INTERNATIONAL UNIVERSITY LIAISON INDONESIA

BACHELOR'S THESIS

STUDY OF FREE FLIGHT TRAJECTORY OF RKX-450 UNDER SINGLE STUCK FIN

By

Daniel Alpine
11201701002

Presented to the Faculty of Engineering and Life Sciences
In Partial Fulfilment Of the Requirements for the Degree of

SARJANA TEKNIK
In
AVIATION ENGINEERING

FACULTY OF ENGINEERING AND LIFE SCIENCES

BSD City 15345
Indonesia
January 2022

APPROVAL PAGE

STUDY OF FREE FLIGHT TRAJECTORY OF RKX-450
UNDER SINGLE STUCK FIN

DANIEL ALPINE
11201701002
Presented to the Faculty of Engineering
In Partial Fulfillment of the Requirements for the Degree of

SARJANA TEKNIK
In
AVIATION ENGINEERING

FACULTY OF ENGINEERING AND LIFE SCIENCES

Triwanto Simanjuntak, PhD	__________
Thesis Advisor	Date

Dipl.-Ing. Sentot Wahjoe Goeritno, MSi	__________
Dean of Faculty of Engineering and Life Sciences	Date

EXAMINERS APPROVAL PAGE

Name of Examiner 1
Examiner 1 Date

Name of Examiner 2
Examiner 2 Date

Name of Examiner 3
Examiner 3 Date

STATEMENT BY THE AUTHOR

I hereby declare that this submission is my own work and to the best of my knowledge, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any educational institution, except where due acknowledgement is made in the thesis.

Daniel Alpine	
Student	Date

ABSTRACT

STUDY OF FREE FLIGHT TRAJECTORY OF RKX-450
UNDER SINGLE STUCK FIN

by

Daniel Alpine

Triwanto Simanjuntak, PhD, Advisor

Lapan's RKX-450 rocket will be the rocket model for this thesis. The objective of the thesis is to analyze the effect caused by single stuck fin to RKX-450 free flight. The rocket is remodeled using Onshape, a 3D drawing application to confirm the value of inertia as well as the center of gravity of the rocket. Missile DATCOM is used to generate rocket aerodynamic derivatives data. Numerical calculation and simulation are done in MATLAB and Simulink. Then, simulation results are visualized using MATLAB to be analyzed. Analysis is carried out by comparing the trajectory obtained from the simulation of the ideal rocket which we call here the Nominal Trajectory, with the trajectory of the rocket rocket that failed. The failure in question is in the form of canard deflection. The results show that stuck-deflected fin in a rocket causing the rocket to flight off-track. There is a tendency for the relative motion of the rocket in the X axis to point toward the negative, when the fin stuck angle increases. on the X axis, the largest deviation value against the nominal trajectory can be seen in the case of canard deflection of 10 degrees, which is -200 m deviation. As for the Z axis, the largest deviation value can be seen at the canard deflection time of 5 degrees, which reaches 45 m deviation. Further, negative stuck angle -1 deg fin brings out a different result that the positive stuck angle +1 deg fin.

Keyword: *Rocketry, Natural Motion, Stuck Fin, Simulation*

ACKNOWLEDGEMENTS

First and foremost I am extremely grateful to my supervisor, Triwanto Simanjuntak, PhD for his invaluable advice, continuous support, and patience during my Bachelor Degree Research study. His immense knowledge and plentiful experience have encouraged me in all the time of my academic research and daily life. I would like to thank all the members in the International University Liaison Indonesia. It is their kind help and support that have made my study and life a wonderful time.

Finally, I would like to express my gratitude to my parents, and family. Without their tremendous understanding and encouragement in the past few years, it would be impossible for me to complete my study.

Contents

List of Figures

List of Tables

List of Abbreviations

LAPAN	**L**embaga **A**ntariksa dan **P**enerbangan **N**asional
RKX	**R**ocket **K**endali e**X**perimental
ISS	**I**nternational **S**pace **S**tation
RPM	**R**otation **P**er **M**inute
UNOOSA	**U**nited **N**ations **O**ffice for **O**uter **S**pace **A**ffair
SGD	**S**ustainable **D**evelopment **G**oal

Dedicated to my parents

CHAPTER 1
INTRODUCTION

1.1 Background

In this thesis, the effect of single stuck fin to RKX-450 free flight is investigated.RKX-450 is a rocket developed by the Indonesia National Institute of Aeronautics and Space (LAPAN). RKX-450 is a single-stage rocket with a body diameter of 450 mm. It has a length of 7170 mm from nose to aft. RKX itself stands for Roket Kendali eXperimental which means that the rocket is controllable.

RKX-450 rocket is categorized as a sounding rocket or research rocket. Its intended primary purpose is to perform experimental purposes during suborbital flight. The rocket is used to carry experimental instruments from 48 to 145 km above the earth's surface. During the mission, the RKX-450 rocket head and body will not separate.

Every rocket development consumes a lot of time, effort, and cost. Besides, with current technology in Indonesia, a rocket can only be launched once. This means if there is failure or damage that interferes with the mission of the rocket either during launch or after being in flight, relaunching the new rocket would be very prohibitive. This, of course, will provide an enormous loss in terms of time and cost to the company. Therefore, in designing a rocket, we want to increase the success rate of the rocket in completing its mission

To increase the RKX-450 rocket success rate in completing its mission, firstly we need to address what failures that might affect the rocket mission. One failure that will be addressed in this thesis is canard faults. Canard faults that are mentioned here are several conditions when there are one or two canards that are stuck in a certain deflection angle. These conditions of course will affect the rocket's flying attitude, and will deflect the rocket fly out of its proper trajectory.

This thesis aims to analyze the effect of single stuck fin to RKX-450 rocket trajectory. Hopefully from this thesis, rocket scientists can have a better understanding of the effect of rocket stuck fin to the rocket flight mission.

1.1.1 Recent Advances in the World of Rocketry

In the history of rocket development began to be carried out because of the need or urgency in the form of a state of war. technology began to be developed by the superpowers during world wars 1 and 2. Countries such as America, Germany, Russia at that time were competing to develop rocket technology in the form of missiles or combat missiles that were very effective in warfare.

After going through the war period, rocket technology is still continuing, starting from the big countries and then followed by developed countries. At that time, a country's rocket technology could be seen as the strength and capability of that country both in the military and scientific fields. This is where the big countries competed to create new innovations in the rocket industry such as launching rockets into space, launching to the moon, developing satellite technology, to the formation of the International Space Station (ISS) in earth orbit.

In today's era, the goal of developing rockets has shifted from just showing the strength of a country. According to the United Nation, the development of space-based technology is aimed at offering benefits to humanity(Nations, 2018).

There are four points that will be pursued by The United Nations Office for Outer Space Affairs (UNOOSA) in Space Technology.

- Space for sustainable development;
- Space for everyone;
- The (R)evolution in the Space Sector;
- New realities in space.

The first point is the space for sustainable development. The list of space applications that affect the Earth is almost endless, and many other valuable contributions are currently being developed or researched. To assess the impact of space technology on the Sustainable Development Goals, UNOOSA will show in early 2018 that 65 of the 169 goals that underpin the Sustainable Development Goals are directly related to earth observation and the use of navigation satellites. The adoption of the Sustainable Development Goals provides UNOOSA with an additional framework, working on all activities and initiatives to promote and promote the use of space to contribute to the achievement of the 17 goals. We take a cross-cutting approach aimed at contributing to the use of space science and technology as a valuable tool for achieving the Sustainable Development Goals.

One of the key issues we are addressing in this regard is addressing large gender disparities through the Space for Women project, with more women and girls proactive and equal in space science, regenerative technology, innovation and exploration. It is about encouraging and empowering to play a key role. In connection with SDG 11 on Sustainable Cities and Communities, UNOOSA aims to improve the use of space technology for emergency response to mitigate disaster risk, save lives and protect property. We maintain a UN space-based information platform for management and emergency response. damage.

The next concern is room for everyone. Due to the wide range of uses in space, all countries need to be assisted to access the benefits of space-based technologies that enable sustainable development. As more countries invest financial and political capital in the space environment and the world becomes more and more dependent on space, UNOOSA is committed to making the benefits of space available to everyone anywhere. is. UNOOSA launched the Manned Space Technology Initiative in 2010 to give countries access to the benefits of space technology and applications. More countries are engaged in manned spaceflight and other space exploration-related activities under this initiative. Human Space Technology Initiative provides a platform for sharing information, facilitating cooperation between space and non space countries, and encouraging emerging and developing countries to engage in space exploration and benefit from space applications. increase.

This program allows educational and research institutions in developing countries to deploy small cube sized satellites from the International Space Station using the JAXA Kibo module. Playing an important role in bridging the division of space by providing appropriate opportunities provided by countries with space capabilities to institutions in developing countries with little or no prospect of conducting space related scientific research.

(r)Evolution of the space sector. Today, 4,444 space agencies in more than 70 countries and territories are working to deepen their knowledge of space and apply space science and technology to improve the lives of people around the world. Of the 553 objects registered with UNOOSA last year, 489 were satellites. 3 With the increased ability to release multiple satellites in a single launch, the total number of such objects has nearly doubled from the previous record of 242 set in 2014 and is being developed worldwide. .. Launching a series of satellites for the same purpose and forming constellations is a further evolution of the traditional way such objects are deployed.

1.1.2 Urgencies of rocket Development

Such tendencies display how area era is evolving and function a pertinent instance of the way the governance of the distance surroundings is turning into an increasing number of multifaceted. nine Such numbers make area a fair greater appealing assignment whilst growing extra demanding situations to coverage, regulation, technological know-how and era.

Then, our area society subject is likewise into debating new realities in area. The governance of area, defined as humanity‘s maximum expansive international commons, has come to be an increasing number of mature because of the developing variety of actors, each governmental and non-governmental, in addition to new technology and processes including public-non-public partnerships and personal investment initiatives. Since the very starting of area sports within side the overdue 1950s, the United Nations, via the Committee at the Peaceful Uses of Outer Space , has served because the venue for debating ventures in outer area, country wide endeavors, global area regulation and demanding situations to the manner we behavior area sports. As the worldwide facilitator for such discussions, and serving because the Committee at the Peaceful Uses of Outer Space secretariat, UNOOSA performs a main function in assisting the intergovernmental coverage making process. The Global Goals are designed to together cope with international demanding situations.

With more and more more actors, inclusive of an increasing number of States and personal entities getting into the distance arena, the arena nowadays reveals itself on the identical decisive crossroads as in 1957, quickly after the release of

Sputnik. From assisting international efforts, to using area era for sustainable development, to retaining the normative framework governing sports within side the area surroundings, the United Nations has a protracted legacy of facilitating global cooperation in outer area.

1.1.3 Challenges of Rocket Development

In spite of all the urgency, rocket industry development has some challenges to overcome.There are several challenge of rocket development all around the world. First challenge is the cost. not many country has a stable economy excessive economical power. in the other hand, rocket technology development are quite expensive. Therefore, as we can see most country that has big influence in rocket industry are wealthy and stable countries like United states, Russia, and China.

1.1.4 Private Rocket Companies

SpaceX is one of the companies that has a big role in the development of the rocket industry. This American private company is growing quite rapidly seeing they were only built in 2002. The main purpose of the establishment of this company by Elon Musk is to reduce the cost of space flight and also to enable the colonization of the planet Mars.

FIGURE 1.1: Left: Space-X Starship; Top-right: Space-X Dragon and Falcon 9; Bottom-left: Space-X reusable rocket (SpaceX, 2022)

Fig. 1.1, provides an overview the space launch vehicle development has been done by Space-X. Firstly to be mentioned, on the left there is the SpaceX Falcon

9 with its reusable rocket. Falcon 9 is a rocket that was developed as a heavy lift vehicle. As a double stage rocket, Falcon 9 from the beginning was designed to be reusable. SpaceX developed and embeds control technology on the Falcon 9's first stage rocket, which allows the first stage section to return and make a vertical landing on earth. Finally in 2015, SpaceX made history with the first time the first stage or booster from Falcon 9 successfully returned and made a vertical landing. The reusable rocket significantly cuts the cost of space transportation that Space X can do. As a result, Space X even dares to give a 10% discount for customers who choose to use the first-stage reused falcon.

