducing the height of the landing gear
- Increasing the wheelbase
- A combination of the three points.

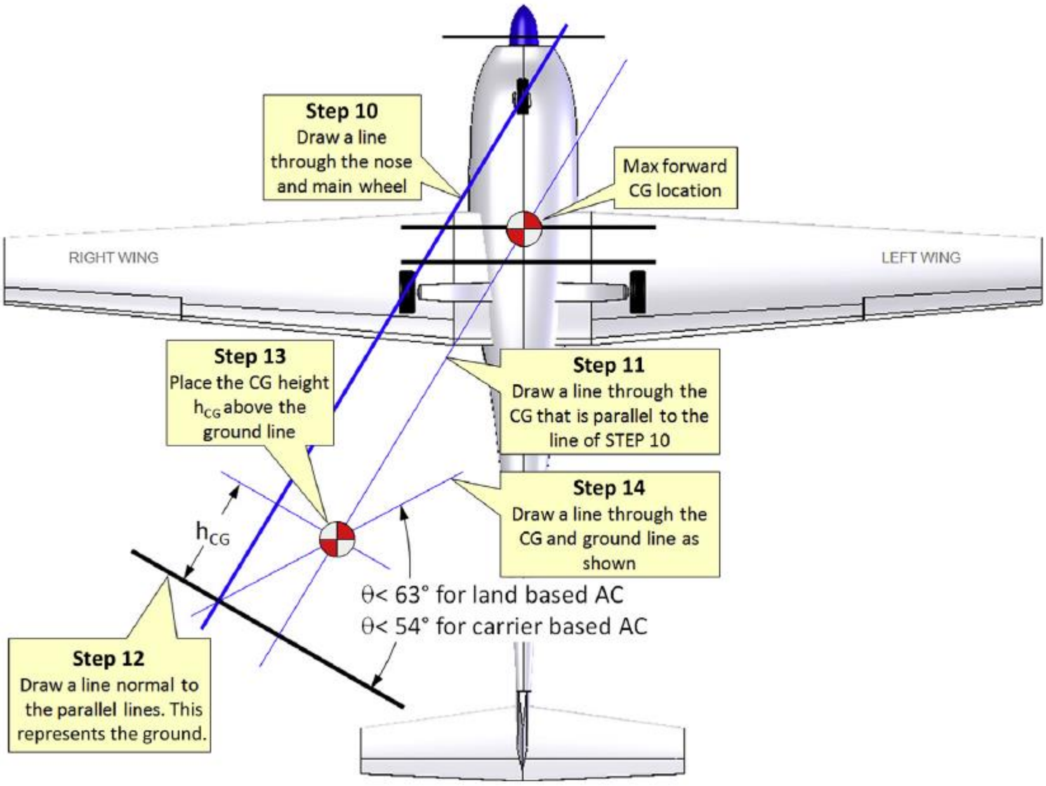

Figure 23 - Steps 10 to 14 of the landing gear geometry definition [13].

3.2. Type of retraction

Before picking the type of retraction to be used for the aircraft, several procedures must be followed as this section presents the hardest step upon designing a retractable landing gear solution. With the landing gear arrangement and wheels position defined, an evaluation must be done regarding where to store the landing gear in the aircraft. The most common places to store the landing gear after retraction are either in the fuselage or wings and in some cases additional compartments could be incorporated into the fuselage to store the wheels after retracting.

Defining the best place to store the wheels is not difficult, the difficulty lies in designing a simple, light, and robust mechanism to reposition the wheels from point A to point B. An evaluation of the several available positions and the complexity for each of the movements must be made. Despite a position appearing initially favorable, the required complexity of the mechanism to retract the landing gear may invalidate it in favor of another area.

The retraction movement has also a great impact on the travel of the center of gravity of the aircraft, so travel must be considered as the landing gear usually represents from 2.5 to 5 %

of the MTOW (Maximum takeoff weight). Due to this, an evaluation must be done with the landing gear deployed and retracted to analyze the impact on the aircraft.

Another major issue is identifying zones where the landing gear cannot move through. One clear example of this issue arises when a frame exists in the path of retraction, making it almost impossible to have enough clearance for the landing gear to pass through without compromising the structure. Another example is a requirement for a certain zone of the aircraft to be occupied with a payload or component that leaves no space for the landing gear to retract to that position. Figure 24 presents the most common fuselage structure components that must be considered upon deciding the retraction path.

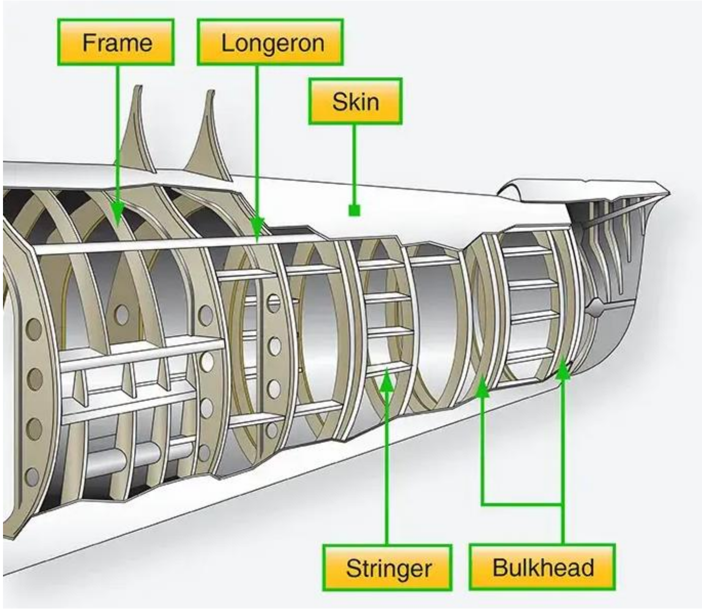

Figure 24 - Fuselage structure components [13]**.**

The aircraft geometry is also of huge importance, as some solutions are deemed suitable or not depending on it. For instance, a high or mid wing almost certainly invalidates the option to retract the landing gear to the wing, as the required length and weight would be a major disadvantage even if the wing retraction seemed ideal, causing most aircraft with high wings to retract the landing gear to the fuselage. A visual aid is present in Figure 25 to differentiate between the three most common wing positions. As it can be seen, the landing gear length greatly differentiates from one to another.

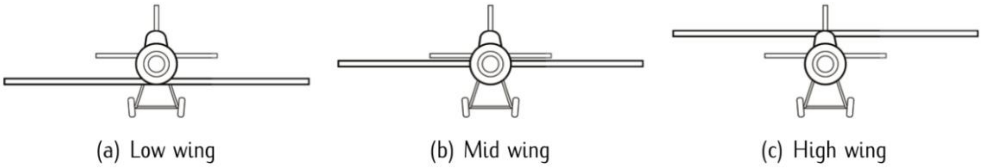

Figure 25 - Common wing positions [36].

