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INSTITUTE OF AEROSPACE ENGINEERING
LETECKÝ ÚSTAV

REUSABLE LAUNCHER FLIGHT MISSION
MISE VÍCENÁSOBNĚ POUŽITELNÉ NOSNÉ RAKETY

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Assignment Bachelor's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Reusable launcher flight mission

Brief Description:

Reusable launchers are currently going through intensive development. The technologies needed to return of launcher first stage to the ground have already been tested but it will take a long time till these reusable stages replace the classic ones. This work is devoted to the flight mission design of the launcher's first stage with the aim of a controlled landing on Earth.

Bachelor's Thesis goals:

– mission description of a reusable launcher
– a mission design of the launcher reusable first stage

Recommended bibliography:

DANĚK, V. Mechanika kosmického letu. Brno: Akademické nakladatelství CERM, 2018, s. 264-290. ISBN 978-80-7204-984-4.

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ABSTRACT

This thesis is split into two main parts which are also the main objectives. The aim of the first part is to describe a mission of a reusable launcher. Firstly, the topic of reusable launch systems and their development until today was approached. Most importantly, the operational reusable launch vehicles are described with the explanation of each booster's flight mission. Furthermore, alongside some important launch vehicles in development, there is a separate chapter listing the first stage's return options.

The second part is practical with the aim of designing a mission of the launcher reusable first stage. For the calculations, the parameters were chosen according to a current Falcon 9 rocket, from which the final velocity and altitude at which the first stage separates, were analytically calculated. For the return and overall flight mission, a MATLAB script was written to calculate and plot all necessary parameters and characteristics. In the end, the altitude for the engine reignition was also determined to safely land on the ground.

KEYWORDS

Reusable, Launch vehicle, Launch system, Booster, Rocket, Propulsion, Propellant, Flight mission, Space

ABSTRAKT

Tato práce je rozdělena do dvou hlavních částí, které jsou také hlavní cíle. Cílem první části je popis mise vícenásobně použitelného prvního stupně nosné rakety. V této části je nejdříve přiblíženo téma znovupoužitelných kosmických systémů a jejich vývoj do současné doby. Hlavně jsou však v této části popsány operačně používané vícenásobně použitelné nosné rakety, kde u každé z nich je poté popsána jejich letecká mise. Dále jsou zmíněny některé důležité nosné rakety ve vývoji a také jaké jsou způsoby návratu prvního stupně.

Druhá část je praktická a cílem je návrh mise návratu prvního stupně nosné rakety na zemi. Pro výpočty byly zvoleny parametry podle současné rakety Falcon 9, ze kterých byla analyticky vypočtena finální rychlost a výška, ve které se první stupeň oddělí od zbytku rakety. Pro návrat a celkový let byl pomocí programu MATLAB napsán skript, který vypočítal a vykreslil potřebné parametry a charakteristiky. Díky tomu bylo také zjištěno, v jaké výšce bude potřeba znovu zažehnout motory, aby první stupeň bezpečně přistál na zemi.

KLÍČOVÁ SLOVA

Vícenásobně použitelný, Nosná raketa, Kosmický systém, Odpalovací zařízení, Raketa, Vesmírná mise

ROZŠÍŘENÝ ABSTRAKT

Cílem této bakalářské práce je popsat misi vícenásobně použitelného prvního stupně nosné rakety a zároveň také navrhnout misi návratu tohoto stupně zpět na zemi.

Nejdříve je v této práci objasněno, co vlastně vícenásobně použitelné kosmické systémy znamenají. Na rozdíl od běžných vícestupňových raket, jejichž stupně shoří v atmosféře, se jedná o systém, jehož komponenty nebo i celý systém jsou po konci mise zotaveny. Poté tedy jde buď to o částečně obnovitelný kosmický systém, anebo o úplně obnovitelný. Nicméně, díky obnovitelnosti musí tyto systémy nést přebytečný náklad, například v podobě doplňkových systémů, přistávacích noh nebo paliva pro přistání. Konkrétně v případě vícenásobně použitelného prvního stupně nosné rakety záleží na druhu návratu. Může se jednat o padákové systémy u přistávání do oceánu nebo o stabilizační trysky, roštová kormidla, přistávací nohy a přebytečné palivo u motorického přistávání na plošině. Jednotlivé způsoby návratu jsou poté v práci podrobněji přiblíženy.

Dále jsou v práci popsány jednotlivé operačně používané vícenásobně použitelné nosné rakety s podrobným vysvětlením jejich letecké mise. Jako první jsou zmíněny nosné rakety na tuhé palivo Solid Rocket Boosters (SRB), které byly součástí programu Space Shuttle. Jednalo se vlastně o úplně první vícenásobně použitelný kosmický systém, jelikož raketoplán i obě nosné rakety byly zotaveny. Pouze odhazovací nádrž s externím palivem nebyla zachována a shořela v atmosféře. Celý Space Shuttle byl v provozu mezi lety 1981-2011. Hlavním důvodem ukončení tohoto programu byly nenaplněné finanční očekávání. Provoz tohoto systému vyšel dráž, než kdyby se jeho jednotlivé části nezachovávaly.

Obecně výhodou raket na tuhé palivo je jejich množství tahu i přes jednoduchý design a nezvýšenou potřebu ochlazování. Nicméně, po jejich zažehnutí je již nemožné motor zastavit a kontrolovat tah a většinou hoří až do doby, kdy dojde palivo. Konkrétně u SRB je motor sestaven z několika postupně zažehovaných segmentů, tudíž jakási možnost zastavení před dohořením celého paliva se zde vyskytuje, ale není to okamžité.

V současnosti se tedy ve větším množství využívají rakety na kapalné palivo, kterým je věnován zbytek teoretické části. První takovou raketu je raketa New Shepard od společnosti Blue Origin, která jako první dokázala úspěšně vertikálně přistát po překročení Kármánovy hranice, což je hranice mezi zemskou atmosférou a kosmickým prostorem ve výšce 100 km. Tato raketa je vyvíjena pro komerční suborbitální kosmické lety a po několika již úspěšných testovacích misích je aktuálně naplánována mise i s lidskou posádkou na červenec 2021. Tento let proběhne s nejnovější verzí New Shepard NS4 a momentálně je otevřené aukce, ve které se draží místo na tomto letu.

Další nosnou raketou je dnes nejznámější, nejvíce používaná dvoustupňová raketa Falcon 9 od společnosti SpaceX. Jedná se o první orbitální raketu s vícenásobně použitelným prvním stupněm a momentálně už má přes 100 úspěšných misí a přes 70 úspěšných přistání prvního stupně. Tyto přistání probíhají buď na pevnině, anebo častěji na autonomní plovoucí přistávací plošině (ASDS) v oceánu. Kromě vynášení družic nebo zásobovacích misí pro mezinárodní vesmírnou stanici (ISS), slouží rakety Falcon 9 také pro mise s posádkou. V dubnu 2021 dokonce došlo k dopravení lidské posádky na ISS pomocí opakovaně použitého prvního stupně.

Jako poslední zmíněnou operačně používanou vícenásobně použitelnou nosnou raketou je raketa Electron od společnosti Rocket Lab. Electron stejně jako Falcon 9 je dvoustupňová částečně obnovitelná nosná raketa, nicméně oproti Falconu 9 je skoro čtyřikrát menší a slouží tedy konkrétně pro vynášení malých satelitů na oběžnou dráhu. Ve většině případů obsahuje ještě třetí stupeň zvaný kickstage, který slouží k přesnému navedení nákladu na oběžnou dráhu. Všechny hlavní části motoru této rakety jsou pomocí aditivní výroby vytisknuty a zároveň tyto motory jako první využívají elektricky poháněná turbočerpadla.

Pro srovnání všech těchto operačně používaných raket je dále vytvořena tabulka se základními parametry těchto raket.

Mimo rakety již v provozu jsou v další kapitole zmíněny dvě rakety, které jsou momentálně ve vývoji. Jedná se o rakety od již zmiňovaných společností, konkrétně Starship od SpaceX a New Glenn od Blue Origin. New Glenn bude na rozdíl od New Shepard již orbitální raketou a Starship by měla být plně obnovitelná a v budoucnu nahradit Falcon 9 i Falcon Heavy. Starship je vyvíjena hlavně pro budoucí mise na Měsíc a Mars a bude tedy schopná nést nejen náklad, ale i lidskou posádku.

Z hlediska návratu prvních stupňů jsou zmíněny čtyři hlavní způsoby, které korespondují s již zmíněnými raketami. Nejjednodušší je přistání pomocí padákových systémů na hladině oceánu. Tohoto způsobu bylo využito již u pomocných nosných raket SRB systému Space Shuttle a současně se využívá u rakety Electron. Cílem zotavení prvního stupně rakety Electron je však zachycení hákem při klesání na padácích pomocí helikoptéry, nicméně nejdříve budou provedeny tři zkušební lety s přistáním na hladině oceánu. U obou těchto způsobů se nevyužívá opětovného zažehnutí motorů pro zpomalení, ale ke snížení rychlosti zde slouží čistě padáky. Opětovné zažehnutí motorů se využívá u zbylých dvou způsobů návratu, a to u návratu na startovací plošinu a také u přistání ve směru letu na ASDS. Oba tyto způsoby jsou využívány u raket Falcon 9 a konkrétně u rakety New Shepard se přistává čistě na pevnině, jelikož se jedná pouze o vertikální suborbitální kosmický let. Ke stabilizaci stupně zde slouží roštová kormidla a trysky v horní části stupně. Přistání je čistě automatické a je řízeno výpočetní jednotkou stupně, která ze zpracovaných dat vyhodnocuje polohu, rychlost a podobně.

Další část práce je již praktická a je věnována návrhu mise návratu prvního stupně nosné rakety zpět na zemi. Vstupní data jsou zvolena podle dostupných parametrů rakety Falcon 9. Z těchto dat je analyticky vypočítán specifický impuls, množství přebytečného paliva určeného k přistání a také finální rychlost a výška, ve které se prvním stupeň oddělí od zbytku rakety. Dále byl ještě napsán jednoduchý skript v programu MATLAB, který vykreslil závislost rychlosti a výšky na čase až do vypnutí motorů, kdy zároveň dojde k oddělení druhého stupně s nákladem.

Pro sestup atmosférou a následné přistání prvního stupně byly nejdříve zvoleny souřadnicové soustavy s kinematickými veličinami, dále popsány působící síly a sepsány pohybové rovnice. Mimo to byly také popsány ostatní parametry, které při běžné misi F9 ovlivňují průběh letu, ale pro výpočty nebyly brány v úvahu.

Pro numerický výpočet byl napsán skript v programu MATLAB, který byl vytvořen pro průběh celé mise, jelikož první skript byl pouze pro vertikální let. V tomto skriptu se uvažuje gravitační klopení pro řízení trajektorie letu. Kvůli tomu museli být mírně upraveny i kinematické vazby a pohybové rovnice.

Na závěr tedy došlo k vykreslení výsledné trajektorie a závislostí sklonu dráhy letu, rychlosti a hmotnosti na čase. Z tohoto byl zjištěn čas, ve kterém první stupeň nosné rakety dosáhne maximální výšky a sklon dráhy je v tomto případě nulový. V tomto čase dojde mimo změnu koeficientu odporu i k otočení stupně, aby sestupoval atmosférou s motory napřed a ty poté mohly v daném čase znovu zažehnout a zpomalit stupeň pro bezpečné přistání.

Čas, ve kterém motory opět zažehnou byl pečlivě zvolen, aby první stupeň přistál s rychlostí blízké nule ve zhruba nulové výšce. Při pozdějším zážehu by došlo k prudkému nárazu na zem, a tak ke zničení stupně. Zároveň při dřívějším zážehu by stupeň ještě před dotknutím se země začal znova stoupat.

BIBLIOGRAPHY

METELKA, Dominik. Reusable launcher flight mission. Brno, 2021. Available also at: https://www.vutbr.cz/studenti/zav-prace/detail/132761. Bachelor's Thesis. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Institute of Aerospace Engineering. Supervisor Pavel Zikmund.

DECLARATION OF AUTHETICITY

I hereby declare that the thesis ‘Reusable launcher flight mission’ was prepared as my own work under the supervision of Ing. Pavel Zikmund, Ph.D. and all the relevant information sources used for this thesis are properly cited and included in the list of references.

In Brno, 21st May 2021

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Dominik Metelka

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1. INTRODUCTION

At first, the major achievement for humankind was launching an object into space. With gaining knowledge about the spaceflight, a competition called ‘Space race’ between the Soviet Union (USSR) and the United States (US) had started to prove their superior capability in spaceflight industry. During this period of time, both countries significantly contributed to the field of astronautics. The USSR launched the first artificial satellite, placed a human into orbit as well as performed the first multi-person crewed spaceflight and a spacewalk. US not far behind reduced the lead and overtook USSR by successful crewed landings on the Moon during the Apollo program.

At this time, the only objective was to explore space and push the boundaries that seemed insurmountable before. Affordability, sustainability or effect on the environment were of little importance in the early days of space travel. Nowadays, with the increase in space debris, pollution, and overall carbon footprint, these factors are more important than ever. With increased interest from companies to launch their products into space alongside an effort to pursue space tourism, the aforementioned factors must be taken into consideration.

Another main reason is also the obvious technological development over the last decades which has also heavily impacted the space industry and aerospace in general. For instance, today’s smartphones have memory storage more than million times higher and processor more than 100 000 times more powerful than Apollo 11 computer. Even calculators are more powerful than a computer that landed man on the Moon.

Therefore, a development of reusable launch system started. Not all attempts however fulfilled the requirement of reducing the overall cost in comparison to expendable launch system. The most common and simple part being reused was earlier the orbiter. Nevertheless, at the moment there are reusable launch vehicles whose launches already became a routine matter. Currently, there are partially reusable systems in operation however fully reusable launch systems are already in development which also goes hand in hand with the development of more sustainable rocket fuel.

In this thesis, I will compare the operational reusable launch vehicles with explaining each vehicle’s flight mission and list the differences in their return options. Nevertheless, mainly I will be focusing on designing a flight mission of the launcher reusable first stage in MATLAB with the aim of finding the time of engines reignition to provide a safe touchdown.

2. REUSABLE LAUNCH SYSTEM

A reusable launch system is a launch system where a part of the system, or all of its components, are recovered after the mission. The recovered parts are utilized afterwards for a later reuse. On the flip side, there are expendable launch systems whose components are not being recovered after the mission and mostly burn in the atmosphere after the re-entry. That means, they are directly designed to be used only once. Due to supplementary systems, landing gear and an extra amount of propellant that is required for the stage landing and recovery, the reusable launch systems need to carry an extra weight. After a successful landing, a launcher needs to undergo a process of refurbishment before its reuse. The price of that simply depends on the type and a design of this launcher. Different reusable launch systems have also a different number of reuses before a retirement. This number could however differ even for the same type and it strictly depends on the condition after being refurbished. The number of launches for individual boosters increases over time thanks to the major ongoing development in this industry [1][2].

In general, a launch vehicle is a rocket-propelled vehicle used to carry a payload from Earth's surface to space. The launchers carrying a payload to Earth orbit are usually designed as multistage rockets. The rocket therefore has two or more stages that separates during the flight. Single-stage rockets are currently only suborbital [4].

2.1 History

The beginning of the first use of rockets dates back to 1232 when the Chinese experimented with the gunpowder during their war with Mongols. Bamboo tubes filled with gunpowder were attached onto the arrows which represented a truly simplified solid-propellant rocket. The tube containing the gunpowder was capped at one end and opened at the other one. After the ignition, the burning of the powder immediately started to produce fire, smoke, and gas which produced a thrust by escaping from the free end. By being attached to an arrow, the 'rocket' had some sort of a guidance system as well that kept the rocket headed in one direction [3].