Then, beside the Falcon 9 picture it is shown SpaceX Dragon. Dragon is a space vehicle developed by SpaceX that is intended as a cargo or crew carrier. SpaceX Dragon is also in a reusable design where it can return to Earth after reaching orbit and completing its mission. In 2010, SpaceX became the first private company to launch Dragon as a commercially operated spacecraft into orbit and successfully recovered it. Two years later, in 2012, Dragon became the first private spacecraft to be rendezvous and attached to the International Space Station as part of NASA's resupply service program.

Lastly, the image on the left of the figure shows the SpaceX Starship. Staship is the latest project being developed by SpaceX. Staship was created with the aim of being used as a means of commercial transportation that can transport passengers through space travel. In addition, Starship is also a fully reusable launch system where not only the first stage can return to earth and make a vertical landing, but also the second stage. This of course is a manifestation of the ideals of SpaceX, especially Elon as its founder who wants to build a colony on Mars.

Staship is a very large space vehicle. its overall structure is even larger than NASA's Saturn V. The spacecraft, which consists of two stages, has a height of up to 120 m and a diameter of 9 m. Starship itself is a space vehicle that is placed on top of a booster called Super Heavy. In May 2021, the Starship SN15 test run was successful with the giant rocket landing back on the ground

Another American private company working in the space vehicle industry is none other than Blue Origin. The company founded by Jeff Bezos in 2000 has a vision that is more or less similar to Space x, namely to make access to space cheaper and more reliable. Blue Origin is an aerospace manufacturer and provider

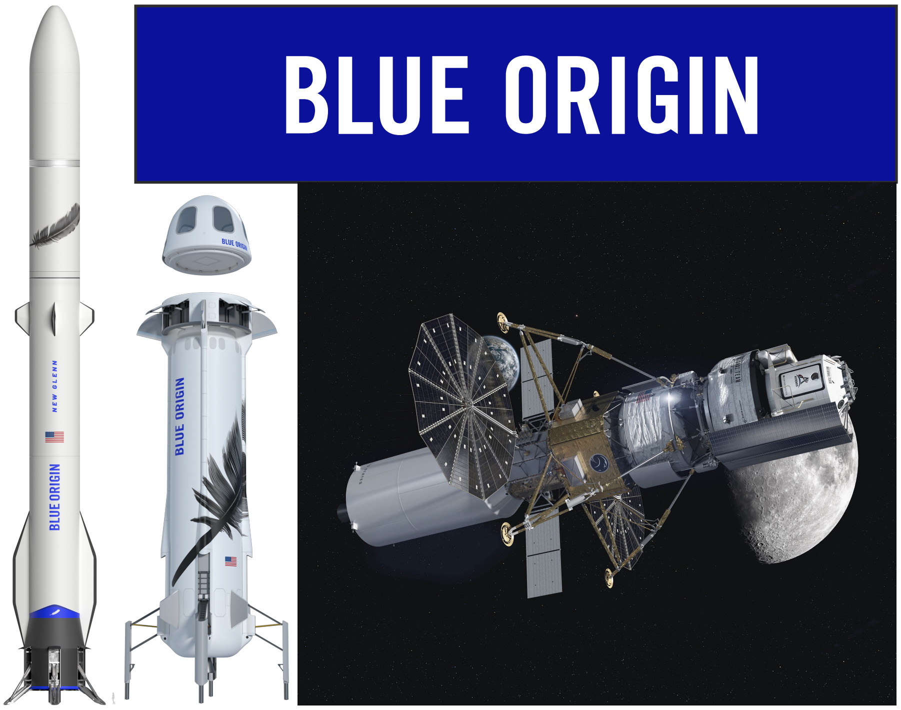

FIGURE 1.2: Left to right: New Glenn; New Shepard; HLS National Team (Origin, 2021)

of sub-orbital spaceflight services.

New Shepard is shown in theFig. 1.2 at the middle. Shepard is a sub-orbital spaceflight system consisting of a booster on top of which is a capsule for crew or cargo. In other words Shepard is a single stage rocket. Shepard is also a reusable rocket whose booster is equipped with the ability to return to a vertical landing after separation from the capsule. The capsule itself will follow the trajectory of the launch and land by parachute.

Left to the Shepard there is the New Glenn. Glenn is an orbital launch vehicle that is still in development by Blue Origin. It is scheduled that the first New Glenn will be launched in 2022. This space vehicle described as a two-stages rocket with a diameter of 7 m and estimated height of 98 m. Just like the New Shepard, the first stage of New Glenn will be reusable, so it will be able to perform vertical landing.

1.1.5 Rocket Development in Indonesia

Referring to the latest spacecraft technology of NASA called Orion which has the capacity to reach deep space beyond the moon and Mars, there are at least three lesson learned for Indonesia if it wants to develop rocket technology. First, development of rocket technology needs a long and sustainable process. Second, research and development technology need long term funding. Third, it needs experts and professional staffs, including from relevant scientists (Elisabeth, 2018).

Indonesia has LAPAN, an institution that has the authority to develop technology Indonesian space agency, including satellites and rockets, as well as other relevant research institutes or universities in the fields of aerospace and space. To support this space technology, The Government of Indonesia has enacted Government Regulation Number 45 of 2017 concerning the Master Plan Space Administration. Even though in reality, Indonesia still has to pursue aspects of mastery of rocket technology. Meanwhile, cooperation with other countries or becoming a member of the regime international organizations such as the Missile Technology Control Regime (MTCR), do not automatically get advantages in improving and mastering national rocket technology .

Indonesia's interest in being a member of this informal regime depends on dynamics at the global level and urgency at the national level, but all things need to be weighed against the pros and cons with a cost and approach benefit analysis (CBA). The urgency of developing national space technology is based on existing and necessary regulations immediately realized with long-term projections. While the challenges faced are related to the government's political commitment is not yet full, the research and development budget is relatively limited, the understanding of the Indonesian people is minimal (even against), and the focus of business is still limited to utilization yet on investment in advanced technology for a better life.

According to LAPAN quoted from (LAPAN, 2014). In the past few years, LAPAN has developed several technologies in the rocket field. Some of these technologies have been used for the benefit of the wider community, especially the Indonesian nation and also for the development of science. Some of the programs that have been carried out by LAPAN are as follows.

- LAPAN A1, A2, A3, and A4 Satellite;

- Flight test of Rocket Sonda (rocket for research purposes);
- Liquid Propellant rocket and engine development;
- Electric Ducted Fan (EDF) rocket development.

Figure 1.3: Lapan A2 Satellite

Fig. 1.3 shows LAPAN-A2 Satellite. LAPAN-A2 is the newest satellite made by the National Institute of Aeronautics and Space. This satellite, which is entirely built in Indonesia, is designed for three missions namely earth observation, ship monitoring and amateur radio communication. Weighing around 78 kg, the LAPAN-A2 satellite carries an Automatic Identification System (AIS) payload. With this technology, LAPAN-A2 can identify ships that will cross the LAPAN A2 coverage area. In addition, the Earth observation mission will use a digital earth observation camera with a 4 band multispectral scanning camera. The camera has a resolution of 18 m with a coverage of 120 km and a camera resolution of 6 m with a coverage of 12 km x 12 km.

FIGURE 1.4: Lapan RX-450 Double-stage Rocket (Media, 2020)

So far, Lapan has conducted several research and developments in the field of rockets by launching experimental rockets. The RX450-5 rocket Fig. 1.4, which was just launched in 2020, is an experimental rocket with a diameter of 450 mm, and is one of the outputs of research, development and engineering activities at Pustekroket. It is also the baseline for a rocket with a range of more than 100 kilometers which will be the beginning of the development of a two-stage rocket. The RX450 has specifications in the form of a diameter of 46 mm, a length of 7.16 m, a single stage, and a ballistic rocket (Media, 2020).

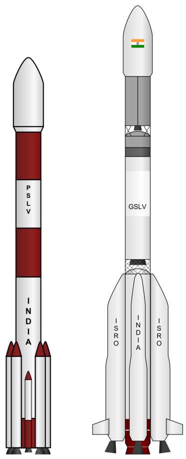

FIGURE 1.5: India PLSV and GLSV Rocket

Lapan is aiming to provide their own launch vehicle for developing satellites. LAPAN's rocketry vision by 2039:

- by 2030 launch of Satellite Launch Vehicle (SLV) 2

- by 2036 launch of PSLV (polar) and GLSV (Geosynchronous). Example of India's PLSV and GLSV is in Fig. 1.5

The figure showing the example of Polar and Geosynchronous Satellite Launch Vehicle (PLSV and GLSV) developed by India Space Research Organization. LAPAN vision by 2039 is that Indonesia can have and launch their own PLSV and GLSV to space.

1.2 Problem Statement

- How the fault affect the rocket trajectory;
- Analyze the trajectory of a failed RKX-450 rocket model

1.3 Research Objectives

The objectives of this research are to investigate:

- To develop a simulation for RKX-450 Rocket to simulate the rocket trajectory;
- To compare the trajectory accuracy between a reference model (RKX-450 model without canard fault), a fault rocket

1.4 Research Scope and Limitation

The research scopes of this thesis are:

- The atmospheric model is the ISA model;
- The spherical model gravity is adopted;
- The control action considered to be actuated instantaneously.

1.5 Significance of the Study

The results of this research are expected:

- Potential use for LAPAN. The analysis of this single fin stuck effects to rocket flight was first demonstrated for the flight of the National Institute of Aeronautics and Space RKX-450 rocket. However, it is possible that the results of this thesis can be used as a reference for future Indonesian rockets;
- This thesis can provide a quantitative description of how canard fault may affect accuracy and reliability of RKX-450 rockets.

CHAPTER 2
LITERATURE REVIEW

2.1 Atmospheric Model

Atmosphere model that is used is:

- International Standard Atmosphere (ISA). ISA model is used to compute Reynolds number in missile datcom.
- COESA Atmosphere Model from Simulink.

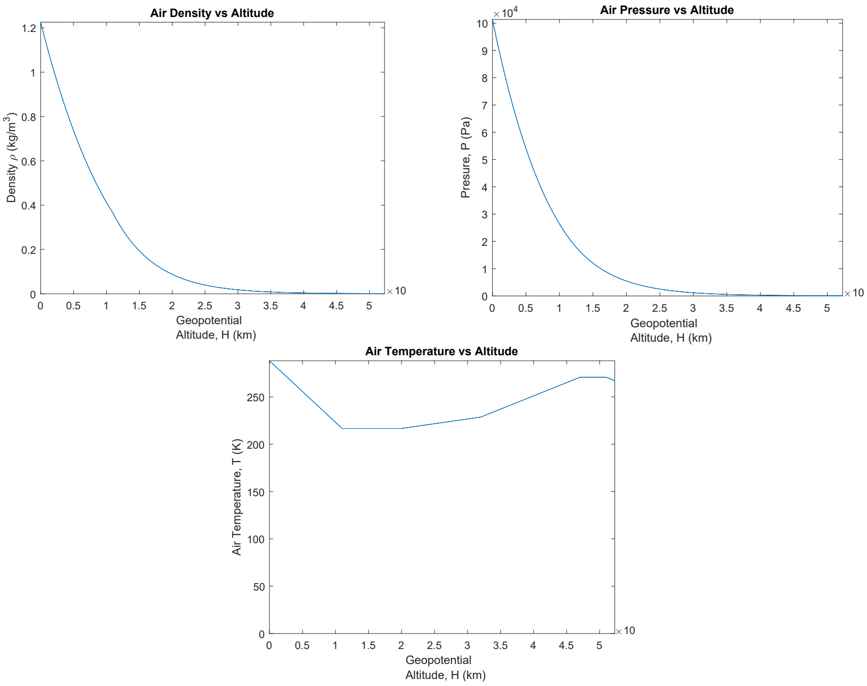

FIGURE 2.1: Atmospheric density, pressure, and temperature with respect to altitude

2.2 Gravity Model

Gravity formula from (Cornelisse et al., 1979):

$$F_g = G\frac{Mm}{(h+r_e)^2} = mg_{(h)}e_z \tag{2.1}$$

Represented in each body frame:

$$F_g = mg(h)\begin{bmatrix} -\sin\Theta \\ \cos\Theta\sin\Phi \\ \cos\Theta\cos\Phi \end{bmatrix} \tag{2.2}$$

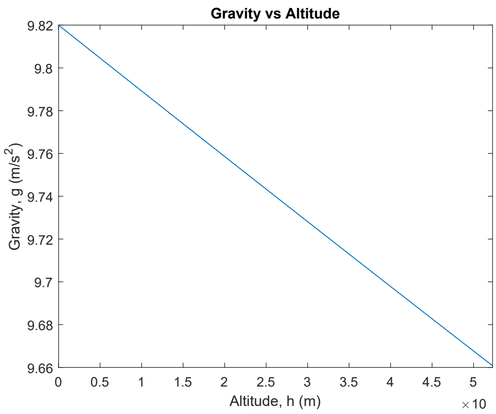

FIGURE 2.2: Gravity variation with respect to altitude

2.3 Cases of faults investigated

In this thesis we consider stuck rocket fin at a deflection angle as the fault case. This stuck condition can drive the rocket away from the desired initial trajectory. Illustration of stuck rocket fin can be see in Fig. 2.3 below.

