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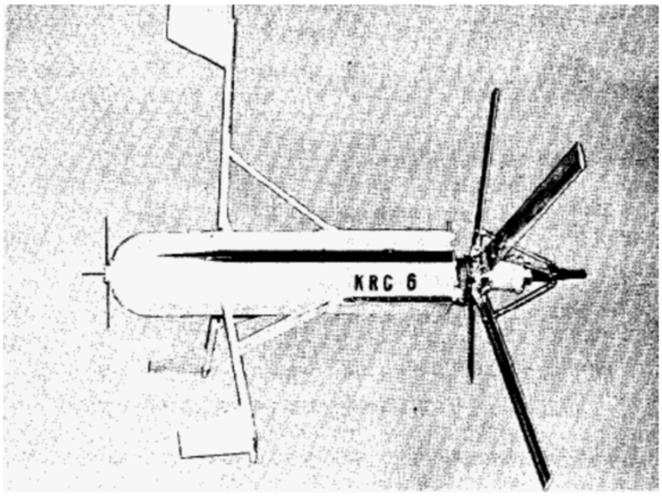

Pararotor Recovery System Design

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Project in Aerospace Engineering

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Executive Summary

This report provides a comprehensive analysis of spacecraft recovery systems, emphasising the aerodynamics of the rotor during autorotation. Subjects covered include parachute use in space missions, controlled thrust vector systems, and crucial part recovery for heavy-lift launchers. The study assesses the benefits and drawbacks of recovery methods and suggests a unique rotating wing design for secure landings. It emphasises Mars exploration, evaluates a spinning entry vehicle experimentally, and supports reusable parts. Numerical simulations, Prandtl tip loss functions, and blade element momentum theory are used to investigate aerodynamic characteristics.

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Abbreviations

SMART	Sensible Modular Autonomous Return Technology
ULA	United Launch Alliance
EDL	Entry, Descent, and Landing
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
MAR	Mid-Air Retrieval
RLVs	Reusable Launch Vehicles
SSA	Students' Space Association
SAR	Search and Rescue
NASA	National Aeronautics and Space Administration

Nomenclature

Greek Symbols

α	Angle of attack
$\bar{M}_\beta$	Aerodynamic moment
Ω	Rotational velocity
ϕ	Inflow angle
ψ	Azhimutal position
ρ	Density
ρ	Lock number
θ	Pitch angle

Roman Symbols

$\mathrm{d}D$	Section drag force
$\mathrm{d}F_x$	Section horizontal force
$\mathrm{d}F_z$	Section vertical force
$\mathrm{d}L$	Section lift force
$\mathrm{d}y$	Width of a elementary section blade length
$\vec{N_b}$	Number of blade
$\vec{P_h}$	Rotational propulsion force
$\vec{T}$	Vertical Propulsive force
$\vec{U_P}$	Vertical velocity component
$\vec{U_R}$	Transverse velocity component
$\vec{U_T}$	Horizontal velocity component
$\vec{U}$	Inflow velocity

c	Blade chord
C_d	Drag coefficient
C_l	Lift coefficient
h	Altitude
p	Local pressure
R	Distance from the axis to the tip of the blade
r	Adimensional blade length
r_0	Distance from the axis to the beginning of the blade
T	Local temperature

Chapter 1

Introduction

1.1 Motivation

The space race between the United States and Russia was a reality that drove technological advances since then. Reaching the moon was an inherent goal in this competition won by the United States. For years, only government agencies have conducted space missions primarily for scientific purposes. With the demand for space missions, it became necessary to look at space vehicles from a different perspective, with the goal of making them profitable [1]. An example of this change in the paradigm of space travel is the Space Shuttle programme, a reusable spacecraft that allowed multiple flights and therefore contributed to the construction of the International Space Station (ISS). However, in recent years, the "space race" has been dominated mainly by private companies [1–3]. These companies have undergone significant technological processes with the aim of reaching space.

There is currently a slow but steady increase in private companies involved in space commerce [4]. There are several causes and/or development reasons for this trend, and technological progress is playing a crucial role in making space travel not only more financially accessible, but also safer [5]. Technological advancement also has brought about clear improvements in other areas, such as telecommunications [6, 7].

Safety issues are critical for proper functioning and sense of space missions to, minimising risk to human life and cargo loss [5]. These safety issues are something NASA has taken into account [8], since the early days of human space travel and more recently other international agencies to improve the risk analysis of space travel. However, economic problems compel private companies to minimise the operating costs per space mission. An increase in the performance of both launchers and the remaining stages is inherent and necessary for the expansion of a new space ecosystem that underlies this technological progress [6]. This space ecosystem is based on launcher systems, space platforms, manufacturing processes, and materials [6], which form the basis for studies that are currently being conducted.

To address economic challenges, one of the systems that has been extensively studied and becomes crucial during a space mission is the Entry, Descent, and Landing (EDL) system [9]. NASA initially employed parachute systems, figure 1.2, for the recovery of astronaut capsules [10]. Nowadays, SpaceX [2] and many other companies are making efforts onstudies about the use a recovery system based on a controlled thrust vector, as

Figure 1.1: Parachute recovery system (from: https://en.wikipedia.org/)

Figure 1.2: Controlled thrust vector recovery system (from: https://www.space.com/)

shown in figure 1.2.

When comparing these two methods, it can be seen that both have advantages and disadvantages [11]. The parachute system can achieve acceptable performance at a reduced cost, but it lacks control over both the descent speed and trajectory, making the vehicle's entry and/or recovery unpredictable [12]. On the other hand, the controlled thrust vector system allows control over both the descent speed and trajectory, allowing a safe and controlled landing at the desired location. However, this system has disadvantages in its development and installation [12]. Firstly, extra fuel is needed to execute the landing stage, adding mass to the launch and requiring larger and more powerful engines. Second, there is not only the cost of the entire system, but also the cost of the additional fuel. Finally, this system is complex and susceptible to various failures, such as observed in several SpaceX tests [2].

With the goal of overcoming the disadvantages and ensuring the advantages of both methods, it is intended to develop a recovery system with a rotary wing, figure 1.3, under the effect of autorotation. This system has been under development over the years [9], but it has never been put into practice, possibly due to lack of technology and economic interest [11]. Nevertheless, this is a recovery method that offers the possibility of re-usability, manoeuvrability, and economic viability. Furthermore, considering the use of the rotary wing in autorotation, as required in a helicopter, it is possible to make a controlled and safe landing.

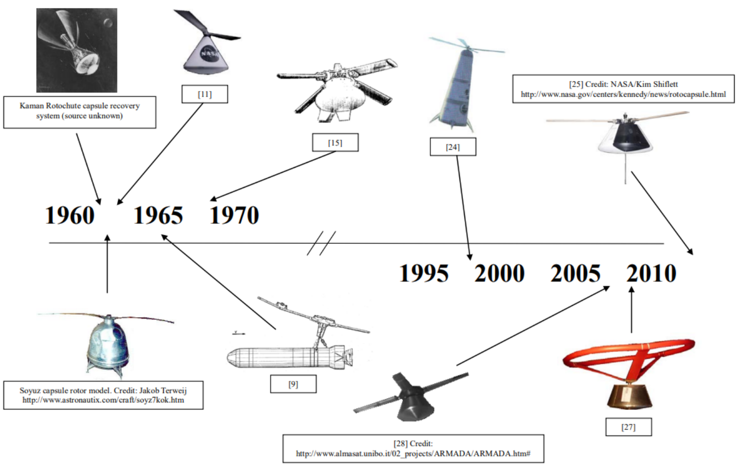

Figure 1.3: Different rotary wing recovery system over the last years, taken from [9]

For these reasons and considering technological advancements, it is asserted that this recovery method is undoubtedly a topic still open and with a long way to go. Thus, the viability and characteristics of the system, as well as the phenomenon of autorotation, are the topics addressed in this present work.