Fig. 2.1: Chinese Fire-Arrows [3]

These Chinese Fire-Arrows (Fig. 2.1) are being called as the predecessor of today's rockets however the development of reusable launch space systems and overall rockets that we know nowadays did not begin until several centuries later. The first project dedicated to a reusable launch system is dated to the first half of the twentieth century, between the years 1935 and 1945 to be specific. This liquid-propellant rocket-powered suborbital bomber was being developed by Austrian aerospace engineer Eugen Sänger in the Nazi Germany and was called the Silbervogel project which translates to "Silver bird". Due to economic reasons the project was not brought to light. Nevertheless, the technologies developed during this project have been used till today. For instance, regenerative cooling of the rocket engine by its fuel. The majority of rocket engines still uses this or a similar technology where the fuel or oxidizer flows in tubes around the engine bell to cool the nozzle and pressurize the fluid. Moreover, the calculations and experiments were later used for the US STS Space Shuttle Program [4].

STS Space Shuttle program was actually the first operational reusable space vehicle with the first flight in 1981 although the development started in 1968. At first, the proposed idea was to develop a fully reusable spaceplane using a crewed fly-back booster. Due to an immense complexity and economic reasons, the concept shifted towards designing of reusable solid rocket boosters and an expendable external tank which carried a reusable orbiter. Space Shuttles have already been retired from service because of technical and economic reasons. During their 30-year lifetime, Space Shuttles were more expensive to operate than if they would be an expendable launch system. The main reason of reusability is to lower the costs of launches therefore space shuttles did not truly meet the requirements [1][4][7].

2.2 Current state

Nowadays, Space Exploration Technologies Corp. (SpaceX) plays the most significant role in launcher reusability and is far ahead of everybody else. This American aerospace manufacturer's Falcon 9 rocket launches and successful landings have almost been a routine matter for couple of years now. The launches are mainly part of the Starlink mission which is a satellite internet constellation that will consist of thousands of small satellites in low Earth orbit providing satellite internet access. Nevertheless, SpaceX's rockets are even used by NASA and as it could be seen from Fig. 2.2, they basically filled the gap after the Space Shuttle retirement in 2011 [5][8].

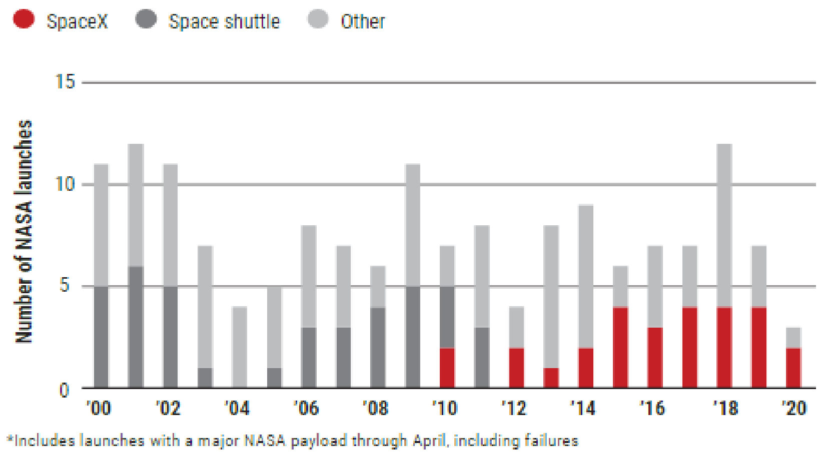

Fig. 2.2: Shares of NASA's launches [8]

Alongside partially reusable launch vehicle in terms of the Falcon 9 and Falcon Heavy rockets, SpaceX is currently working towards a fully reusable launch vehicle under the Starship program. SpaceX's Starship spacecraft (second stage) and Super Heavy rocket (booster stage) together referred to as simply 'Starship' is designed to carry both crew and cargo to Earth orbit as well as the Moon, Mars and even beyond but more about that in chapter 4.2 [9][10][14].

Another American private aerospace manufacturer who is developing reusable launch systems is Blue Origin. Their vision is mostly commercial spaceflight which is coming to reality thanks to the New Shepard suborbital launch vehicle which was the first launch vehicle to perform vertical take-off with successful autonomous vertical landing (VTVL). At the moment, there is already an opened auction to have a seat on the first crewed flight in July 2021. An orbital launch vehicle named New Glenn is also in development and it is, similar to Falcon 9, a two-stage rocket with a reusable first stage [11][12][13][15][74].

As obvious as it is, USA is truly the leading power in spaceflight reusability today whereas other countries and space agencies have not yet surpassed the development stage. The only slight exception is Rocket Lab which was founded in New Zealand however with its headquarters in Long Beach, California, it is once again a US company. They have developed a two-stage (sometimes three-stage) partially recoverable orbital launch vehicle named Electron. As of now, Electron is the only reusable orbital-class small rocket [20].

Apart from that, everything else is either under development or in a project phase. For example, ESA signed contracts in December 2020 to start developing a reusable first stage launcher Themis [16].

China is also researching the reusability of their launch vehicles. In particular, the Long March 8 rocket that had its first flight at the end of December 2020 will eventually be reusable. Apparently, the research and development of the reusable variant was proceeding well and therefore the first test is planned before the end of this year to verify key vertical landing technologies [17][18][19].

3. OPERATIONAL LAUNCH VEHICLES

3.1 Space Shuttle Solid Rocket Boosters (NASA)

The first solid-propellant rockets designed for crewed spaceflight, the largest and most powerful solid-propellant engines ever flown as well as the first designed for reuse are the Space Shuttle Solid Rocket Boosters (SRB) developed for NASA [4][21][22]. The propellant mixture consists of an ammonium perchlorate (oxidizer, 69%), aluminium (fuel, 16%), iron oxide (a catalyst, 0,4%), Polybutadiene acrylonitrile (PBAN binder, 12.04%), and an epoxy curing agent (1.96%) and by itself the propellant weighed approximately 500 metric tonnes. As it cand be seen from the Fig. 3.1, it had an 11-point star-shaped perforation in the forward motor segment (Section A-A) and a double-truncated-cone perforation in each of the aft segments [22].

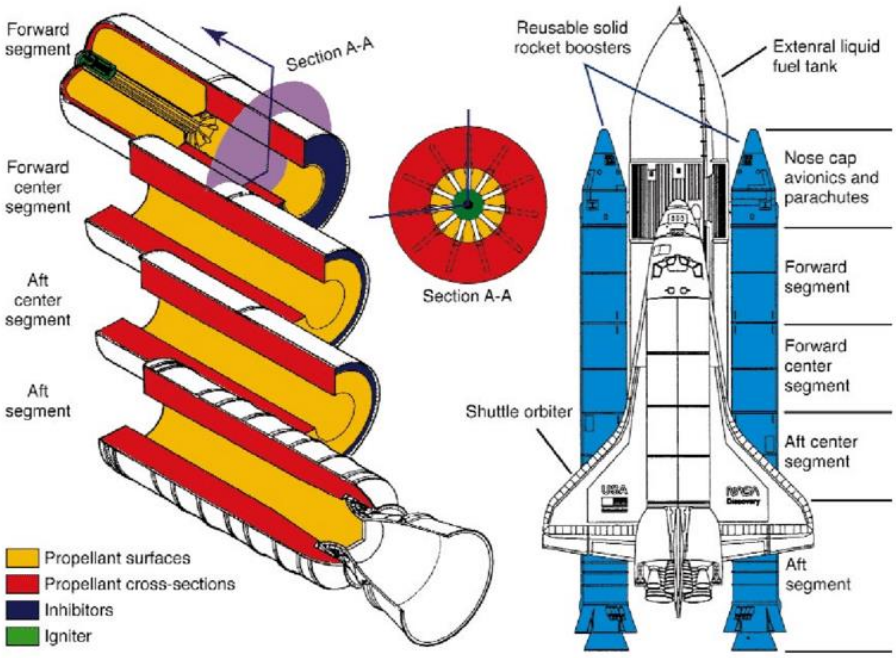

Fig. 3.1: Solid Rocket Booster layout [23]

Two SRBs provided most of the necessary thrust for Space Shuttle (71,4%) which consisted of, besides both SRBs, an external fuel tank (ET) and a reusable orbiter. Although SRBs were also used for the Atlas V and ESA's Ariane 5 launches, they were part of an expendable launch system and therefore were not recovered afterwards [22][24].

The development of SRBs dates back to 1969 when the Space Transportation System (STS) was proposed. The vision was to create a fully reusable system however it was too complex and expensive to do so. Therefore, it ended up as the partially reusable configuration known today as Space Shuttle. The SRBs were expected to possibly undergo even 10 reuses. The first flight took place in April 1981 and since then the Space Shuttle with 5 orbiter vehicles in total have had 135 missions over the 30-year lifetime with last being in July 2011. Unfortunately, two of the orbiters (Columbia and Challenger) suffered catastrophic accidents and 14 astronauts lost their lives [1][4][26].

Even though the boosters and orbiter were reusable, the total cost of these 135 missions would be smaller with an expendable launch system. Due to economic and also technical reasons and thus unfulfilled expectations, the Space Shuttles were retired in 2011. [1][4]

Overall, the main disadvantage of solid propellant boosters is their lack of ability to be controlled after ignition and that is why they must generally burn until exhaustion, unlike liquid propellant or cold-gas propulsion systems. In comparison to liquid propellant rockets, the SRBs are able to provide large amounts of thrust with having a relatively simple design and without any significant refrigeration. The amount of thrust produced for their size is genuinely great [25].

Flight mission

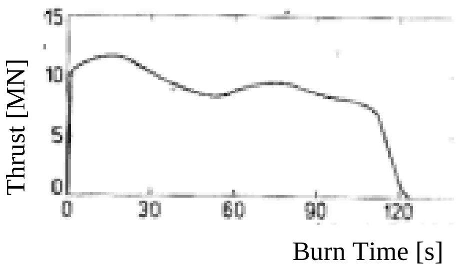

Fig. 3.2: SRB Sea Level Thrust [21]

The two reusable SRBs supported the weight of the whole system at the mobile launcher platform by four hold-down posts on each booster that fit into corresponding support posts on the platform. They were fastened by hold-down bolts that held the SRB and launcher platform posts together. Each bolt had a nut at each end, the top one being a frangible nut. The top nut contained two NASA standard detonators (NSDs), which were ignited at solid rocket motor ignition commands. Afterwards, SRBs provided the main thrust to carry the shuttle to an altitude of about 46 km. At a lift-off, the thrust of each booster was approximately between 11,8 and 13,8 MN at sea level. That was 20 seconds after lift-off gradually reduced to about 9,3 MN corresponding to a force of 3 g at the point of maximum dynamic pressure (max Q). After that, it was increasing again but still within the 3 g limit. SRBs peaked at an altitude of approximately 67 km so they travelled little bit over 20 km due to inertia after the separation which was at the velocity of 1460 m/s. Then, SRBs performed a free-fall until an altitude of 4,8 km when the pilot parachute was deployed to stabilize the boosters. Further, the conical part separated on its own parachute simultaneously as the main SRB's parachutes deployed 1,7 km above sea level. Both boosters and their conical part landed in ocean at the velocity of 14 m/s approximately 250 km from the launch site. Afterwards, the parts were refurbished and reused [21][22][24].

3.2 New Shepard (Blue Origin)

Blue Origin's suborbital launch vehicle New Shepard developed mainly for commercial spaceflight is the first rocket that has vertically landed back on Earth after reaching the outer space defined by the Kármán line at the altitude of 100 kilometres. This fully reusable vehicle consists of two main parts: propulsion module and a crew capsule. The propulsion module uses a single Blue Origin BE-3 bipropellant rocket engine fuelled by a mixture of a liquid hydrogen (LH2) and a liquid oxygen (LOX). The crew capsule separates roughly at the peak altitude and consists of six seats for future passengers with each having its own window as seen at Fig. 3.3 alongside with the founder of Blue Origin, Jeff Bezos. The propulsion module performs a powered vertical landing, whereas the crew capsule lands using parachutes [4][11][15][30].

a) Jeff Bezos, Founder of Blue Origin   b) Crew Capsule Interior

Fig. 3.3: New Shepard Crew Capsule [27][28]

The launch site where all New Shepard modifications have been launched from is Blue Origin's suborbital launch facility called Launch Site One which is located near the town of Van Horn in West Texas. It is also mentioned in Fig. 3.4 which is dedicated to the New Shepard flight mission profile. The altitude of the facility is given in feet and translates to approximately 1130 meters above mean sea level (MSN) [11].

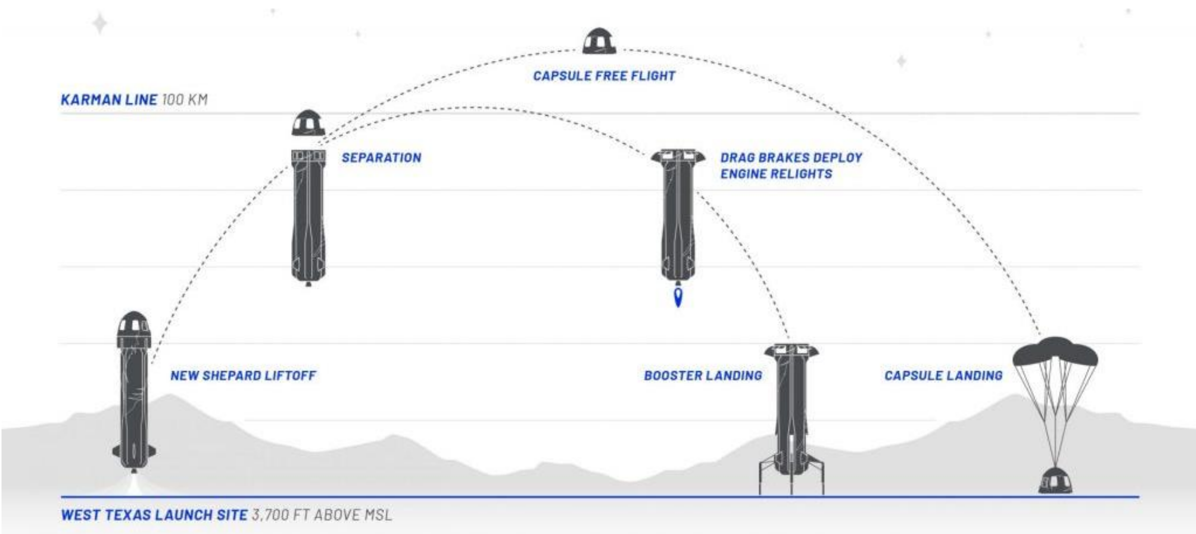

Fig. 3.4: New Shepard Flight Mission [11]

The flight of the New Shepard rocket that landed back was overall a second flight because the first vehicle New Shepard 1 (NS1) which took off on 29 April 2015 was only partially successful due to the capsule recovery and a crash of the booster. It reached the altitude of 93,5 km therefore the outer space was not accomplished. Thus, the first successful vertical take-off and landing (VTVL) happened on 23 November 2015 with the New Shepard 2 (NS2) where both parts were recovered. First flight with the reused NS2 vehicle took place two months after and since then it has made three other successful launches and landings [30].

The last flight of NS2 whose only objective on 5 October 2016 was to test the in-flight abort system and the loss of the booster was presumed, ended up unexpectedly with a successful landing of both capsule and a booster. Launch abort system (LAS) otherwise called as launch escape system (LES) is a safety system that separates the capsule from the launch vehicle anytime during the ascent or even before the launch in case of emergency. Specifically, in case of NS2's last flight the solid-fuel abort motor was fired circa 45 seconds after lift-off causing a separation from the propulsion module. Further, the capsule descended under parachutes. Due to the aerodynamic forces that this separation causes it had been assumed by Blue Origin who even stated it before the launch that the propulsion module would be lost. However, it still performed a safe landing therefore the abort test was a major success [29][30].

After this flight which led to NS2's retirement, few improvements were made such as enhanced recovery hardware to increase reusability and increased thermal protection. All of the mentioned enhancements put together the New Shepard 3 (NS3) part of which was also the new upgraded Crew Capsule 2.0 with the largest windows ever flown on a spacecraft, according to Blue Origin. The first flight happened on 12 December 2017 and overall, it has completed 7 successful flights before the NS4 was introduced. First flight being on 14 January 2021, the NS4 is said to be the first crewed NS vehicle. Next mission (NS-15) on 14 April 2021 included an 'Astronaut Rehearsal' so NS-16 in July 2021 should already have passengers [30][31][74].