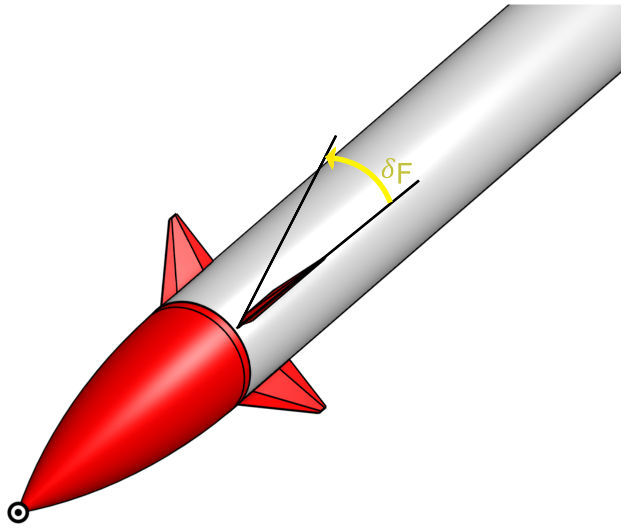

FIGURE 2.3: Stuck fin at a deflection angle

2.4 Rocket

2.4.1 Rocket Definition

A rocket is a spacecraft that uses a propellant or other liquid substance to obtain thrust from its engine. This rocket engine utilizes a reaction to push the payload's exhaust into the opposite direction. Rocket can also mean a type of engine. Like most engines, it burns fuel. When a rocket engine burns fuel, it sends the hot gas out of its back. Compared to air breathing engines, rockets are more powerful and lightweight. They can reach velocities of over 6,000 kilometers per second in space. In addition, their capabilities allow them to generate large accelerations (MSFC, 2015).

A rocket is a vehicle that contains a propellant, a nozzle, and a place to put it. It can also have multiple engines, a directional stabilization device, and a structure that can hold these components together. High-speed atmospheric rockets have an aerodynamic fairing, which typically holds the payload. These components are typically used in conjunction with other components such as wheels and wings.

2.4.2 Flight Dynamic of a Rocket

Broadly speaking, the dynamics of flying a rocket can be likened to the flight dynamics of an airplane. Like an airplane, the flying dynamics of a rocket are also influenced by the 6-degree of freedoms. 6-degree of freedom can be divided into three translational motions and 3 rotational motions (roll, pitch, yaw). In rockets, translational motion is influenced by the thrust generated from propulsion, drag force, and also gravity. whereas, the rotational motion of the rocket is largely due to aerodynamic moments created by the rocket geometric and control surfaces which are called fin or canard.

2.4.3 Reference Frames

In order to derive the equation of motion of a rocket, various of Rocket Reference Frames are used (Cornelisse et al., 1979).

- Inertial Reference Frame (X, Y, Z)

$$E = \begin{bmatrix} e_X \\ e_Y \\ e_Z \end{bmatrix} \tag{2.3}$$

- Rotating Geocentric Reference Frame (Xg, Yg, Zg)

$$E_g = \begin{bmatrix} e_{X_g} \\ e_{Y_g} \\ e_{Z_g} \end{bmatrix} \tag{2.4}$$

- Vehicle-centered Horizontal Reference Frame (Xv, Yv, Zv)

$$E_v = \begin{bmatrix} e_{X_v} \\ e_{Y_v} \\ e_{Z_v} \end{bmatrix} \tag{2.5}$$

- Vehicle Reference Frame (x, y, z)

$$E_r = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \tag{2.6}$$

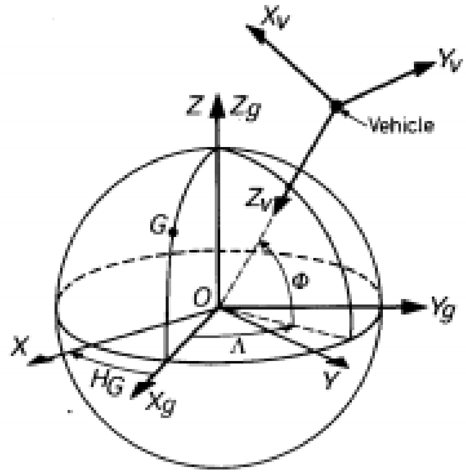

FIGURE 2.4: Reference Frames (Cornelisse et al., 1979)

The relation between those reference frames are:

- Inertial and Rotating-geocentric reference frame

$$E_g = A_g * E \tag{2.7}$$

, Where Ag is a rotational matrix given by

$$A_g = \begin{bmatrix} \cos H_G & \sin H_G & 0 \\ -\sin H_G & \cos H_G & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.8}$$

- Rotating geocentric and Vehicle-centered horizontal frame

$$E_v = A_{v_g} E_g \tag{2.9}$$

, Where Ag is a rotational matrix given by

$$A_{vg} = \begin{bmatrix} -\sin\Phi\cos\Lambda & -\sin\Phi\sin\Lambda & \cos\Phi \\ -\sin\Lambda & \cos\Lambda & 0 \\ -\cos\Phi\cos\Lambda & -\cos\Phi\sin\Lambda & -\sin\Phi \end{bmatrix} \tag{2.10}$$

- Vehicle-centered horizontal and Vehicle frame

$$E_r = A_{r_v} E_v \tag{2.11}$$

, Where Ag is a rotational matrix given by

$$A_{rv} = \begin{bmatrix} C\theta C\psi & C\theta S\psi & -S\theta \\ -C\phi S\psi + S\phi S\theta C\psi & C\phi C\psi + S\phi S\theta S\psi & S\phi C\theta \\ S\phi S\psi + C\phi S\theta C\psi & -S\phi C\psi + C\phi S\theta S\psi & C\phi C\theta \end{bmatrix} \tag{2.12}$$

Then, assume that Ar is is a transformation matrix which transform unit vectors from Inertial frame into Vehicle frame.

$$E_r = A_r E \tag{2.13}$$

$$A_r = E_r E^T = \begin{bmatrix} e_x e_X & e_x e_Y & e_x e_Z \\ e_y e_X & e_y e_Y & e_y e_Z \\ e_z e_X & e_z e_Y & e_z e_Z \end{bmatrix} \tag{2.14}$$

$$A_r = A_{r_v} A_{v_g} A_g \tag{2.15}$$

2.4.4 Dynamical Equation

The Equation of Motion of a rocket can be written as

$$M \frac{dV_c m}{dt} = F_S + F_c + F_{rel} \tag{2.16}$$

$$\int_M r \left(\frac{d\omega}{dt} r \right) dM + \int_M r\omega(\omega r) dM = M_{cm} + M_c + M_{rel} \tag{2.17}$$

, where

$$
\begin{aligned}
&F_S = \text{Translation Force of system S;}\\
&F_c = \text{Coriolis Force;}\\
&F_{rel} = \text{Relative Force}\\
&M = \text{Total (constant) mass of the system;}\\
&r = \text{Position vector from the center of mass to the center of Forces.}
\end{aligned} \tag{2.18}
$$

We can derive The Equation of Motion of a rocket into :

$$
\begin{aligned}
M\frac{du}{dt} &= M(vr - wq) + F_x + M_{g_x} + X_a,\\
M\frac{dv}{dt} &= M(wr - uq) + F_y + M_{g_y} + Y_a,\\
M\frac{dw}{dt} &= M(ur - vq) + F_g + M_{g_z} + Z_a,\\
I_{xx}\frac{dp}{dt} &= -p\frac{dI_{xx}}{dt} + rq(I_{yy} - I_{zz}) + mx_e(y_e q + z_e r) + L',\\
I_{yy}\frac{dq}{dt} &= -q\frac{dI_{yy}}{dt} + pr(I_{zz} - I_{xx}) + mqx_2^e - x_e F_z + z_e F_x + M',\\
I_{zz}\frac{dr}{dt} &= -p\frac{dI_{zz}}{dt} + pq(I_{xx} - I_{yy}) + mrx_2^e - x_e F_y + y_e F_x + N'.
\end{aligned} \tag{2.19}
$$

2.4.5 Rocket Fault

Throughout history, there are a lot of accident that happen in airspace industry even aircraft or rocket. Ironically, all spacecraft technology that people has develop until today are all products of flight failures. From these failures humans can find problems that can occur and make preventions for a better and safer future of aviation.

The difference between a rocket and an ordinary airplane is that it is an expensive technology. usually a rocket is developed over a long period of time and only to carry out one flight mission. failure, of course, must be avoided as much as possible so that the funds that have been spent on development are not wasted.

The following are some of the failures that can occur during a rocket launch

- Miscalculated Flight Mission

- Flight Instruments Malfunction
- Separation Failure (for double stage rocket)
- Control Instrument Malfunction
- Telemetry Data Loses

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Physical modeling of RKX-450;

To start the experiment we need to model the rocket RKX-450 in order to help us during the experiment.

First of all, the authors recreated the 3-dimensional model of the RKX-450 rocket. This model is based on the estimated dimensions of the rocket that have been determined by LAPAN. Making this model using the Onshape application.

Onshape itself is a web-based drawing application that can be accessed with a computer browser. Web-based means that this Onshape application must be accessed online with an internet network. The advantage that Onshape provides is that all user work is stored in the cloud, which means that users can easily access the designs they want to work on from any computer as long as there is internet. Onshape also provides a Shared Design feature that allows multiple writers to work on a design simultaneously. These advantages are of course very helpful for a project team, especially during a pandemic like now.

Below are the result of physical modeling in Onshape.