1.2 Topic Overview

When it comes to helicopter emergency manoeuvres, autorotation is one of the most important skills that pilots use in the event of a failure of the engine [13]. This method uses a controlled fall that starts with reducing the collective pitch control. Then it uses upward airflow to provide lift, maintain rotation of the rotor blade, and postpone descent. To maintain control throughout the manoeuvre, the pilots adjust the direction and attitude of the helicopter using cyclic control. The pilot performs a flare, further slowing the descent velocity as the helicopter gets closer to Earth by lowering the collective a little. Because auto-rotation is a skill that is acquired via extensive training, it is a dependable way for pilots to land safely in the event of unplanned power outages, which greatly enhances aviation safety in general.

Comparably, more sophisticated technologies have replaced conventional parachute systems in the investigation of recovery systems in space missions. In particular, the controlled thrust vector recovery system poses development, installation, and cost issues despite providing precise control over the descent speed and trajectory [14]. In light of these factors, a novel method using a rotary wing recovery system under autorotation effect appears in light of these factors. This method has been developed for years, but it has not been put into practice, probably because of financial and/or technological limitations.

By combining the benefits of controlled thrust vector and parachute systems, the suggested rotary wing recovery system promises maneuverability, economic feasibility, and reusability. Using autorotation, similar in a helicopter, the technology ensures a safe and controlled landing. This recovery approach is still a promising and unexplored area in the rapidly changing field of technical developments, and further research is necessary to fully realise its potential. The complex properties of the system and the phenomenon of auto-rotation serve as the main topics of current research.

1.3 Objectives

Previous studies have been conducted to explore the use of auto-rotation phenomena as a recovery method for spacecraft vehicles. Specifically, the master's thesis by Marques [11] investigated the phenomena in axial flight, demonstrating through simulations that the system functions as expected. However, certain aerodynamic considerations and assumptions were made in order to initiate the initial simulation approach.

The next proposed steps include the examination of horizontal motion (glide), blade flapping motion, high angles of attack, and other aerodynamic effects. So this work has as its main objective continue the work developed using rotor recovery systems. To do so, the following objectives are defined:

- Research on recovery methods and comparison
- Study the phenomena of autorotation

- State of the art of rotary wings aerodynamics

1.4 Document Outline

The document is divided into two parts regarding the state of the about rocket recovery methods and the principle of autorotation exploring mathematical models.

The chapter 2 reviews the state of rocket recovery today, examining a range of devices from simple parachutes to sophisticated propulsive landing systems. It analyses descent, atmospheric re-entry, and precise landing successes and difficulties. To find opportunities for innovation and efficiency in space missions, the role of machine learning in improving recovery processes and autonomous navigation is emphasised.

Focusing on autorotation, a crucial idea in aerodynamics, chapter 3 examines the fundamental mathematical models behind it. Examining how self-sustaining rotating objects, such as helicopter rotors, function without engine power, the study breaks down factors including airspeed, blade pitch, and rotor design. It provides insights on forecasting and managing autorotation through the presentation of equations and simulations. Applications in the real world demonstrate how these models may be used practically in engineering and aviation, which helps to clarify the fundamentals of aerodynamics.

Chapter 2

Spacecraft Recovery Methods

In this chapter, the intention is to conduct an analysis of the state of the art regarding retrieval methods to comprehend the technological advancements made in recent years. The aim is also to understand how retrieval methods with autorotation have been utilised. Thus, information on some scientific articles from the past few years is presented.

Nowadays the technology advancements are being developed in order to recovery the most expsensive parts of a rocket, specially the booster. The research paper **Rocket Booster Recovery Analysis** [15], from China Satellite Maritime Tracking and Control Department, provides an extensive analysis spanning over a 12-year period, focussing on the development, testing, and methodology of recovery systems in sounding rockets by the Students' Space Association (SSA) at Warsaw University of Technology. The paper delves into the design, development, and testing of parachute-based recovery systems across various rockets, encompassing the design methodology, parachute shapes, deployment schemes, and deployment force analyses.

The methodology, design, and testing procedures used by SSA are detailed in the research paper. It highlights the iterative nature of the recovery system design process, involving steps such as defining mission scenarios, preliminary functional requirements, and critical parameters. The design process encompasses CAD modelling, calculations, and ground testing, leading to flight tests for real-world performance validation. Post-flight data analysis, including GNSS position, static pressure, and acceleration, is crucial for evaluating the characteristics of the recovery system and comparing them with the assumed values during the design phase.

The comprehensive overview of recovery systems provided in the paper extends beyond individual rocket projects. The results of the material and functional tests contribute to a broader understanding of recovery system design and testing processes. The document serves as a repository of experiential knowledge, offering lessons learned and best practices that transcend individual projects.

Furthermore, the research paper serves as a valuable resource for individuals and organisations involved in sounding rocket recovery system development. The detailed methodologies, insights, and lessons learned from SSA's 12-year experience provide a foundation for advancing recovery system design, testing, and implementation. The paper offers practical knowledge that can be leveraged by researchers, engineers, and organisations in the aerospace industry to enhance their own recovery system projects.

In conclusion, the research paper not only provides a comprehensive analysis of recovery system development but also provides valuable information on the iterative and challenging nature of the process. SSA's extensive experience, presented in a systematic and detailed manner, positions the paper as a key resource for the advancement of recovery system technologies in the field of aerospace engineering.

Another study about recovery system using a parachute. The paper **Parachute-Payload System Flight Dynamics and Trajectory Simulatio** [16], looks at many uses and air features of parachutes in space jobs. It talks a lot about structure details, how things interact with nearby wind speed moving around them. The task of making a reliable parachute model is hard. This comes mainly from issues such as slow, messy, and divided airflow flying around in the sky. A complete computer method to simulate, (figure 2.1) interactions between parachutes and fluids is shown.

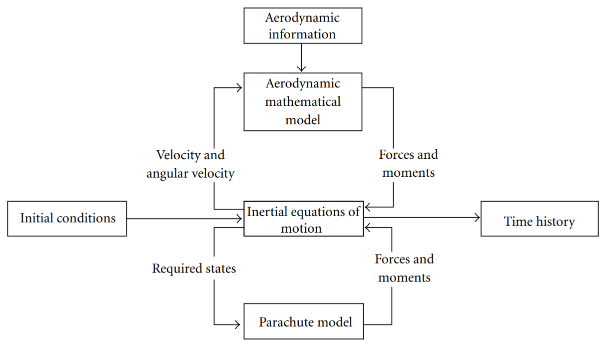

Figure 2.1: Flow chart of the simulation model, from [16]

Parachutes are made to slow down and balance things during flight. Their shape is really important for this job. Different parachute types are made for many uses, including pilot, dragging, or slow-down. There are also ones used for going down safely outside the plane and extracting people who need help inside a burning building. This includes making sure they land just right at aircraft strip to keep from damage stuff around there.

The paper explains the hard part of making a good model for parachute movement. It highlights how structure and air flow are connected together. It talks about how fixed or steady-state conditions can affect balance. This might change the way both things being held back by parachutes and their load move, based on possible separation of air around them. The need to accurately check balance for a successful mission is shown, along with ways to measure how things move.

The second part of the paper focuses on balance and imbalance in round shapes, such as large cone angles or ball-shaped containers when entering planets or air. It also discusses problems with measuring things that help probes and space capsules stay balanced. It talks about the shortcomings of analytical methods and wind tunnel tests. It promotes making numerical data available for use. The study looks at how parachutes and payloads react when they move fast or slow, as well as the influence of fluid flow on them. It also compares different computer models to see which one works best for these situations.

In the end, this paper gives a complete look at how parachutes are used and their flying features in space. It shows the complicated workings and problems of taking parachute actions, focussing on how important it is to get the correct balance for successful tasks. The full study looks at how parachutes work with air pressure.