As previously mentioned, not only must the landing gear retraction address all these issues, but it must also be as light as possible while ensuring that it is rigid enough to sustain heavy landings and strong impacts.

In summary, to decide the best approach for the type of retraction to implement, here are some of the characteristics that must be considered:

- Landing gear deployed position
- List of favorable retracted positions
- Areas/zones that must be avoided
- Aircraft geometry
- Dimension of the landing gear (Structure and wheels)
- Complexity, weight and rigidity of the solution

Depending on the position to retract to, there may be a requirement for the landing gear to fold or unfold, which has the benefit of being more compact but with the added difficulties of being heavier, more complex and more expensive.

3.3. Shock absorption

To be able to pick an existing solution for the shock absorption, an initial dimensioning must be made to find out the required diameter and stroke length. To proceed with this, the touchdown kinetic and potential energy must be determined, through a series of equations [23]:

$$E_t = 0.5(W_L)\left(\frac{v_z^2}{g}\right) + (W_L - L)s_s \tag{1}$$

- E_t – Touchdown energy in J
- W_L – Weight of the aircraft at landing in kg
- v_z – Vertical touch rate in m/s

- g – gravity in m/s^2
- L – Lift at landing in N
- s_s – Shock absorber stroke length in m

An assumption is made that all the energy at touchdown ends up being absorbed by the main landing gear, and that respective energy absorbed can be calculated with the following equation:

$$E_{absorbed} = W_L N_g (\eta_s s_s) \tag{2}$$

In which:

- $E_{absorbed}$ – Energy absorbed by the main landing gear in J
- N_g – Landing gear load factor
- η_s – Shock absorber efficiency

The values for the landing gear load factor and efficiency are presented in Table 3 and Table 4 respectively:

Table 3 - Gear Load Factors [37]**.**

Aircraft Type	N_g
Large Bomber	2.0-3.0
Commercial	2.7-3.0
General aviation	3.0
Air Force fighter	3.0-4.0
Navy fighter	5.0-6.0

Table 4 - Shock Absorber Efficiency [37].

Type	Efficiency
Steel Leaf Spring	0.50
Steel Coil Spring	0.62
Air Spring	0.45
Rubber Block	0.60
Rubber Bungee	0.58
Oleo-Pneumatic Fixed Orifice	0.65-0.80
Oleo-Pneumatic Metered Orifice	0.75-0.90
Tire	0.47

To continue with the dimensioning, W_L must be defined, through the following equation [23]:

$$W_L = n_s P_m \tag{3}$$

Where:

- n_s – Number of main gears struts
- P_m – Maximum static load per main strut in kg

Resulting in the following equation:

$$E_{absorbed} = n_s P_m N_g (\eta_s s_s) \tag{4}$$

Using equations 1 and 4, a relation can be made by equating the touchdown energy to energy absorbed to obtain the shock absorber stroke length.

$$n_s P_m N_g (\eta_s s_s) = 0.5(W_L)\left(\frac{v_z^2}{g}\right) + (W_L - L)s_s \tag{5}$$

A simplification can be made, if the lift generated during landing equals the weight of the aircraft, making the potential energy term inconsequential. With this simplification applied, the shock absorber stroke length can be calculated by:

$$s_s = \frac{\left[\frac{0.5(W_L)\left(\frac{v_z^2}{g}\right)}{n_s P_m N_g}\right]}{\eta_s} \tag{6}$$

Using the previous equation 6, a further simplification can be made:

$$s_s = \frac{v_z^2}{2gN_g\eta_s} \tag{7}$$

With this final equation, the value required for the stroke length will be obtained in meters and further converted to inches, as it is the most common unit in datasheets. Additionally, some conclusions can be reached regarding the importance of the aircraft parameters on the stroke length required, such as realizing that parameters such as weight do not come into account when dimensioning the required length. When searching for an appropriate market solution, some leeway must be added as a safety margin, with an appropriate value of around 0.75 to 1 inch.

To finalize the dimensioning of the shock absorber, the diameter of the inner struct can be estimated by the following equation, with the variable P_m in pounds for this equation [23]:

$$d_s = 0.041 + 0.0025{P_m}^{0.5} \tag{8}$$

Where:

- d_s – diameter in ft

As was done with the stroke length, this value will also be further converted to inches to facilitate searching for an adequate solution in datasheets.

With the diameter and stroke length obtained, a solution can be implemented for the appropriate aircraft as long as all the required parameters are obtained previously.

3.4. Braking system

To decide which braking solution to implement on the aircraft, some values must be previously acquired. The methodology involves calculating the required energy absorption and braking torque based on the aircraft’s mass, touchdown speed and geometry of the brakes. Properly dimensioning a brake is critical to ensure a safe and effective stop during landing.

The first step is to determine the landing kinetic energy (LK_e) to be absorbed by the brakes when landing. To obtain this value, the MTOW and the landing speed must be applied to the following formula:

$$LK_e = \frac{1}{2}mv^2 \tag{9}$$

Where:

- LK_e – Landing kinetic energy in J
- m – mass in kg
- v – landing speed in m/s

The value obtained will be the required energy to be absorbed by the braking system. As the braking system is composed of two brakes, the LK_e will be divided by 2 to account for each one. The selected brakes must be able to handle at least the value achieved.

The second value to be calculated is the braking force (F_b) necessary to achieve a desired deceleration rate. To obtain this force, Newton’s second law will be used:

$$F_b = m * a \tag{10}$$

Where:

- F_b – Braking force required in N
- m – mass in kg
- a – deceleration rate in m/s^2

With this value obtained, the next step is to calculate the required braking torque (T_b).

$$T_b = F_b * r_{eff} \tag{11}$$

Where:

- T_b – Braking torque in Nm
- r_{eff} – braking effective radius in m

To obtain the braking effective radius, contact must be made with the brakes supplier due to this value corresponding the radius of the brake pad point of contact in relation to the axis of rotation of the wheel.

These calculations will provide the two main values required for selecting a braking solution, the absorbed energy and braking torque, which the final option must surpass.

These values obtained can and should be converted to imperial units, as was done in chapter 3.3. because most suppliers provide their datasheets and catalogs with these units.

4. Results

In the present chapter, the results achieved will be presented, following the methodology presented in chapter 3.

4.1. Landing gear arrangement

The first step towards defining the landing gear position is to follow the guidelines previously mentioned in chapter 3.1., using all the information already acquired. To begin, the following parameters were defined:

- Aircraft side view in a cruise attitude with the mean geometric chord on the side view, as seen in Figure 26.