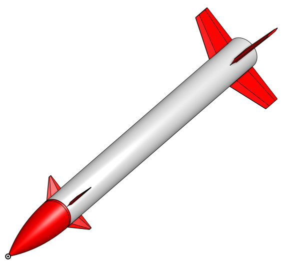

Figure 3.1: RKX-450 Rocket Model

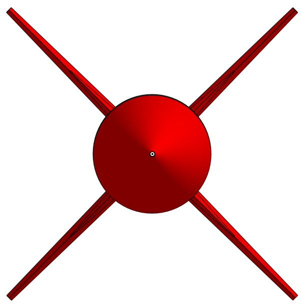

Figure 3.2: RKX-450 Rocket Model Front View

Figure 3.3: RKX-450 Rocket Model Side View

3.1.1 Free Body Diagram

To have a better vision on all the of forces and moments acting on the rocket, then it is essential to have a free body diagram. Using free body diagram author can make assumption of where the location of each force and moment, and how it affect the rocket mechanics. Free body Diagram is made in 3 planes which are:

- Longitudinal Plane

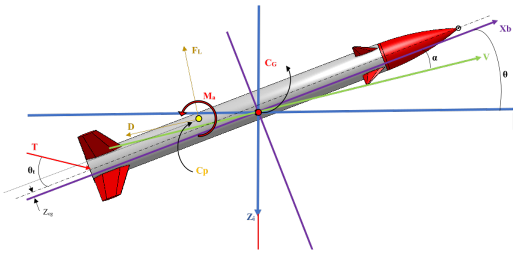

FIGURE 3.4: RKX-450 FBD Longitudinal

- Lateral Plane

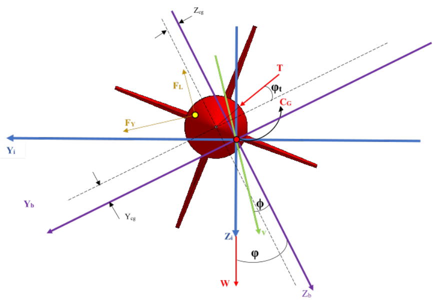

FIGURE 3.5: RKX-450 FBD Lateral

- Directional Plane

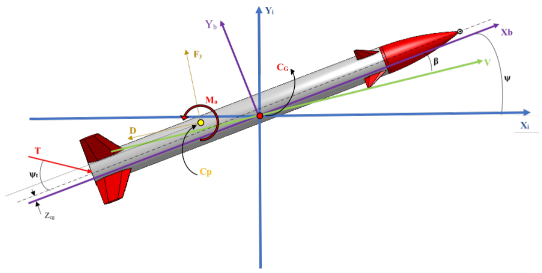

FIGURE 3.6: RKX-450 FBD Directional

3.2 Mass Profile Breakdown;

Moment of Inertia can be told as a resistances of a body to any rotational movement. This means the bigger the inertia of an object, the bigger its tendency to rotate. Basic equation of Inertia is written as:

$$I = \frac{L}{W}, \tag{3.1}$$

where I is moment of inertia, L is angular momentum, and w is angular acceleration.

The angular momentum of a rigid body that rotates about an axis that passes through the origin of the local reference frame is actually the product of the object's moment of inertia and its angular velocity. You can use this inertia tensor equation, which is below, to classify the inertial data we have (Kwon, 1998).

$$\begin{aligned}
&I_{xx} \equiv \sum_i^1 m_i(y_i^2 + z_i^2) \qquad I_{yy} \equiv \sum_i^1 m_i(z_i^2 + x_i^2) \qquad I_{zz} \equiv \sum_i^1 m_i(x_i^2 + y_i^2) \\
&I_{xy} = I_{yx} \equiv -\sum_i^1 m_i x_i y_i \\
&I_{xz} = I_{zx} \equiv -\sum_i^1 m_i x_i z_i \\
&I_{yz} = I_{zy} \equiv -\sum_i^1 m_i y_i z_i
\end{aligned} \tag{3.2}$$

Then It is known that the Inertia tensors of the empty body is:

Moment of Inertia	
I_{xx}	44.3
I_{yy}	2323.1
I_{zz}	2323.1
I_{xy}	-0.0182
I_{xz}	-0.025
I_{yz}	-0.0134

TABLE 3.1: RKX-450 Moment of Inertia

3.3 Generate Aerodynamics Derivatives in Missile DATCOM;

Missile preliminary design requires rapid and economical estimation of the aerodynamics of a wide variety of missile configuration designs. The final shape and aerodynamics are highly dependent on the subsystem used, such as payload size, propulsion system choice, and launch mechanism, so designers must be able to accurately predict different configurations. The basic purpose of Missile Datcom is to provide predictive accuracy suitable for pre-design and aerodynamic design tools that can easily replace the way users adapt to a particular application (Auman et al., 2008).

Datcom or Data Compendium is the best collection of data and knowledge related to aerodynamic stability and control prediction methods. From this data set, researchers can infer basic stability and control derivatives of flying objects.

Datcom is an independent organization. You can determine the complete set of derivatives of any flight condition and composition without relying on external information. This book is intended as a preliminary design before collecting test data. We always recommend using reliable test data instead of Datcom. However, in many cases you can use datcom in combination with test data.

3.3.1 How to Use Missile Datcom;

To easily understand Missile Datcom, User has to know about the Input/Output Scratch Files used by Missile Datcom. There are 14 file units that are used by Missile Datcom Program. The table below will show all the files and their functions.

Unit	Name	Usage	Subroutine
2	for002.dat	Namelists for the input "case" are read from unit 8 and written to unit 2.	READIN
3	for003.dat	Plot file of aerodynamic data, written at user request (using PLOT card) to unit 3	PLOT3 PLTTRM PLTUT9
5	for005.dat	User input file read from unit 5	CONERR
6	for006.dat	Program output file written to unit 6	PRINTS PRIIOM
8	for008.dat	User input cards read from unit 5 are written to unit 8 after they have been checked for errors.	CONERR
9	for009.dat	Body geometry data, written at user request to unit 9	SBODY
10	for010.dat	Body pressure coefficient data at angle of attack, written at user request to unit 10 when using PRESSURES card.	SOSE VANDYK HYPERS
11	for011.dat	Fin pressure coefficient data, written at user request to unit 11 when using PRESSURES card	FCAWPF
12	for012.dat	Body pressure coefficient and local Mach number at zero angle of attack, written at user request to unit 12 when using PRESSURES card	SOSE
20	for020.dat	Total configuration force and moment coefficient data, damping derivatives and flight conditions, written at user request (using PLOT card). File is formatted for use with software developed with Adaptive Modeling Language (AML).	PLOT20
21	for021.dat	Total configuration force and moment coefficient data, damping derivatives, flight conditions and control deflections, written at user request (using PLOT card). File is formatted for use with the Aviator Visual Design Simulator (AVDS).	PLOT21
22	for022.dat	Configuration geometry file compatible with the commercial software package Tecplot. Only geometry for the body and fins are printed. No geometry is provided for inlets or probuterances.	TECGRD
42	for042.csv	All standard data written in rows and columns with headers	PLOT42
43	for043.csv	Fin data written in rows and columns with headers	PLOT43

Table 3.2: Datcom Input/Output Logical Units (Auman et al., 2008)

To summarize the Table 3.2, the program runs in "batch" mode. The user prepares the input file according to the specified rule. You must rename this file to "for005.dat" before running the program. Then double-click the executable file to run the program. The program is then run to create the output file requested by the case input. The primary output files for006.dat and for042.csv are always written. See Section 4 of this report for more information on what is contained in this output file. Optional output files for plots, geometry, and pressure distributions are written only on request.

User-created input files are used to define the rocket's configuration. To simplify the definition process, Datcom uses a classification method that divides rocket parts into a list of multiple names. The names in the list of names have been chosen to have a mnemonic relationship with their physical meaning. Each component of the configuration requires a separate NAMELIST input.

- $FLTCON$ = Flight Condition Inputs
- $REFQ$ = Reference Quantity Inputs
- $AXIBOD$ = Asymmetric Body Geometry Inputs
- $FINSET1$ = Fin 1 Geometry Inputs
- $FINSET2$ = Fin 2 Geometry Inputs
- $DEFLCT$ = Panel Deflection inputs

Flight Condition Inputs used to define every point and/or condition where the rocket flight through.

- $NALPHA$ = Number of rocket flight pitch angle.
- $ALPHA$ = Rocket pitch angles
- $NMACH$ = Number of mach number
- $MACH$ = Mach Numbers
- REN = Reynolds Numbers

Reference Quantity Inputs contains references as shown below.

- $SREF$ = Reference area.

- $LREF$ = Longitudinal reference length.
- $LATREF$ = Lateral reference length.
- XCG = Longitudinal position of CG measured from rocket nose.
- ZCG = Vertical reference of CG.
- $ROUGH$ = Surface roughness height.
- RHR = Roughness Height Rating.

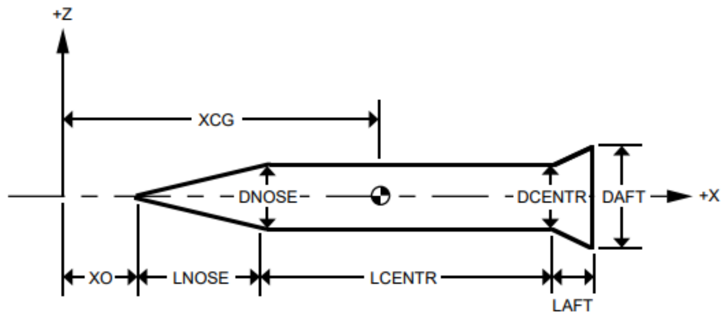

Figure 3.7: DATCOM Rocket Body Dimension (Auman et al., 2008)

After that, there is AXIBOD namlist which stancs for Asymmetric Body Geometry. This Inputs are used to define the rocket body dimensions in Missile Datcom. Following are all the inputs parameter used:

- $TNOSE$ = Nose Type. (1 = OGIVE)
- $LNOSE$ = Nose length
- $DNOSE$ = Nose diameter at base.
- $LCENTR$ = Center body length.
- $DCENTR$ = Center body diameter at base.

I do not define the aft part of the rocket because it is only 2 stage rocket.

FINSETs namelist are used to define each set of fins that is attached in the rocket. It defines the fin or cannard geometry and also position from respect to the rocket body.

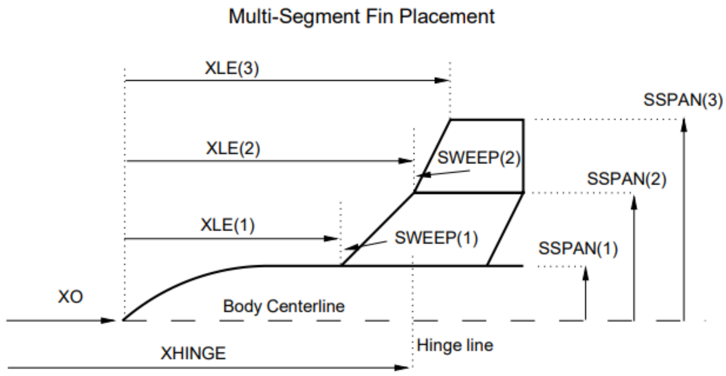

Figure 3.8: Fin Definition in Missile DATCOM (Auman et al., 2008)

Here is all parameters that is used to define RKX 450 fins.

- $SECTYP$ = Airfoil section type. (HEX)
- $NPANEL$ = Number of panel in the fin set.
- $PHIF$ = Roll angle of each fin measured clockwise from top vertical center looking forward.
- XLE = Distance from the rocket nose to the fin leading edge.
- $SSPAN$ = Semi-span locations.
- $CHORD$ = Panel chord at each semi-span location.
- STA = Chord station used in measuring sweep.

Lastly, there is DEFLCT namelist which stands for Panel Deflection Inputs. This inputs can be used to define deflection angle of each panel from each fin set.

- $DELTA1$ = Deflection angle for each panel in finset 1.
- $DELTA2$ = Deflection angle for each panel in finset 2.

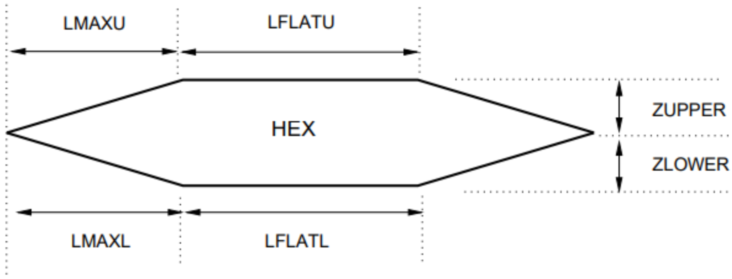

FIGURE 3.9: HEX Airfoil Definitions (Auman et al., 2008)

3.4 Derive the Rocket Equation of Motion;

3.4.1 Reference Frames

In order to derive the equation of motion of a rocket, various of Rocket Reference Frames are used.