In the other hand over the years new recovery methods have been under developed. The research **A**

recovery system for the key components of the first stage of a heavy launch vehicle [17] outlined in the mentioned article focuses on conducting a feasibility study of a recovery system aimed at reusing the engine and engine frame of an existing heavy launch vehicle, especially the Ariane 6 launcher. This study is based on the work of 10 Bachelor Aerospace students at Delft University of Technology and aims to explore the integration of novel recovery system elements into an existing launcher design to enable partial reusability.

The innovative recovery concept discussed in the study encompasses several crucial aspects, including recovery of the engine bay, protection and deceleration during reentry, parafoil-guided descent, and mid-air retrieval by a helicopter, figure 2.2. The study also focusses on the evaluation of 2different recovery system concepts, providing detailed mission profiles, figure 2.3, and discussing the integration of the proposed system with the launcher.

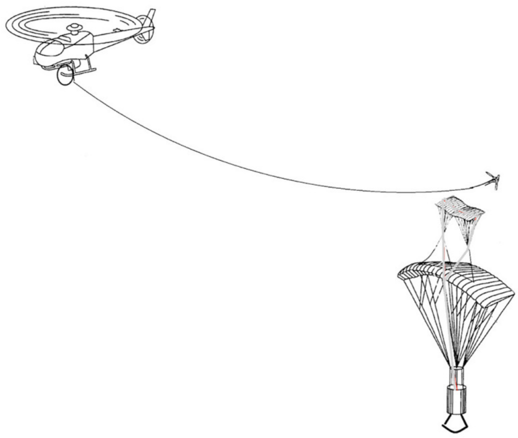

Figure 2.2: Mission profile for the mid-air recovery concept, from [17]

The proposed recovery system can be effectively integrated into the existing launcher design and has the potential to reduce the cost per launch of an Ariane 6 by 15%. The article provides comprehensive discussions of the technical feasibility, potential cost reduction, and integration into the existing launcher design.

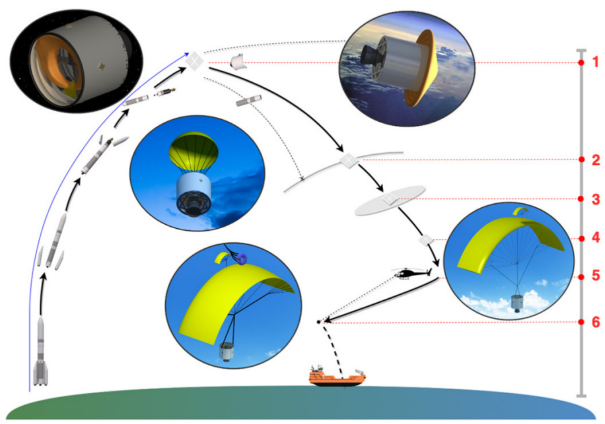

Figure 2.3: An overview of the catch mechanism using a tandem parafoil configuration, from [17]

Moreover, the study recommends further investigation to improve various aspects of the recovery system, such as heat flux modelling during reentry, system controllability, materials for reusability, packaging configuration, and options for engine reignition. The paper emphasises the importance of continuous improvement and further research for enhancing the design and operational feasibility of the proposed recovery system. This emphasis reflects a commitment to ongoing improvement and the iterative nature of engineering design, offering a pathway for achieving greater efficiency and cost-effectiveness of launch vehicle operations.

The authors provide several recommendations for potential improvements in the recovery system design. A significant suggestion is to conduct a more accurate heat flux model during reentry to determine whether it is feasible to use an insulator instead of an ablator, which could potentially reduce the mass of the aeroshell by 30%. This weight reduction could enhance the reusability and sustainability of the Vulcan Aft Bay (VuAB) recovery system.

Additionally, the authors propose a more detailed stability and controllability assessment to ascertain whether any active control elements are necessary during reentry and aeroshell discarding. This assessment could lead to the implementation of control mechanisms that enhance the safety and efficiency of the recovery process. Another important recommendation involves the improvement of parachute and parafoil materials to allow reuse after contact with ocean water. By improving the reusability of these materials, the overall costs of the recovery system could be reduced while simultaneously increasing its sustainability.

These potential improvements highlight the authors' focus on maximising the efficiency and sustainability of the recovery system design, aligning with the broader trend in the space market towards cost reduction and reusability. In summary, the research not only presents a feasible recovery system for the Ariane 6 launcher but also advocates for ongoing improvements to ensure long-term viability and environmental sustainability in space exploration.

In the paper **Performance Efficient Launch Vehicle Recovery and Reuse** [18], which delves into the historical evolution and recent progress in the recovery and reuse of launch vehicle assets, with a specific focus on the economic viability and practical aspects of asset recovery. A large part of the paper is devoted to investigating the United Launch Alliance's (ULA) Sensible Modular Autonomous Return Technology (SMART) reuse scheme, figure 2.4, for recover booster modules in their Vulcan launch vehicle. In particular, the employment of the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) and Mid-Air Retrieval (MAR) technologies in ULA's booster module recovery strategy is highlighted by the utilisation of atmospheric entry, descent, and landing (EDL) technology. The study also offers details on scaling plans, investigation of next-generation materials, and current HIAD development operations.

An essential aspect of the discussion revolves around the economic implications of reusable versus expendable launch vehicles, with a keen focus on the performance ratio as a pivotal metric. eq. 2.1, is use to calculate the reuse index as a metric for recovery methods.

$$I = p\left\{k\left[\frac{F}{n} + \frac{1}{n}\left(\frac{C(RHW)}{C(B)}\right) + \frac{C(RR)}{C(B)}\right] + (1-k)\right\} \tag{2.1}$$

In the given framework, several key parameters are employed to assess the economic implications of reusability in launch systems. The reuse index (I) serves as a metric quantifying how many times a system can be effectively reused. The performance ratio (p) provides a means of comparing the performance of an expendable system to that of a reusable counterpart. The fraction k denotes the proportion of the production

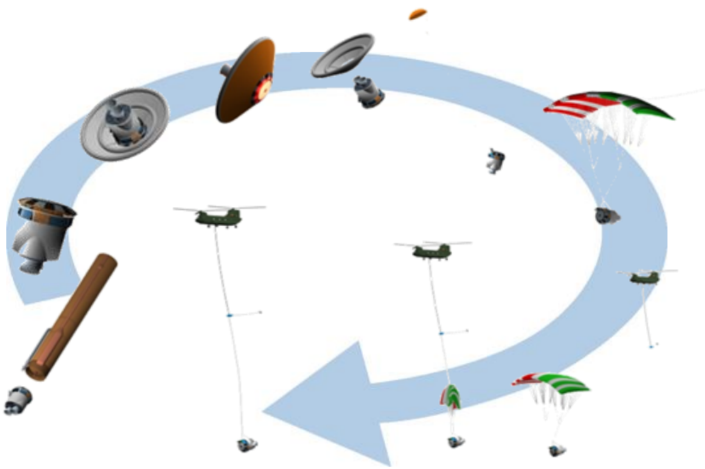

Figure 2.4: ULA's SMART Reuse Approach, from [18]

cost of reusable hardware relative to the overall cost of an expendable launch service. A factor F is introduced to model the increase in production unit cost when the production rate decreases by a factor n. The variable n itself signifies the number of uses the system undergoes. Additionally, the costs associated with recovery and reuse are partitioned into $C(RHW)$, representing the expense tied to recovery hardware that will be reused, $C(B)$, denoting the production cost of the reusable hardware, and $C(RR)$, covering the expended costs associated with recovery operations and refurbishment. Collectively, these parameters contribute to a comprehensive analysis of the economic viability and trade-offs associated with the integration of reusability in launch system architectures.