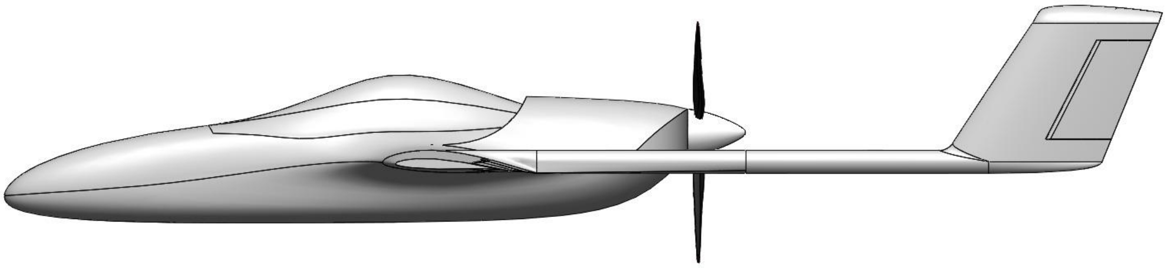

Figure 26 - Aircraft side view

- Top or bottom view of the aircraft, as displayed in Figure 27.

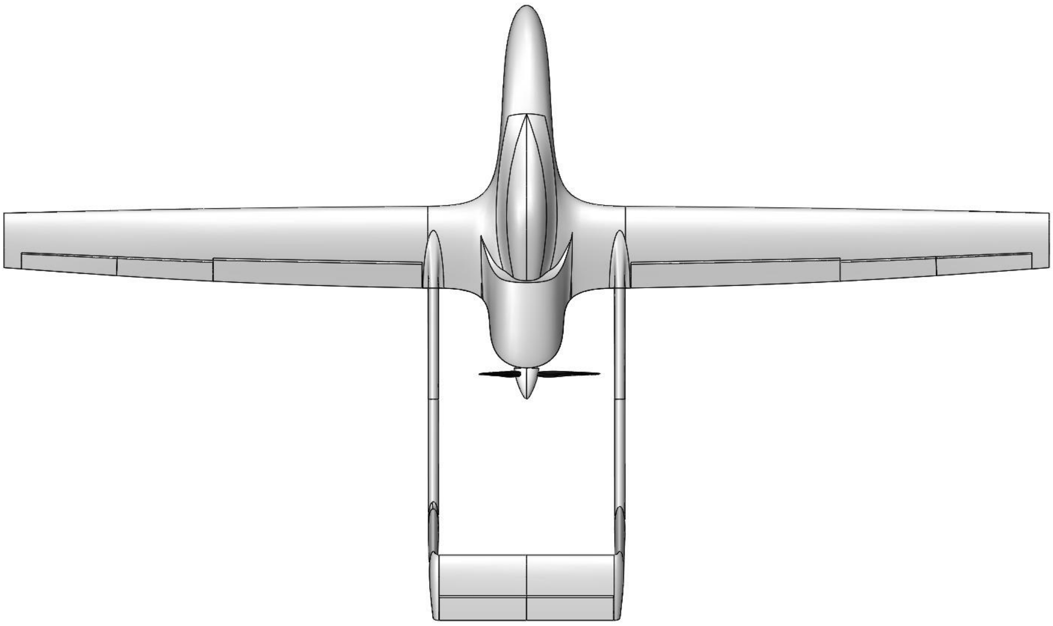

Figure 27 - Aircraft top view

- Completed CG envelope.

With the aforementioned parameters set, the series of steps mentioned previously were followed to ensure the correct positioning of the landing gear. The first steps were to define the forward and aft CG limits. The forward CG limit was set at 300 mm distance from the origin of the drawing, and the aft cg limit was assigned a value of 100 mm from the forward cg limit, equating to 15% of the MGC. Both these steps can be seen on Figure 28.

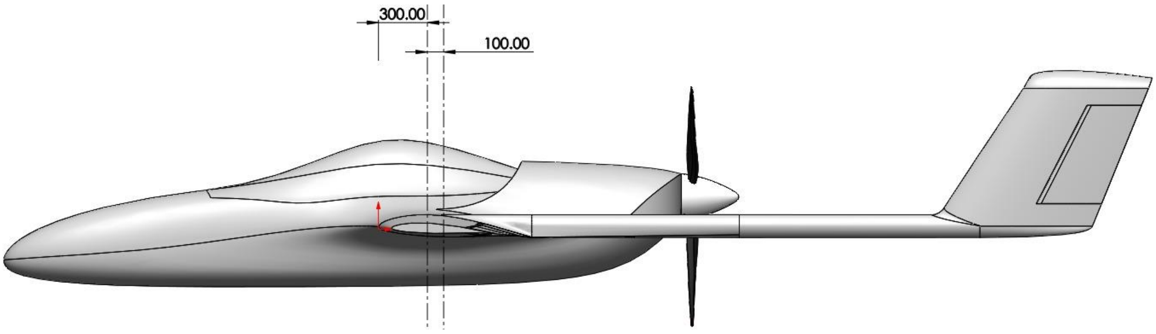

Figure 28 - CG and forward CG definition

The next steps consists in drawing two horizontal lines, one indicating the highest CG location, which in the present project corresponds to a line distanced 115.9 mm from the propeller center and the other one defining the propeller strike limit which is set distanced at least 7 inches from the tip of the propeller for the tricycle configuration. In order to calculate the propeller strike limit, equation 12 must be followed which uses the following variables:

- Propeller Diameter – 1700 mm
- Propeller Safety Margin – 177.80 mm or 7 in

In Figure 29, a distance of 1027.80 mm was set from the prop center, which was obtained by the following equations [13]:

$$Propeller\ Strike\ Limit = \frac{Propeller\ Diameter}{2} + Propeller\ Safety\ Margin \quad (12)$$