- Inertial Reference Frame (X, Y, Z)

$$E = \begin{bmatrix} e_X \\ e_Y \\ e_Z \end{bmatrix} \tag{3.3}$$

- Rotating Geocentric Reference Frame (Xg, Yg, Zg)

$$E_g = \begin{bmatrix} e_{X_g} \\ e_{Y_g} \\ e_{Z_g} \end{bmatrix} \tag{3.4}$$

- Vehicle-centered Horizontal Reference Frame (Xv, Yv, Zv)

$$E_v = \begin{bmatrix} e_{X_v} \\ e_{Y_v} \\ e_{Z_v} \end{bmatrix} \tag{3.5}$$

- Vehicle Reference Frame (x, y, z)

$$E_r = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \tag{3.6}$$

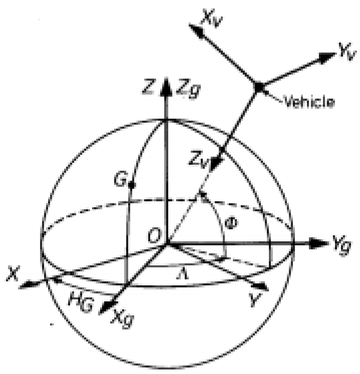

FIGURE 3.10: Reference Frames (Cornelisse et al., 1979)

The relation between those reference frames are:

- Inertial and Rotating-geocentric reference frame

$$E_g = A_g E \tag{3.7}$$

, Where Ag is a rotational matrix given by

$$A_g = \begin{bmatrix} \cos H_G & \sin H_G & 0 \\ -\sin H_G & \cos H_G & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.8}$$

- Rotating geocentric and Vehicle-centered horizontal frame

$$E_v = A_v g E_g \tag{3.9}$$

, Where Ag is a rotational matrix given by

$$A_{vg} = \begin{bmatrix} -\sin\Phi\cos\Lambda & -\sin\Phi\sin\Lambda & \cos\Phi \\ -\sin\Lambda & \cos\Lambda & 0 \\ -\cos\Phi\cos\Lambda & -\cos\Phi\sin\Lambda & -\sin\Phi \end{bmatrix} \tag{3.10}$$

- Vehicle-centered horizontal and Vehicle frame

$$E_r = A_{rv}E_v \tag{3.11}$$

, Where Ag is a rotational matrix given by

$$A_{rv} = \begin{bmatrix} C\theta C\psi & C\theta S\psi & -S\theta \\ -C\phi S\psi + S\phi S\theta C\psi & C\phi C\psi + S\phi S\theta S\psi & S\phi C\theta \\ S\phi S\psi + C\phi S\theta C\psi & -S\phi C\psi + C\phi S\theta S\psi & C\phi C\theta \end{bmatrix} \tag{3.12}$$

Then, assume that Ar is is a transformation matrix which transform unit vectors from Inertial frame into Vehicle frame.

$$E_r = A_r E \tag{3.13}$$

$$A_r = E_r E^T = \begin{bmatrix} e_x e_X & e_x e_Y & e_x e_Z \\ e_y e_X & e_y e_Y & e_y e_Z \\ e_z e_X & e_z e_Y & e_z e_Z \end{bmatrix} \tag{3.14}$$

$$A_r = A_{rv}A_{vg}A_g \tag{3.15}$$

3.4.2 Dynamical Equation

The Equation of Motion of a rocket can be written as

$$M\frac{dV_c m}{dt} = F_S + F_c + F_{rel} \tag{3.16}$$

$$\int_M r(\frac{d\omega}{dt}r)dM + \int_M r\omega(\omega r)dM = M_{cm} + M_c + M_{rel} \tag{3.17}$$

, where
F_S = Translation Force of system S
F_c = Coriolis Force
F_{rel} = Relative Force
M = Total (constant) mass of the system
r = Position vector from the center of mass to the center of Forces

Scalar force equations:

$$\begin{aligned}
m\dot{u} &= m(rv - qw) + F_{x_{ext}} \\
m\dot{v} &= m(pw - ru) + F_{y_{ext}} \\
m\dot{w} &= m(qu - pv) + F_{z_{ext}} \\
I_{xx}\dot{p} &= qr(I_{yy} - I_{zz}) - \frac{dI_{xx}}{dt}p + M_{x_{ext}} \\
I_{yy}\dot{q} &= rp(I_{zz} - I_{xx}) - \frac{dI_{yy}}{dt}q + M_{y_{ext}} \\
I_{zz}\dot{r} &= qr(I_{xx} - I_{yy}) - \frac{dI_{zz}}{dt}r + M_{z_{ext}}
\end{aligned} \tag{3.18}$$

Finally we can derive The Equation of Motion of a rocket into :

$$
\begin{aligned}
M\frac{du}{dt} &= M(vr - wq) + F_x + M_{g_x} + X_a,\\
M\frac{dv}{dt} &= M(wr - uq) + F_y + M_{g_y} + Y_a,\\
M\frac{dw}{dt} &= M(ur - vq) + F_g + M_{g_z} + Z_a,\\
I_{xx}\frac{dp}{dt} &= -p\frac{dI_{xx}}{dt} + rq(I_{yy} - I_{zz}) + mx_e(y_eq + z_er) + L',\\
I_{yy}\frac{dq}{dt} &= -q\frac{dI_{yy}}{dt} + pr(I_{zz} - I_{xx}) + mqx_2^e - x_eF_z + z_eF_x + M',\\
I_{zz}\frac{dr}{dt} &= -p\frac{dI_{zz}}{dt} + pq(I_{xx} - I_{yy}) + mrx_2^e - x_eF_y + y_eF_x + N'.
\end{aligned}
\tag{3.19}
$$

3.5 Datcom to Simulink;

After constructing an input file and rename it to ”for005.dat”, the next step is to executing Missile Datcom application. The application will generate several output files. the primary output files is ”for006.dat”. if the missile datcom found that the input file is flawless, than the total configuration aerodynamics will be provided in this file in summary form. aerodynamic outputs will be written for each mach number specified.

The aerodynamics are summarized as a function of angle of attack. For Static aerodynamic there are 5 types of output given:

- Static Aerodynamic for Body Alone
- Fin 1 Alone Static Aerodynamic
- Fin 2 Alone Static Aerodynamic
- Static Aerodynamic Body-Fin Set 1
- Static Aerodynamic for Body-Fin Set 1 and 2

Aerodynamic data that we will use in the simulation must be taken only from the Static Aerodynamic for Body-Fin Set 1 and 2 output.

Static Aerodynamic Derivative Coefficient.

- C_N - Normal force coefficient
- C_M - Pitching moment coefficient
- C_A - Axial force coefficient
- C_Y - Side force coefficient
- C_n - Yawing moment coefficient
- C_l - Rolling moment coefficient
- C_{N_α} - Normal force coefficient derivative with α
- C_{M_α} - Pitching moment coefficient derivative with α
- C_{Y_β} - Side force coefficient derivative with β
- C_{n_B} - Yawing moment coefficient derivative with β
- C_{l_B} - Rolling moment coefficient derivative with β
- C_L - Lift coefficient
- C_D - Drag coefficient
- C_L/C_D - Lift to drag ratio
- X_{CP} - Center of pressure position, measured from the moment reference

The dynamic derivatives are summarized as a function of angle of attack in the user specified units. All derivatives are in the body axis system, with assumed rates of rotation also in that system. Dynamic Derivative have 3 types of outputs:

- Body Alone Dynamic Derivatives
- Body + 1 Fin Sets Dynamic Derivatives
- Body + 2 Fin Sets Dynamic Derivatives

Aerodynamic data that we will use in the simulation must be taken only from the Body + 2 Fin Sets Dynamic Derivatives.

Dynamic Derivative Coefficient

- C_{N_q} Normal force coefficient due to pitch rate
- C_{M_q} Pitching moment coefficient due to pitch rate
- C_{A_q} Axial force coefficient due to pitch rate
- $C_{N_{\dot{\alpha}}}$ Normal force coefficient due to rate of change of angle of attack
- $C_{M_{\dot{\alpha}}}$ Pitching moment coefficient due to rate of change of angle of attack
- C_{Y_R} Side force coefficient due to yaw rate
- C_{n_r} Yawing moment coefficient due to yaw rate
- C_{l_r} Rolling moment coefficient due to yaw rate
- C_{Y_p} Side force coefficient due to roll rate
- C_{n_p} Yawing moment coefficient due to roll rate
- C_{l_p} Rolling moment coefficient due to roll rate

Next step, in order to use data from Missile Datcom in simulink, we have firstly to import those series of data into Matlab environment. To Execute this task we can use a function in Matlab which is called "Datcomimport". This function allow us to extract all the data from Datcom output file into a group of arrays.

After that we can parse all the imported data according to the data that we need. This parsing step is important because we do not use all the data given by missile datcom in our simulation. As an example, we only use static aerodynamic data for body-fin set 1 and 2 out of the other 4 static aerodynamic data given.

Finally, by parsing the data we can directly write them into Matlab Workspace. Workspace can be described as a temporary storage that can be accessed by all Matlab environment platform like Simulink. So by importing the data into workspace, then we can use the data in Simulink.

3.6 Rocket Simulation in Simulink MATLAB;

The Simulation is made in Simulink, Matlab. It is used to simulate rocket RKX450 behavior and trajectory by calculation aerodynamic data given by Missile Datcom.

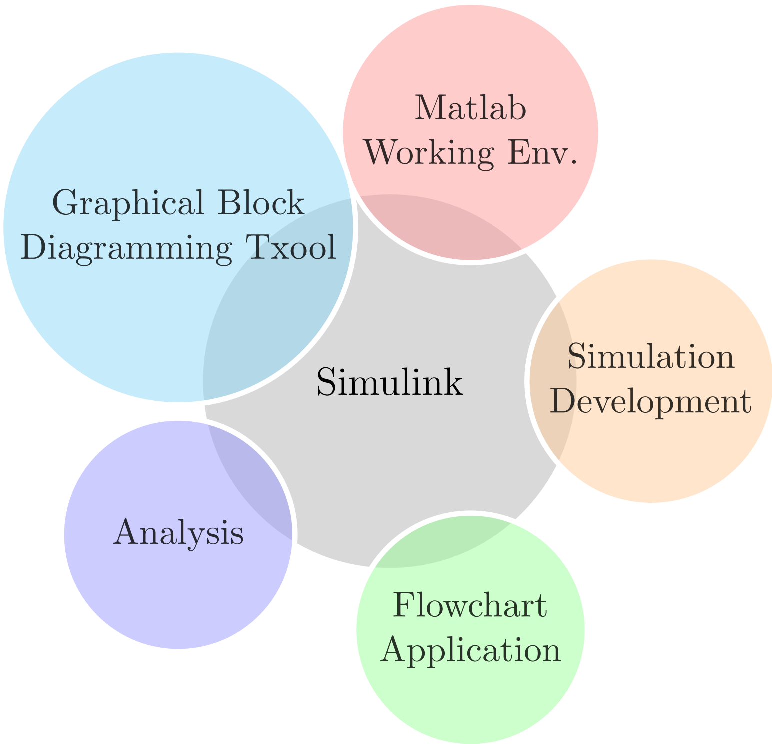

FIGURE 3.11: Overview of simulink

This simulation is made by relying on the block set contained in simulink, namely the 6DOF Block. There are several different 6DOF block sets that are often used as such.

- 6DOF (Euler Angles)
- 6DOF (Quaternion)
- 6DOF ECEF (Quaternion)
- 6DOF Wind (Quaternion)
- 6DOF Wind (Wind Angles)
- Custom Variable Mass 6DOF(s)
- Simple Variable Mass 6DOF(s)

For rocket RKX-450 simulation, author use Custom Variable Mass 6DOF (Quaternion). This block implements a quaternion representation of six-degrees-of-freedom equations of motion of custom variable mass with respect to body axes. It considers the rotation of a body-fixed coordinate frame (Xb, Yb, Zb) about a flat Earth reference frame (Xe, Ye, Ze) (MathWorks, 2022). Quarternion method is preferred because it respect to body axes. Figure below shows the 6DOF Block.