Flight mission

New Shepard lifts off vertically from the launch site in West Texas and accelerates due to singular BE-3 engine for approximately two and a half minutes before it cuts off. BE-3PM powers the propulsion module (PM) and is propelled by high performing liquid oxygen and liquid hydrogen. This propellant was also used for the Space Shuttle's orbiter main engines. At full throttle, the engine generates 490 kN of thrust at sea level. After the engine cuts off, the pressurized capsule separates and coasts into space with the altitude being slightly above the Kármán line. The capsule then deploys parachutes and lands safely. On the other hand, the booster performs a free-fall. To help to control the descent as it re-enters the atmosphere, air flows through a ring at the top of the booster which moves the centre of pressure. Moreover, four wedge-shaped fins deploy as well to provide aerodynamic stability. At the speed of sound, eight large drag brakes are deployed to reduce the speed by half. Engine relights and performs another burn that slows the booster down to 8 km/h to provide a safe landing on retractable landing legs [11][32].

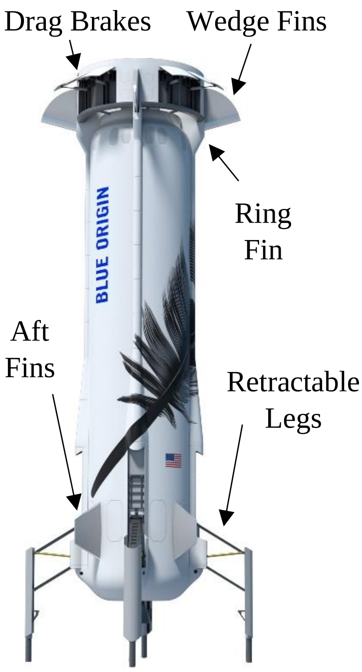

Fig. 3.5: Propulsion Module [11]

3.3 Falcon 9 (SpaceX)

At the moment, the most important launch vehicle in terms of reusability and also the world's first orbital class reusable rocket is the Falcon 9 (F9) manufactured by SpaceX in the United States. Overall, it has already had 117 launches, 77 landings and 60 re-flown rockets as of 21 May 2021 and there are plenty of missions planned ahead. It is a partially reusable two-stage-to-orbit medium-lift launch vehicle. The first stage which is reusable is powered by 9 Merlin 1D engines that use cryogenic liquid oxygen (LOX) and rocket-grade kerosene (RP-1) as propellant. The thrust-to-weight ratio (TWR) of this engine is exceeding 150 which is the best of any rocket engine in history. The second stage of the rocket is not reused after the mission but it is also powered by a singular Merlin engine that is optimized for vacuum [4][33][38].

Falcon 9 is also part of the most powerful operational rocket in the world, Falcon Heavy. It is composed of three Falcon 9 rockets whose 27 Merlin engines altogether generate almost 23 MN of thrust at sea level. Due to this phenomenal power, Falcon Heavy is able to lift into orbit nearly 64 metric tonnes of payload [34].

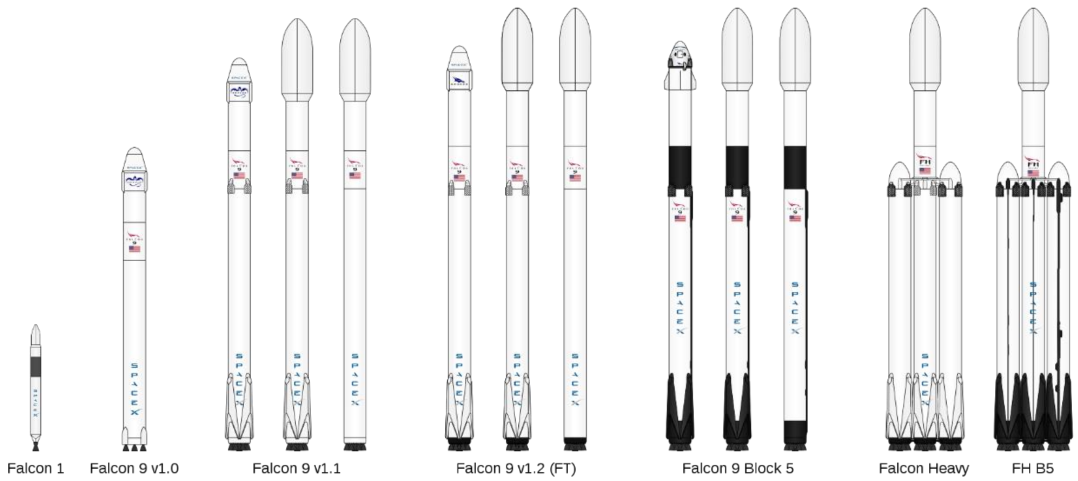

Fig. 3.6: SpaceX launch vehicles [36]

The development of the first F9 version simply named as Falcon 9 v1.0 started in 2005 and comes from the SpaceX's first rocket Falcon 1. The first flight happened however 5 years after in June 2010. From the start, the F9 rockets were developed to be at least partially reusable but it took few years until some progression with later versions was made. Even Elon Musk, the founder of Space X, admitted that they were inexperienced with the development of the first version and improvements needed to be made. Therefore, the Falcon 9 v1.1 was born. The improvements were for instance, the new Merlin 1D engines and also the configurations of these engines changed as seen from Fig. 3.7 from a square grid to so called "octaweb" [35].

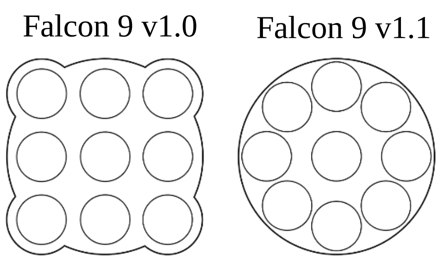

Fig. 3.7: Falcon 9 Engine Configurations [37]

In terms of reusability, Falcon 9 v1.1 also added landing legs and grid fins which increased the overall weight of the rocket by 60 % which got balanced by the 60 % thrust increase. First launch was scheduled in September 2013 which happened to be also the first commercial mission with a private customer. Until the retirement of this version in the January 2016, it conducted fifteen launches [35].


Fig. 3.8: Falcon 9 fairing [42]

Nevertheless, the first successful version to perform a safe powered vertical landing was the following F9 v1.2 otherwise called as "Full Thrust" (FT). The launch took place on 22 December 2015 so shortly after the first VTVL in general executed by Blue Origin's New Shepard. The first stage of the rocket performed a successful propulsive landing back on a ground pad and in April 2016 also on an autonomous spaceport drone ship (ASDS). F9 FT also accomplished the first flight of a reused stage in March 2017. During this flight, the fairing which is the aerodynamic cover used to protect the payload during launch also remained intact due to thrusters and parachutes that caused a safe ocean landing. Overall, the first stage represents, as stated by Elon Musk, 60% of the total cost of the rocket and together with a fairing approximately 70%. These parts are therefore from the reusability standpoint truly substantial. There has been a recovery of the fairing during other missions which even included a catching in a net (Fig. 3.8). Nevertheless, as of April 2021, SpaceX is no longer attempting to catch payload fairings in a net. Instead, all fairings are recovered from the water after a soft splashdown [4][40][41].

The latest Full Thrust Block 5 configuration was introduced in May 2018. It improved performance, reliability, and life of the vehicle, as well as ensured the vehicle's ability to meet critical government requirements for crewed and non-crewed missions. Primary objective of Falcon rockets is to deliver the payload whereas the recovery is secondary. Therefore, the launch outcome of the FT version has always been successful so far even though there have been few boosters crashed landings. Based on the Lewis point estimate of reliability, this rocket is the most reliable orbital launch vehicle currently in operation. The boosters are designed for 10 flights and the booster with serial number B1051 has already had 10 successful flights with the last one being on 9 May 2021 so it is possible that SpaceX will go over this designed limit in near future [4][39][43][72].

Falcon 9 rockets have been also used for resupplying the International Space Station (ISS). In this case, a reusable cargo spacecraft Dragon developed also by SpaceX have been used instead of a payload fairing. This spacecraft was later improved into SpaceX Dragon 2 which is either crewed (Crew Dragon) or simply carries cargo (Cargo Dragon). After returning to Earth, it splashes into the ocean using parachutes. The first crewed flight of the Crew Dragon spacecraft as well as the first flight ever operated by a commercial provider happened during the Crew Demo-2 mission (DM-2) on 30 May 2020. The spacecraft is equipped with an integrated LES part of which are eight SuperDraco engines that are capable of separating from the rocket and accelerating away in case of emergency. Major improvement from its predecessor is also the autonomous docking to the ISS [4][44][45].

Second crewed flight took place on 16 November 2020. It has been named Crew-1 and it was the first launch with a full-production crew due to DM-2 having only two members. The crew has already safely returned back to Earth [46][73].

Fig. 3.9: SpaceX Crew-2 [47]

After the DM-2 mission, the spacecraft was recovered and reused for the SpaceX Crew-2 mission on 23 April 2021 equipped with a new thermal shield. Simultaneously, this four-member crew has been the first in history to fly with a reused first stage. To be specific, the booster that was used is from the previous Crew-1 mission. Moreover, this crew consisting of from left to right two NASA astronauts, one ESA and one JAXA astronaut replaced the four members of Crew-1 at the ISS [45].

Flight mission

Firstly, the nine Merlin engines of the first stage ignite. The rocket computer commands the launch mount to release the vehicle. Falcon 9 lifts off vertically from the launch pad with the engines altogether producing 7,607 kN of thrust at sea level. The payload F9 can carry to low Earth orbit (LEO) is 22,800 kg and 8,300 kg in case of geostationary transfer orbit (GTO).

Approximately 2,5 minutes into flight, the first-stage engines are shut down which is called main-engine cut-off (MECO). At this point, Falcon 9 is about 70-80 km high with the speed around 8000 km/h. Three seconds after MECO, the stages separate. The first stage needs to have enough fuel to execute a powered landing. After the separation, the first stage performs a flip maneuver due to thrusters and the engines ignite making a boostback burn. The engine thrust slows the stage down by almost a half reducing the distance from the launch pad. In case of ground landing, three engines are ignited compared to just one in case of ASDS landing. The landing is fully autonomous. It is controlled by a computer unit of the stage, which processes input data from the devices and evaluates for example the speed of the stage and its position. Guidance is executed using GPS, INS and a beacon which is either located on the ground pad or on the ASDS. The control unit controls the thrust and the thrust vector. For stabilization there are grid fins around the stage and thrusters at the top.

At the time of re-entering the atmosphere, a second ignition with three engines known as the re-entry burn occurs. This slows the stage enough for a safe re-entry and also prevents damaging of the engines by a fast-moving flow of air. Grid fins are then deployed to stabilize the booster. Before landing, the third and the last ignition is made to slow the booster down for a safe landing that is either on the ground pad or on a drone ship which is shown at Fig. 3.10 [4][33][48].

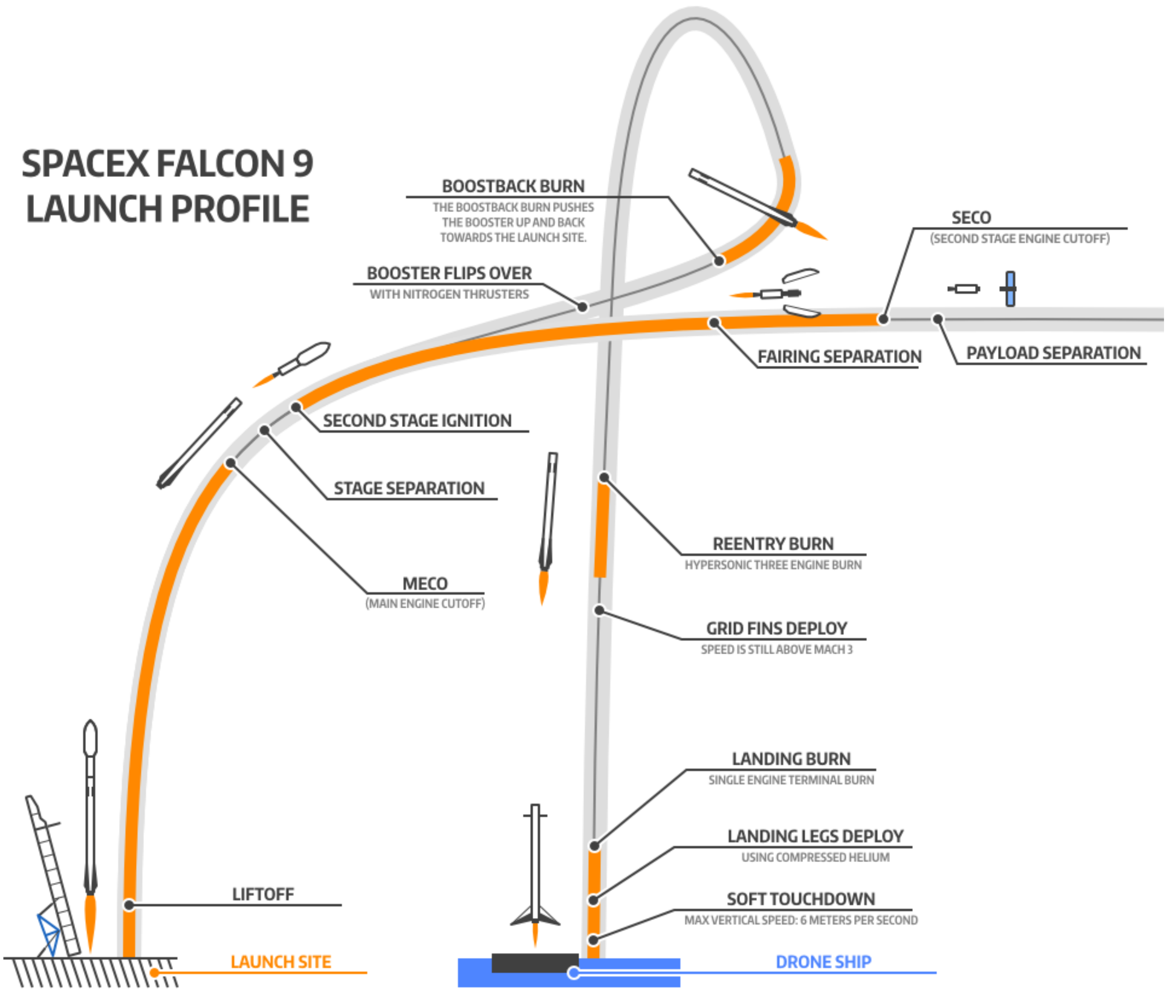

Fig. 3.10: Falcon 9 Launch Profile [49]

3.4 Electron (Rocket Lab)

Another significant partially recoverable two-stage-to-orbit launch vehicle is Rocket Lab's Electron whose engines were the first to use electric motor to drive the propellant pumps. Rocket Lab is a US private aerospace manufacturer that was founded in New Zealand. All of the Electron rockets so far have launched from the New Zealand launch site (Launch Complex 1) however the first Electron flight from the Launch Complex 2 in Virginia is scheduled for 2021 [50].

Electron is currently the only reusable orbital-class small rocket and it has been designed specifically to place small satellites like CubeSats into low Earth orbit (LEO). It has already deployed over 100 satellites. Electron was not planned to be reusable at first but on 6 August 2019 Rocket Lab changed their vision and announced their plan to attempt the first stage reusability. Unlike other companies, the decision to make the first stage reusable was not to reduce the launch costs in the first place. The main reason was to increase the launch rate without the need of company's expansion because they were simply unable to build enough rockets. The ultimate goal is to perform a mid-air recovery of the first stage using a helicopter so it can be captured by a hook while descending under a parachute but more about that in the chapter 5.4 In-air-capturing (IAC). That makes for a quick refurbishment and could be reused almost immediately [20][49][51].

However, to get to this point, there will be 3 splashdown recoveries at first to collect the necessary data. The first one already happened in November 2020 and ended up successfully as expected. Second flight attempting to recover the booster took place in May 2021 and was the first to sport reused components. It featured an improved thermal shield because the one on the previous mission apparently "took a real beating" according to Rocket Lab's founder, Peter Beck (Fig. 3.11). Even though the first stage was still safely recovered, the mission was overall unsuccessful due to second stage shut down shortly after the separation. The last splashdown test should happen in the second half of 2021 and after that Rocket Lab will move to the mid-air recovery attempts [51][52][75].