$$Propeller\ Strike\ Limit = \frac{1700\ mm}{2} + 177.80\ mm \quad (13)$$

$$Propeller\ Strike\ Limit = 1027.80\ mm \quad (14)$$

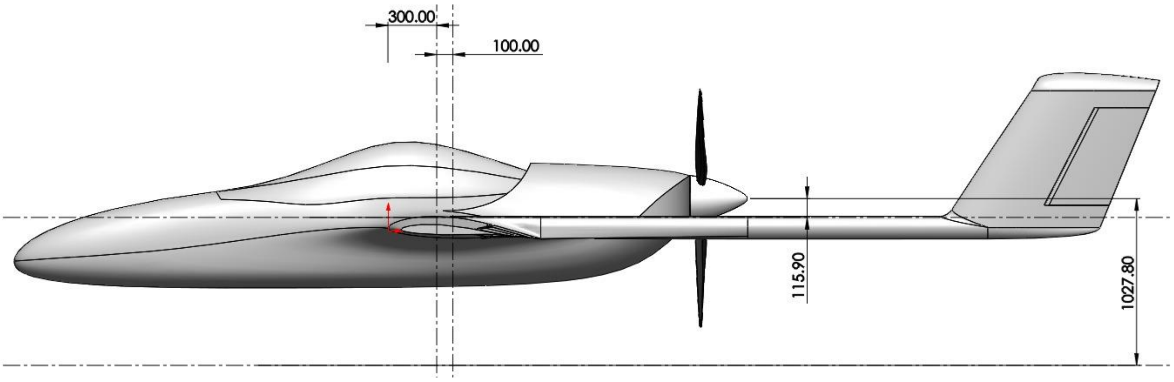

Figure 29 - Propeller strike line definition

The next step is to draw the tail line strike, angled at 12 degrees, which corresponds to the aircraft stall angle for the current aircraft. This line represents the ground during takeoff and flare. However, upon the placement of the tail strike line it was found that the propeller was intersecting the line, thus making the propeller the first point of contact on takeoff, which can easily be seen in Figure 30. With this in mind, the line drawn was placed at the tip of the propeller. For step 6, a line, also angled at 12 degrees is drawn passing through the intersection between the propeller line and the aft CG. The final step is to draw a vertical line in the intersection between these two lines.

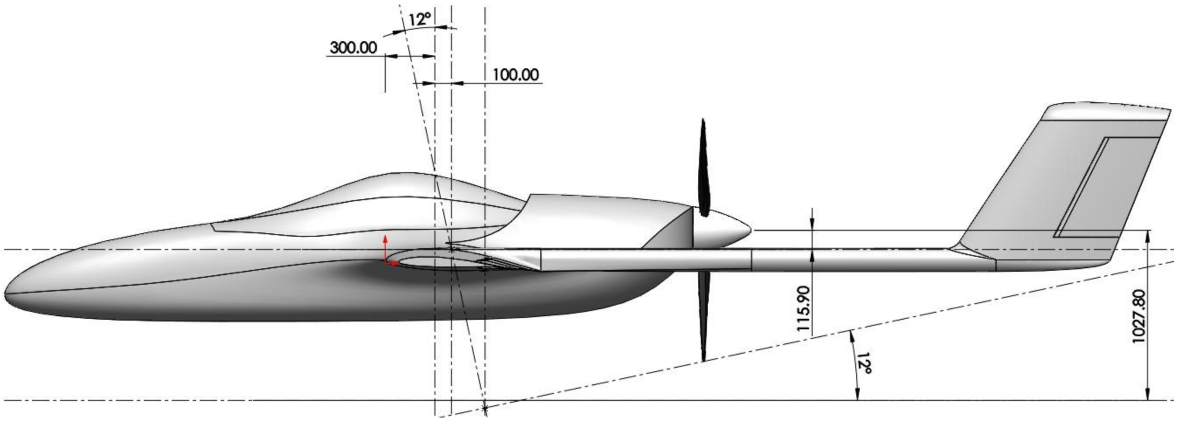

Figure 30 - Tail strike line and vertical wheel position line

Following this, both the main and nose landing wheels can be positioned. To place the main landing gear, simply use the intersection point defined previously which will serve as the contact point between the tire and the ground. To help visually, an additional horizontal line was drawn which represents the ground. For the front landing gear, the wheel must be placed on the same horizontal line, forward enough to ensure that the wheel does not carry more than 20% of the weight when the center of gravity is at the forward limit, but also making sure that there is enough clearance in the front for the landing gear to retract. In Figure 31, both the wheels are already visible, in the position defined by the previous steps as well as the h_{cg}, that is defined as the height dimension between the ground and the upmost cg limit, represented by the leftmost dimension of 957.27 mm. This value will be used in the next steps to help determine the maneuverability of the aircraft.

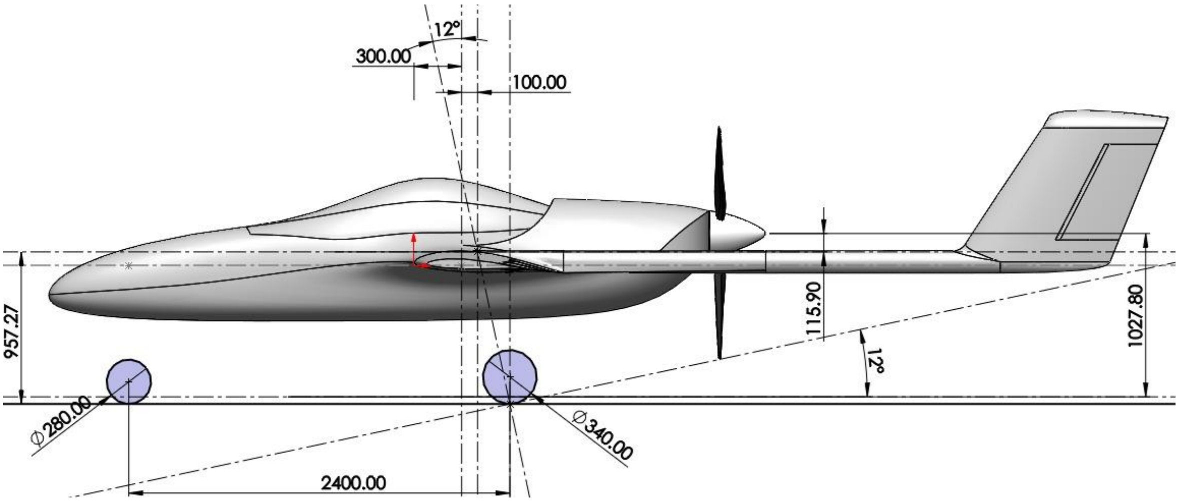

Figure 31 - Final steps towards wheels side position

The last step to finalize the placement of the landing gear is to verify the stability of the aircraft during taxiing and ground procedures. These steps help make sure that the wheels are correctly distanced horizontally, and that the wheelbase is enough for the required maneuverability. If the following steps result in an angle superior to the limit, steps must be taken to reduce this value to a suitable one. Using a view from the bottom of the aircraft, an initial line is placed through the center of the front and main landing gear, which must be defined with a set value distanced from the center, with this value depending in the result of the next steps. Then, a parallel is drawn passing through the forward cg. After this, a perpendicular line is sketched which represents the ground. With these steps already prepared, the value obtained previously, h_{cg}, can be used to distance another line, this one parallel to the previous one. A final line is inserted, passing through the two intersections established in the previous steps. This angle resulted in 60.21 degrees, as seen in Figure 32, which is inferior to the limit value of 63 degrees. If the aircraft in question was intended for a carrier-based mission, this value would have to be inferior to 54 degrees, which in the current case, is not required. As mentioned earlier, to reduce this value, the horizontal distance between the main landing wheels (Wheel-track) could be increased as well as increasing the distance between the axis of the front and main landing gear. If due to geometry limitations there was not a possibility of increasing these values further, another solution would be to reduce the height of the landing gear or a combination of the three solutions provided.