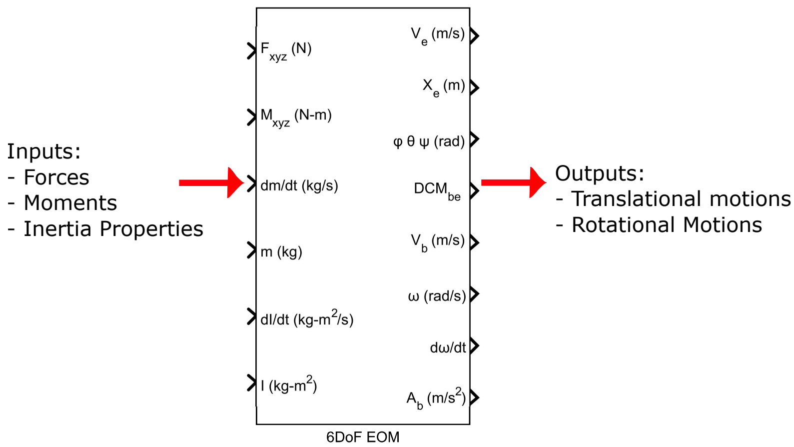

FIGURE 3.12: Custom Variable Mass 6DOF (Quaternion)

Finished simulation model for is shown below.

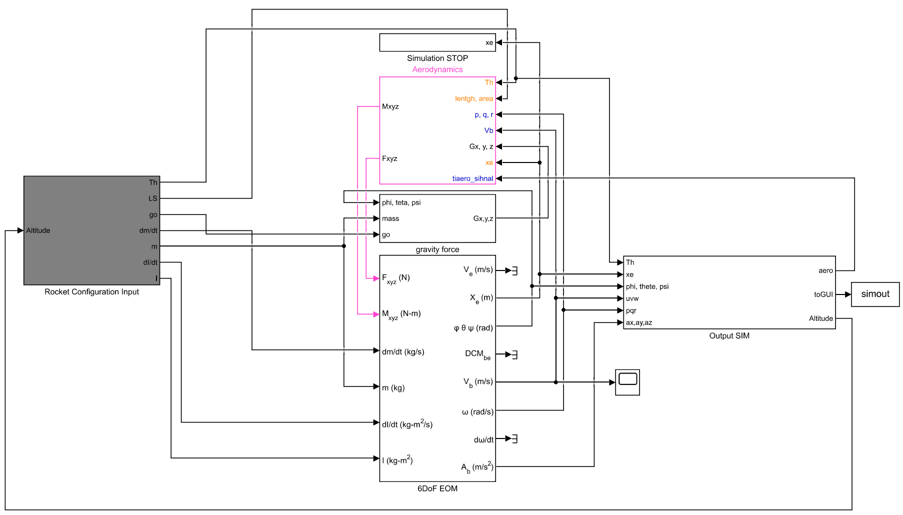

FIGURE 3.13: RKX450 Simulation

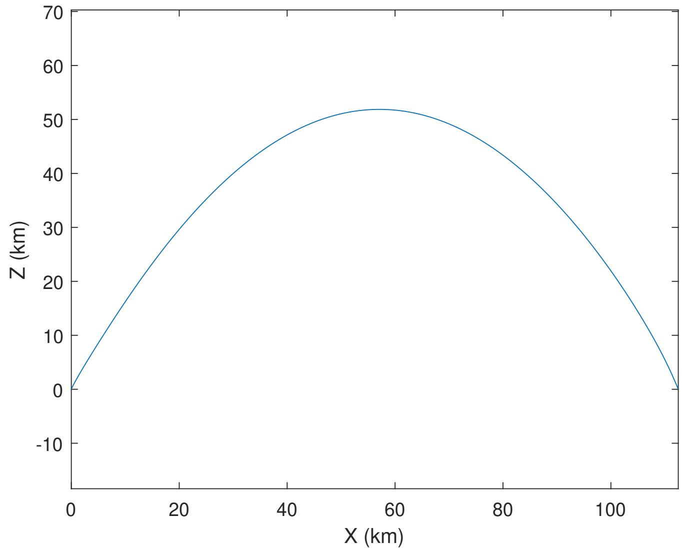

FIGURE 3.14: Nominal Trajectory

3.7 Simulation for Ballistic Trajectory;

Ballistic trajectory shows the rocket path that the rocket going through. in this simulation it is assume that the rocket fly without any disturbance or forces whether from the environment or from the rocket itself. in the other word, the RKX 450 ballistic trajectory simulation is to shown the ideal rocket flight trajectory.

3.8 Introduce some rocket failures into the simulation model;

If a control panel or two stuck at a certain deflection angle the rocket will changes its attitude because of the control panel fault. This condition will resulting in big trajectory deviation. PHIF is a command in datcom to define the position of measured clockwise from top vertical center (looking forward from behind the missile) as shown in Fig. 3.15.

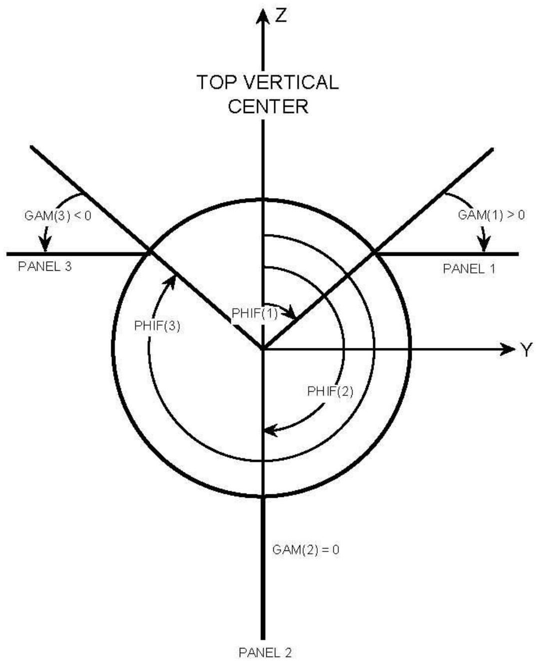

FIGURE 3.15: Control panels position (Auman et al., 2008)

RKX-450 fin numbering defined by datcom are as shown in Fig. 3.16 below.

3.8.1 Rocket Control Panel Stuck in a certain deflection angle

The control panel is an instrument used to control the attitude of the rocket in the air. that way, we can control the direction of motion of the rocket according to its flying mission. but there is a possibility where this control panel malfunctions. Malfunctions that usually occur are situations where the control panel is stuck. The staking of the control panel in can be caused by a number of factors starting from manufacturing errors, external debris or icing that occurred during flight. This is where the problem can arise if the control panel is stuck at a certain angle of attack. this will cause the rocket to continue to rotate or undergo a change in attitude which in turn will change its trajectory.

In this thesis, we will define the condition when rocket control panel(s) stuck at a certain angle as a fault. We set the deviation angle of the control panel to be compared by 3, 5, 7, and 10 degree. Those Fault cases are:

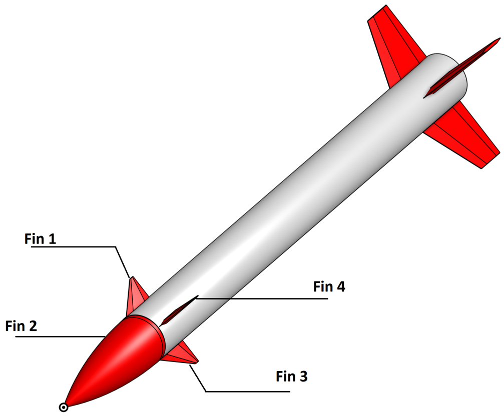

Figure 3.16: Control panels position

- Canard 1 deflected at 1°;
- Canard 1 deflected at 3°;
- Canard 1 deflected at 5°;
- Canard 1 deflected at 7°;
- Canard 1 deflected at 10°.

CHAPTER 4
RESULTS AND DISCUSSIONS

There are 2 kinds of simulations that will be carried out on the RKX-450 rocket. The two simulations are:

- Simulation of RKX-450 Ballistic Trajectory
- Simulation of RKX 450 with failures

As mentioned in section 3.8.1, The fault condition that was simulated in this thesis is a condition where a single fin or control panel is stuck at a deviation when it is deflected.

- Canard 1 deflected at 1°;
- Canard 1 deflected at 3°;
- Canard 1 deflected at 5°;
- Canard 1 deflected at 7°;
- Canard 1 deflected at 10°.

Thus, the result from ballistic trajectory simulation will play a role as parameter control in this thesis. Whereas, all the fault cases will be our variables.

4.1 Simulation of Ballistic Trajectory;

Ballistic trajectory shows the rocket path that the rocket going through. In this simulation it is assume that the rocket fly without any disturbance or forces whether from the environment or from the rocket itself. in the other word, the RKX 450 ballistic trajectory simulation is to shown the ideal rocket flight trajectory.

Ideal ballistic trajectory is shown in the Fig. 4.1 below.

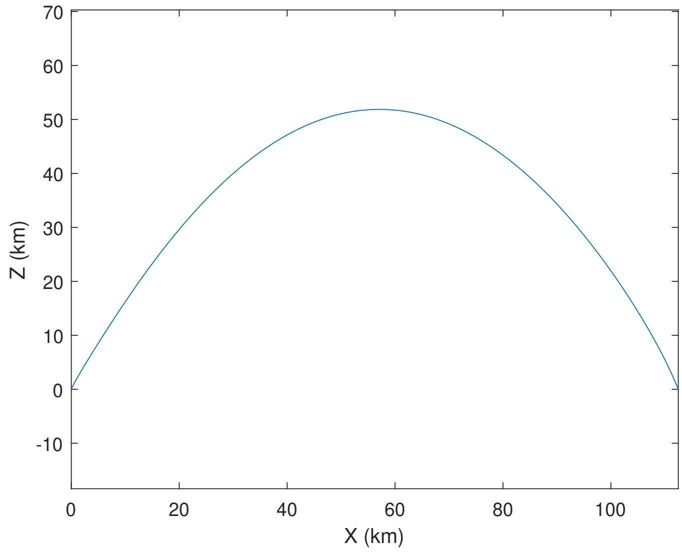

FIGURE 4.1: RKX-450 Nominal Trajectory

From Fig. 4.1 we can see that the rocket flight form a ballistic trajectory shape in X-Z plane. We can say that X axis shows range which is lies on the ground, while Z axis pointing up which define height. The graph shows that from our simulation the rocket flight to 51.87 km height at peak and it goes as far as 112.49 km in range.

4.2 Simulation of rocket dynamics with failures;

In this section, we want to see the rocket trajectory result when failures applied to the rocket. The failure rocket cases are described in section 3.81.

Figure 4.2 shows the comparison of the nominal rocket trajectory with the trajectory of the fault rocket cases that have been made. From this figure we can see that the faulty rocket trajectory shows high instability. This causes the trajectory of the fault rocket to differ greatly from the nominal trajectory of the rocket.

Summarize of Fig. 4.2, with the increase fin deflection angle, the more it will cause the rocket to fly toward the negative X direction. Whereas, the rocket reach highert Z (or height) when the rocket fly to the minimum X direction.

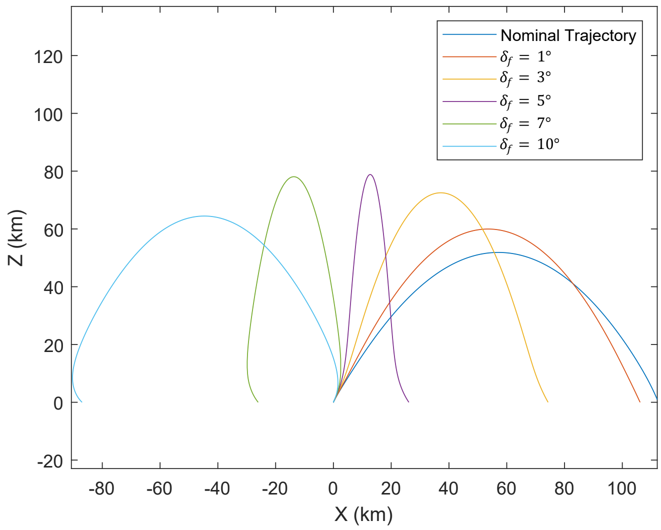

FIGURE 4.2: Nominal Trajectory vs Single Fin Stuck Fault Cases Trajectories

Stuck Angle	Range (km)	Height (km)
0 deg	112.4857	51.8674
1 deg	106.1504	59.9631
3 deg	74.3105	72.5090
5 deg	26.1150	78.8321
7 deg	-26.0423	78.0737
10 deg	-87.0096	64.4569

TABLE 4.1: Fin stuck angle vs Range vs Height

Table below shows the maximum final range and maximum height of rocket RKX-450. The furthest range is 112.49 km reached when the rocket fly without failure ,or fin stuck angle. The highest point is when the rocket fin stuck at 5° angle, where that rocket reached 78.83 km.