The authors explore the challenges and advantages associated with the return to launch site scenario, elucidating its significant impact on economic considerations. The paper further outlines the HULA concept, an upcoming flight experiment in HIAD technology development that involves a 6 m diameter aeroshell and serves as a secondary payload on a ULA Atlas V launch vehicle. Also, extends its exploration to MAR of heavy Earth-returning space systems, detailing a successful MAR demonstration and proposing a conceptual design for scalable systems. The study's scope, methodology, reference missions, and CONOPS are thoroughly discussed. Additionally, insights are provided into the development of a gas generator system for HIAD technology and the standardisation of HULA's secondary payload height and interfaces to accommodate diverse mission opportunities.

In conclusion, the authors underscore the potential of incremental advancements in planetary recovery systems, emphasising their role in reducing the cost of space access. The relevance of the SMART concept is highlighted in achieving a substantial reduction in access costs after a single reuse.

Another study was also done by Mohamed M. Ragab.[10] extensively delves into the subject of reusable rockets, offering insights into historical challenges, and proposing strategies to reduce costs associated with space travel. The comprehensive analysis encompasses the development of Reusable Launch Vehicles (RLVs) and underscores the importance of exploring alternative methods for recovery, particularly in the competitive commercial space launch market.

The paper meticulously examines the merits and drawbacks of reusing space objects, focusing predominantly on approaches for retrieving nonpropulsive space entities, such as deceleration through air friction or delayed ground contact. The research encompasses novel Entry, Descent, and Landing, EDL, technologies, including HIAD impact reducing airbags and mid-air interception techniques. These advances play a pivotal role in enabling cost-effective reuse of components within the launch system.

Furthermore, the paper introduces a "reuse score" as a metric to quantify the financial implications of space access. It was previously stated in Eq. 2.1 from [18]. It underscores the significance of assessing the value of different components and stages for effective reuse, emphasizing the inclusion of all associated costs related to refurbishment and reuse. In Figure 2.5, the outcomes of SMART versus Booster Fly Back employing retro-propulsion are illustrated. SMART proves to be financially viable after a few uses, whereas the latter attains profitability. The study also explores the impact of these factors on operational efficiency, product development, and successful space missions.

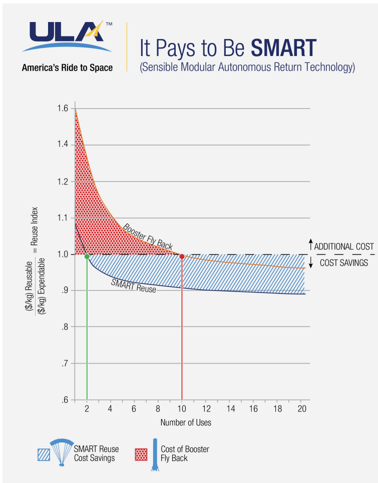

Figure 2.5: Reuse index vs. number of uses for SMART and Booster Fly Back

The findings of the paper align with a discourse on the economic feasibility of reusing rocket components. Acknowledging historical scepticism surrounding the profitability of reuse, the article emphasises a paradigm shift driven by advances in technology and enhanced expertise in both the government and industry sectors. The article underscores the necessity of collaboration among various launch providers, particularly in areas like EDL strategies. Notable initiatives, such as NASA's goals for Mars exploration and ULA's endeavours to recover the Vulcan booster, are discussed, with a spotlight on emerging technologies like HIAD.

Ultimately, the article presents an optimistic perspective regarding the feasibility of refurbishing and reusing components from rocket vehicles, showcasing promising technological innovations, collaborative efforts, and positive outcomes for the space industry as a whole.

In conclusion, the paper provides a succinct overview of major aerospace companies such as Space-X, Airbus, and ULA, actively engaged in reclaiming and reusing their space vehicles. Collaborative efforts between thegovernment and industry in space exploration are highlighted as a promising avenue to enhance the economic viability of rocket reuse in the future.

The last studies to be presented have the same objective, improving spacecraft for Mars exploration. Both delve into autoration phenomena as the first uses it as a recovery method. The collaborative research paper [19], aimed to assess the feasibility of using a machine equipped with a unique autorotation system for Mars missions, specifically focusing on pinpoint landing and hazards avoidance capabilities. This innovative approach, known as the ARMADA (AutoRotation in Martian Descent And Landing) project, explored the use of a telescopic rotor mounted on top of a Viking-like aeroshell.

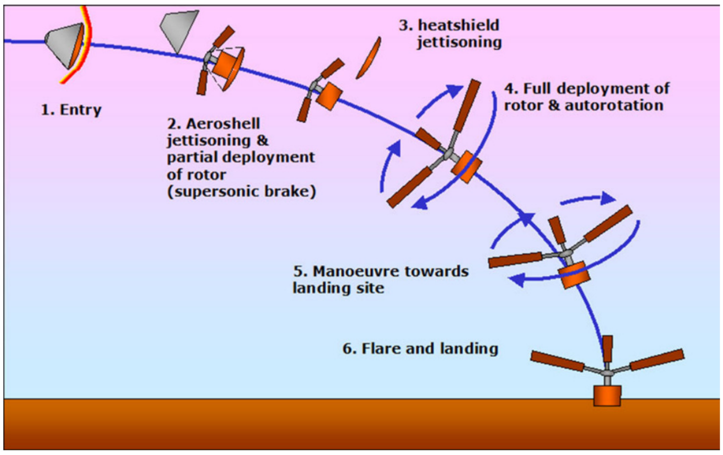

Figure 2.6: Conceptual representation of ARMADA entry descent and landing scenario, from [19]

Under the ESA contract's General Study Programme, the research focused on creating and testing hardware prototypes for the autorotation system, emphasizing a folding rotor with long-reach blades. The chosen design featured a telescopic wheel at the top of a container, following comparisons of various disc configurations. The study highlighted the significance of the rotating part's weight and size in the context of Mars missions, influencing the overall weight of the vehicle in space and its landing speed.

Tests were conducted in supersonic and transonic wind tunnels at the Von Karman Institute of Fluid Dynamics, as well as low-speed tests at the University of Bologna. The results indicated the stability of the rotor at different angles and revealed two operational modes, stalled and unstalled, with significant differences in speed changes. The findings from the study, when compared with other research, supported the notion that a rotor with foldable blades is a viable option for safe landings on Mars.

The ARMADA project proposed a landing sequence involving the deployment and extension of blades at specific supersonic and subsonic Mach numbers for Mars. The autorotation system, positioned below the back shell of the lander, is designed to decelerate the descent, with the craft descending in its fully deployed and extended configuration. The project aims to provide a proof-of-concept validation for the deployable rotor with extendable blades, showcasing its potential benefits for future Mars missions. The research underscored the importance of further investigation to enhance the autorotation system's performance during descent and ensure safe landings on Mars.

To put it simply, the paper [19] gave a lot of experimental results to show that using a rotor with foldable blades for landing on Mars is possible. It provided important insights into the feasibility of the ARMADA concept and its potential to facilitate a safe landing on Mars. The study emphasised the need for continued research to optimise the auto-rotation system for Mars missions, considering factors such as rotor weight and size, which significantly impact the overall performance of the vehicle.

On the other hand, in their article published in 2021 [20], discuss using drones to learn more about Mars.

In particular, it focusses on creating a special airplane for science and assisting future Mars explorers. It shows new tech updates for exploring Mars, the issues of using flying things on planet Mars and how aircraft might help give nice big views or close looks at strange stuff discovered there. It is being used rovers that move across the surface into small space stations in orbit above it. It is important to make something new that helps us see more while showing difficult land areas in detail.