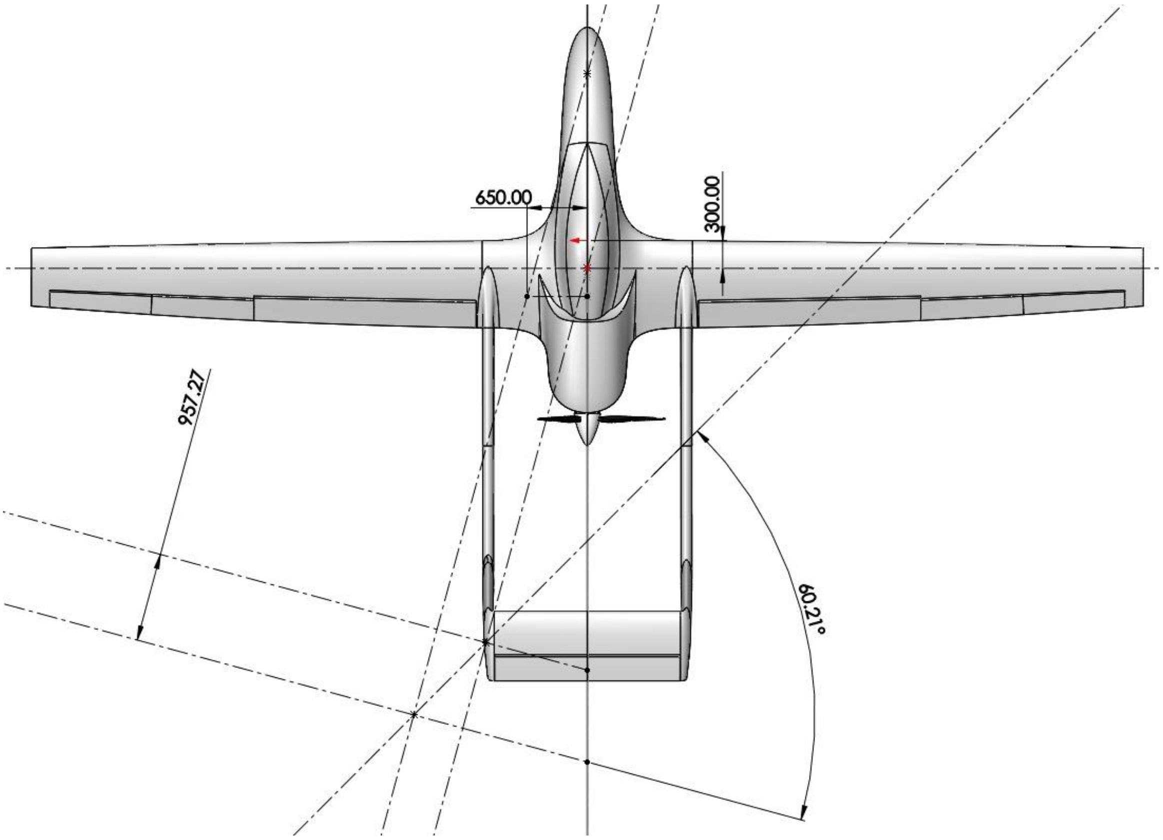

Figure 32 - Taxiing maneuverability verification

With these steps finalized, the aircraft has the landing gear arrangement defined, and in Figure 33, Figure 34 and Figure 35 the final position can be seen.