Figure 4.3 determines the relative motions of the RKX-450 rocket on the X axis. It can be seen that with every increase in the angle of deflection of the fins, a tendency for the relative motion of the rocket on the X axis to point toward the negative. This tendency is shown by the relative motion line for the fin with the deflection having a smaller gradient with increasing deflection angle. Starting from the fin deflection of 7°, the relative motion gradient on the X axis becomes

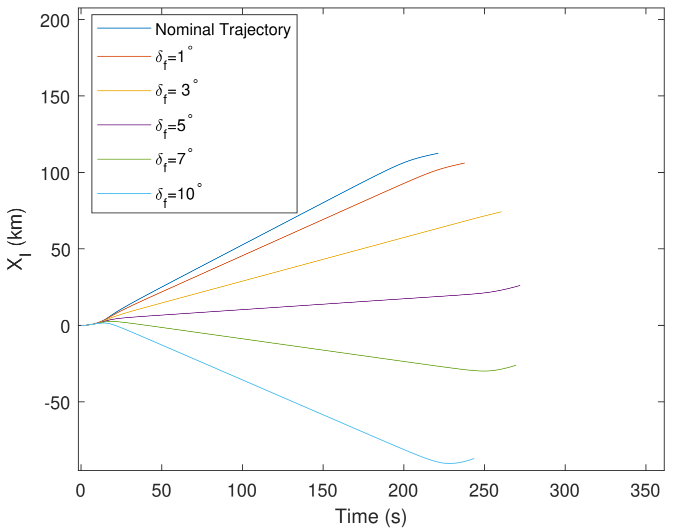

FIGURE 4.3: Relative Motion in X axis

negative. Thus, we can see that the final x values of nominal trajectory reached 112.5 km, while oppose to that the final point of rocket with 10° is -87 km.

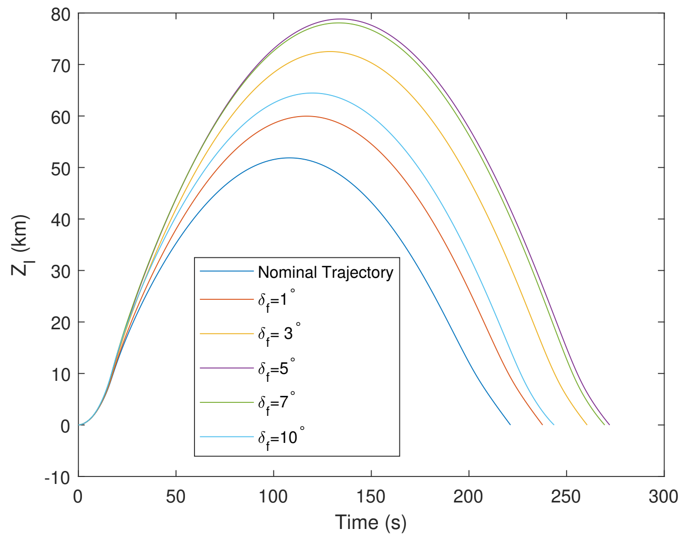

FIGURE 4.4: Relative Motion in Z axis

Figure 4.4 determines the relative motions of the RKX-450 rocket on the Z axis. In this graph, the nominal trajectory has the lowest apogee compared to other cases, which is only up to a height of about 51.8 km. The highest apogee is achieved by a rocket flying with a fin deflection of 5 degrees. The rocket flew to a height of 78.8 km.

The following is a description of each line in Fig. 4.5

- Δx_1 = Deviation of X in Case 1 with respect to Nominal Trajectory's;
- Δx_2 = Deviation of X in Case 2 with respect to Nominal Trajectory's;
- Δx_3 = Deviation of X in Case 3 with respect to Nominal Trajectory's;
- Δx_4 = Deviation of X in Case 4 with respect to Nominal Trajectory's;
- Δx_5 = Deviation of X in Case 5 with respect to Nominal Trajectory's;

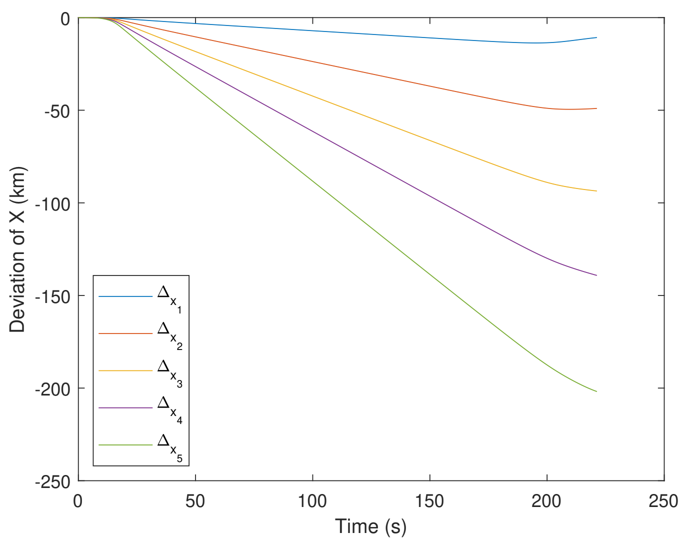

FIGURE 4.5: Deviation of x with respect to nominal trajectory over time

$$\Delta X_{1,2,3,4,5} = X(t)_{case1,2,3,4,5} - X(t)_{NominalTrajectory} \quad (4.1)$$

Figure 4.5 shows the value of deviation X from each case with nominal trajectory. Looking at Fig. 4.5, we can conclude from the deviation of X that value X in each fault case is smaller than the X value in the nominal trajectory, therefore the deviation of the X value in Fig. 4.5 has a negative gradient. Apart from that, this is also evidence that as the fin deflection angle increases, the X value will also be more negative when compared to the nominal trajectory.

The following is a description of each line in Fig. 4.6

- Δz_1 = Deviation of Z in Case 1 with respect to Nominal Trajectory's;
- Δz_2 = Deviation of Z in Case 2 with respect to Nominal Trajectory's;
- Δz_3 = Deviation of Z in Case 3 with respect to Nominal Trajectory's;
- Δz_4 = Deviation of Z in Case 4 with respect to Nominal Trajectory's;
- Δz_5 = Deviation of Z in Case 5 with respect to Nominal Trajectory's;

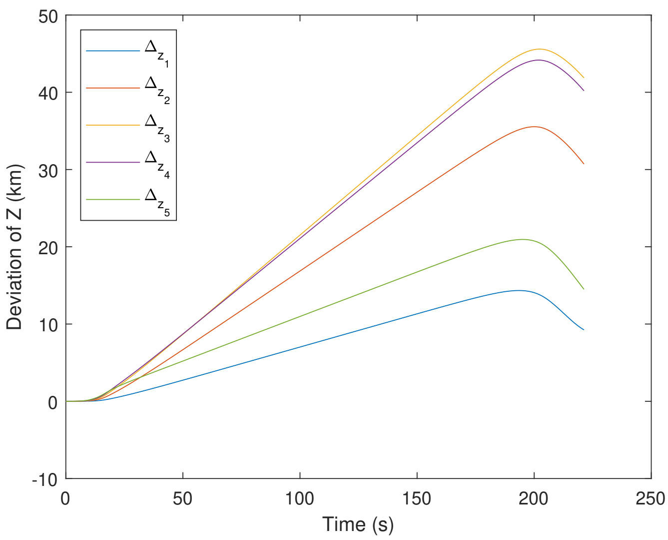

FIGURE 4.6: Deviation of z with respect to nominal trajectory over time

$$\Delta Z_{1,2,3,4,5} = Z(t)_{case1,2,3,4,5} - Z(t)_{NominalTrajectory} \tag{4.2}$$

Figure 4.6 shows the value of deviation Z from each case with nominal trajectory. Looking at Fig. 4.6, we can conclude that the deviation of the Z value in Fig. 4.6 has a Positive gradient. This pattent shows that the Z values in the nominal trajectory is the smallest compared to the fault cases Z. In the ΔZ_3 line we can see that from the maximum deference or deviation between Nominal Trajectory Z value to fault cases Z value can reach 45 km.

4.2.1 Negative Stuck Angle

Later founded that the result given by deflected fin with positive deflection angle are different to the result given by deflected fin with negative deflection angle. As the result, we need to analyze as well the behavior of negative din stuck angle to RKX-450 trajectory. Below is the trajectory comparison of RKX-450 with negative stuck angle.

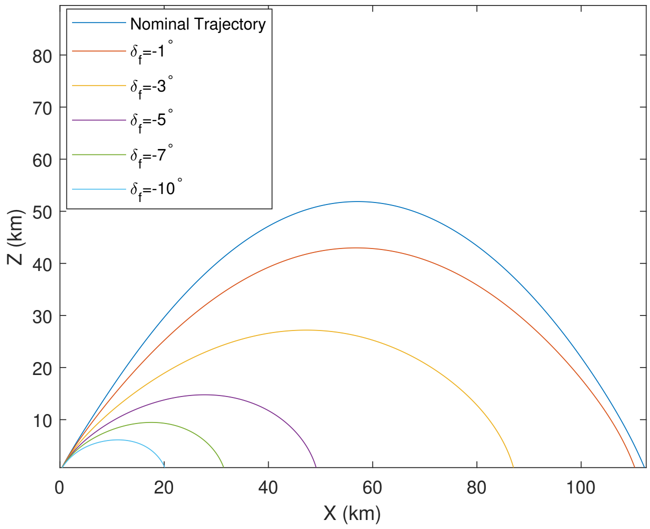

FIGURE 4.7: Negative stuck angle trajectory

Figure 4.7shows that in contrast to the positive deflection angle, the negative fin deflection angle causes the rocket trajectory to become smaller in the X and Z Axis. It can be seen that the more negative the fin deflection angle, the smaller the parabolic motion of the rocket. But different from before, there is no rocket movement that leads to the negative X axis.