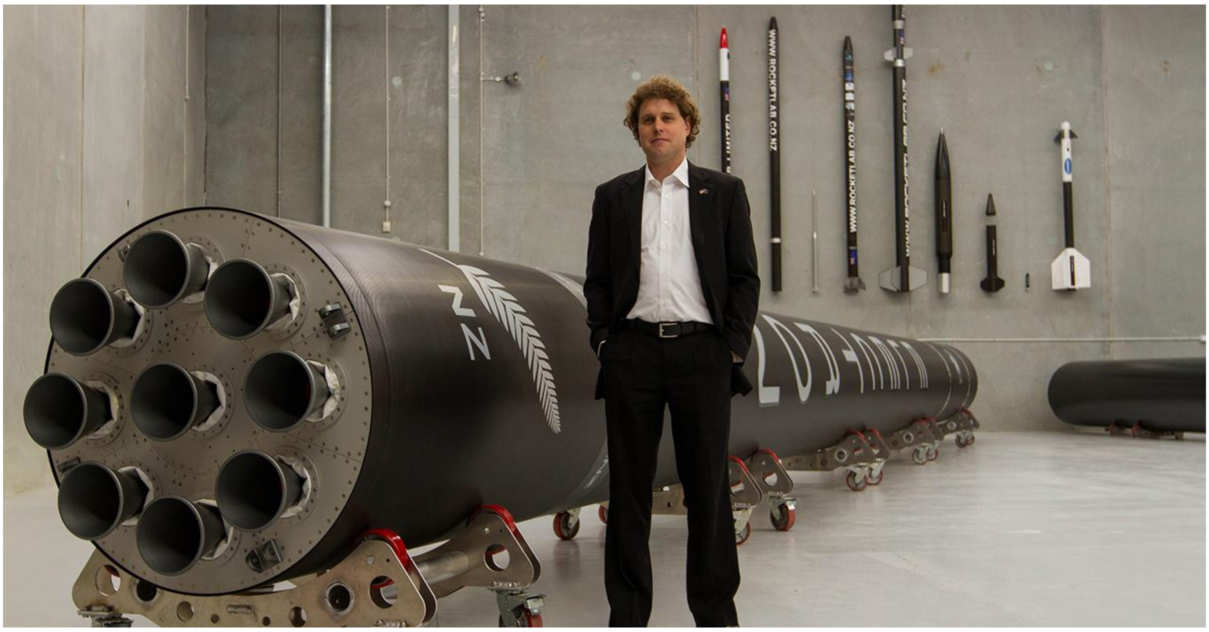

Fig. 3.11: Founder of Rocket Lab Peter Beck standing next to Electron [54]

The rocket consists of two stages and a kick stage that can deploy multiple payloads to unique orbits on the same mission. The first stage of the rocket is powered by 9 Rutherford engines using the same propellant as the Falcon 9 (LOX/RP-1). Second stage is powered by one adjusted for vacuum. All of the primary components of the engine are 3D-printed and therefore it is the first oxygen/kerosene engine to use additive manufacturing for all these components inside of the engine such as the thrust chamber, injector pumps or main propellant valves. Even the components of the Curie engine that powers the kick stage are 3D-printed. Additionally, the Rutherford engines also use the octaweb engine configuration like Falcon 9 as seen from Fig. 3.11 [49][53].

Fig. 3.12: Kick Stage [20]

Flight mission

At first, 9 Rutherford engines powering the first stage are ignited and then produce 190 kN of thrust at sea level during the lift-off. After around two and a half minutes, the first stage is travelling at a speed of around 7000 km/h. The first stage is almost like a fuel tank so at the altitude of 70 to 80 km when the fuel is burned, the stage separates. The engines on the stage are shut down and the reaction control system orients the stage for an ideal re-entry so it survives the heat and pressure during the descent. Electron therefore uses an aerothermal decelerator thus using the atmosphere to slow down the rocket. To be specific, the booster needs to be slowed down from 8.5 times to 0.01 times the speed of sound in about 70 seconds without having a fuel to perform a re-entry burn like F9's first stage. After decelerating to less than twice the speed of sound, a drogue parachute is deployed to stabilize the stage and to increase drag. As the stage is approaching the sea level, a large main parachute is deployed to make a soft splashdown landing [20][53][56].

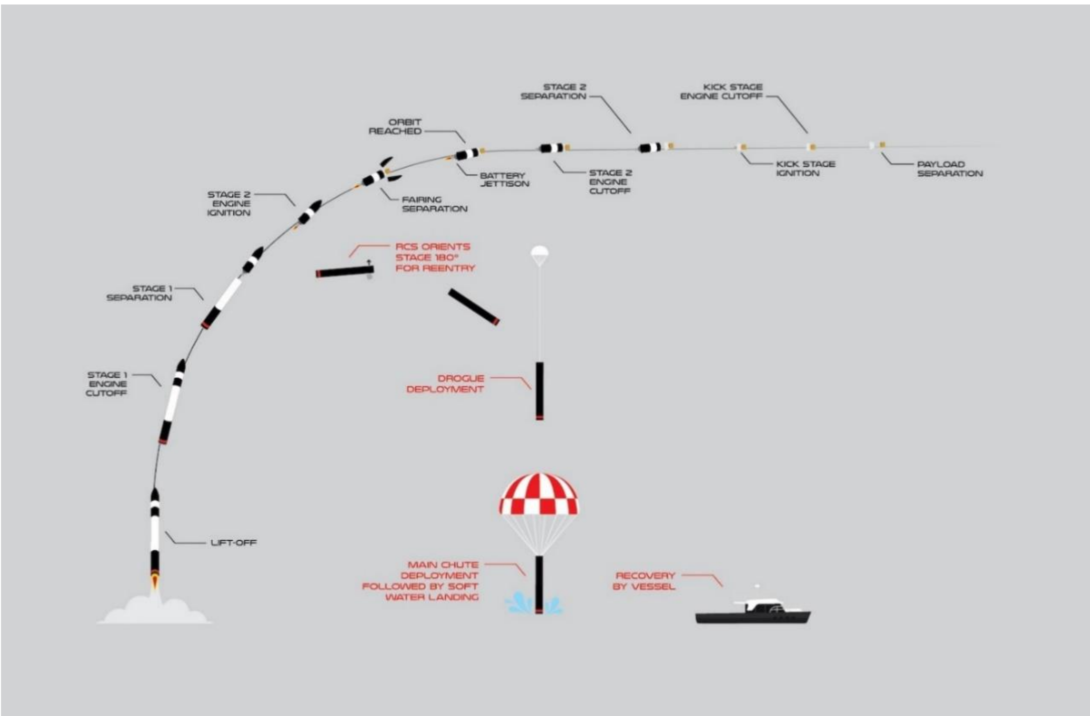

Fig. 3.13: Electron Flight Mission [55]

3.5 Overview

This serves as a brief overview of the operational reusable launch vehicles. Nevertheless, some of the launchers differ so much that it is hard to compare them. Therefore, I would like to explain some parts to avoid misunderstanding. SRBs were part of the Space Shuttle thus the payload and the cost refer to the whole system and not a singular SRB. Additionally, the SRB is powered by solid propellant mixture explained in the chapter 3.1 Space Shuttle Solid Rocket Boosters (NASA) which is simply shortened to PBAN-APCP.

New Shepard is a suborbital rocket developed for space tourism therefore it does not carry any payload to an orbit. That is also the reason why the price is not mentioned because this vehicle is not used by private companies or space agencies to deploy a payload into an orbit. However, there are 6 seats inside of the capsule to carry passengers and the price for the ticket in the future is said to be 200,000 US dollars or so [57].

In case of the Falcon 9 and Electron rocket, it is pretty straightforward. There is at first given the height of the rocket and then in the brackets the height of the reusable first stage. For Falcon 9 there is also the height of the interstage included because it lands back together with the first stage and also contains the grid fins used for stabilization. The cost refers to the cost of the launch and it should be taken as an approximate value. It can obviously differ from mission to mission and it might change as the reusability is getting higher.

Tab. 3.1: Reusable Launch Vehicles Overview [11][20][22][33]

	SRB	**New Shepard**	**Falcon 9 (first stage)**	**Electron (first stage)**
Height	45,46 m	18 m	70 m (47,7 m)	18 m (12,1 m)
Diameter	3,71 m	3,7 m	3,66 m	1,2 m
Engine	1x	1x BE-3	9x Merlin	9x Rutherford
Propellant	PBAN-APCP (solid)	LH2/LOX (liquid)	LOX/RP-1 (liquid)	LOX/RP-1 (liquid)
Lift-off Thrust	12,000 kN	489 kN	7,607 kN	190 kN
Payload to orbit	24,400 kg (LEO) 3,810 kg (GTO)	-	22,800 kg (LEO) 8,300 kg (GTO)	300 kg (LEO)
Cost (US$, millions)	450	-	61,2	6

4. LAUNCH VEHICLES IN DEVELOPMENT

4.1 New Glenn (Blue Origin)

Besides a suborbital rocket for space tourism, Blue Origin has also been developing a heavy-lift two-stage orbital launch vehicle named New Glenn. The design work for this project has already started in 2012 and it was scheduled to fly in 2020. That was later delayed to 2021 and then in February 2021, Blue Origin announced to push back the launch even further to late 2022. As seen from the Fig. 4.1, with the height of 98 meters it is a truly big rocket. Falcon Heavy which is currently the most powerful rocket looks pretty small in comparison. The diameter of the rocket and also the fairing is 7 meters so the fairing capacity has twice the payload volume of any existing launch vehicle [13][59][60].

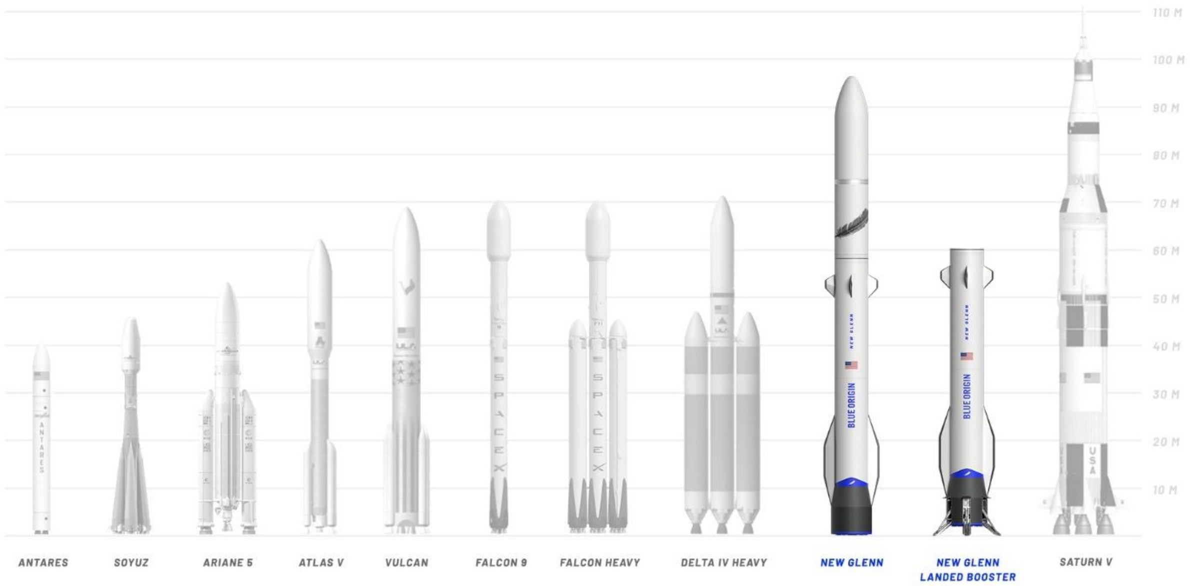

Fig. 4.1: New Glenn Height Comparison [13]

New Glenn's reusable first stage will be powered by 7 BE-4 engines that have been developed alongside this rocket from 2012. They use liquefied natural gas (LNG) and LOX as propellant. LNG has been picked over kerosene that is the fuel in both Falcon 9 and Electron due to its high efficiency, availability, low cost, clean combustion characteristics and also the ability to self-pressurize its tank. Seven of these engines altogether generate 17,100 kN of thrust at sea level. BE-4 engines will be along Blue Origin's own rockets also used to power the first stage of United Launch Alliance's Vulcan launch vehicle [13][58].

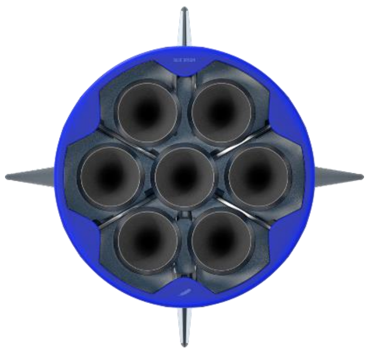

Fig. 4.2: BE-4 Layout [13]

New Glenn will lift of from Launch Complex 36 at Cape Canaveral, Florida. After the first stage gives enough boost to the second stage to deliver the payload, the stages then separate. Second stage ignites its two LH2/LOX BE-3U engines afterwards producing 1,100 kN of thrust in total. That altogether gives enough power to be capable of carrying either 45,000 kg of payload into LEO or 13,600 kg into GTO. After the separation, the booster performs a safe vertical landing downrange on a moving ship and if everything goes right, it is designed for 25 flights [13].

4.2. Starship (SpaceX)

Along already successful partially reusable launch vehicles, SpaceX is also developing a fully reusable two-stage-to-orbit super heavy-lift launch vehicle. The whole system is called simply Starship and it consists of a first booster stage named Super Heavy and a second stage also referred to as Starship. It is planned to replace Falcon 9 and Falcon Heavy launch vehicles as well as the Crew Dragon and Cargo Dragon spacecraft with the aim of carrying both crew and cargo to not only Earth orbit but the Moon, Mars and possibly other planets as well. [9][10][14]

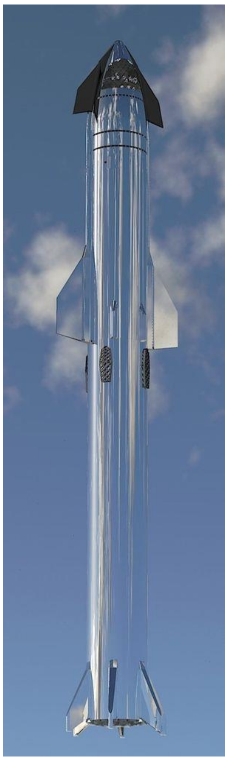

Fig. 4.3: Starship [61]

Starship is powered by Raptor engines that produce more than twice the thrust of Merlin engines used by Falcon rockets. Super Heavy booster is said to have 28 of these engines that produce 72 MN of thrust which makes it the world's most powerful launch vehicle ever developed. With that thrust, it can carry 100 metric tonnes to Earth orbit. Additionally, the Starship spacecraft will be powered by 6 Raptor engines with 3 of those being optimized for vacuum conditions. Raptor is not only more powerful than Merlin but it also uses cryogenic liquid methane (CH4) as a fuel instead of RP-1 kerosene alongside LOX as an oxidizer. Methane is inexpensive, burns cleaner so there is less clogging of the engines with deposits but most importantly it could be produced on Mars [10][14].

Both stages together will have the height of 120 m and 9 m in diameter therefore the payload fairing has even larger usable volume than New Glenn's 7 m in diameter fairing. Unlike Blue Origin, SpaceX has already made and tested few prototypes of the Starship spacecraft. They tested firing of the engines at first, then low altitude flight tests and as of April 2021, there has been 4 flight tests with prototypes Starship SN8 – SN11 reaching an altitude of at least 10 km. The next flight in May 2021 was already with the version SN15 due to major improvements. Before SN15, all high-altitude tests have ended up with the spacecraft crash during the landing. It was the first to perform a successful vertical landing after a flip maneuver and a horizontal 'belly flop' free-fall. That serves to increase drag and reduce terminal velocity due to larger surface area with flaps as seen from Fig. 4.4. Only SN10 was close but it exploded shortly afterwards due to low thrust at landing hence hard touchdown [10][62][63][76].