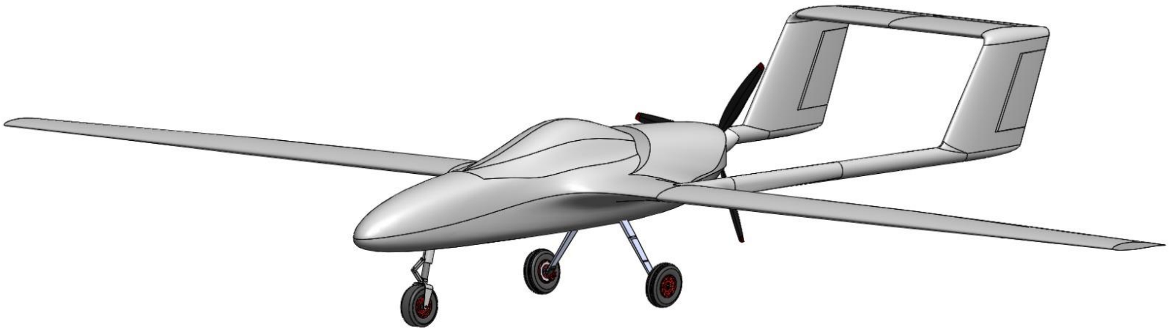

Figure 33 - Isometric view of the landing gear position

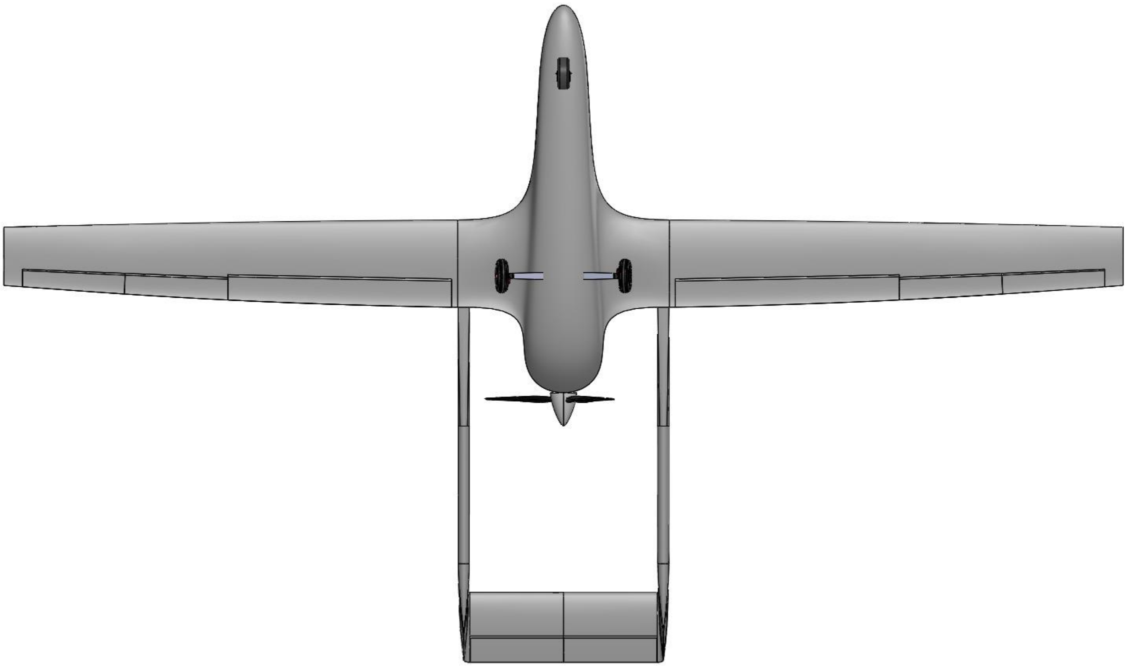

Figure 34 - Top view of the landing gear position

Figure 35 - Front view

4.2. Type of retraction

With the landing gear position defined, the next step is to decide where to store it during flight. As stated in chapter 3.2., the main challenge is to correctly identify the location most favorable to retract the landing gear to. To expedite this process, the list presented in the methodology chapter will be modified with additional information:

- Landing gear deployed position
    - Defined in the previous chapter, 4.1.
- Areas/zones that must be avoided
    - Underbelly of the aircraft due to payload requirements
    - Rear part of the aircraft due to engine placement

These restricted areas are identified in Figure 36, with a red color, with the green areas depicting the required length of the landing gear if retracted to the front as the back area cannot be used.

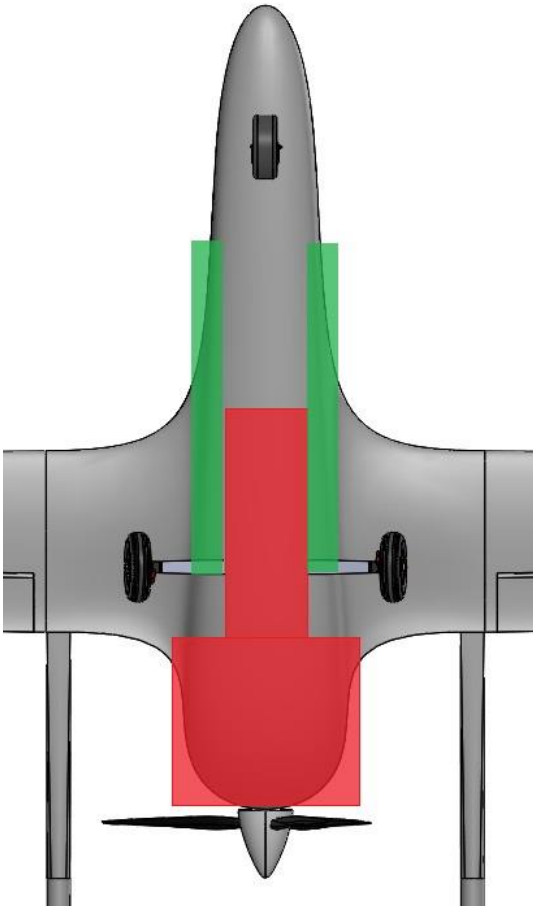

Figure 36 - Areas to avoid

- Aircraft geometry
    - Mid wing invalidating wing retraction solutions due to extended length
- List of favorable retracted positions
    - Side of the fuselage
    - Additional wheel bays

The other two components of the list will be different depending on the position defined for the landing gear, thus not requiring an initial focus.

- Dimension of the landing gear (Structure and wheels)
- Complexity, weight, and rigidity of the solution

With the preliminary points established, two apparent positions seem more favorable, making each of them a candidate for the final position. The next step involves analyzing the feasibility of each candidate as well as the complexity for the retraction movement.

Both solutions utilize the same basic area of the fuselage, the sides. However, one of them involves adding additional bays to the exterior while the other one will occupy volume inside the aircraft when retracted. With this in mind, a comparison must be made between the two solutions to decide which one is more suitable for the project’s needs.

Opting for a solution with the wheels stored inside the fuselage is optimal in regard to drag and endurance, as this solution does not imply any modification to the exterior of the aircraft, so it presents less drag when compared to adding additional bays to the exterior, thus increasing the volume of the aircraft. These two points are one of the most important aspects to keep in mind as the main focus of the aircraft is to fly as long and as efficiently as possible, so minimizing drag is a major advantage.

However, utilizing wheel bays has several advantages, despite the extra drag and weight added. Besides ensuring that no volume is restricted inside the aircraft, enabling additional payload or fuel, having a separate region for such a vital component of the aircraft may be an important decision, as it serves as a safety measure, so that in any worst-case scenario, the landing gear can still deploy. But the main advantage comes from the possibility of changing configurations, so that if required that the aircraft does not have a retractable landing gear, the wheel bays can simply be removed, and a fixed landing gear can be used instead. By using this system, the aircraft ends up having two possibilities for the landing gear depending on the mission, one with a retractable landing gear and another with a fixed one.

With the two options compared, and despite the major disadvantage of causing more drag in the aircraft, the solution chosen was of adding additional wheels bays for the retractable landing gear.

In regard to the retraction mechanism itself, the solution deemed more fit for the aircraft is an electric actuator, similar to the one present in Figure 37, mainly due to their reliability and weight efficiency, as the landing gear structure must be lighter than most available on the market due to the weight limitations thus not requiring any excessive power, and the mechanism will not have folding linkage in the strut of the landing gear, as despite the advantages of resulting in a more compact solution, the additional weight and complexity of the mechanism would make it so that the disadvantages would outweigh the advantages.

Figure 37 - Electromechanical Linear Landing Gear Actuator with Integrated Emergency Backup [38]**.**

This actuator must have an emergency backup system, as in case of emergency, the landing gear must always deploy, making this parameter one of the most crucial requirements when selecting a suitable actuator.

In Figure 38, a retraction system can be observed, with a movement similar to the desired for the project, currently being developed by the company Dark Aero, for their prototype airplane.

Figure 38 - Dark Aero 1 Landing Gear [39]**.**

4.3. Shock absorption

With the methodology already defined above and the previous steps already elaborated, the next step is to proceed with dimensioning of the required stroke and diameter for the shock absorber. After obtaining these values, extensive online or catalog research should be done to find the better suited options for the system.

To start the dimensioning of the stroke, the following variables must be obtained:

- Vertical touch rate in m/s
- Gravity in m/s^2
- Landing gear load factor
- Shock absorber efficiency

With all these values obtained, the vertical wheel travel or stroke can be calculated using the equation 7, mentioned in chapter 3.3.