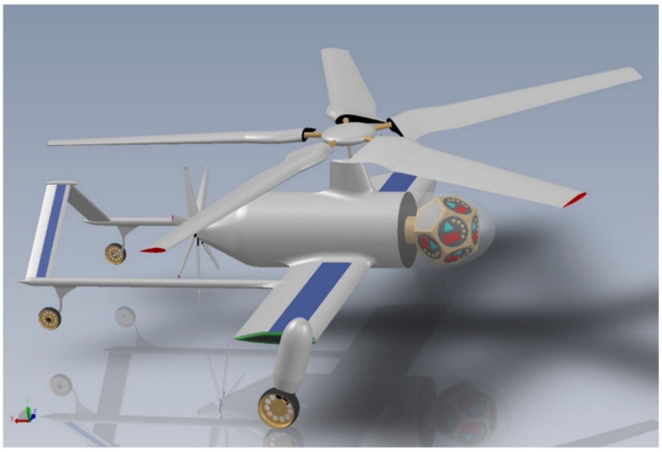

Figure 2.7: Spider Gyroplane: a prospective view, from [20]

Rovers such as Curiosity on Mars clearly display these problems. Rovers struggle with moving, navigating rough terrain, and viewing steep slopes. The article states that these borders hinder rovers from being effective in scientific studies and aiding future Mars explorers. It discusses the issues caused by Mars' atmosphere, such as low air pressure. This changes how are build and use flying things to work right there. In spite of several disadvantages, the paper says that gyroplanes are the best form of transportation since they can carry a significant amount of cargo and start and finish trips in a small amount of area.

The article talks about how a gyroplane could solve the issues with modern exploration systems. It also discusses helping plans to make human communities on Mars. Tasks such as Search and Rescue (SAR), moving important supplies, and being a connection for audio/video communication are highlighted. The gyroplane is recommended as a good vehicle to solve these issues and assist greatly with future Mars exploration and living there.

Talking about things in space, like air features and water's role on Mars and also dirt dust. We discuss the issues and good things of flying planes on Mars using science equations in a fair way. The Spider gyroplane is discussed as a possible solution. It shows how to balance the airplane's front weights using this way. The paper discusses key points that support planes in flying. It also compares kinds of spaceships good for Mars journeys and suggests three possible jobs like checking out the area, taking photos from above in the sky, and moving stuff between locations.

The paper starts by making a flying car for Mars. It demonstrates that we must make it work on its own because humans might one day live on Mars and scientists will conduct tests there too. It displays that individuals join forces in thoughts, study techniques, and examining facts. It doesn't discuss issues with different interests or gaining money from outside sources.

In conclusion of the state-of-the-art research on space vehicle recovery techniques, it is clear to argue that attention is being paid to the investigation of ground-breaking space travel innovations. The studies under discussion have been crucial in illuminating cutting-edge methods and tools that could fundamentally alter how we conduct space exploration and recovery.

Scientists and engineerings have been looking into several ways to improve spacecraft recovery, and using rotary wings has received a lot of attention. This approach shows promise as an effective recovery strategy. The research have demonstrated not only the practicability of rotary wings but also their capacity to offer flexible and adaptive solutions within the demanding environment of space missions.

Chapter 3

The Principle of Autorotation

This section aims to conduct a theoretical background review of rotor aerodynamics under autorotation phenomena, incorporating the mathematical models, simulations, and experimental results.

3.1 Blade Element Momentum Theory

Blade Element Momentum Theory (BEMT) is a close approximation with relatively simple computational effort. BEMT was developed by combining momentum theory and blade element theory [21, 22]. First and foremost, it is crucial to establish a baseline model for rotor aerodynamics, as depicted in Figure 3.1. The model defines geometric properties by highlighting a blade element (in black). BEMT involves computations considering blade elements at a distance y from the blade root, each with an infinitesimal width, $\mathrm{d}y$, [21–25]. The aerodynamic load is then integrated over the blade length $R - r_0$. For each blade element, illustrated in Figure 3.2, a defined blade element includes induced velocities, aerodynamic forces, and relative angles.

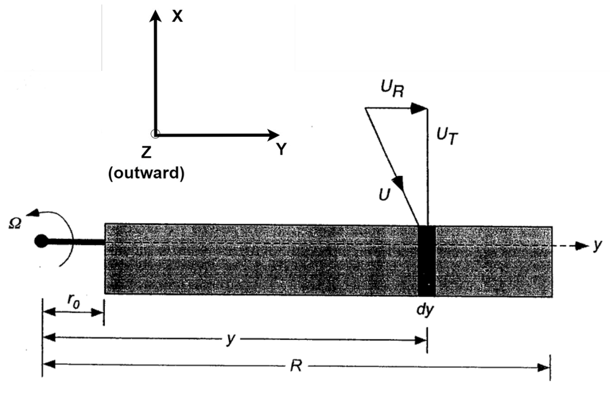

Figure 3.1: Blade geometric properties, adapted from [22].

The phenomenon of auto-rotation's principle is based on the presence of airflow, $\vec{U}$, through the blade, inducing rotational motion and thus generating the necessary propulsion. The main objective is to generate a propulsive force, $\vec{T}$, which compensates for gravitational force, counteracting the forces and facilitating a reduction in landing speed. To formulate this phenomena, Eq. 3.1 and Eq. 3.2, define the integral over blade radius, R, vertical thrust $\vec{T}$ and horizontal root rotational propulsion force, $\vec{P_h}$. This definition include the

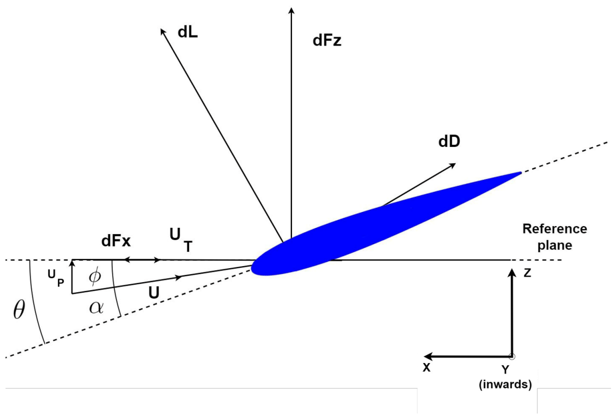

Figure 3.2: Incident velocities and aerodynamic forces applied at a blade element, from the author

blade elements vertical, $\mathrm{d}F_z$, and horizontal, $\mathrm{d}F_x$, forces generated by the aerodynamic force, $\mathrm{d}L$, as shown in Figure 3.2. Additionally, it is crucial to emphasise the significance of considering the number of blades, N_b, as the thrust force exhibits a direct proportionality to this factor [22].

$$\|\vec{T}\| = \int_{r_0} n^R N_b \mathrm{d}\vec{F_z} \tag{3.1}$$

$$\|\vec{P_h}\| = \int_{r_0}^{R} N_b \mathrm{d}\vec{F_x} \tag{3.2}$$

where the vertical, $\mathrm{d}F_z$, and horizontal, $\mathrm{d}F_x$, forces, adpated from [22, 26], are

$$\mathrm{d}\vec{F_z} = \mathrm{d}\vec{L}\cos\phi + \mathrm{d}\vec{D}\sin\phi \tag{3.3}$$

$$\mathrm{d}\vec{F_x} = \mathrm{d}\vec{L}\sin\phi - \mathrm{d}\vec{D}\cos\phi. \tag{3.4}$$

Here, ϕ represents the inflow incident angle formed between the vertical and horizontal velocity vectors. Consequently, in order to calculate the vertical and horizontal force, and subsequently the thrust and propulsion forces, it is imperative to determine the infinitesimal lift, $d\vec{L}$, and drag, $d\vec{D}$, forces. This can be achieved by incorporating thin airfoil theory [27, 28]. From this theory, we can introduce the lift and drag equations, as shown in Eq. 3.5 and Eq. 3.6 respectively

$$\mathrm{d}\vec{L} = \frac{1}{2}\rho\|\vec{U}\|^2 c C_l dy \tag{3.5}$$

$$\mathrm{d}\vec{D} = \frac{1}{2}\rho\|\vec{U}\|^2 c C_d \mathrm{d}y \tag{3.6}$$

Hence, it becomes evident from Eq. 3.5 and Eq. 3.6 that both the lift and the drag forces on the aerofoils are influenced by various parameters, each exhibiting distinct variations. The density, ρ, is notably affected by altitude and flow temperature, while the incident velocity, $\vec{U}$, is contingent upon the dynamic movement of the vehicle. The remaining parameters include the airfoil chord, c, and the lift or drag coefficients, C_l and C_d respectively. The chord remains constant and independent of the flow but may change along the blade span due to the taper effect on geometry. In conclusion, the subsequent sections aim to investigate how these factors influence and alter the aerodynamic performance of a rotary wing during auto-rotation phenomena.