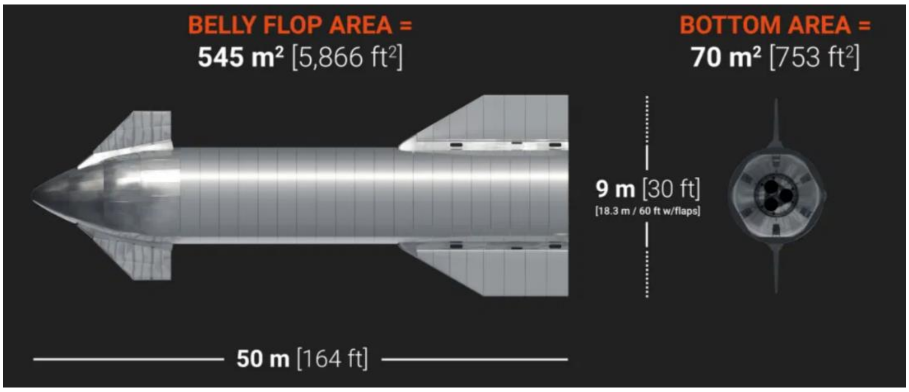

Fig. 4.4: Starship Surface Area [62]

Moreover, NASA has selected SpaceX as part of the Artemis program to develop the first commercial spacecraft that will carry the next two US astronauts to land on the Moon [64].

5. RETURN OPTIONS

5.1 Rocket-powered return flight (RTLS)

This option which simply stands for “Return to launch site” (RTLS) means that the rocket returns autonomously to the launch site or to a ground pad close to it. In this case, the engines are also being used for an additional ignition (boostback) that brings the stage closer to the landing site. Then, the engines are obviously used for deceleration through atmosphere re-entry and after that for a soft vertical landing. The first VTVL of SpaceX’s Falcon 9 performed this option and brought back the booster back in December 2015. For this purpose, a specific landing zone called LZ-1 and LZ-2 has been constructed in Cape Canaveral, Florida and LZ-4 in Vandenberg, California. There is an excessive amount of fuel needed for the booster to return back to the launch site therefore this option is used for low performances, carrying smaller payloads or LEO missions like for example sending cargo to the ISS and so on [2].

5.2 Down-range landing (DRL)

Another return option that is commonly used by SpaceX and even more than RTLS is down-range landing (DRL). That is because the performance loss is significantly reduced in comparison to RTLS. The booster does not need additional firing that brings the stage above an on-shore pad and the landing is performed on an artificial sea-going platform or on a ship. Due to safety reasons, the launches typically take place in the direction of the sea therefore ASDS offers a flexibility to the missions. The size of the SpaceX’s drone ship platform is 91 by 52 m and it is autonomous. The platform needs additional tugboats that brings the stage back to the port which typically takes 4 to 5 days. After that, transportation equipment is needed to move the booster to the refurbishment site. Therefore, even with the reduced performance losses and fuel amount that DRL has over RTLS, the overall cost is levelled out by an additional infrastructure investment and operation costs [2][65].

5.3 Splashdown

Splashdown landing is heavily used for landing of crewed spacecrafts such as SpaceX Dragon at the moment. It was used before for Apollo, Mercury and Gemini programs as well. Besides spacecrafts, this method has been also used for recovering the SRBs in Space Shuttle program or currently with the Electron rockets developed by Rocket Lab to recover its first stage. After descending enough through atmosphere re-entry, parachutes are deployed and a capsule or a booster then lands in water. Afterwards, it is hoisted by a recovery ship which transports it to the mainland [66].

5.4 In-air-capturing (IAC)

This option is really similar to the splashdown method however the stage is captured by an aircraft before landing into water. That is the vision for the recovery of Rocket Lab’s Electron to catch it mid-air by a helicopter while it is slowly descending under parachutes. In March 2020, Rocket Lab already successfully performed IAC however only with Electron test stage by taking it up with another helicopter which dropped it afterwards. Second helicopter then snagged it with a grappling hook at the altitude of approximately 1,500 meters while it was descending under parachutes and took that stage safely back to land [67].

6. FLIGHT MISSION

In this chapter I will demonstrate calculations for a rocket's first stage mission with the aim of a controlled landing back to Earth. For the calculations I have chosen parameters of the Falcon 9 rocket from [33][39][68] and the calculations and theory are provided by [69].

6.1 Launch and ascent

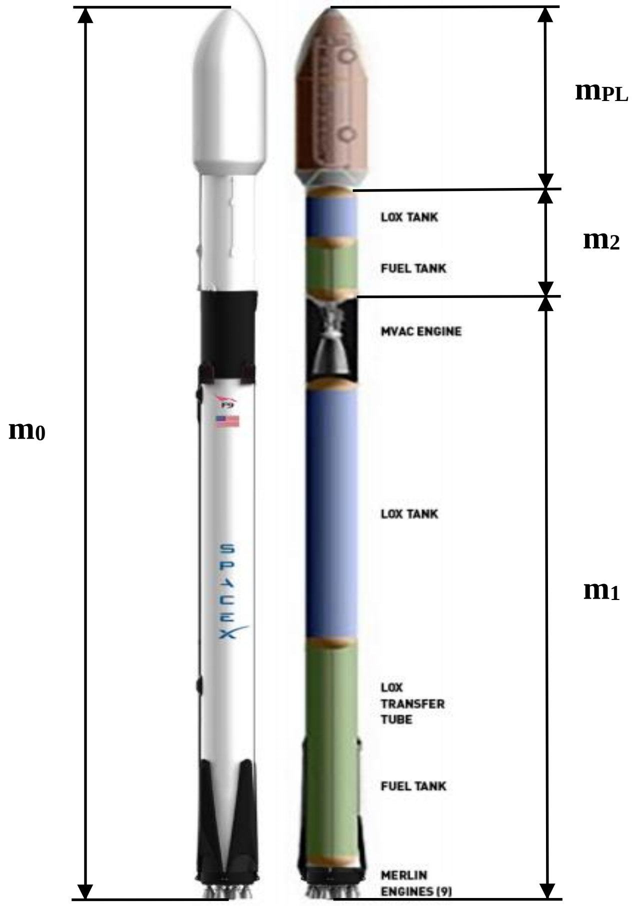

Fig. 6.1: Falcon 9 Mass Distribution [39]

At first, the overall mass m_0 needs to be specified which is the weight of the Falcon 9 rocket at lift-off as stated in [33] and the carried payload together. For the payload I chose the weight of 60 Starlink satellites each having the mass of 260 kg.

$$m_0 = 549\,054 + 15\,600 = 564\,654\ kg \tag{6.1}$$

The overall initial mass consists of the mass of each stage m_1, m_2 and the payload m_{PL} which is the weight of the 60 Starlink satellites with the fairing. Additionally, m_1, m_2 are the sum of so-called dry mass m_E with the propellant mass m_P. The propellant mass of the first stage m_{P1} is given by Federal Aviation Administration (FAA) in [70].

$$m_1 = m_{E1} + m_{P1} = 25\,600 + 411\,000 = 436\,600\ kg \tag{6.2}$$

$$m_2 = m_{E2} + m_{P2} = 4\,000 + 107\,500 = 111\,500\ kg \tag{6.3}$$

$$m_{PL} = m_0 - (m_1 + m_2) = \\ = 564\,654 - (436\,600\ +\ 111\,500) = 16\,554\ kg \tag{6.4}$$

Additional input parameters are given such as gravitational acceleration $g(h)$ and first stage's thrust at sea level F_1 produced by 9 Merlin engines that is much greater than a drag force D which could therefore be neglected during an ascent. Further parameters are constant mass flow rate estimation $\dot{m}_{P1}$ made by Professor Aaron Ridley in [71] and burn time t_{f1}.

$$g(h) = g_0 = 9{,}80665\ ms^{-2}$$

$$F_1 = 7\ 607\ kN$$

$$\dot{m}_{P1} = 2\ 100\ kgs^{-1}$$

$$t_{f1} = 162\ s$$

Specific impulse I_{SP1} which is one of the main parameters to assess the efficiency of a reactive propulsion is calculated by dividing a thrust with a mass flow rate [69].

$$I_{SP1} = \frac{F_1}{\dot{m}_{P1}} = \frac{7\ 607\ 000}{2\ 100} = 3\ 622{,}38\ ms^{-1} \tag{6.5}$$

Knowing the burn time t_{f1} and mass flow rate $\dot{m}_{P1}$ it is possible to calculate how much propellant will be burned during the ascent $m_{P1_{ascent}}$ and how much of it will be left for a propulsive landing $m_{P1_{landing}}$.

$$m_{P1_{ascent}} = t_{f1} \cdot \dot{m}_{P1} = 162 \cdot 2\ 100 = 340\ 200\ kg \tag{6.6}$$

$$m_{P1_{landing}} = m_{P1} - m_{P1_{ascent}} = 411\ 000 - 340\ 200 = 70\ 800\ kg \tag{6.7}$$

The final velocity of the first stage V_{f1} at the time t_{f1} is given by following equation (6.8) and the speed dependence on time until the main engines cut-off at t_{f1} was created in MATLAB and can be seen from the Fig. 6.2.

$$\begin{aligned} V_{f1} &= I_{SP1} \cdot \ln\left(\frac{m_0}{m_0 - \dot{m}_{P1} \cdot t_{f1}}\right) - g_0 \cdot t_{f1} = \\ &= 3\ 622{,}38\ \cdot \ln\left(\frac{564\ 654}{564\ 654 - 2100 \cdot 162}\right) - 9{,}80665 \cdot 162 = \\ &= 1\ 753{,}12\ ms^{-1} \end{aligned} \tag{6.8}$$

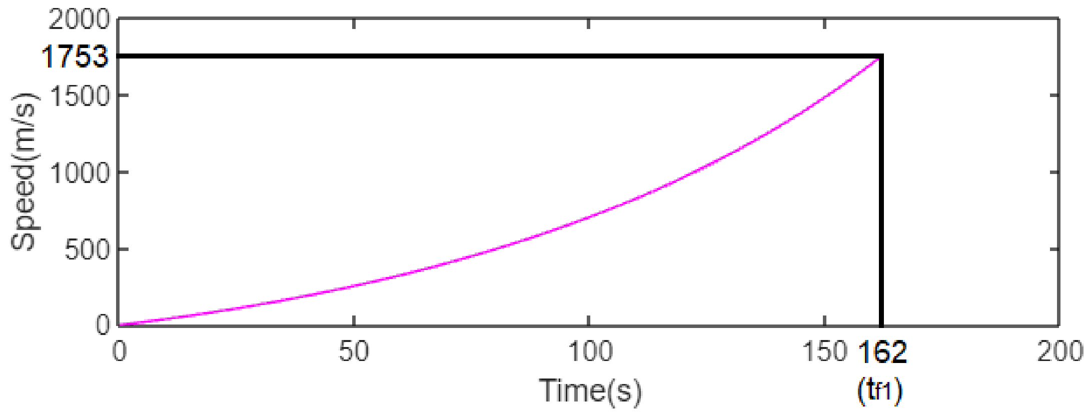

Fig. 6.2: Speed dependence on time until MECO

With calculating the mass number μ it is then possible to also obtain the final height h_{f1} at the time t_{f1}. The mass number μ is the mass at lift-off m_{01} divided by the final mass during MECO m_{f1} which is the initial mass m_0 subtracted by the burned propellant mass $m_{P1_{ascent}}$.

$$\mu = \frac{m_{01}}{m_{f1}} = \frac{m_0}{m_0 - m_{P1_{ascent}}} = \frac{564\,654}{564\,654 - 340\,200} = 2{,}516 \tag{6.9}$$

$$\begin{aligned} h_{f1} &= I_{SP1} \cdot \frac{m_{f1}}{\dot{m}_{P1}} \cdot (\mu - 1 - \ln(\mu)) - \frac{1}{2} \cdot g_0 \cdot \left(\frac{m_{f1}}{\dot{m}_{P1}}\right)^2 \cdot (\mu - 1)^2 \\ &= 3\,622{,}38 \cdot \frac{224\,454}{2100} \cdot (2{,}516 - 1 - \ln(2{,}516)) - \\ &\quad - \frac{1}{2} \cdot 9{,}80665 \cdot \left(\frac{224\,454}{2100}\right)^2 \cdot (2{,}516 - 1)^2 = \\ &= 100\,982{,}1\,m \end{aligned} \tag{6.10}$$

To ensure and check that the final altitude/height is correct, similar formula however without the mass number μ was used in MATLAB to calculate and show the altitude dependence on time during the burn time.

$$h(t) = \frac{I_{SP1}}{\dot{m}_{P1}} \cdot \left[(m_0 - \dot{m}_{P1} \cdot t) \cdot ln \frac{m_0 - \dot{m}_{P1} \cdot t}{m_0} + \dot{m}_{P1} \cdot t\right] - \frac{1}{2} \cdot g_0 \cdot t^2 \tag{6.11}$$

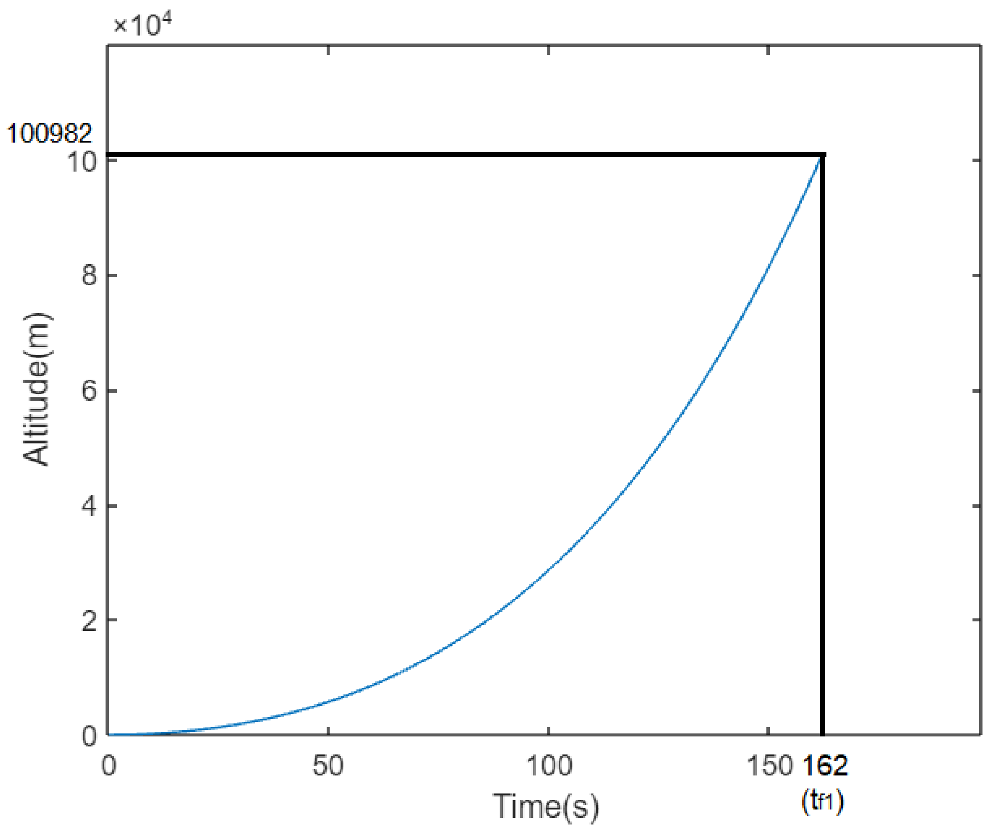

Fig. 6.3: Altitude dependence on time until MECO

6.2 Descent and landing

At first, it is necessary to define a coordinate system, in which the motion of the returning stage will be described and also other parameters such as kinematic quantities or forces.

6.2.1 Coordinate system

The origin of a coordinate system is set to the centre of gravity ($0 \equiv T$). The primary coordinate system (x, y, z) is bound to the body which is shown in Fig. 6.4 on a body of a return module. The plane of symmetry is defined by the longitudinal x axis and the z axis which is perpendicular. Together with the lateral axis y, which is perpendicular to the plane of symmetry, they create right-handed coordinate system.