To dimension the shock absorber for this project, the following values were assigned to each of the variables:

- Vertical touch rate – 3.05 m/s
- Gravity – 9.81 m/s^2
- Landing gear load factor – 3.0
- Shock absorber efficiency – 0.8

By applying these values to equation 7, the following value can be obtained:

$$s_s = \frac{3.05^2}{2 * 9.81 * 3 * 0.8} \tag{15}$$

$$s_s = \ 0.198\, m \tag{16}$$

Converting this value from m to inches we get the result of 7.8 inches, and with the safety margin of 1 inch, we get a required stroke length of 8.8 inches.

To calculate the diameter of the struct, the only value needed is the maximum static load per main gear, which will be applied to equation 8. The value for the maximum static load was obtained by the following equation:

$$Load\ per\ strut = \frac{W_L}{2} \tag{17}$$

$$Load\ per\ strut = \frac{600}{2} \tag{18}$$

$$Load\ per\ strut = 300\ kg \tag{19}$$

After obtaining this value, a conversion was made to pounds.

- Maximum static load per strut – 661.39 lbs

By applying this value in equation 8, the diameter value can be obtained.

$$d_s = 0.041 + 0.0025{P_m}^{0.5} \tag{20}$$

$$d_s = 0.041 + 0.0025 * 661.39^{0.5} \tag{21}$$

$$d_s = 0.105\ ft \tag{22}$$

Converting this value to mm from feet, a value of 32 mm is obtained for the diameter of the cylinder appropriate for the shock absorption requirements.

With these two values obtained, a solution with similar or higher values shall be obtained to provide the necessary shock absorption requirements.

A very simplified solution with the acquired dimensions was modeled just to exemplify the required oleo strut as well as serving as a component for the landing gear system. Figure 39 and Figure 40 display the modeled solution in an isometric and section view with some of the interior components modeled.

Figure 39 – Oleo Pneumatic model

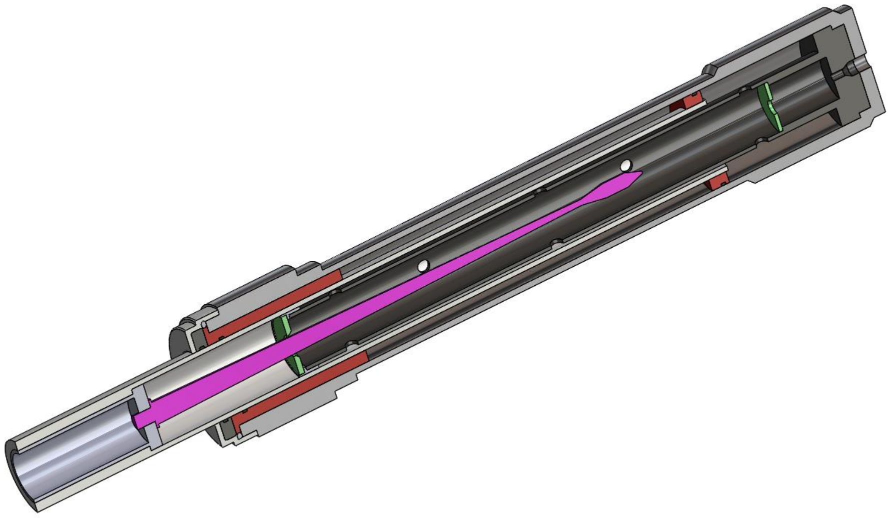

Figure 40 - Oleo Pneumatic model section view

The displayed oleo-pneumatic shock absorber, coupled with a torque link to the landing gear structure will provide the required dampening. The torque link has the purpose of connecting the two telescoping cylinders as well as preventing the relative rotation of the piston, thus maintaining wheel alignment during taxing [40].

4.4. Braking system

The last step regarding the landing gear structure is to dimension the braking system to ensure it meets the requirements of the aircraft. As explained in the methodology section

3.4, the equations presented there will be applied to discover minimum braking requirements.

The first step relies in calculating the landing kinetic energy (LK_e) with equation 23 and 24, which requires the following values:

- Weight of the aircraft – 600 kg
- Landing speed – 29.85 m/s

$$LK_e = \frac{1}{2} * 600 * 29.85^2 \tag{23}$$

$$LK_e = 267306.75\,J \tag{24}$$

The value obtained is in joules, however, it will be converted to ft.lbf as most manufacturers provide the datasheets in imperial units, making it 197155.34 ft.lbf.

As the landing gear has two brakes, this value must be divided, equation 25 and 26, to account for each one.

$$LK_e\ per\ brake = \frac{197155.34}{2} \tag{25}$$

$$LK_e\ per\ brake = 98577.67\ ft.lbf \tag{26}$$

When selecting a suitable brake, a precaution must be made to ensure it is able to absorb at least 98465.8 ft-lbf.

For the braking force, a deceleration value had to be defined. A worst-case scenario was assumed, in which there was a need to land the aircraft in a short runway, around 400m. With this value in mind, the deceleration value can be obtained due to previous information regarding the landing speed, of 58 knots, presented in chapter 2.3.

$${v_f}^2 = {v_i}^2 + 2 * a * d \tag{27}$$

Where:

- v_f – Final velocity in m/s
- v_i – Landing velocity in m/s
- a – deceleration in m/s^2
- d – Distance required in meters

The landing speed must be converted to m/s, resulting in the value of 29.84 m/s. These values can now be applied in equation 28.

$$0^2 = 29.84^2 + 2 * a * 400 \tag{28}$$

$$a = -1.11\, m/s^2 \tag{29}$$

This value is rounded to 2 m/s^2 as a safety margin and can be further used to calculate the required force and torque.

By using equation 10 we get the following:

$$F_b = 600 * 2 \tag{30}$$

$$F_b = 1200\, N \tag{31}$$

As was done for the kinetic energy, this value will also be converted to lbf due to manufacturers datasheets, resulting in a value of 269.77 lbf.

$$F_b\ per\ brake = \frac{269.77}{2} \tag{32}$$

$$F_b\ per\ brake = 134.86\ lbf \tag{33}$$

The last step is to obtain the required braking torque (T_b), by multiplying the value above by the braking effective radius, done in equations 34 and 35. This value was obtained through consulting several catalogues and finding a suitable solution for the calculations done above. If the torque calculation obtained is below the limit set by the manufacturer, then the brake can be considered appropriate and be selected.

The value for the effective braking radius obtained is 3.9 in. As stated in chapter 3.4, this value was obtained by contacting a suitable brake supplier and receiving this dimension, measuring from the axis of rotation to the point of contact of the brake pad.

$$T_b = 134.86 * 3.9 \tag{34}$$

$$T_b = 525.95\ lbf.in \tag{35}$$

Each brake must be able to produce at least 1315.16 lbf.in of torque to brake the aircraft in safety, for the conditions predetermined.