3.1.1 Incident velocity

The incident velocity, $\vec{U}$, considered in equations 3.5 and 3.6 is given by a combination from the body's vertical descent velocity, $\vec{U_P}$, and the blade horizontal velocity $\vec{U_T}$ [22]

$$\vec{U} = \vec{U_P} + \vec{U_T} \tag{3.7}$$

and the incident angle of attack α is given, as can be seen in figure 3.2, by the difference of the pitch angle, θ, and the inflow incident angle, ϕ,

$$\alpha = \theta - \phi \tag{3.8}$$

the inflow incident angle is given by the velocity vector U angle with the horizontal reference plane.

$$\phi = \arctan\left(\frac{U_P}{U_T}\right) \tag{3.9}$$

3.1.2 Flow Density

The mass of an object or substance per unit volume is referred to as its density. It is a basic physical characteristic that indicates how densely packed matter is in a specific amount of space. Understanding the behaviour and properties of materials in diverse contexts, such as buoyancy, fluid dynamics, and structural stability, requires an understanding of density, which is fundamental to many scientific fields, including physics, chemistry, and engineering. [29].

In this application, density variations arise primarily from two distinct phenomena. Firstly, as the vehicle undergoes descent movement, atmospheric temperature and pressure with altitude occur, figure 3.3, resulting in corresponding variations in density [30, 31]. Secondly, when accounting for compressible effects, the transsonic regime induces high-pressure gradients that give rise to shock waves, causing significant density fluctuations. These fluctuations play a crucial role in influencing the aerodynamic efficiency of airfoils [27]. Lastly, in the context of high tip Mach numbers for a rotor [22], increased skin friction coefficients lead to heat generation, thereby introducing variations in flow temperature and subsequently impacting density.

Density Variation Model

For predicting air temperature, T in $^{\circ}C$, pressure, p in kPa, and density, ρ in Kg/m^3 variations with altitude h, in meters, NASA's Gleen Research Center proposes a Earth Atmosphere Model [31] which considers of three distinct zones with separate curve fits for the troposphere, lower stratosphere, and upper stratosphere. Within the troposphere, spanning from the Earth's surface to 11 km, the temperature decreases linearly with altitude, following the equation:

$$T = 15.04 - 0.00649 \cdot h \tag{3.10}$$

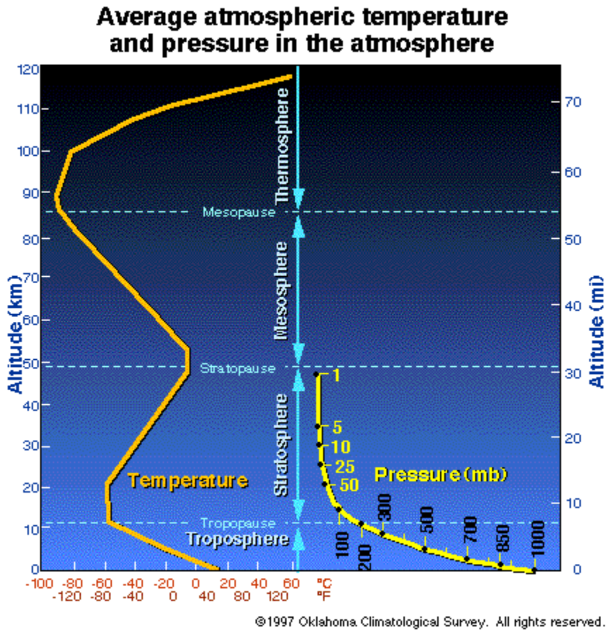

Figure 3.3: Variation of temperature and pressure along atmosphere altitude, from [32].

Simultaneously, the pressure experiences an exponential decrease and is described by the following equation [31]:

$$p = 101.29 \cdot \left(\frac{T + 273.1}{288.08}\right)^{5.256} \tag{3.11}$$

Moving into the lower stratosphere, which extends from 11 to 25 km, the temperature remains constant at -56.46$^\circ C$, while the pressure decreases exponentially:

$$T = -56.46 \tag{3.12}$$

$$p = 22.65 \cdot \exp(1.73 - 0.000157 \cdot h) \tag{3.13}$$

For altitudes exceeding 25 km in the upper stratosphere, the temperature experiences a slight increase with altitude.

$$T = -131.21 + 0.00299 \cdot h \tag{3.14}$$

$$p = 2.488 \cdot \left(\frac{T + 273.1}{216.6}\right)^{-11.388} \tag{3.15}$$

In all atmosphere zones, the density is calculated using the equation of state [31]:

$$\rho = \frac{p}{0.2869 \cdot (T + 273.1)} \tag{3.16}$$

These equations provide a comprehensive representation of the temperature, pressure, and density profiles within the troposphere, lower stratosphere, and upper stratosphere. Figure 3.4 shows how the model predicts the variations of temperature, pressure, and density with altitude.

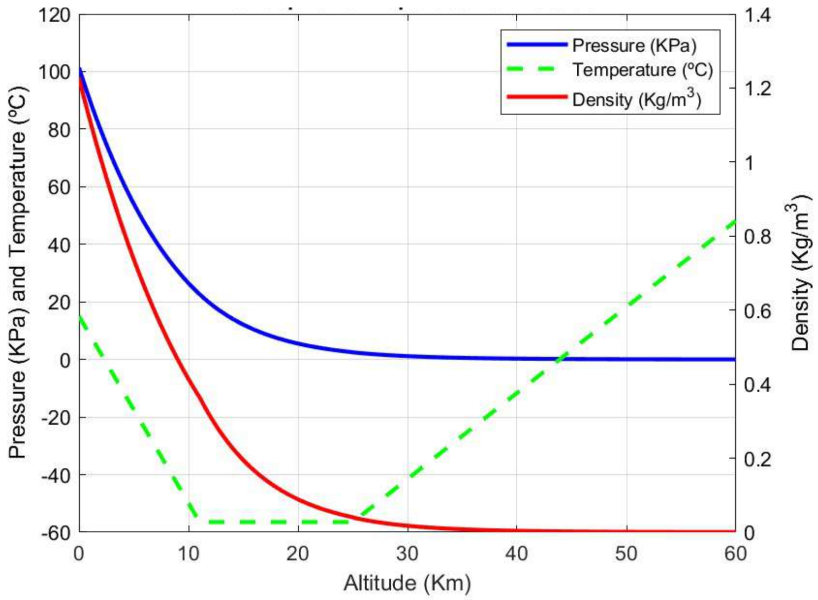

Figure 3.4: NASA model for atmosphere proprieties, from the author

3.1.3 Tip Loss Function

In the context of helicopter rotor or wind turbine rotor systems, an inherent challenge arises as the blades near the tips experience a higher velocity compared to those near the hub. This speed differential introduces complications such as increased drag, heightened turbulence, and the formation of tip vortices, spiral patterns of rotating air trailing behind the rotor blade tips [22]. These tip vortices signify a notable source of energy loss, which contributes to a reduction in overall system efficiency. Over the years, various strategies have been studied to mitigate this tip loss, including optimising rotor blade shapes, adjusting blade twists, and incorporating advanced aerodynamic features.

Efforts to address tip loss also involve the application of the Prandtl tip loss function [22**?**]. Prandtl tip loss is the decrease in aerodynamic efficiency that propeller or rotor blades undergo as they get closer to their tips as a result of following vortices that are created as they go through the air. Overall efficiency is reduced as a result of this phenomenon. Within the field of aerodynamics, the Prandtl tip loss function is a mathematical instrument that is specifically utilised to model and quantify this phenomenon [22]. Its main purpose is to take into account the induced velocity caused by the tip vortices and then modify the effective inflow velocity that the blade experiences at the tip.