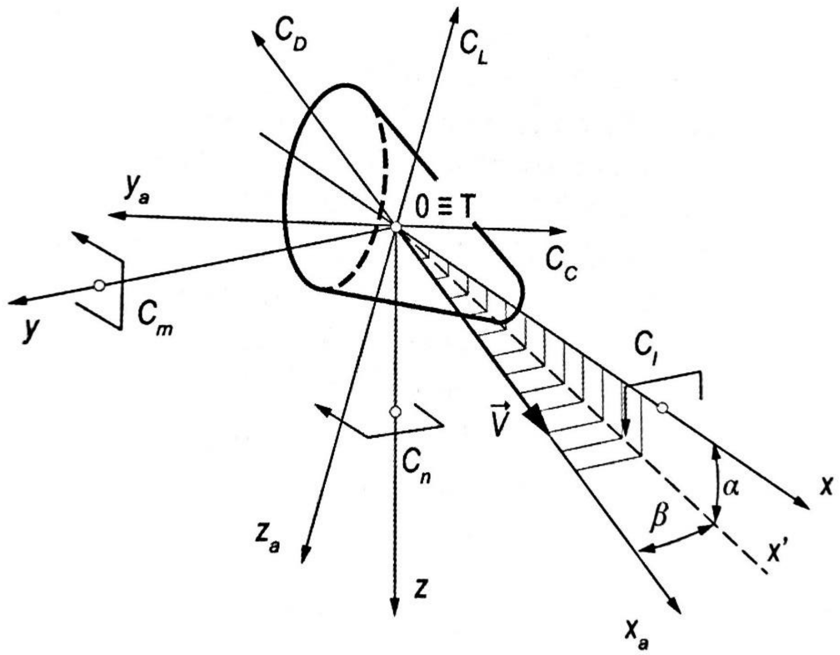

Fig. 6.4: Coordinate System [69]

Another coordinate system being used is the aerodynamic coordinate system (x_a, y_a, z_a). So called drag axis x_a is identical to the flight velocity vector $\vec{V}$. With the perpendicular lift axis z_a which lies within the plane of symmetry (x, z) as well as the transverse axis y_a they also create a right-handed coordinate system.

In this aerodynamic coordinate system are defined the coefficients of aerodynamic forces and moments. The aerodynamic forces which are lift L, drag D and transverse force C have their positive values in the negative direction of aerodynamic coordinate system axes (coefficients C_L, C_D, C_C). These coefficients as well as the moment coefficients depend on the angle of attack α and the yaw angle β (sideslip).

The last coordinate system is connected to the Earth. The trajectory of the flight path is plotted in this system in 6.3 Calculations. 2D system with altitude h and distance x variables has been used to show the trajectory of the proposed rocket.

6.2.2 Kinematic quantities

For calculations of descending through atmosphere, the kinematic quantities are important to determine the position and velocity of the descending object. Flight path angle γ which is the angle between the instantaneous tangent to the flight path and the local horizontal plane is one of the kinematic quantities and it could be seen in Fig. 6.5.

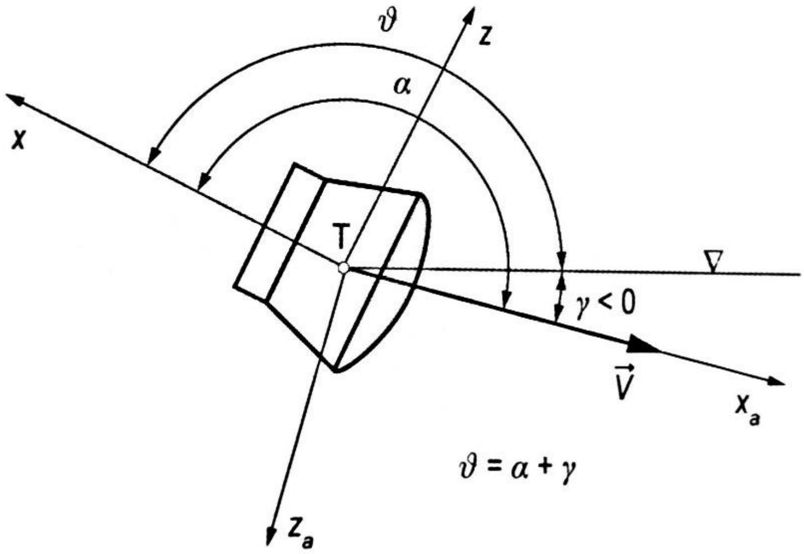

Fig. 6.5: Relations between angles for atmospheric descent [69]

Typically for descending, the flight path slope is negative so the velocity vector $\vec{V}$ points under the local horizontal plane. Therefore, the flight path angle γ is also negative. Furthermore, there is the longitudinal inclination of the aircraft ϑ which in other literature could be marked as Θ. This angle is equal to the sum of the already mentioned angle of attack α and the flight path angle γ.

6.2.3 Forces

Other than already mentioned aerodynamic forces, there are also other forces impacting the vehicle. During launch and ascent, it is mainly the propulsive force called thrust F that during the descent has no effect except for the propulsive landing when the engines are reignited. Nevertheless, during the whole flight mission there is an impact of gravitational force G which is the current mass m multiplied by gravitational acceleration g.

$$G = m \cdot g \tag{6.12}$$

Knowing the coefficients C_L, C_D, air density ρ, velocity V and projected area S, the aerodynamic forces lift L and drag D can be calculated as follows:

$$L = C_L \cdot \frac{1}{2} \cdot \rho \cdot V^2 \cdot S \tag{6.13}$$

$$D = C_D \cdot \frac{1}{2} \cdot \rho \cdot V^2 \cdot S \tag{6.14}$$

Due to the booster’s shape, lift forces could be neglected ($C_L = 0$).

6.2.4 Additional effects

In addition to already stated effects during the launch, there are effects especially during the proposed Falcon 9 launch that significantly influence the flight. However, they are not included in the calculations.

After lift-off, the launch vehicle is steered by a thrust vector control (TVC) which gimbals and throttles the engines. The process during gimbaling is called pitch over, after which the vehicle goes through gravity turn where gravity is used for further steering and trajectory optimization.

The thrust vector is commanded by the guidance subsystem and then converted to reference pitch and yaw angles $(\theta_{ref}(t), \psi_{ref}(t))$ and thrust magnitude $T_{ref}(t)$. Their time dependence during ascent until engine cut-off is shown in the following Fig. 6.6 [77].

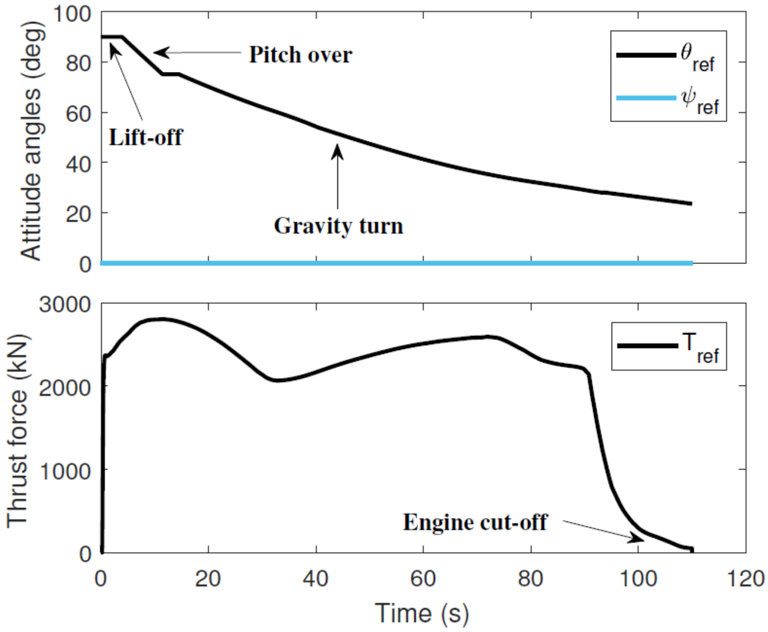

Fig. 6.6: Ascent attitude and thrust references [78]

To provide attitude control under zero or low thrust, two pairs of grid fins are installed at the top of the first stage. Additionally, there are also two pairs of cold gas thrusters for low dynamic pressure conditions. The cold gas stored inside F9 is nitrogen to be specific. The fins as well as the thrusters ensure stability mainly during the descent to increase precision and accuracy in control of the landing [39][77][78].

Tab. 6.1: Ascent attitude control [39]

Pitch, yaw	Gimbaled engines	Gimbaled engine Nitrogen gas thrusters
Roll	Gimbaled engines	Nitrogen gas thrusters
Coast attitude control	Nitrogen gas thrusters (recovery only)	Nitrogen gas thrusters

6.2.5 Equations of motion

To set up the equations of motion, it is needed to set the assumptions first.

- Spherical Earth with a homogeneous central gravitational field.
- The gravitational force acts in the direction of the geocentric normal.
- Rotation of Earth is not considered. The entrance characteristics do not depend on the place and direction of atmosphere re-entry.
- The atmosphere is motionless to Earth.
- The trajectory of descent in the atmosphere lies in one plane given by Earth's large circle. An exception may be a return with the possibility of a side maneuver of a spacecraft.
- Propulsive forces are not considered unless it is said otherwise

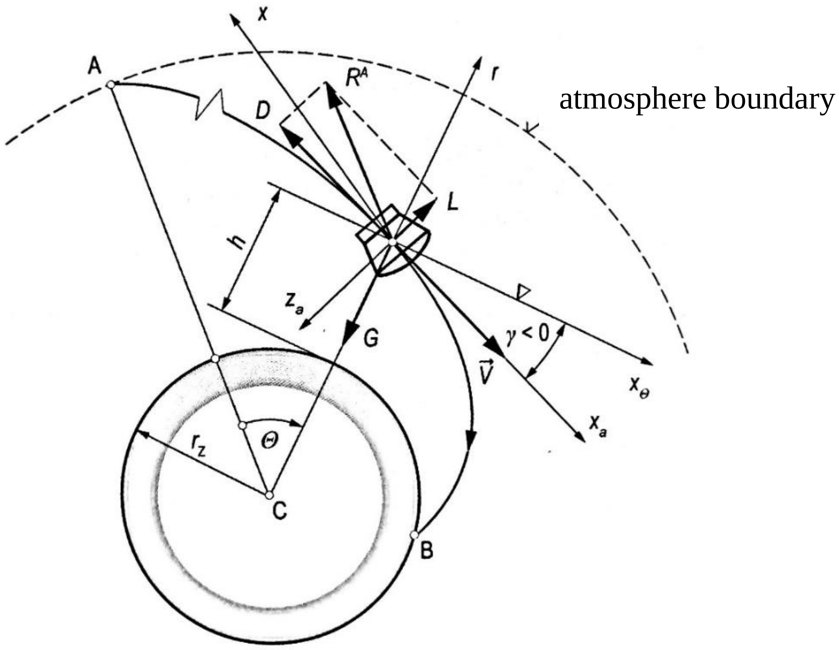

Fig. 6.7: Forces acting on the vehicle during atmosphere descent [69]

According to Fig. 6.7, the kinematic bonds that show the change of distance x and altitude h with speed components in each axis, can be written as follows:

$$V \cdot \cos(\gamma) = r\dot{\Theta} = \dot{x}_\Theta = \frac{dx}{dt} \tag{6.15}$$

$$V \cdot \sin(\gamma) = \dot{r} = \dot{h} = \frac{dh}{dt} \tag{6.16}$$

Another important parameter during return calculations is the ballistic coefficient B which depends on the drag coefficient C_D, projected area S and mass m.

$$B = \frac{C_D \cdot S}{m} \tag{6.17}$$

After substituting mentioned aerodynamic forces (6.13),(6.14) and ballistic coefficient (6.17) into standard equations of motion where r_Z is the Earth radius, at the end these equations look like this:

$$\dot{V} = -B \cdot \frac{1}{2} \cdot \rho \cdot V^2 - g \cdot \sin(\gamma) \tag{6.18}$$

$$V \cdot \dot{\gamma} = B \cdot \left(\frac{C_L}{C_D}\right) \cdot \frac{1}{2} \cdot \rho \cdot V^2 - \cos(\gamma) \cdot \left(g - \frac{V^2}{r_Z + h}\right) \tag{6.19}$$

During atmospheric descent below an altitude $h = 100 - 120\ km$, the atmosphere is isothermal. Therefore, the air density dependence on the altitude could be written as:

$$\rho = \rho_0 \cdot e^{-\frac{h}{H_m}} \tag{6.20}$$

The constant $\rho_0 = 1{,}225\ kgm^{-3}$ according to International Standard Atmosphere (ISA) and it is the initial air density at sea level. Together with the constant $H_m = 6700\ m$ they should provide a close value to a real atmosphere density at each altitude.

6.3 Calculations

All calculations and characteristics in this chapter were accomplished with a written MATLAB script. The script is written for the whole trajectory of the rocket hence from the lift-off to propulsive landing. After setting the vector length, the initial conditions are therefore:

$$x_0 = 0\ m$$

$$h_0 = 0\ m$$

$$V_0 = 0\ ms^{-1}$$

$$\gamma_0 = \frac{89{,}999}{180 \cdot \pi}\ rad$$

$$m_0 = 564\ 654\ kg$$

Unlike the calculations and MATLAB figures from 6.1 Launch and ascent which were strictly for a vertical ascent during burn time, this script uses the gravity turn as a trajectory optimization to steer the vehicle. As I mentioned in 6.2.4 Additional effects, there is no TVC considered in these calculations therefore no throttling and gimbaling of the engines and thus thrust vectoring. For this reason, the thrust is constant $F_1 = 7\ 607\ kN$ and the initial path angle is set to 89,999 instead of 90 degrees so the gravity turn is efficient and the angle could be integrated. For calculating in MATLAB, the angle had to be converted into radians.

Using the gravity turn, the kinematic bonds are slightly different from (6.15) and (6.16) in the horizontal plane which relates to the centre of Earth as the centre of gravitational field. Therefore, the Earth mean radius r_Z needs to be incorporated. Nevertheless, the vertical plane stays unchanged.

$$\frac{r_Z}{r_Z + h} \cdot V \cdot \cos(\gamma) = \dot{x}_g = \frac{dx}{dt} \tag{6.21}$$

$$V \cdot \sin(\gamma) = \dot{h} = \frac{dh}{dt} \tag{6.22}$$

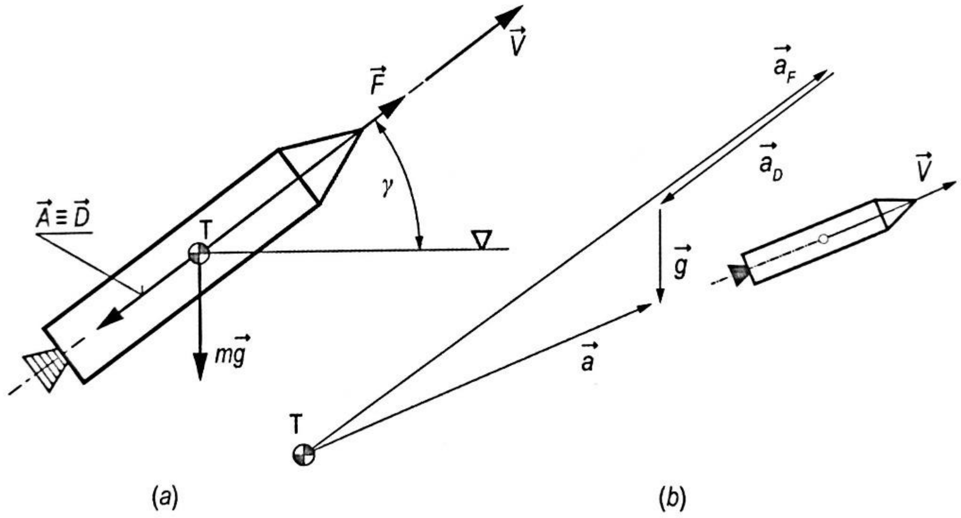

Fig. 6.8: Gravity turn [69]

Besides kinematic bonds, the equations of motion for the calculations were also changed from the equations of motion (6.18) and (6.19) used strictly for descent as well as due to no considered lift ($C_L = 0$) to following:

$$\dot{V} = \frac{F}{m} - \frac{D}{m} - g \cdot \sin(\gamma) \tag{6.23}$$

$$-V \cdot \dot{\gamma} = \cos(\gamma) \cdot \left(g - \frac{V^2}{r_Z + h}\right) \tag{6.24}$$

The equation (6.24) similar to the kinematic bonds stays unchanged throughout the whole flight mission however due to MECO at $t_{f1} = 162\ s$ and then engines reignition before landing, (6.23) needs to be changed respectively. When the engines are cut off, there is no thrust so the change of speed depends on drag and gravity.

$$\dot{V} = -\frac{D}{m} - g \cdot \sin(\gamma) \tag{6.25}$$

At specific time, the engines are reignited to safely land the booster on the land or ASDS. The stage uses retro propulsion to provide thrust in opposite direction of the motion to slow down for landing therefore the thrust component in the equation needs to be negative.

$$\dot{V} = -\frac{F}{m} - \frac{D}{m} - g \cdot \sin(\gamma) \tag{6.26}$$

During an ordinary Falcon 9 launch, the engines are gimballed and throttled and during the return mission, the engines are reignited three times. Firstly, the boostback burn uses three engines followed by the re-entry burn also with three engines and at the end the landing during which a single engine is reignited.