In summary, the values required for the braking system are as follows:

- Energy absorption per brake: 98577.67 ft.lbf
- Braking torque per brake: 525.95 lbf.in

These values are then to be used while procuring brakes datasheets from manufacturers, such as the Figure 41, which displays a possible solution for the braking requirements.

Figure 41 - Beringer aero braking system [41].

As it was previously presented in chapter 2.4., there are still many other steps to take when deciding the final type and solution for braking the aircraft, however two of those presented, the anti-skid system and material of the brakes will be considered when picking the appropriate brake from manufactures datasheets and if necessary, air brakes will be further implemented if the brakes selected end up not being powerful enough for the missions operated.

5. Conclusion

As the current project comes to a close, some conclusions can be reached which will help determine what future tasks must be done to develop a fully defined solution. As was done throughout the project, the conclusion will also be divided into four parts to summarize the results reached through the document. As the full development of a landing gear would be far more extensive than the duration of writing this project, a chapter regarding future works will follow explaining and detailing what must still be done in order to reach a real-life solution, ready to be implemented and tested.

As was done and mentioned previously, the first part to be addressed in the conclusion is the landing gear arrangement definition. The arrangement was selected as the first to be done as it was critical for some of the other parts and due to this, the first steps of defining the landing gear arrangement were done early on, with the aircraft in a very draft state, without a well-defined structure which would impact the overall progress as it was critical to have a side and top view, as well as the CG envelope, which resulted in some mishaps and some modifications throughout the project. With the continuous development of both the aircraft and the landing gear, the current defined position will probably still undergo changes, however, the groundwork is already set and can be easily redone to suit the new structure.

Concerning the retraction type, the main focus was to first identify which areas of the aircraft could and could not be used, with this step proving to be a difficult one as the initial fuselage design deemed it almost impossible to fit the landing gear anywhere. Due to this, a different approach was idealized, with the retractable landing gear being a possible feature of the aircraft, by adding exterior bays to the sides of the aircraft, providing a storage solution that would have no impact on the current design. Several other problems, such as the proximity to the engine and the choice of a mid-wing design made other retraction movements difficult to idealize, thus leaving only one possible alternative, with the wheels retracting to the front of the fuselage, against the wind, but with the added benefit of being easier to deploy in case of emergency. The mechanism for retracting the whole system will be an electric actuator, with a great focus on backup systems and a state of always deployed in case of emergency.

For the shock absorption chapter, the main focus was to pick and dimension a suitable solution, to then select an appropriate product capable of the loads calculated. To do this, an initial analysis was done regarding the available options and the advantages and disadvantages of each. After this step, the option that seemed more suited for the requirements was an oleo pneumatic with a telescopic structure due to several benefits compared to the alternatives. With the option selected, the next steps involved defining the required variables for the dimensioning and solving the equations to find out the necessary travel and diameter of the cylinder. The final solution was then drafted in a 3D model to then be integrated along the continuation of the landing gear development. However, as the cylinder is to be acquired from a manufacturer, the next step should be to find a suitable solution in catalogues, and then modify the drafted design to fit the purchasable oleo-pneumatic, thus ensuring that the design matches the final product received.

For the chapters regarding the braking system, a similar approach to the one used for the shock absorption was used, with an initial analysis of the required steps to take and which aspects to include in the system. However, the main goal was to dimension the brakes, which resulted in a series of equations with parameter such as the mass, landing speed and deceleration rate used to calculate the energy absorption required as well as the torque, thus enabling the next step of procuring products that fit these values. After finding some alternatives, the next step is to compare them in terms of the additional features, such as the material of the brakes and whether or not the system includes an anti-skid solution, as both features can be significantly advantageous.

The project, with the current prototype designed present in Figure 42, ends up being a simple start to the full development of a landing gear system, however, the main objectives were met and are able to sustain the continued development of further steps. As stated, if required, any of the dimensioned parts can be easily changed, as both the structure and mission can alter, resulting in different requirements and goals.

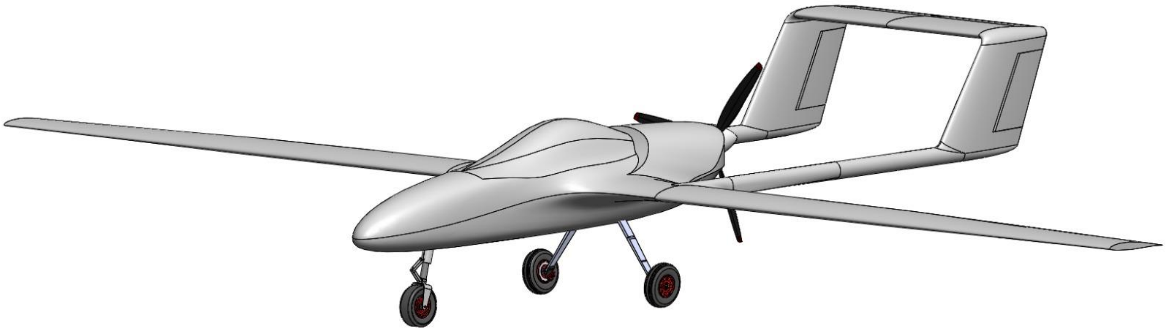

Figure 42 - Aircraft prototype

6. Future works

As this project is related to a continuous development of an aircraft, the requirements and goals suffer constant changes, which in turn equates to several values and geometries used throughout the project to alter slightly. With this in mind, the project must be regarded as a first proposal for the landing gear solution, with several steps to be taken before developing and presenting a complete first solution. The solution briefly covers some requirements as well as suggests a possible geometry regarding the retraction movement. As stated in the methodology chapter, steps like dimensioning and completely designing the retracting mechanism must be done as well as ensuring that all the requirements set by the EASA documentation are met, which results in an extensive development of the structure. Only after these steps can the first landing gear prototype be considered finished, proceeding to the testing/simulation path.

The main goal of these tests will be to evaluate the effectiveness of the solution in the aircraft through several simulations to decide what needs to be altered. After deciding on a final version, the next steps require physical tests to landing gear structure in several landing and takeoff scenarios to ensure that it is structurally sound and if there is any chance to reduce the weight of the structure if needed, as the solution being light remains one of the top priorities.

With the mechanical solution validated, several other steps must be addressed, with one of the most critical ones making sure that the system is safe and redundant, as the proposed solution represents a retractable landing gear, in case of emergency it must extend and remain locked.

After ensuring that all the failure points are met, that the structure meets all the mechanical requirements and that the solution is adequate for the aircraft, then the development of the landing gear can be concluded.

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