In the book of professor Leishman [22], the Prandtl's Tip Loss function is addressed considering two different cases: 1) no tip losses at the rotor root; 2) tip losses in tip and root of the rotor. For the first case, function which estimates a lift variation is given by equation 3.17,

$$F = \frac{2}{\pi} \cos^{-1} \left(\exp\left(-f\right) \right) \tag{3.17}$$

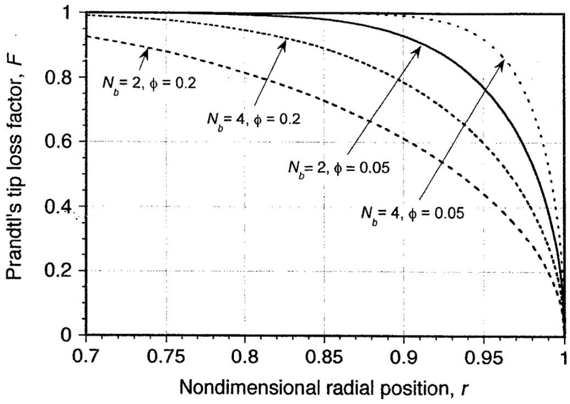

Figure 3.5: Prandtl Tip Loss function versus radial position for two- and four-bladed rotor, from [22]

where f is a function of the geometric properties of the blade and the inflow angle $\phi = \frac{\lambda(r)}{r}$

$$f_{tip} = \frac{N_b}{2}\left(\frac{1-r}{r\phi}\right) \tag{3.18}$$

Applying the the factor F to the lift distribution over the blade radius, the figure 3.5 presents how the function varies with the number of blades and the inflow angle over the radius of the blades. From the figure 3.5, is possible to see that this function does not consider the tip loss in the rotor center, as the function is the maximum value in the beginning of the rotor.

However, this assumption is not physically correct and then the second option appears in [22]. For considering the loss of tips at the root of the blade, the equation 3.19 is considered.

$$f_{root} = \frac{N_b}{2}\left(\frac{r}{(1-r)\,\phi}\right) \tag{3.19}$$

For combining root and tip losses, the factor f considered is the combinations of 3.17 and 3.19. The combination of root and tip losses is presented in figure 3.6. From this figure, it is possible to conclude that, as in the tip, the root as a significant decrease in the lift force.

$$F = F_{root}F_{tip} \tag{3.20}$$

From a recent study conducted in 2017, S.F. Ramdin [33] presented a master thesis where Prandtl Tip Losses Where assessed. In his work, the Prandtl tip loss factor as a correction factor in Blade Element Momentum (BEM) theory was studied for wind turbine blade design. The study explores four key parameters in the derivation of the Prandtl tip loss factor, resulting in 72 variations. A comparison with Computational Fluid Dynamics (CFD) and vortex method tip loss factors reveals the need for accurate induced velocity extraction from CFD computations. The ECN's AWSM code, validated against the New Mexico experiment, is employed for vortex method results. The assessment spans five rotors across various operational conditions, highlighting the sensitivity of Prandtl tip loss factors to tip speed ratios. Notably, four locally evaluated Prandtl tip loss factors emerge as the most effective, providing information on improving BEMT accuracy and contributing to more efficient wind turbines and enhanced load predictions.

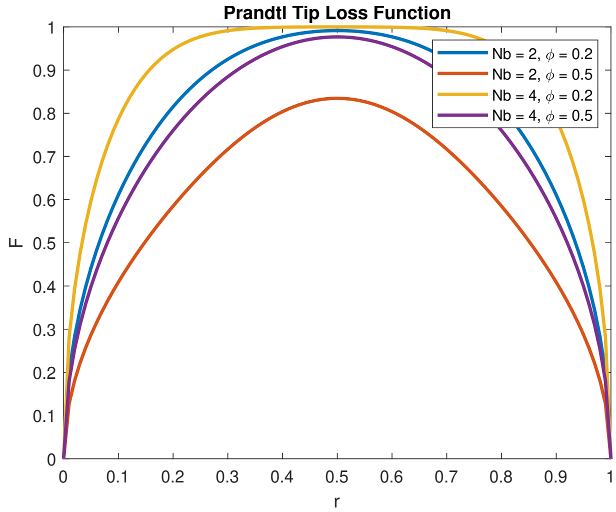

Figure 3.6: Prandtl tip losses function, considering both root and tip losses, for two- and four-bladed rotor and two different inflow angles, ϕ, from the author

As an alternative to the calculation factor F presented in [22], S.F. Ramdin [33] derives a complete expression for the Prandtl tip loss function, eq. 3.21. In this approach, the tangential velocity V_t is considered.

$$F = \frac{2}{\pi} \arccos \left[\exp \left(-\frac{N_b}{2} \frac{R - r_1}{r_2} \frac{\sqrt{V_n^2 + V_t^2}}{V_n} \right) \right] \tag{3.21}$$

Also in his work, S.F. Ramdin [33] refers to two other different approaches for factor F. The first approach is commonly known as the Prandtl-Glauert tip loss factor, eq. 3.22. The second approach was proposed by Burton, eq. 3.23.

$$F_{\text{Glauert}} = \frac{2}{\pi} \arccos \left[\exp \left(-\frac{N_b}{2} \left(\frac{R - r}{r} \right) \frac{1}{\sin \phi(r)} \right) \right] \tag{3.22}$$

$$F_{\text{Burton}} = \frac{2}{\pi} \arccos \left[\exp \left(-\frac{N_b}{2} \left(\frac{R - r}{r} \right) \sqrt{1 + \left(\frac{\lambda(r)}{1 - a(r)} \right)^2} \right) \right] \tag{3.23}$$

3.1.4 Flapping

Once considering that the vehicle movement also has a horizontal component, due to the asymmetry of the flow and dynamic pressure, on the rotor, the aerodynamic forces will be functions of the azimuthal position. If the flapping motion is introduced on the rotor, it is possible to achieve better aerodynamic performance since it is possible compensate for local changes.

For introduce the flapping movement, in [22] the flapping equation is deduced considering an equilibrium point, figure 3.7. The equation presented is centrally hinged blade, meaning that the the blade hinge is located at the rotor center. The general formula of the flapping movement consideres the blade flapping angle as function of azimuthal postion, $\beta(\psi)$,

$$\overset{**}{\beta} + \beta = \gamma \bar{M}_\beta, \quad \overset{**}{\beta} \equiv \frac{d^2\beta}{d\psi^2} \tag{3.24}$$

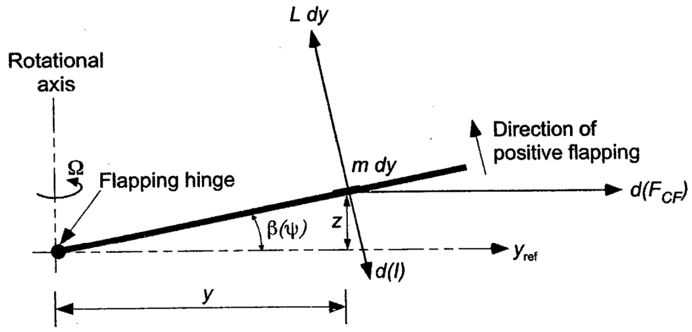

Figure 3.7: Forces acting on an element of a flapping blade, from [22]

However, further reacher has been conducted to understant flapping mothion. The study of Jyoti Ranjan Majhi and Ranjan Ganguli, **Modeling Helicopter Rotor Blade Flapping Motion Considering Nonlinear Aerodynamics** [34], examines the aeroelastic nonlinearities of helicopter rotor blades and how they affect the system's dynamics. Using no linearization of aeroelastic nonlinearities, the paper obtains a general flapping equation that challenges the widely used small flap angle approximations. In the context of nonlinear aerodynamics, the paper examines the validity of these small angle assumptions and demonstrates how, under some flight situations, they might result in erroneous predictions of the blade flap response. Numerical simulations presented in the research show that the small-angle assumptions may not be adequate when taking nonlinear aerodynamics into account. The results highlight the significance of taking large flap angles and induced inflow angles into account when analysing helicopter dynamics, and they offer a thorough model of the flapping equation that does not rely on approximations of small angles.