For this preliminary flight mission design, only one reignition for landing was considered during which all nine Merlin engines ignited and produced a constant thrust.

Furthermore, from optimizing the landing, the end time was set to $tmax = 555\ s$ with a time step $dt = 1\ s$. At $ttop = 327\ s$, the booster reaches the highest altitude during zero flight path angle. At this time, the booster flips so it lands down bottom first and the drag coefficient is changed from $C_D = 0.03$ which was for ascent, when the drag is insignificant due to large thrust, to $C_D = 0.4$ for the descent and landing. This time was determined from the flight path angle characteristics (Fig. 6.9) together with the characteristics of altitude dependence on time.

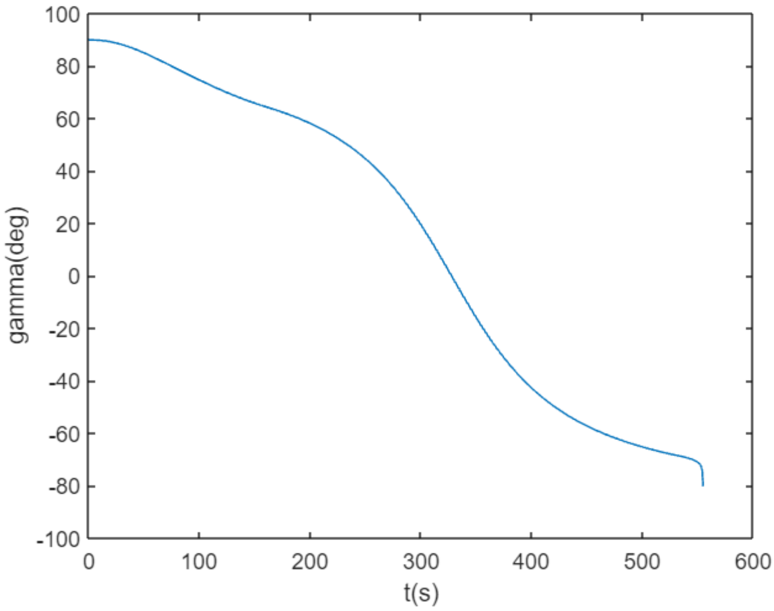

Fig. 6.9: Flight path angle characteristics

At the end of the cycle at $tmax$, the flight path angle $\gamma = -80{,}1487°$ so it lands with approximately 10 degrees inclination. Normally, that would get optimized by thrusters, grid fins and thrust vectoring. The main objective was to land at approximately zero altitude with speed close to zero.

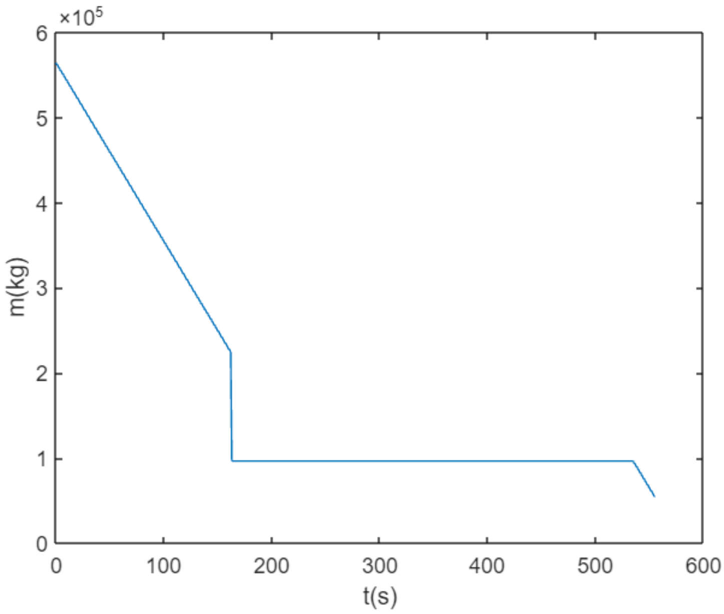

Fig. 6.10: Change of mass during the flight

Cutting off the engines and reigniting them as well as the second stage separation with the payload at $t_{f1} = 162\ s$ also causes an uneven change of mass during the flight. At first, the change of mass during the burn time until the separation equals to $\dot{m}_{P1} = 2\,100\ kgs^{-1}$. After that, engines are stopped and first stage separates. At this time, the mass equals to sum of the first stage dry mass m_{E1} with the propellant reserved for landing $m_{P1_{landing}}$.

$$m = m_{E1} + m_{P1_{landing}} = 25\,600 + 70\,800 = 96\,400\ kg \tag{6.27}$$

Until the reignition at $t = 534\ s$, the mass stays the same. Due to reigniting all engines and thrust being constant, the change of mass afterwards is $\dot{m}_{P1} = 2\,100\ kgs^{-1}$ once again which stays until touchdown. At $tmax$, $m = 54\,400\ kg$ so only $42\,000\ \ kg$ out of $m_{P1_{landing}}$ has been burned. Therefore, it would be possible to fly with less propellant to reduce overall mass.

The main factors for optimization of the landing were speed V and altitude h. If the reignition would happen sooner, the first stage would start ascending again before touching the ground. Moreover, if the reignition would happen later, the booster would crash into ground at high speed.

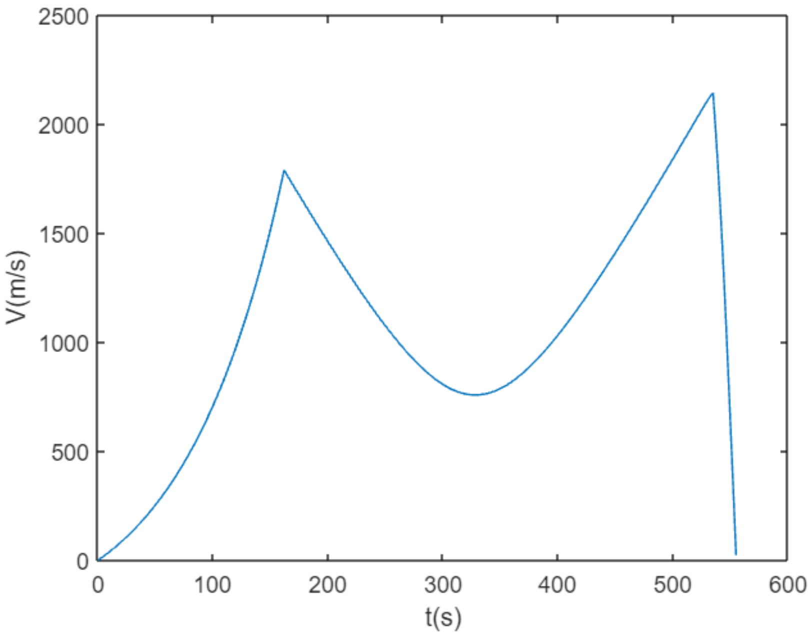

Fig. 6.11: Change of speed during the flight

The speed rises to V_{f1} and then it begins to drop due to MECO. At $ttop$ when $\gamma = 0°$, the booster flips and starts descending hence the speed starts to rise again. The engines are ignited again at $t = 534\ s$ when $V = 2144{,}81\ ms^{-1}$ and they successfully slow down the first stage to a speed slightly above zero for a soft touchdown.

Reignition of all engines at such a high speed would probably cause besides an increased drag coefficient a spontaneous combustion of the rocket due to the aerodynamic heating. That could be prevented by a larger number of controlled reignitions with throttling of the engines to optimize the thrust. As I mentioned before, the engines are reignited three times during an ordinary Falcon 9 return and only part of the engines gets ignited. Therefore, the booster does not go through such an intense aerodynamic heating. That is however outside the scope of this thesis but it might be an idea for future work to also minimize the propellant mass.

The trajectory travelled can be seen in figure below. At the end ($tmax$), the booster lands almost 320 km away from the launch pad at approximately zero altitude. The calculations are approximate and if the time step as well as the time of reignition would be in decimals, the final results would be even more precise and accurate.

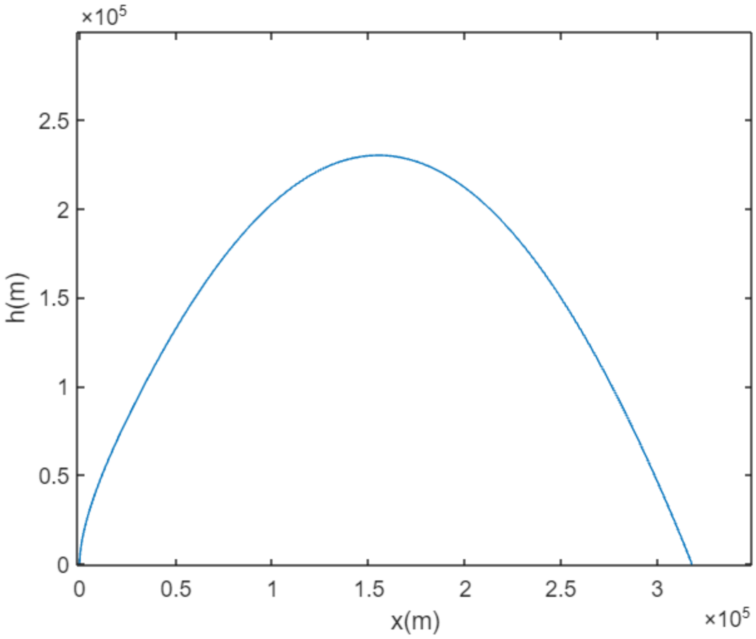

Fig. 6.12: Flight trajectory

7. CONCLUSION

In conclusion, the objective to describe a mission of a reusable launcher was achieved by a detailed explanation of a flight mission for each mentioned operational launch vehicle. For a brief comparison between these launch vehicles, a table displaying the essential parameters was created as a simple overview. Due to the differences in launcher's return, a separate chapter was given to the return options to list and explain each one.

During the practical part, the objective was to design a mission of the launcher reusable first stage which was assessed by choosing the available parameters of the Falcon 9 rocket for further calculations. Firstly, analytical calculations were made for the specific impulse of the rocket, the mass of the propellant needed for propulsive landing as well as for the final velocity and altitude, at which the first stage seperates from the rest of the vehicle.

Furthermore, the coordinate system, kinematic quantities, forces, additional effects and equations of motion were defined. After that, due to the analytical calculations only being for vertical flight, a MATLAB script was written for the whole flight path where gravity turn is used for the vehicle steering.

The script calculated the flight mission trajectory, change of mass, speed and flight path angle in time. Due to that, the time where the booster flips and starts descending was determined as well as the time of reigniting the engines.

Moreover, the script was solved to reignite the engines at specific time so the first stage safely lands on the ground with a speed close to zero. The parameters of the mission could be also further optimized to attain the optimal trajectory of the second stage into orbit after the separation.

REFERENCES

[1] TOMÁNEK, Robert and Jakub HOSPODKA. Reusable Launch Space Systems. *MAD - Magazine of Aviation Development* [online]. 2018, **6**(2), 10-13 [cit. 2021-04-18]. ISSN 1805-7578. Available from: doi:10.14311/MAD.2018.02.02

[2] SIPPEL, Martin and Sven STAPPERT, Leonid BUSSLER, Etienne DUMONT. Systematic Assessment of Reusable First-Stage Return Options, *DLR-SRT* [online]. 2017 [cit. 2021-04-18]. Available from: IAF2010 Paper SpaceLiner (dlr.de)

[3] Brief History of Rockets. *NASA* [online]. 2014 [cit. 2021-04-18]. Available from: Brief History of Rockets (nasa.gov)

[4] TOMÁNEK Robert. *Vícenásobně použitelné kosmické systémy*. Prague, 2017. Available from: F6-DP-2017-Tomanek-Robert-DP1X.pdf (cvut.cz). Czech Technical University in Prague. Master's thesis supervisor Jakub Hospodka

[5] MELECHIN, Petr. Vše o konstelaci Starlink. *ElonX* [online]. 2021 [cit. 2021-04-18]. Available from: Vše o konstelaci Starlink – ElonX

[6] ESA plans demonstration of a reusable rocket stage. *Space Daily* [online]. 2020 [cit. 2021-04-18]. Available from: ESA plans demonstration of a reusable rocket stage (spacedaily.com)

[7] NASA-CR-195281, Utilization of the external tanks of the space transportation system. *WayBack Machine* [online]. 1984 [cit. 2021-04-18]. Available from: Wayback Machine (archive.org)

[8] MANN, Adam. SpaceX now dominates rocket flight, bringing big benefits and risks to NASA. *Science Mag* [online]. 2020 [cit. 2021-04-18]. Available from: SpaceX now dominates rocket flight, bringing big benefits—and risks—to NASA | Science | AAAS (sciencemag.org)

[9] Starship User's Guide. *SpaceX* [online]. 2020 [cit. 2021-04-18]. Available from: Starship Users Guide (spacex.com)

[10] Starship. *SpaceX* [online]. 2021 [cit. 2021-04-18]. Available from: SpaceX - Starship

[11] New Shepard. *Blue Origin* [online]. 2021 [cit. 2021-04-18]. Available from: Blue Origin | New Shepard

[12] New Shepard Seat Reservation. *Blue Origin* [online]. 2021 [cit. 2021-04-18]. Available from: Blue Origin | Reserve a Seat

[13] New Glenn. *Blue Origin* [online]. 2021 [cit. 2021-04-18]. Available from: Blue Origin | New Glenn

[14] Vše o Starship. *ElonX* [online]. 2020 [cit. 2021-04-18]. Available from: Vše o Starship – ElonX

[15] HOWELL, Elizabeth. New Shepard: Rocket for Space Tourism. *Space* [online]. 2018 [cit. 2021-04-18]. Available from: New Shepard: Rocket for Space Tourism | Space

[16] ESA plans demonstration of a reusable rocket stage. *Space Daily* [online]. 2020 [cit. 2021-04-18]. Available from: ESA plans demonstration of a reusable rocket stage (spacedaily.com)

[17] JONES, Andrew. China to test rocket reusability with planned Long March 8 launcher. *Space News* [online]. 2018 [cit. 2021-04-18]. Available from: China to test rocket reusability with planned Long March 8 launcher - SpaceNews

[18] HOWELL, Elizabeth. China launches Long March 8 rocket on debut flight, plans for reusable booster. *Space* [online]. 2020 [cit. 2021-04-18]. Available from: China launches Long March 8 rocket on debut flight, plans for reusable booster | Space

[19] ZHAO, Lei. China's 1st reusable rocket on way, says expert. *China Daily* [online]. 2021 [cit. 2021-04-18]. Available from: China's 1st reusable rocket on way, says expert - Chinadaily.com.cn

[20] Electron. *Rocket Lab* [online]. 2021 [cit. 2021-04-18]. Available from: Electron | Rocket Lab (rocketlabusa.com)

[21] LEJČEK, Lubor. SRB - Startovací motory kosmického raketoplánu. *MEK* [online]. 2003 [cit. 2021-04-18]. Available from: MEK - STS (SRB - Startovací motory kosmického raketoplánu) (kosmo.cz)