Deviation if the stuck angle is negative is shown in figures below.

$$\Delta X_{1,-1,-2,-3,-4,-5} = X(t)_{case1,-1,-2,-3,-4,-5} - X(t)_{NominalTrajectory} \tag{4.3}$$

$$\Delta Z_{1,-1,-2,-3,-4,-5} = Z(t)_{case1,-1,-2,-3,-4,-5} - Z(t)_{NominalTrajectory} \tag{4.4}$$

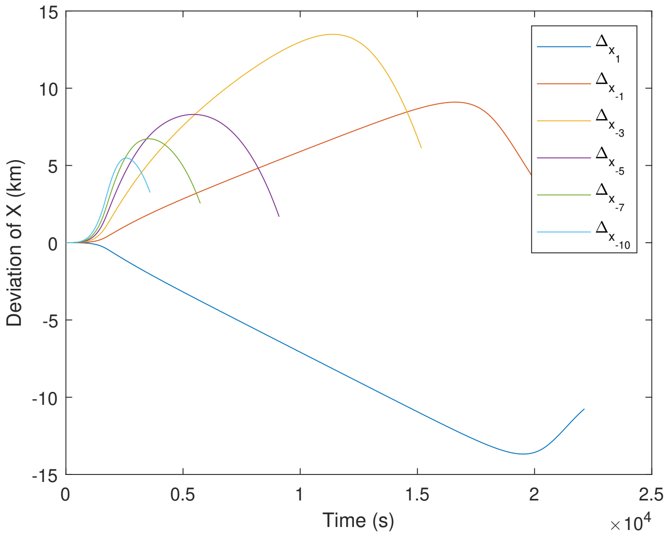

FIGURE 4.8: -1 deg vs 1 deg Deviation of X

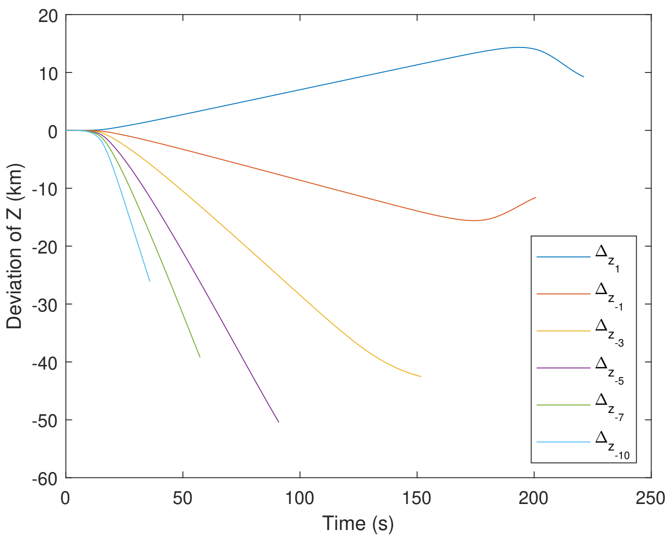

FIGURE 4.9: -1 deg vs 1 deg Deviation of Z

Figure 4.8 and 4.9 shows the difference in deviation between the positive stuck fin angle and negative stuck fin angle based on the nominal trajectory. The most visible difference is the flight time of each case. From a deflection angle of 1 degree to a deflection angle of -10 degrees, the smaller the deflection angle, the shorter the flight time of the rocket. The short flight time of this rocket is because if we look back at Fig. 4.7, the rocket does not have a trajectory that is as far as the nominal trajectory.

4.3 Analysis and Discussion

This rocket trajectory analysis test assesses how the rocket flies when launched with various combinations of canard deflection angles. This describes the condition of the rocket failure when the canard cannot be controlled or jammed.

From all the results, author then do some analysis.

- Stuck-deflected angle make a change in rocket RKX-450 flight trajectory;
- From Fig. 4.2 we can clearly see that the larger the angle of deflection of the fins, the more it will cause the rocket to fly toward the negative X direction;
- Point 2 is then confirmed by looking at Fig. 4.3 which shows the deviation of the X value against the nominal trajectory which leads to a negative direction when the stuck fin angle gets bigger;
- From Table 4.1 we can see that the rocket reach higher Z (height) when the rocket is flying to a minimum X (range) value;
- It turns out that when the angle of the stuck fin is negative it produces different results from the angle of the stuck fin is positive.

The results of this simulation test show that a deflection in the canard will cause the rocket to fly with a trajectory that is not as predicted. So in this simulation test we can conclude that the rocket fault causes instability in the rocket.

CHAPTER 5
SUMMARY, CONCLUSION, RECOMMENDATION

5.1 Summary

Every rocket development consumes a lot of time, effort, and cost. Besides, with current technology in Indonesia, a rocket can only be launched once. This means if there is failure or damage that interferes with the mission of the rocket either during launch or after being in flight, relaunching the new rocket would be very prohibitive. This, of course, will provide an enormous loss in terms of time and cost to the company. Therefore, in designing a rocket, we want to increase the success rate of the rocket in completing its mission.

Lapan's RKX-450 rocket will be the rocket model for this thesis. The objective of the thesis is to analyze the effect caused by single stuck fin to RKX-450 free flight.

The rocket is remodeled using Onshape, a 3D drawing application to confirm the value of inertia as well as the center of gravity of the rocket. Then the aerodynamic derivatives are generated from Missile DATCOM. Those become the basis parameters for the simulation. The numerical calculation and simulation are done in MATLAB and Simulink.

Each fault cases that is mentioned in this thesis are all have their own aerodynamic derivatives data from Missile DATCOM. Hence, the simulation used for every cases are remain the same. The simulation results are visualized using MATLAB.

The analysis is carried out by comparing the trajectory obtained from the simulation of the ideal rocket which we call here the Nominal Trajectory, with the trajectory of the rocket rocket that failed. The failure in question is in the form of canard deflection.

5.2 Conclusion

Comparing and analyzing Nominal Trajectory with all fault rocket trajectory, we get the conclusion that it is proven that continuous canard deflection will cause instability in the rocket. This instability results in a different flying direction from the Nominal Trajectory which is an ideal prediction. As a conclusion for all the results:

- Stuck-deflected fin in a rocket causing the rocket to flight off-track.
- Larger angle of deflection of the fins, causing the rocket to fly toward the negative X direction more. It can be seen in Fig. 4.3 that with every increase in the angle of deflection of the fins, a tendency for the relative motion of the rocket on the X axis to point toward the negative. This tendency is shown by the relative motion line for the fin with the deflection having a smaller gradient with increasing deflection angle. Starting from the fin deflection of 7°, the relative motion gradient on the X axis becomes negative. Thus, we can see that the final x values of nominal trajectory reached 112.5 km, while oppose to that the final point of rocket with 10° is -87 km.
- Higher Z (height) reached when the rocket is flying to a minimum X. In Figure 4.4, the nominal trajectory has the lowest apogee compared to other cases, which is only up to a height of about 51.8 km. The highest apogee is achieved by a rocket flying with a fin deflection of 5 degrees. The rocket flew to a height of 78.8 km.
- Negative stuck fin angle it produces different results from the the positive stuck fin angle. Figure 4.7 shows that in contrast to the positive deflection angle, the negative fin deflection angle causes the rocket trajectory to become smaller in the X and Z Axis. It can be seen that the more negative the fin deflection angle, the smaller the parabolic motion of the rocket. But different from before, there is no rocket movement that leads to the negative X axis.

5.3 Recommendation

Firstly, Author want to recommend for any future research about this topic to use 6DOF blockset in Simulink to simulate aircraft or rocket flight. Simulink will be very helpful for students or researchers because it is equipped with various block sets that can simplify calculations in simulations. In Simulink there is also a feature that the author has not applied in this research, namely integration with the flight gear application. with these two applications (Simulink and Flight Gear) we can make our simulations equipped with better visuals.

The result shows us that the deflected fin will change the rocket flight path. Hence, it is recommended to develop a control system for the rocket. The rocket's control panel is used to keep the spacecraft's attitude in the air. In such cases, the panel can get stuck. This condition can alter the course of the flight by taking a different approach. That is the basis for doing this research to see the effects of canard deflection on the trajectory rocket.

References

Auman, L., Doyle, J., Rosema, C., & Blake, W. (2008, August). MISSILE DATCOM User's Manual - 2008 Revision. , 114.

Cornelisse, J. W., Schöyer, H. F. R., & Wakker, K. F. (1979). *Rocket propulsion and spaceflight dynamics*. London ; San Francisco: Pitman.

Elisabeth, A. (2018). Pengembangan Teknologi Roket: Urgensi Dan Tantangan Bagi Indonesia. In (pp. 10–16). Jakarta, Indonesia. Retrieved 2022-02-04, from `https://puskkpa.lapan.go.id/files_arsip/Adriana_Pengembangan_Teknologi_2017.pdf` doi: 10.30536/p.sinaskpa.ii.2

Kwon, Y.-H. (1998). *Inertia Tensor.* Retrieved 2022-02-04, from `http://www.kwon3d.com/theory/moi/iten.html`

LAPAN. (2014). *Pusat Teknologi Roket.* Retrieved 2022-02-04, from `https://pustekroket.lapan.go.id/index.php/subblog/pages/2014/17/Fokus-Pengembangan-Roadmap-Roket-Peluncur-Satelit`

MathWorks. (2022). *Implement Euler angle representation of six-degrees-of-freedom equations of motion of custom variable mass - Simulink.* Retrieved 2022-02-04, from `https://www.mathworks.com/help/aeroblks/customvariablemass6dofeulerangles.html`

Media, K. C. (2020, December). *LAPAN Baru Saja Luncurkan Roket RX450-5, Apa Tujuannya? Halaman all.* Retrieved 2022-02-04, from `https://www.kompas.com/sains/read/2020/12/05/090600523/lapan-baru-saja-luncurkan-roket-rx450-5-apa-tujuannya-`

MSFC, J. W. . (2015, May). *What Is a Rocket?* Retrieved 2022-02-04, from `http://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-a-rocket-k4.html`

Nations, U. (2018). *Space Technology and the Implementation of the 2030 Agenda.* Retrieved 2022-02-04, from `https://www.un.org/en/chronicle/article/space-technology-and-implementation-2030-agenda`

Origin, B. (2021). *Home.* Retrieved 2022-02-04, from https://www.blueorigin.com/

SpaceX. (2022). *SpaceX.* Retrieved 2022-02-04, from http://www.spacex.com

Appendices

Turnitin Report

18		Internet Source		<1%
19	David M. Henderson. "Applied Cartesian Tensors for Aerospace Simulations", American Institute of Aeronautics and Astronautics (AIAA), 2006	Publication		<1%
20	Lael vonEggers Rudd, Mark J. Lewis. "Comparison of Shock Calculation Methods", Journal of Aircraft, 1998	Publication		<1%
21	es.mathworks.com	Internet Source		<1%
22	Submitted to Blackpool and The Fylde College, Lancashire	Student Paper		<1%
23	Submitted to University of Kent at Canterbury	Student Paper		<1%
24	Submitted to American University of Bahrain	Student Paper		<1%
25	link.umsl.edu	Internet Source		<1%
26	Submitted to St Augustine's College	Student Paper		<1%
27	Submitted to UC, Boulder	Student Paper		<1%

28	mobt3ath.com Internet Source	<1 %
29	Submitted to KDU College Sdn Bhd Student Paper	<1 %
30	Submitted to Middle East Technical University Student Paper	<1 %
31	Submitted to Ohio University Student Paper	<1 %
32	Submitted to University of London External System Student Paper	<1 %
33	Submitted to University of Teesside Student Paper	<1 %
34	docplayer.net Internet Source	<1 %
35	eprints.usm.my Internet Source	<1 %
36	www.earth-prints.org Internet Source	<1 %
37	reshebnikshkola.ru Internet Source	<1 %
38	Brian Fabien. "Chapter 3 Lagrange's Equation of Motion", Springer Science and Business Media LLC, 2009 Publication	<1 %

39	eprints.uwe.ac.uk Internet Source	<1 %
40	ir.lib.uwo.ca Internet Source	<1 %
41	www.komnasperempuan.go.id Internet Source	<1 %
42	Benyamin Ebrahimi, Fahimeh Barzamini. "Aircraft System Identification Using Parametric Approaches and Intelligent Modeling", 2021 IEEE Aerospace Conference (50100), 2021 Publication	<1 %
43	Submitted to Rutgers University, Newark Student Paper	<1 %
44	Submitted to University of Durham Student Paper	<1 %
45	docshare.tips Internet Source	<1 %
46	scholar.uwindsor.ca Internet Source	<1 %
47	www.nrc.gov Internet Source	<1 %
48	"Selected papers from the 2nd International Symposium on UAVs, Reno, Nevada, U.S.A.	<1 %

June 8–10, 2009", Springer Science and Business Media LLC, 2010
Publication

49	etheses.dur.ac.uk Internet Source	<1 %

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	On		

Curriculum Vitae

	Basic Information
Name	Daniel Alpine
Place of Birth	Jakarta
Date of Birth	09, 09, 1999
Address	Jl. Melati II NO. 19B, Kapuk, Cengkareng
Year	**Education**
2017 - present	International University Liaison Indonesia
2015 - 2017	Bunda Hati Kudus Senior High school
2013 - 2015	Seraphine B.U. Junior High school
2008 - 2013	Seraphine B.U. Elementary School