As in [22], the flapping movement is given in [34] in Eq. 3.25

$$\overset{**}{\beta} + \cos\beta \sin\beta = \frac{R}{\Omega^2 I_{\triangle r}} F_z(\psi) r_0 \Delta r \tag{3.25}$$

where β is the flapping angle and Δr is the blade element. For the small angle approximation, eq. 3.26 can be considered.

$$\overset{**}{\beta} + \beta = \frac{R}{\Omega^2 I_{\triangle r}} F_z(\psi) r_0 \Delta r \tag{3.26}$$

In their effort to address the equations at hand, Ranjan Majhi and Ranjan Ganguli, as detailed in [22], employed a numerical solution technique, specifically the Runge-Kutta method, while initialising the process with zero initial conditions. This method facilitates the analysis of the transient behaviour of the system, allowing any initial disturbances to decay naturally. The focus of their approach is on obtaining the eventual steady response of the blade, denoted as $\beta(\psi)$, as it provides valuable insight into the sustained behaviour of the system. Also, the authors provided an model when considering angles of attack after stall that considers the equations 3.27 and 3.28.

$$C_L = \begin{cases} a_0 + a_1 \alpha & \text{for } |\alpha| < \alpha_{\text{stall}} \\ A \sin 2(\alpha - \alpha_0) & \text{for } |\alpha| > \alpha_{\text{stall}} \end{cases} \tag{3.27}$$

and

$$C_D = \begin{cases} d_0 + d_1\alpha + d_2\alpha^2 & \text{for } |\alpha| < \alpha_{\text{stall}} \\ D + E\cos 2(\alpha - \alpha_0) & \text{for } |\alpha| > \alpha_{\text{stall}} \end{cases} \tag{3.28}$$

3.1.5 High Angles of attack

It is crucial to understand and evaluate high angles of attack while studying autorotation phenomena, especially as they relate to rotary-wing aircraft. An essential part of helicopter operations is autorotation, which is the descent of a helicopter using just its upward-moving rotor system to propel it downward while its rotor blades are deactivated. The complicated aerodynamic forces operating on the rotor blades at high angles of attack have a considerable effect on the characteristics of the helicopter's descent. Because of the possible risks and difficulties that come with operating in this aerodynamic regime, large angles of attack must be taken into account in autorotation [22]. For the purpose of improving the safety, effectiveness, and manoeuvrability of helicopters during autorotation and ultimately advancing the field, accurate models and empirical data for the lift and drag coefficients at these extreme angles are essential.

In order to deal with high angles of attack, one can consider David A. Spera's paper, titled **Models of Lift and Drag Coefficients of Stalled and Unstalled Airfoils in Wind Turbines and Wind Tunnels** [26]. This work introduces empirical mathematical models that play a pivotal role in advancing the understanding of lift and drag coefficients for airfoils in wind turbine rotors and wind tunnel fans which operates at high angles of attack. These models are meticulously crafted to accurately predict aerodynamic behaviours, with a specific emphasis on the transition between unstalled and stalled conditions.

Spera's empirical equations are designed with precision, incorporating finite aspect ratio modifications to ensure seamless transitions between different aerodynamic regimes. The comprehensive exploration of lift and drag behaviours, as illustrated in Figures 3.8 and 3.9, showcases the models' ability to predict the intricate aerodynamic performance of various airfoils. The study places particular importance on the post-stall coefficients and aspect ratio adjustments, providing a holistic view of airfoil behaviour in the context of wind tunnel fans and wind turbine rotors.

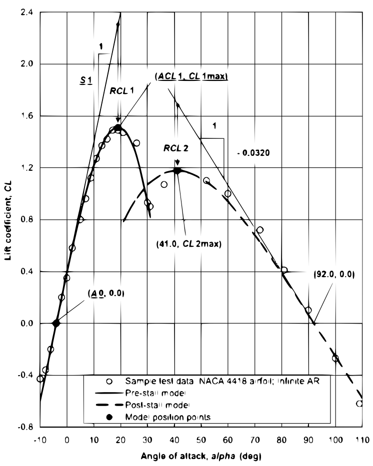

Figure 3.8: *AERODAS* model for lift coefficient, from [26]

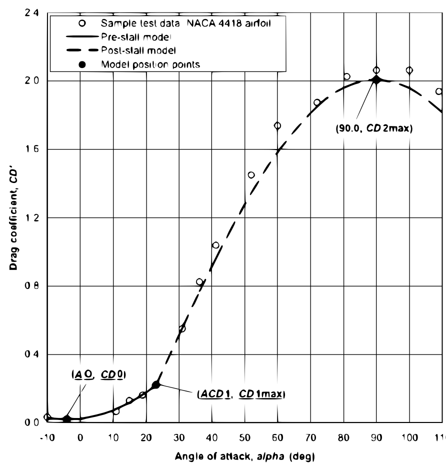

Figure 3.9: *AERODAS* model for drag coefficient, from [26]

The rigorous evaluation of these models against a diverse set of test data demonstrates their commendable accuracy. The focus on transitions between unstalled and stalled situations underscores the practical relevance of Spera's empirical equations. The findings of the paper have profound implications for the design and analysis of wind tunnel fans and turbines, offering a reliable foundation for predicting aerodynamic performance in various scenarios.

In essence, Spera's empirical models stand as a significant contribution to the field, providing a robust framework for the computation of lift and drag coefficients and advancing the understanding of airfoil performance in wind turbines and wind tunnels. The emphasis on practical applications and the successful validation against diverse test data highlight the reliability of the models and their potential impact on the optimisation of aerodynamic behaviours in real-world scenarios.

Chapter 4

Conclusions

The design of recovery systems for spacecraft is thoroughly examined in this work, which focusses on the aerodynamics of the rotor during auto-rotation phenomena. Covers a wide range of topics, including the recovery of critical parts for heavy-lift launchers, controlled thrust vector recovery systems, and the use of parachutes in space missions. This work evaluates the benefits and drawbacks of several recovery techniques, such as controlled thrust vector systems and parachutes, and suggests a novel recovery system with a revolving wing that rotates under auto-rotation for safe and controlled landings.

The study explores how auto-rotation technologies might be used in space missions, especially in relation to Mars exploration. It provides an experimental examination of a rotating entry vehicle intended for Mars landings and assesses the viability of using a vehicle with a unique auto-rotation mechanism. In addition, the paper highlights the necessity, practicality, and possible benefits of reusable components while offering insights into the development of launch vehicle assets over time and the latest developments in this area.

In order to fully understand aerodynamic performance, the study also examines blade element momentum theory, Prandtl tip loss functions, rotor blade flapping motion, and air density fluctuations. Furthermore, the study investigates lift and drag coefficients at high angles of attack, using numerical simulations and empirical modeling to predict aerodynamic behaviors under harsh circumstances.

This study furnishes a comprehensive overview of recovery system development, practical applications, and potential enhancements, accentuating the benefits of ongoing improvements and further exploration in the field of aerospace engineering. Overall, its objective is to address challenges and uncover new possibilities to advance the design, operational feasibility and cost effectiveness of recovery systems in the realm of space exploration.

This study highlights the advantages of continuous advancement and additional research in the field of aeronautical engineering by providing a thorough review of recovery system development, real-world applications, and possible upgrades. Its overarching goal is to overcome obstacles and find new opportunities to advance recovery system design, operational viability, and economics in the space exploration domain.

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