[22] DUMOULIN, Jim. Solid Rocket Boosters. *Kennedy Space Center* [online]. 2016 retrieved [cit. 2021-04-18]. Available from: SOLID ROCKET BOOSTERS (nasa.gov)

[23] Rocket Booster Diagram. *Diagram Database* [online]. Available from: Rocket Booster Diagram - Fusebox and Wiring Diagram layout-ban - layout-ban.sirtarghe.it

[24] KALAŠ, Václav. Pomocné startovací rakety raketoplánu (SRB). *Astro* [online]. 2011 [cit. 2021-04-18]. Available from: Pomocné startovací rakety raketoplánu (SRB) | Kosmonautika | Články | Astronomický informační server astro.cz

[25] Propulsion. *QRG Northwestern University* [online]. 2016 [cit. 2021-04-18]. Available from: What are the types of rocket propulsion? (northwestern.edu)

[26] Space Shuttle Era. *NASA* [online]. 2017 [cit. 2021-04-18]. Available from: Space Shuttle Era | NASA

[27] RIZZO, Cailey. This Is What a Tourist Trip to Space Will Look Like, According to Amazon's Jeff Bezos. *Fortune* [online]. 2017 [cit. 2021-04-18]. Available from: This Is What a Tourist Trip to Space Will Look Like | Fortune

[28] MOSHER, Dave. Jeff Bezos just unveiled the capsule that his rocket company will use to launch tourists into space. *Business Insider* [online]. 2017 [cit. 2021-04-18]. Available from: Blue Origin Reveals Spaceship Mock-Up, Interior Design: Photos (businessinsider.com)

[29] FOUST, Jeff. Blue Origin successfully tests New Shepard abort system. *Space News* [online]. 2016 [cit. 2021-04-18]. Available from: Blue Origin successfully tests New Shepard abort system - SpaceNews

[30] DESISTO, Austin. New Shepard. *Everyday Astronaut* [online]. 2021 [cit. 2021-04-18]. Available from: NS-14 | New Shepard | Everyday Astronaut | Prelaunch Preview

[31] FOUST, Jeff. Blue Origin flies next-generation New Shepard vehicle. *Space News* [online]. 2017 [cit. 2021-04-18]. Available from: Blue Origin flies next-generation New Shepard vehicle - SpaceNews

[32] BE-3. *Blue Origin* [online]. 2021 [cit. 2021-04-18]. Available from: Blue Origin | BE-3

[33] Falcon 9. *SpaceX* [online]. 2021 [cit. 2021-05-21]. Available from: SpaceX - Falcon 9

[34] Falcon Heavy. *SpaceX* [online]. 2021 [cit. 2021-04-18]. Available from: SpaceX - Falcon Heavy

[35] MELECHIN, Petr. Raketa Falcon a její varianty. *ElonX* [online]. 2018 [cit. 2021-04-18]. Available from: Raketa Falcon a její varianty – ElonX

[36] SpaceX Launch Vehicles. *WikiMedia* [online]. 2021 [cit. 2021-04-18]. Available from: 1920px-Falcon_rocket_family6.svg.png (1920×853) (wikimedia.org)

[37] VOPLATKA, Michael. Block 5 – nejlepší Falcon 9 v historii. *Kosmonautix* [online]. 2017 [cit. 2021-04-18]. Available from: Block 5 – nejlepší Falcon 9 v historii – kosmonautix.cz

[38] MELECHIN, Petr. Motory SpaceX: Merlin, SuperDraco, Raptor a další. *ElonX* [online]. 2017 [cit. 2021-04-18]. Available from: Motory SpaceX: Merlin, SuperDraco, Raptor a další – ElonX

[39] Falcon User's Guide. *SpaceX* [online]. 2020 [cit. 2021-04-18]. Available from: Falcon_Users_Guide_082020.pdf (spacex.com)

[40] LOPATTO, Elizabeth. SpaceX even landed the nose cone from its historic used Falcon 9 rocket launch. *The Verge* [online]. 2017 [cit. 2021-04-18]. Available from: SpaceX even landed the nose cone from its historic used Falcon 9 rocket launch - The Verge

[41] Fairing Recovery List. *SpaceXFleet* [online]. 2021 [cit. 2021-04-18]. Available from: Fairing Recovery List - SpaceXFleet.com

[42] MUSK, Elon. Ms Tree catches fairing in her net. *Twitter* [online]. 2020 [cit. 2021-04-18]. Available from: https://twitter.com/elonmusk/status/1295837003444039682

[43] Space Launch Report [online]. 2020 [cit. 2021-04-18]. Available from: Space Launch Report 2020 Launch Stats

[44] Dragon. *SpaceX* [online]. 2021 [cit. 2021-04-18]. Available from: SpaceX - Dragon

[45] MAJER, Dušan. Crew Dragon. *Kosmonautix* [online]. 2021 [cit. 2021-04-18]. Available from: „Pachatel“ Crew Dragon se vrátil na místo činu – kosmonautix.cz

[46] CAWLEY, James. Crew Dragon Docks to Station. *NASA* [online]. 2020 [cit. 2021-04-18]. Available from: Crew Dragon Docks to Station, Hatches Open Soon – Commercial Crew Program (nasa.gov)

[47] SpaceX. SpaceX and NASA completed a full rehearsal of launch day activities with the four Crew-2 astronauts. *Twitter* [online]. 2021 [cit. 2021-04-18]. Available from: https://twitter.com/SpaceX/status/1383772720500903942

[48] SpaceX CRS-6 Mission. *NASA* [online]. 2015 [cit. 2021-04-18]. Available from: SpaceX_NASA_CRS-6_PressKit-2.pdf

[49] Electron User's Guide. *Rocket Lab* [online]. 2020 [cit. 2021-04-21]. Available from: Payload-User-Guide-LAUNCH-V6.6.pdf (rocketlabusa.com)

[50] FOUST, Jeff. First Rocket Lab U.S. launch delayed to 2021. *Space News* [online]. 2020 [cit. 2021-04-21]. Available from: First Rocket Lab U.S. launch delayed to 2021 - SpaceNews

[51] FOUST, Jeff. Rocket Lab to attempt to reuse Electron first stage. *Space News* [online]. 2019 [cit. 2021-04-22]. Available from: Rocket Lab to attempt to reuse Electron first stage - SpaceNews

[52] SHEETZ, Michael. Rocket Lab's next launch will feature second booster recovery, aiming for reusability like SpaceX. *CNBC* [online]. 2021 [cit. 2021-04-22]. Available from: Rocket Lab May launch booster recovery, aiming for SpaceX reusability (cnbc.com)

[53] Electron Launcher of Rocket Lab. *eoPortal Directory* [online]. 2021 [cit. 2021-04-22]. Available from: Electron Launcher of Rocket Lab - Satellite Missions - eoPortal Directory

[54] Rocket Lab's Peter Beck shares his vision. *Juno Investing* [online]. 2019 [cit. 2021-04-22]. Available from: Rocket Lab's Peter Beck shares his vision — JUNO (junoinvesting.co.nz)

[55] CLARK, Stephen. Rocket Lab to attempt booster recovery on next mission. *Spaceflight Now* [online]. 2020 [cit. 2021-04-22]. Available from: Rocket Lab to attempt booster recovery on next mission – Spaceflight Now

[56] SHEETZ, Michael. Rocket Lab unveils plan to land small rockets by catching them with a helicopter. *CNBC* [online]. 2019 [cit. 2021-04-22]. Available from: Rocket Lab plans to reuse small rockets by catching with a helicopter (cnbc.com)

[57] O'CALLAGHAN, Jonathan. Blue Origin Launches And Lands Its First Space Tourism Rocket Of The Year, With Human Flights In Sight. *Forbes* [online]. 2021 [cit. 2021-04-22]. Available from: Blue Origin Launches And Lands Its First Space Tourism Rocket Of The Year, With Human Flights In Sight (forbes.com)

[58] BE-4. *Blue Origin* [online]. 2021 [cit. 2021-04-18]. Available from: Blue Origin | BE-4

[59] New Glenn Launch Vehicle. *Aerospace Technology* [online]. 2021 [cit. 2021-04-18]. Available from: New Glenn Launch Vehicle, United States of America (aerospace-technology.com)

[60] FOUST, Jeff and Sandra ERWIN. Blue Origin delays first launch of New Glenn to late 2022. *Space News* [online]. 2021 [cit. 2021-04-18]. Available from: Blue Origin delays first launch of New Glenn to late 2022 - SpaceNews

[61] Starship. *Marspedia* [online]. 2019 [cit. 2021-04-26]. Available from: Starship - Marspedia

[62] Starship and its Belly Flop Maneuver. *Everyday Astronaut* [online]. 2021 [cit. 2021-04-26]. Available from: Starship and its Belly Flop Maneuver | Everyday Astronaut

[63] MELECHIN, Petr. Testování Starship SN15. *ElonX* [online]. 2021 [cit. 2021-04-26]. Available from: Testování Starship SN15 – ElonX

[64] As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon. *NASA* [online]. 2021 [cit. 2021-04-26]. Available from: NASA Picks SpaceX to Land Next Americans on Moon | NASA

[65] SIMPLÍCIO, P. and A. MARCOS, S. BENNANI. A Reusable Launcher Benchmark with Advanced Recovery Guidance. *The 5th CEAS EuroGNC Conference.* Milano, 2019. Available from: A Reusable Launcher Benchmark with Advanced Recovery Guidance (researchgate.net)

[66] CHANG, Kenneth. NASA Astronauts in SpaceX Capsule Make First Water Landing Since 1975. *The New York Times* [online]. 2021 [cit. 2021-04-26]. Available from: SpaceX Highlights From Crew Dragon and NASA Astronaut Return - The New York Times (nytimes.com)

[67] WALL, Mike. Rocket Lab catches falling Electron booster with helicopter in reusability test. *Space* [online]. 2020 [cit. 2021-04-26]. Available from: Rocket Lab catches falling Electron booster with helicopter in reusability test (video) | Space

[68] Falcon 9. *SpaceFlight Insider* [online]. 2021 [cit. 2021-05-02]. Available from: Falcon 9 - SpaceFlight Insider

[69] DANĚK, V. Mechanika kosmického letu. Brno: Akademické nakladatelství CERM, 2020. ISBN 978-80-7204-984-4

[70] Falcon 9 FT (Falcon 9 v1.2). *SpaceFlight101* [online]. 2017 [cit. 2021-05-02]. Available from: Falcon 9 FT – Rockets (spaceflight101.com)

[71] RIDLEY, Aaron. Getting to Space: It's all about thrust. *The Rocket Science Blog* [online]. 2020 [cit. 2021-05-03]. Available from: Getting to Space: It's All About the Thrust – The Rocket Science Blog (wordpress.com)

[72] SESNIC, Trevor and Colin FLETCHER, Lee KANAYAMA. SpaceX flies historic 10th mission of a Falcon 9 as Starlink constellation expands. *NASA SpaceFlight* [online]. 2021 [cit. 2021-05-15]. Available from: SpaceX flies historic 10th mission of a Falcon 9 as Starlink constellation expands - NASASpaceFlight.com

[73] Crew-1 Astronauts Safely Splash Down After Space Station Mission. *NASA* [online]. 2021 [cit. 2021-05-15]. Available from: Crew-1 Astronauts Safely Splash Down After Space Station Mission | NASA

[74] ROULETTE, Joey. Blue Origin targeting July for first crewed flight, opens auction for a seat. *The Verge* [online]. 2021 [cit. 2021-05-15]. Available from: Blue Origin targeting July for first crewed flight, opens auction for a seat - The Verge

[75] NEAL, Mihir. Rocket Lab suffers failure on Electron's 20th mission. *NASA SpaceFlight* [online]. 2021 [cit. 2021-05-15]. Available from: Rocket Lab suffers failure on Electron's 20th mission - NASASpaceFlight.com

[76] WALL, Mike. SpaceX launches Starship SN15 rocket and sticks the landing in high-altitude test flight. *Space* [online]. 2021 [cit. 2021-05-15]. Available from: SpaceX launches Starship SN15 rocket and sticks the landing in high-altitude test flight | Space

[77] SIMPLÍCIO, Pedro, Andrés MARCOS and Samir BENNANI. Guidance of Reusable Launchers: Improving Descent and Landing Performance. *Journal of Guidance, Control, and Dynamics* [online]. 2019, **42**(10), 2206-2219 [cit. 2021-5-18]. ISSN 1533-3884. Available from: doi:10.2514/1.G004155

[78] SIMPLÍCIO, Pedro, Andrés MARCOS a Samir BENNANI. Reusable Launchers: Development of a Coupled Flight Mechanics, Guidance, and Control Benchmark. *Journal of Spacecraft and Rockets* [online]. 2020, **57**(1), 74-89 [cit. 2021-5-18]. ISSN 0022-4650. Available from: doi:10.2514/1.A34429

NOMENCLATURE

α	[°]	Angle of attack
β	[°]	Yaw angle (sideslip)
γ	[°]	Flight path angle
ϑ	[°]	Longitudinal inclination of the aircraft
μ	[-]	Mass number
ρ	[kgm^{-3}]	Density
ρ_0	[kgm^{-3}]	Air density at sea level
$\theta_{ref}(t)$	[°]	Reference pitch angle
$\psi_{ref}(t)$	[°]	Reference yaw angle
B	[m^2kg^{-1}]	Ballistic coefficient
C	[N]	Transverse force
C_C	[-]	Transverse force coefficient
C_D	[-]	Drag force coefficient
C_L	[-]	Lift force coefficient
D	[N]	Drag force
F	[N]	Thrust
F_1	[N]	First stage thrust at sea level
G	[N]	Gravitational force
g_0	[ms^{-2}]	Gravitational acceleration
h	[m]	Altitude
h_{f1}	[m]	First stage final height
H_m	[m]	Constant
I_{SP1}	[ms^{-1}]	First stage specific impulse
L	[N]	Lift force
$\dot{m}_{P1}$	[kgs^{-1}]	First stage mass flow rate
m_0	[kg]	Initial mass
m_1	[kg]	First stage mass
m_2	[kg]	Second stage mass
m_{E1}	[kg]	First stage dry mass
m_{E2}	[kg]	Second stage dry mass
m_{P1}	[kg]	First stage propellant mass
$m_{P1_{ascent}}$	[kg]	First stage propellant mass for ascent
$m_{P1_{landing}}$	[kg]	First stage propellant mass for landing

m_{P2}	[kg]	Second stage propellant mass
m_{PL}	[kg]	Payload mass
r_Z	[m]	Earth radius
S	[m^2]	Projected area
t_{f1}	[s]	First stage burn time
$tmax$	[s]	End time
$ttop$	[s]	Time at the highest altitude
T	[-]	Centre of gravity
$T_{ref}(t)$	[N]	Reference thrust magnitude
V	[ms^{-1}]	Speed, Velocity
V_{f1}	[ms^{-1}]	First stage final velocity
x	[m]	Distance
x	[-]	Longitudinal axis
x_a	[-]	Drag axis
y	[-]	Lateral axis
y_a	[-]	Transverse axis
z	[-]	Perpendicular axis
z_a	[-]	Lift axis

LIST OF ABBREVIATIONS

ASDS	Autonomous Spaceport Drone Ship
DRL	Down-Range Landing
ESA	European Space Agency
ET	External Tank
F9	Falcon 9
FAA	Federal Aviation Administration
GPS	Global Positioning System
GTO	Geosynchronous/Geostationary Transfer Orbit
IAC	In-Air-Capturing
INS	Inertial Navigation System
ISA	International Standard Atmosphere
ISS	International Space Station
LAS	Launch Abort System
LEO	Low Earth Orbit
LES	Launch Escape System
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
LNG	Liquefied Natural Gas
MECO	Main-Engine Cut-Off
MSN	Mean Sea Level
NASA	National Aeronautics and Space Administration
NS	New Shepard
PM	Propulsion Module
RLV	Reusable Launch Vehicle
RP-1	Rocket Propellant-1
RTLS	Return to launch site
STS	Space Transportation System
SpaceX	Space Exploration Technologies Corp.
SRB	Solid Rocket Booster
TVC	Thrust Vector Control
TWR	Thrust-to-Weight Ratio
US	United States
USSR	Union of Soviet Socialist Republics
VTVL	Vertical-Takeoff, Vertical-Landing

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